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ORIGINAL PAPER

REGIONAL WATER STORAGE CHANGES IN THE YANGTZE RIVER DELTA OVER THE PAST 20 YEARS

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ABSTRACT

Accurately estimating and interpreting the spatiotemporal changes of regional water storage under climate warming are of great value for formulating regional adaptive water management strategies. The Yangtze River Delta, with about 4 % of China's national land area (including Shanghai, Jiangsu, Zhejiang, and Anhui provinces), generates nearly one-fourth of the country's total economic gross domestic product. In this study, we estimate terrestrial water storage (TWS) and groundwater storage (GWS) changes in the Yangtze River Delta from April 2002 to January 2025 by integrating GRACE/GRACE-FO solutions, GLDAS land surface model outputs, groundwater level observations, coal mining records, and provincial water resource bulletins. The results show that GWS variations dominated regional TWS changes, with the linear trends of 0.68±0.12 mm/year (GWS) and 0.88±0.17 mm/year (TWS) after coal mining correction. Marked spatial heterogeneity exists: Shanghai and Zhejiang show strong positive TWS trends (4.89±0.16 and 3.68±0.22 mm/year, respectively), driven by groundwater recovery under strict abstraction controls and artificial recharge; conversely, Jiangsu and Anhui exhibit slight TWS declines, attributed to non-groundwater loss and soil moisture reduction, respectively, with coal mining contributing to local depletion. These subregional values, particularly those for Shanghai, should be interpreted as indicative GRACE-footprint-scale estimates rather than locally precise values. Groundwater level data from monitoring wells corroborate these patterns, with significant increases in Shanghai and Zhejiang and decreases in northern Anhui and Jiangsu.

1. INTRODUCTION

Global warming has actually accelerated global and regional water cycle and caused the frequent occurrence of extreme weather events (Harder et al., 2015; Ummenhofer and Meehl, 2017; Yang et al., 2021). Terrestrial water storage (TWS), as a comprehensive reflection of precipitation, evapotranspiration, runoff, and other processes, can be divided into five components including surface water storage (SWS), soil moisture storage (SMS), snow water storage (SNWS) and canopy water storage (CWS) and groundwater storage (GWS) (Humphrey et al., 2023). Before April 2002, TWS changes were usually indirectly estimated using the water balance equation, however, required high accuracy of input data (Petch et al., 2023) The successful launch of GRACE satellite in 2002 (Tapley et al., 2004, 2019) and its follow-on mission GRACE-FO (Landerer et al., 2020) provided a new way to directly monitor and estimate the TWS changes (Mo et al., 2022; Wang et al., 2024). Considering that the SMS, SNWS, and CWS changes normally be estimated directly using GLDAS data, therefore one can derive GWS changes by subtracting SMS, SNWS, and CWS components from TWS changes (Chao et al., 2020; Feng et al., 2022; Li et al., 2024; Wang et al., 2024), which can be further validated with the available limited groundwater monitoring wells (Feng et al., 2022; Huan et al., 2023; Xie et al., 2018; Liu, 2022).

Since 2002, numerous studies have investigated TWS and GWS changes at global and regional scales by employing multisource monitoring techniques and datasets, such as GRACE/GRACE-FO, GLDAS land surface model outputs, and groundwater level well data. In the early stage, Strassberg et al. (2007) firstly successfully captured irrigation-induced seasonal groundwater changes in the U.S. Great Plains that were significantly correlated with well log records, thereby validating the feasibility of GRACE for groundwater monitoring in semi-arid regions. Rodell et al. (2007) further confirmed in Mississippi River Basin that the larger the basin, the higher the agreement between GRACE-derived groundwater changes and measured water well levels. With the accumulation of data series, a large amount of studies found that some typical regions showed a significant declined TWS change rate mainly due to the groundwater loss, such as Northwestern India (Rodell

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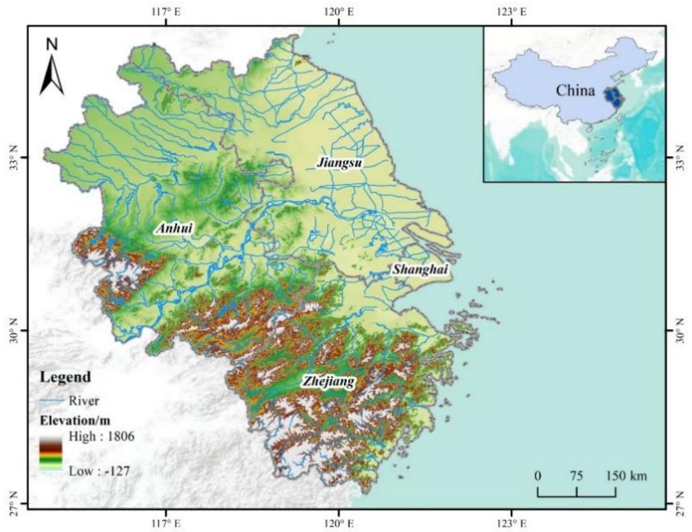

Fig. 1 Study region of the Yangtze River Delta.

et al., 2009), U.S. Central Valley (Scanlon et al., 2012), Middle East (Voss et al., 2013), North China Plain (Feng et al., 2013, 2022) and China Loess Plateau (Xie et al., 2018; Zhang et al., 2025), etc. Xie et al. (2018) revealed that groundwater on the Loess Plateau decreased at −0.65 cm/year, with rates reaching as high as −1.5 cm/year in the eastern mining areas, primarily due to unsustainable coal mining. Agricultural irrigation and industrial extraction are the main drivers of groundwater loss in these regions. These studies actually confirmed the potential of GRACE for groundwater assessment in data-sparse regions (Feng et al., 2013; Rodell et al., 2009; Voss et al., 2013). It should be noted that mass loss due to coal mining should be deducted from TWS change when indirectly estimating GWS change.

