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Research Article

Dynamic evolution characteristics and influencing mechanisms of groundwater in the Zoige Plateau

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Abstract: The Zoige Plateau, situated on the eastern edge of the Qinghai-Tibet Plateau, exhibits complex groundwater dynamics influenced by alpine hydrological processes and climatic variability. This study investigates the spatiotemporal evolution of groundwater in the Zoige alpine basin from 2002 to 2024 using an integrated approach that combines in-situ monitoring, GRACE satellite observations, and GLDAS model outputs. Using the Innovative Trend Analysis (ITA) method alongside conventional statistical techniques, we identified both seasonal fluctuations and long-term depletion trends. Groundwater levels exhibited clear wet–dry season contrasts and a cumulative decline of up to 2.3 m in grassland flatlands, corresponding to a long-term depletion rate of 0.4 cm/a as indicated by GRACE-derived groundwater storage. The most significant declines occurred in grassland zones, driven by wetland degradation and elevated evapotranspiration, while mountain regions showed slower losses (~0.1 cm/a) primarily supported by sustained snowmelt recharge. Through the integration of multi-source datasets, this study highlights the spatial heterogeneity and key drivers of groundwater variation, providing a robust framework for sustainable groundwater management under climatic and anthropogenic pressures in alpine wetland systems.

Keywords: Zoige Plateau; Groundwater dynamics; GRACE; Spatiotemporal variation; Climate change

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Introduction

Water resources in alpine regions are integral to the global hydrological cycle, yet their dynamics are profoundly influenced by the unique geographical and climatic conditions of high-altitude environments (Chen et al. 2019). The Zoige Plateau, located at the eastern edge of the Qinghai-Tibet Plateau, exemplifies such a region, characterized by abundant water resources and intricate hydrological processes (Li et al. 2018). As a critical component of the so-called "Asian Water Tower" this plateau contributes significantly to the headwaters of major rivers, including the Yellow River, through snowmelt, precipitation, and groundwater recharge (Beaudon et al. 2017). However, escalating impacts from climate change—such as glacier retreat, permafrost degradation, and shifting precipitation patterns—combined with intensifying anthropogenic activities, threaten the sustainability of these water resources, posing challenges to both ecosystems and downstream water security (Kang et al. 2010; Yang et al. 2019). Understanding the spatiotemporal variability of water resources in this region is thus essential for effective resource management and conservation.

Recent research has increasingly focused on the hydrological responses of alpine regions to global warming. Studies indicate that accelerated glacier retreat and permafrost thawing significantly alter surface runoff and groundwater recharge patterns (Smith et al. 2005; Huss and Hock, 2018). For

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instance, Chen et al. (2020) highlighted the sensitivity of the Qinghai-Tibet Plateau's hydrological system to variability in the Asian monsoon variability, amplifying uncertainties in water availability. Similarly, Zhao et al. (2019) demonstrated that permafrost degradation and changing precipitation regimes disrupt groundwater recharge, potentially leading to regional water shortages. The IPCC (2021) further underscores that these climate-induced changes—coupled with altered precipitation and freeze-thaw cycles—pose profound challenges to water resource management in alpine zones. Bao et al. (2024) emphasized that such hydrological shifts on the Qinghai-Tibet Plateau have cascading effects on downstream ecological and socio-economic systems, underscoring the urgency of a more systematic and integrative investigation.

Despite these advances, significant gaps remain in understanding the dynamic evolution of groundwater resources in alpine settings like the Zoige Plateau. While remote sensing and numerical models, such as SWAT and MODFLOW, have been widely employed to analyze surface water dynamics (Immerzeel et al. 2010; Soncini et al. 2017), groundwater responses to climate change are less studied due to limited ground-based data and methodological constraints. Traditional trend analysis methods often fail to capture the non-linear and spatially heterogeneous nature of groundwater changes (Zakwan, 2021). Consequently, the integration of multi-source data and the application of innovative analytical approaches is needed to comprehensively assess groundwater variability and its drivers in such complex environments.

This study addresses these gaps by focusing on the Zoige Plateau, leveraging ground monitoring data alongside GRACE gravity satellite and GLDAS hydrological model outputs. Employing the Innovative Trend Analysis (ITA) method, we systematically investigate the spatiotemporal evolution of groundwater resources under climate change. Unlike conventional approaches, ITA offers a flexible and intuitive framework to detect non-linear trends, thereby enhancing our understanding of groundwater dynamics. Our objectives are to: (1) Elucidate the spatial and temporal patterns of groundwater variation, (2) identify key climatic and environmental drivers, and (3) provide a scientific foundation for sustainable water resource management in the region. This integrated approach not only bridges existing research deficiencies but also offers decision-making support for alpine ecosystem conservation.

1 Study area

The study area is located in the upper reaches of the Yellow River Basin, along the eastern margin of the Qinghai-Tibet Plateau, covering Zoige County and parts of Hongyuan County in Sichuan Province, China (Fig. 1a). Based on the digital elevation model (DEM) (Fig. 1b), the elevation ranges from 3,200 m to 4,800 m above sea level, exhibiting significant topographic heterogeneity characterized by high mountain ranges, plateau hills, and intermountain basins, with the Zoige Basin as the central geomorphic unit. The region experiences a cold and humid alpine climate, with low annual mean temperatures and distinct seasonal precipitation. Annual precipitation ranges from approximately 600 mm to 800 mm, primarily concentrated from May to October (accounting for over 85% of the total). Snowmelt and seasonal rainfall serve as the main water sources, sustaining a typical alpine wetland ecosystem of critical hydrological and ecological importance (Li et al. 2014).

The White River and Black River, two major tributaries within the study area, play pivotal roles in the regional hydrological system by facilitating surface water flow and influencing groundwater dynamics (Fig. 1b). To support detailed analysis, the study area is divided into four distinct areas based on topographic characteristics, including elevation, slope, and geomorphic units (Fig. 1c): (1) The northeastern high mountain area, characterized by rugged, high-elevation terrain; (2) the Zoige grassland flat area, a broad plateau hosting extensive wetland systems with well-developed peat layers; (3) the southern high mountain area, marked by rugged, elevated terrain; and (4) the White River valley area, a lower-elevation corridor aligned with the White River's course, characterized by well-developed sedimentary layers.

2 Data and methods

2.1 Data sources

Groundwater Monitoring Data: This study utilizes data collected from groundwater monitoring wells situated throughout the study area, primarily across the Zoige grassland and along the White River. The dataset encompasses variations in groundwater levels and depths from September 2018 to October 2023.

Remote Sensing Data: Terrestrial water stor-