The Yangtze River Delta (YRD) (Fig. 1), one of China's most economically important regions, with just 4 % of national land area, however, contributes 25 % of China total economic GDP, which plays a great and valuable role in national development. Rapid urbanization has intensified hydrological and ecological conflicts, putting growing pressure on water resources. Therefore, it is valuable to accurately estimate the TWS and GWS change, and interpreting the potential causes is essential for assessing water resource capacity, optimizing allocation, and managing hydrological disasters. Some previous publications mainly focused on studying the TWS and GWS changes in Yangtze River Basin (Long et al., 2015; Chen et al., 2021; Wang et al., 2025), however, few studies comprehensively investigated the facts and causes of water storage change in Yangtze River Delta. Tao et al. (2021) combined the GRACE and GLDAS land surface model outputs to investigate the groundwater storage changes in Anhui province, found that there existed a declined trend for the period from April 2002 to June 2017, similar for the Jiangsu province (Gao et al., 2024). To sum up, we comprehensively analyze the water storage changes in the Yangtze River Delta using multisource datasets for the period April 2002 to January 2025. Because the spatial resolution of GRACE/GRACE-FO is about 300 km, it remains difficult to accurately resolve water storage changes in Shanghai; therefore, the city-level results are interpreted as indicative trends within the GRACE footprint rather than precise local estimates.

2. ADOPTED DATASETS, AND PROCESSING METHODS

2.1. *GRACE AND GRACE-FO DATA*

Three GRACE/GRACE-FO mascon solutions from CSR (Center for Space Research, DOI: 10.15781/cgq9-nh24, Save et al., 2016; Save, 2020), JPL (Jet Propulsion Laboratory, https://podaactools.jpl.nasa.gov/drive/files/all Data/tellus/L3/mascon/RL06, Watkins et al., 2015; Wiese et al., 2016), and GSFC (Goddard Space Flight Center, https://earth.gsfc.nasa.gov/geo/data/grace-mascons, Loomis et al., 2019) were used to estimate the TWS changes in the Yangtze River Delta from April 2002 to January 2025. Note that for all three mascon solutions, the C_{20} and C_{30} coefficients are replaced with the solutions from Satellite Laser Ranging via Technical Note 14 (Loomis et al., 2020). The degree-1 coefficients (Geocenter) are added back with Technical Note 13 (Landerer, 2019) using the methods from Sun et al., (2016); Swenson, Chambers, and Wahr (2008). A glacial isostatic adjustment (GIA) correction has been applied based on the ICE6G-D model from Peltier et al. (2018).

2.2. *GLDAS MODELS*

To indirectly derive GWS change by subtracting the non-GWS components from GRACE-based TWS changes, GLDAS land surface model outputs driven

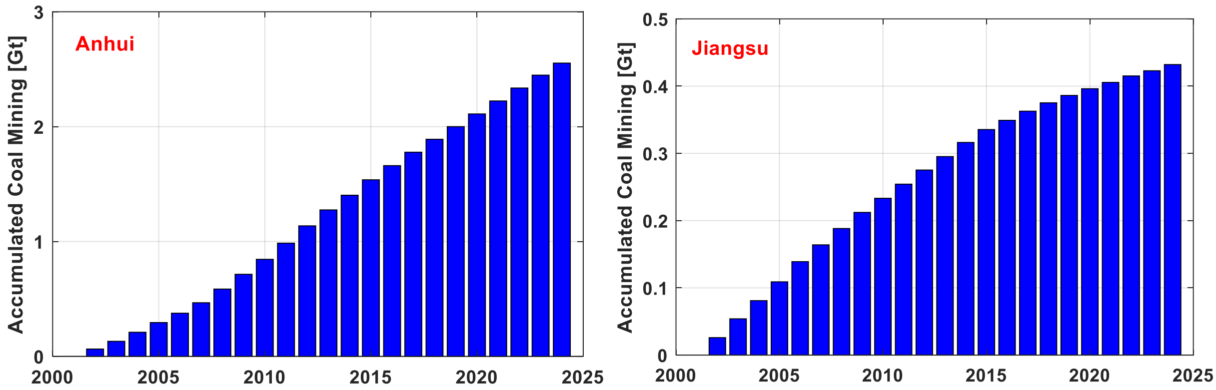

Fig. 2 The accumulated coal mining outputs of Jiangsu and Anhui Provinces for the period of 2002–2024.

by GLDAS forcing data were commonly used to estimate variations in soil moisture, snow water, and canopy water storage. In this study, we adopted monthly GLDAS Noah model outputs (Beaudoing and Rodell, 2020a) and VIC model outputs (Beaudoing and Rodell, 2020b) with 1°×1° spatial resolution from April 2002 to January 2025, which can be downloaded from the website https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1/summary?keywords=GLDAS, without including the groundwater component. Because consistent monthly surface water storage observations for lakes, rivers, and reservoirs across China are not available for the full study period, explicit surface water storage variations were not removed in this study; this omission may introduce systematic errors, particularly around large lakes such as Taihu and Chaohu and reservoir-dense areas. To clearly define and distinguish the boundaries, all datasets were interpolated to a 0.25°×0.25° grid size.

2.3. GROUNDWATER LEVEL WELL OBSERVATIONS

To further evaluate the reliability of the inferred GWS changes in the YRD, groundwater level observations from nine monitoring wells including three Shanghai wells (Chongming, Fengcheng High School, and Shanghai University), two Zhejiang wells (Tongxiang and Longyou), two Anhui wells (Wuhe and Chaohu), and two Jiangsu wells (Guanyun and Nantong) were adopted. Because the well records cover shorter and inconsistent periods than the full GRACE/GRACE-FO record (April 2002-January 2025), they are used only as a qualitative consistency check of the sign and general magnitude of trends, not for exact intercomparison or quantitative validation.

2.4. OTHER RESOURCE DATASETS

The annual water resource data for precipitation, surface water, and groundwater (2002–2024) were sourced from the Water Resources Bulletin of the Yangtze River Delta (covering Shanghai, Zhejiang, Jiangsu, and Anhui). A comprehensive investigation revealed that within this region, only Jiangsu and Anhui Provinces host coal mining industries, which are primarily concentrated in northern Anhui (Suzhou, Huaibei, Bozhou, Fuyang, Huainan, and Bengbu) and Jiangsu (Xuzhou). Annual coal mining production data for Jiangsu and Anhui Provinces (2002–2024), solely comprising the Yangtze River Delta's coal mining activity, were compiled from provincial statistical yearbooks, as illustrated in Figure 2.

Coal-mining correction was converted to equivalent water height (EWH) as $\Delta\mathrm{EWH}_{\mathrm{coal}}$,

$$\Delta\mathrm{EWH}_{\mathrm{coal}} = M_{coal}/(\rho_w S) \quad (1)$$

where, M_{coal} is the cumulative annual coal mining amount, ρ_w is the density of water 1000 kg/m^3, and S is the latitude-weighted area of the study region. We assume that the mined coal represents removed subsurface mass; because consistent information on mining depth and associated formation-water volume is unavailable, no additional depth-dependent void-water term was introduced. Annual production from the listed prefectures was summed by province and uniformly averaged over each corresponding provincial area, then converted to a linear EWH trend over 2002–2024.

3. YRD WATER STORAGE CHANGE

3.1. TEMPORAL ANALYSIS

Three GRACE/GRACE-FO mascon solutions were adopted to estimate TWS changes in the Yangtze River Delta. Owing to 33 missing months in these solutions from April 2002 to January 2025—including an 11-month gap between two GRACE missions—the corresponding months were excluded from the GLDAS data. The YRD regional mean TWS change series are shown in Figure 3, revealing the consistency between the mascon solutions (CSR, JPL, and GSFC) and the GLDAS land surface model outputs despite amplitude differences attributable to distinct processing strategies. For all TWS estimates and their

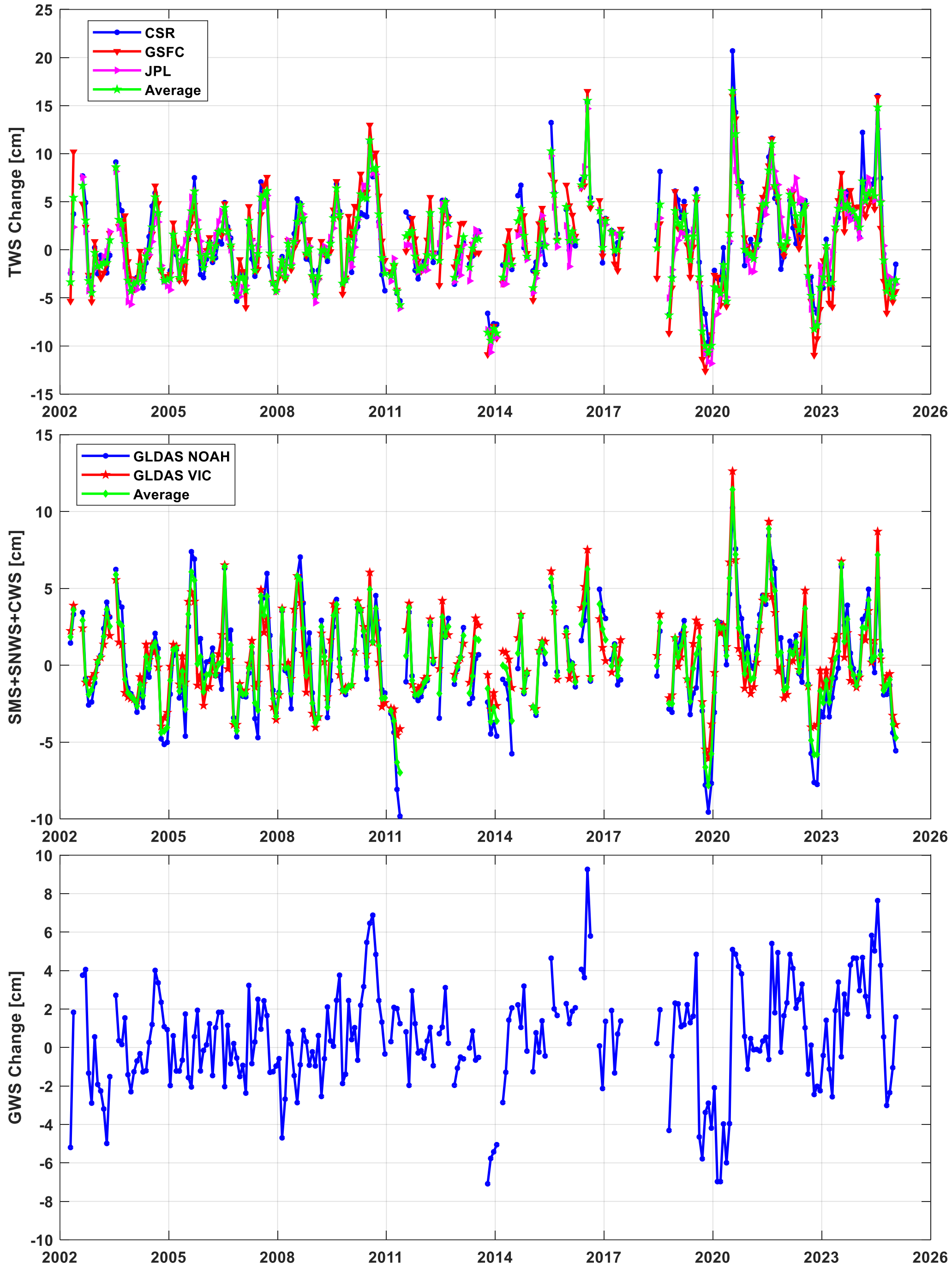

Fig. 3 Changes in TWS and its components in the YRD (2002.4–2025.1).

components inferred from the GRACE/GRACE-FO mascon solutions and GLDAS land surface model outputs, annual/semiannual amplitudes and linear trends were coestimated using the least-squares fitting method, with uncertainties expressed as 1-sigma errors (Table 1). After correcting for the impacts of coal mining (-0.04±0.01 mm/year), the GRACE/GRACE-FO solutions yielded a mean TWS change rate of 0.88±0.17 mm/year, which differed from the GLDAS-derived rate of 0.20±0.12 mm/year. This resulted in an inferred GWS change rate of 0.68±0.12 mm/year, demonstrating that GWS dynamics dominate TWS variations in the Yangtze River Delta Basin.

However, the relatively coarse spatial resolution of GRACE/GRACE-FO (~300 km) limits fine-scale analysis, particularly for Shanghai. Thus, the provincial-level results should be interpreted as indicative trends within the GRACE footprint rather than precise local estimates. The estimated water storage changes for the four regions are shown in Figure 4, with statistical summaries provided in

Table 1 Statistical results of annual and semiannual amplitudes and linear trends of regional mean water storage changes in the YRD (2002.4–2025.1). EWH denotes equivalent water height.

	Index	Annual Amplitude [cm] Phase [deg]	Semiannual Amplitude [cm] Phase [deg]	Linear Trend [mm/year]
TWS GRACE/GRACE-FO	CSR	[3.38±0.31] [193.2±5.2]	[2.56±0.31] [74.9±6.9]	1.10±0.16
	JPL	[3.33±0.32] [184.8±5.5]	[1.29±0.32] [79.6±14.3]	0.92±0.16
	GSFC	[2.66±0.38] [188.0±8.3]	[1.90±0.38] [74.1±11.6]	0.50±0.20
	Average	[3.12±0.32] [188.7±6.0]	[1.92±0.32] [75.7±9.7]	0.84±0.17
SMS+SNWS+CWS GLDAS	NOAH	[1.63±0.26] [193.2±9.2]	[1.67±0.26] [96.4±9.0]	0.10±0.14
	VIC	[2.29±0.19] [174.4±4.7]	[1.16±0.19] [60.5±9.4]	0.29±0.10
	Average	[1.94±0.22] [182.2±6.5]	[1.34±0.22] [81.8±9.4]	0.20±0.12
Coal mining (EWH)		——	——	-0.04±0.01
GWS: GRACE/GRACE-FO - GLDAS		[1.21±0.23] [199.2±10.8]	[0.60±0.23] [61.8±22.0]	0.68±0.12

Table 2 Statistical results of annual/semiannual amplitudes and linear trends of water storage changes for the four YRD sub-regions (2002.4–2025.1). EWH denotes equivalent water height.

Basin	Type	Annual Amplitude [cm] Phase [deg]	Semiannual Amplitude [cm] Phase [deg]	Linear Trend [mm/year]
Jiangsu	TWS: GRACE/GRACE-FO	[1.48±0.30] [246.1±11.7]	[2.00±0.32] [88.7±8.7]	-0.45±0.16
	SMS+SNWS+CWS: GLDAS	[1.94±0.25] [237.8±7.5]	[2.22±0.25] [92.3±6.5]	0.66±0.13
	Coal mining (EWH)	——	——	-0.17±0.01
	GWS: GRACE/GRACE-FO - GLDAS	[0.52±0.26] [33.8±22.4]	[0.26±0.26] [304.3±58.9]	-0.94±0.14
Anhui	TWS: GRACE/GRACE-FO	[4.06±0.37] [193.4±5.2]	[2.19±0.37] [74.1±9.7]	-0.48±0.19
	SMS+SNWS+CWS: GLDAS	[2.07±0.27] [192.8±7.4]	[1.55±0.27] [83.1±9.9]	-0.28±0.14
	Coal mining (EWH)	——	——	-0.85±0.01
	GWS: GRACE/GRACE-FO - GLDAS	[2.00±0.25] [194.1±7.1]	[0.70±0.25] [53.9±21.3]	+0.65±0.13
Zhejiang	TWS: GRACE/GRACE-FO	[4.94±0.42] [164.5±4.9]	[1.63±0.42] [58.9±14.8]	3.68±0.22
	SMS+SNWS+CWS: GLDAS	[3.15±0.24] [146.2±4.3]	[0.53±0.24] [38.0±24.5]	0.42±0.12
	GWS: GRACE/GRACE-FO - GLDAS	[2.19±0.30] [191.3±7.9]	[1.15±0.30] [68.3±15.1]	3.26±0.16
Shanghai	TWS: GRACE/GRACE-FO	[3.08±0.31] [274.2±5.7]	[1.64±0.30] [116.9±10.7]	4.89±0.16
	SMS+SNWS+CWS: GLDAS	[1.86±0.24] [168.2±7.3]	[0.97±0.24] [64.7±13.9]	0.52±0.12
	GWS: GRACE/GRACE-FO - GLDAS	[4.01±0.30] [300.6±4.2]	[1.30±0.30] [153.4±13.0]	4.37±0.15

Table 2. The results indicate that Anhui and Jiangsu Provinces experienced slight TWS losses, with mean TWS change rates of –0.48±0.19 mm/year and – 0.45±0.16 mm/year, respectively. After removing the GLDAS-derived SMS+SNWS+CWS components and applying coal-mining corrections (- 0.85±0.01 mm/year for Anhui and - 0.17±0.01 mm/year for Jiangsu), the inferred GWS trend in Anhui becomes positive (+0.65±0.13 mm/year), whereas Jiangsu remains negative (-0.94±0.14 mm/year). Thus, the negative TWS trend in Anhui is mainly associated with declines in non-groundwater components and mining-related mass loss rather than a net GWS decrease. By contrast, TWS trends in Shanghai and Zhejiang were positive, at 4.89±0.16 mm/year and 3.68±0.22 mm/year, respectively, alongside GWS change rates of 4.37±0.15 mm/year and 3.26±0.16 mm/year, respectively; these values reflect groundwater recovery over the past two decades, with GWS changes dominating the long-term TWS trend. They should be interpreted as GRACE-footprint-scale estimates, especially in Shanghai. This study aims to support a high-resolution understanding of groundwater dynamics and to inform targeted, sustainable water management strategies.

3.2. SPATIAL ANALYSIS

To further analyze the spatial distributions, the linear trends and annual/semiannual amplitudes of TWS and GWS changes were examined (Fig. 5). The results reveal pronounced negative TWS trends in northern regions, with GWS trends exhibiting similar spatial patterns after the removal of TWS components derived from GLDAS land surface model outputs. By contrast, Shanghai and Zhejiang exhibited positive TWS and GWS growth rates, largely due to groundwater protection policies—particularly in

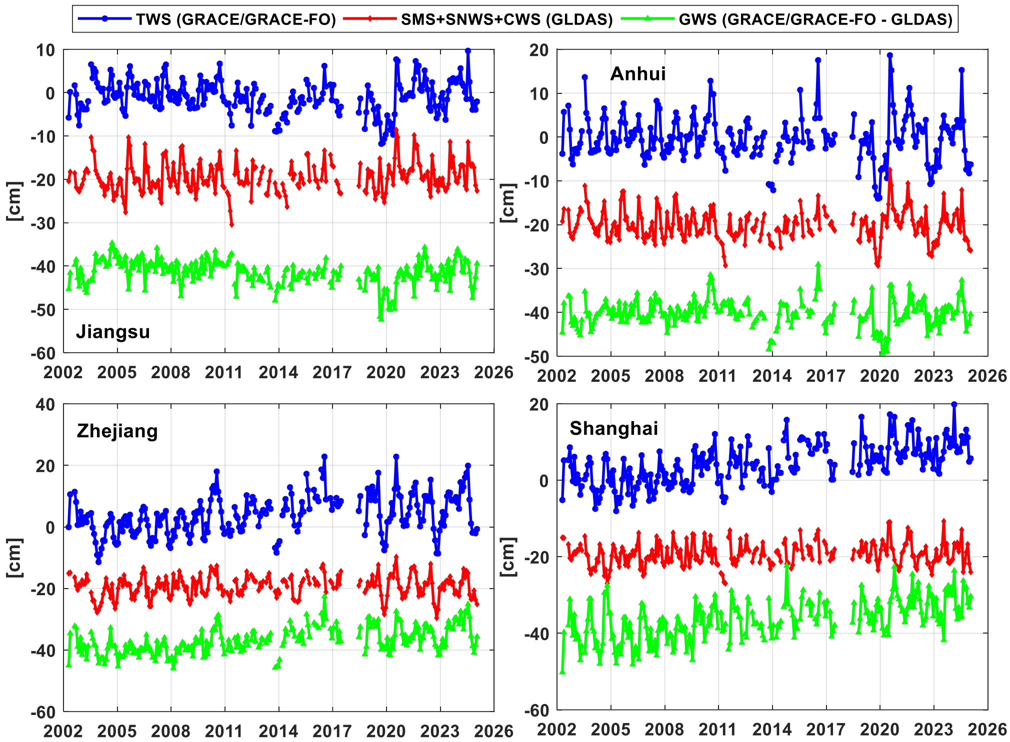

Fig. 4 The water storage changes for four YRD sub-regions. Note: The graphs have been vertically shifted to enhance data visibility.

Shanghai, where nearly all water demand is met by surface water, with minimal groundwater extraction. Anthropogenic activities, including agricultural irrigation, industrial development, and fossil fuel extraction (notably coal mining), also contribute significantly to water depletion. To account for coal-mining impacts, annual production outputs were converted to EWH and spatially averaged across the relevant provincial areas (Anhui: Suzhou, Huaibei, Bozhou, Fuyang, Huainan, Bengbu; Jiangsu: Xuzhou; see Figure 5d). Notably, Figure 6 highlights substantial differences between the annual and semiannual amplitude distributions of TWS and GWS, reflecting distinct seasonal dynamics.

To qualitatively compare the estimated TWS and GWS change rates with groundwater well observations, nine YRD well series of water level changes are shown in Figure 7. Notably, the recorded water level represents the distance from the wellhead to the water surface; therefore, a decrease in water level indicates a rise in groundwater storage. From Figure 7, we can find that three Shanghai wells presents a significantly increasing trends in water level (i.e., decreasing distance values), indicating a considerable recovery of groundwater levels due to sustained recharge efforts. This pattern was consistent with observations in Zhejiang Province, where wells such as those in Tongxiang and Longyou also showed positive trends. Due to differing time spans, the well data are used only to confirm the sign and general magnitude of trends, not for exact intercomparison. For Shanghai and Zhejiang Province, all five wells exhibited rising water levels—exemplified by rates of +1.59 m/year at Chongming and +1.80 m/year at Shanghai University—directly contributing to the positive GWS change rate. However, decreases were observed in wells such as Wuhe (Anhui) (- 0.12 m/year) and Guanyun (Jiangsu) (-0.11 m/year), indicating the occurrence of localized depletion. Moreover, this groundwater loss, likely driven by high water consumption due to intensive coal mining in northern Anhui and Jiangsu, may be a primary factor contributing to pronounced decline in GWS in these locations. Furthermore, overextraction of groundwater in neighboring urban areas may have contributed water storage decline in the study region due to hydraulic connectivity of underlying aquifers.

Besides, the yearly precipitation, surface water consumption, and groundwater consumption data, were obtained from provincial water resources bulletin, which encompasses Shanghai, Anhui, Jiangsu, and Zhejiang Provinces, to further interpret the potential causes of the estimated TWS and GWS changes. The annual mean precipitation and surface water and groundwater consumption data series are presented in Figure 8. The four regions have different water consumption structures because of the differences in policy interventions adopted and prevalent hydrological conditions. In Anhui Province, both surface water and groundwater consumption increased significantly from 2003 to 2010 because of rapid economic and social development. After 2010,

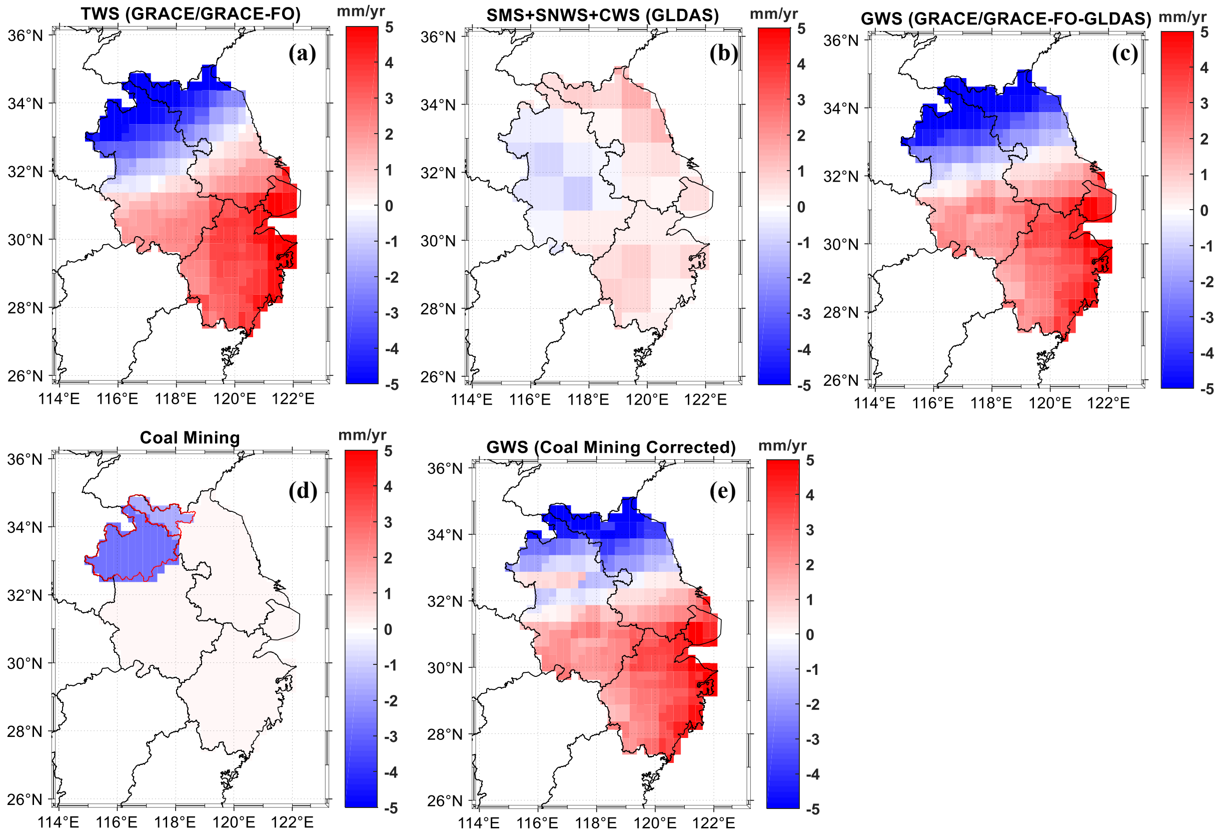

Fig. 5 Linear trend spatial distributions (a) TWS, (b) SMS+SNWS+CWS, (c) GWS inferred from GRACE/GRACE-FO-GLDAS, (d) coal mining, and (e) GWS inferred from GRACE/GRACE-FO-GLDAS-coal.

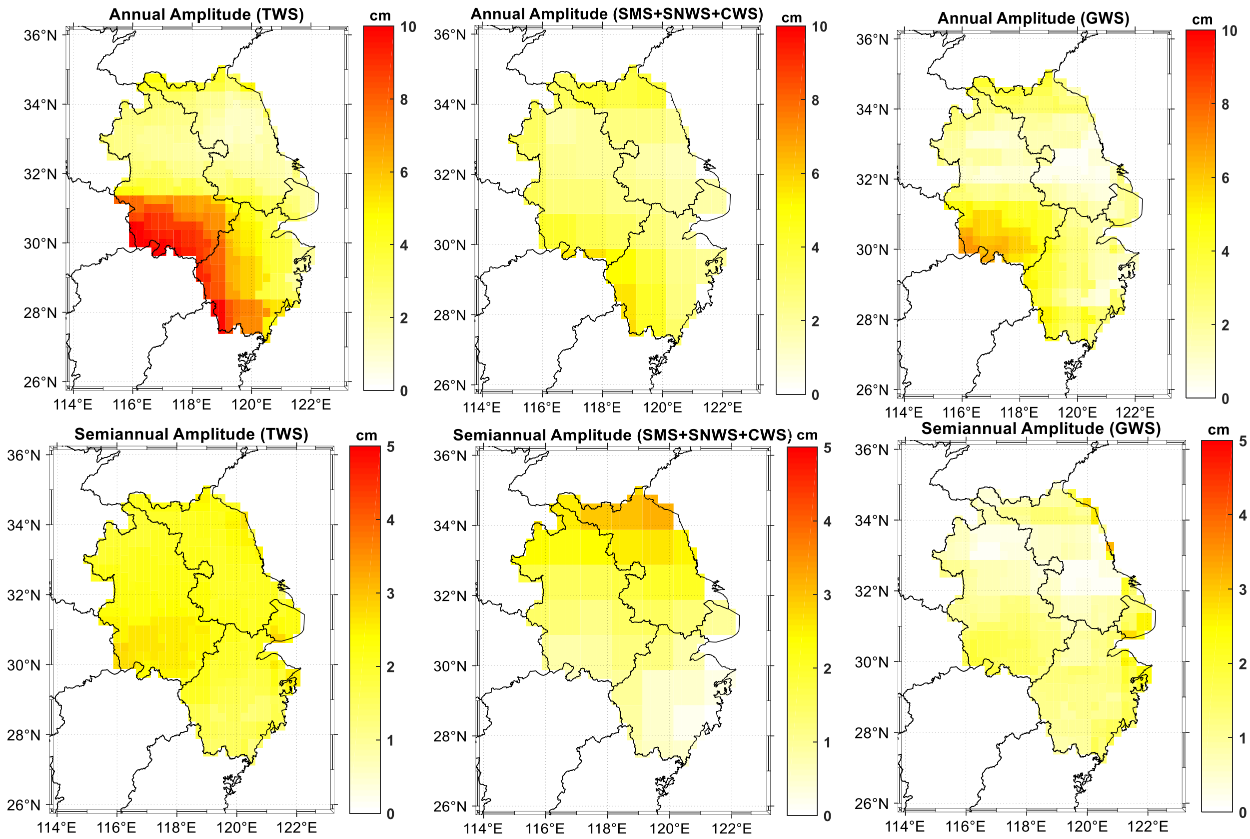

Fig. 6 Spatial distributions of annual (Row 1) and semiannual (Row 2) amplitudes of YRD water storage changes (2002.4–2025.1)

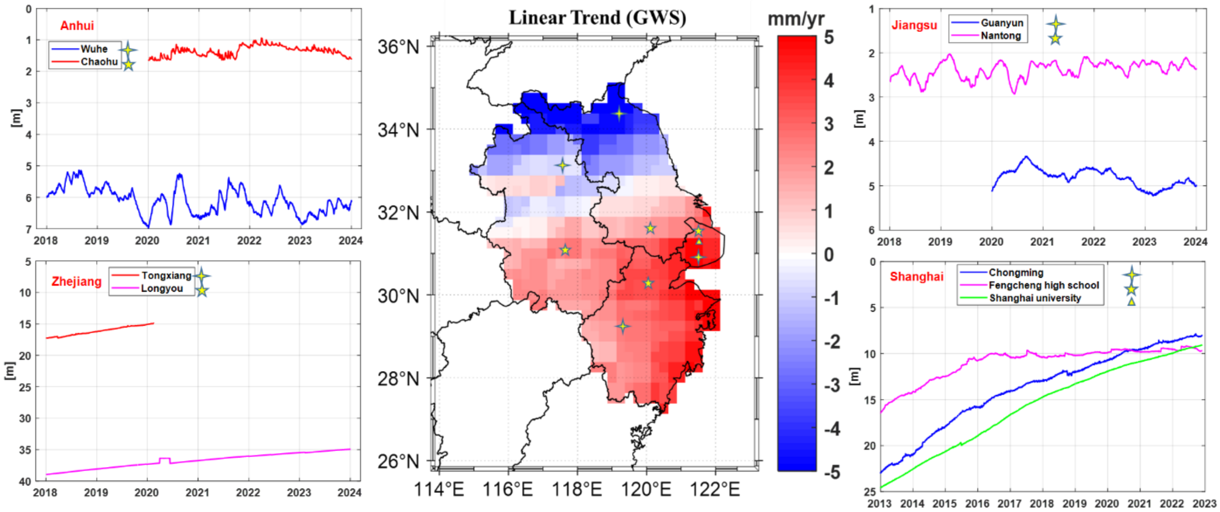

Fig. 7 Groundwater-level well series in the YRD.

Table 3 Groundwater level change rates for nine YRD wells.

Province	Groundwater well	Time-span	Linear Trend [m/year]
Anhui	Wuhe	2018.1.1-2023.12.31	-0.12
	Chaohu	2020.1.1-2023.12.31	+0.05
Jiangsu	Guanyun	2020.1.1-2023.12.31	-0.11
	Nantong	2018.1.1-2023.12.31	+0.05
Shanghai	Chongming	2010.1.1-2022.11.27	+1.59
	Fengcheng high school	2010.1.5-2022.11.27	+0.52
	Shanghai University	2010.1.1-2022.11.27	+1.80
Zhejiang	Tongxiang	2018.1.1-2023.12.31	+1.16
	Longyou	2018.1.1-2023.12.31	+0.65

surface water use remained high, while groundwater consumption declined steadily, largely because of governmental policies aimed at groundwater protection and extraction control. In Jiangsu Province, groundwater consumption steadily decreased from 1.484 billion m^3 in 2004 to 210 million m^3 in 2024, contributing to mitigation of regional groundwater depletion. To avoid the increase in land subsidence caused by anthropogenic activities, especially groundwater extraction, Shanghai and Zhejiang have implemented a series of groundwater management protection measures, including extraction limits and artificial recharge programs. Annual groundwater abstraction in Shanghai decreased from 96 million m^3 in 2004 to just 0.88 million m^3 in 2024; however, groundwater recharge was 15 million m^3. In addition, annual precipitation in Shanghai has increased relatively gradually, which may have further contributed to groundwater recovery. Similarly, Zhejiang Province exhibited parallel trends in surface and groundwater usage, highlighting a broader regional transition toward sustainable water governance. In summary, the patterns indicate that groundwater recovery in Shanghai and Zhejiang is largely attributable to the adopted groundwater protection policies, supplemented by artificial recharge initiatives and, in some cases, favorable precipitation increases.

4. CONCLUSIONS

In this study, TWS and GWS changes in the YRD are estimated by adopting multisource datasets. The regional mean TWS change rate was 0.88±0.17 mm/year (after coal mining correction), with a GWS rate of 0.68±0.12 mm/year, indicating that GWS dominated TWS variations. The TWS change rates of Shanghai and Zhejiang were 4.89±0.16 mm/year and 3.68±0.22 mm/year, respectively, which exhibited significant positive trends driven mainly by groundwater recovery due to the adoption of groundwater management protection policies and artificial recharge. However, Anhui and Jiangsu Provinces have relatively small negative TWS change rates (–0.48±0.19 and –0.45±0.16 mm/year, respectively). In Anhui, the positive inferred GWS trend after coal-mining correction suggests that the TWS decline is mainly related to non-groundwater components and mining-related mass loss, whereas Jiangsu shows a negative inferred GWS trend. The groundwater level data from nine monitoring wells qualitatively support the results; water level in the wells located in Shanghai and Zhejiang rose markedly

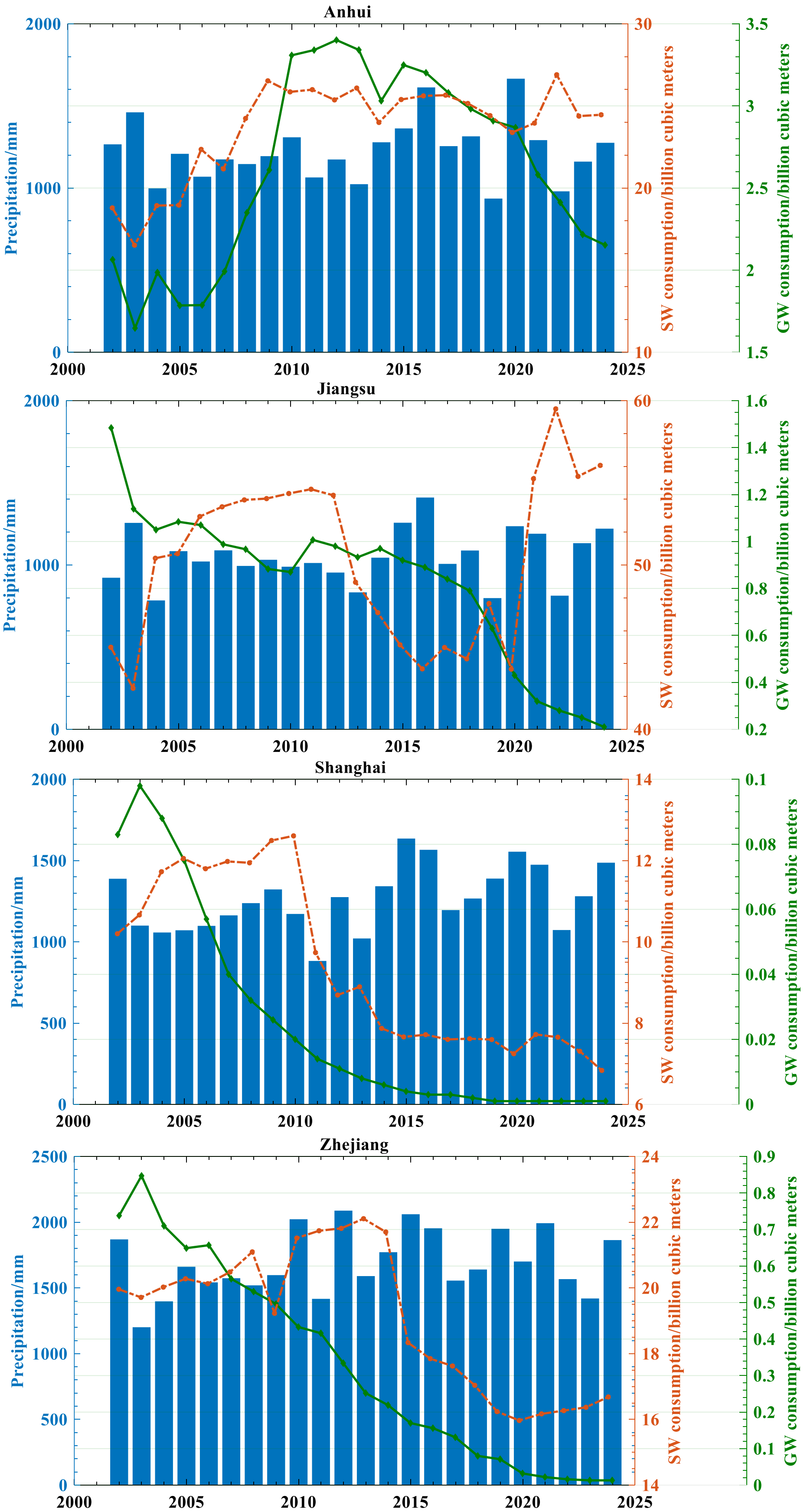

Fig. 8 Annual mean precipitation, surface-water consumption, and groundwater consumption for four YRD subregions over the period April 2002 to January 2025.

(e.g., Chongming +1.59 m/year), whereas that in the wells located in northern Anhui and Jiangsu declined (e.g., Wuhe –0.12 m/year), which may be partly due to water consumption from coal mining. These findings highlight the effectiveness of sustainable groundwater management in mitigating depletion and underscore how water storage responds to adopted water protection policies and anthropogenic activities.

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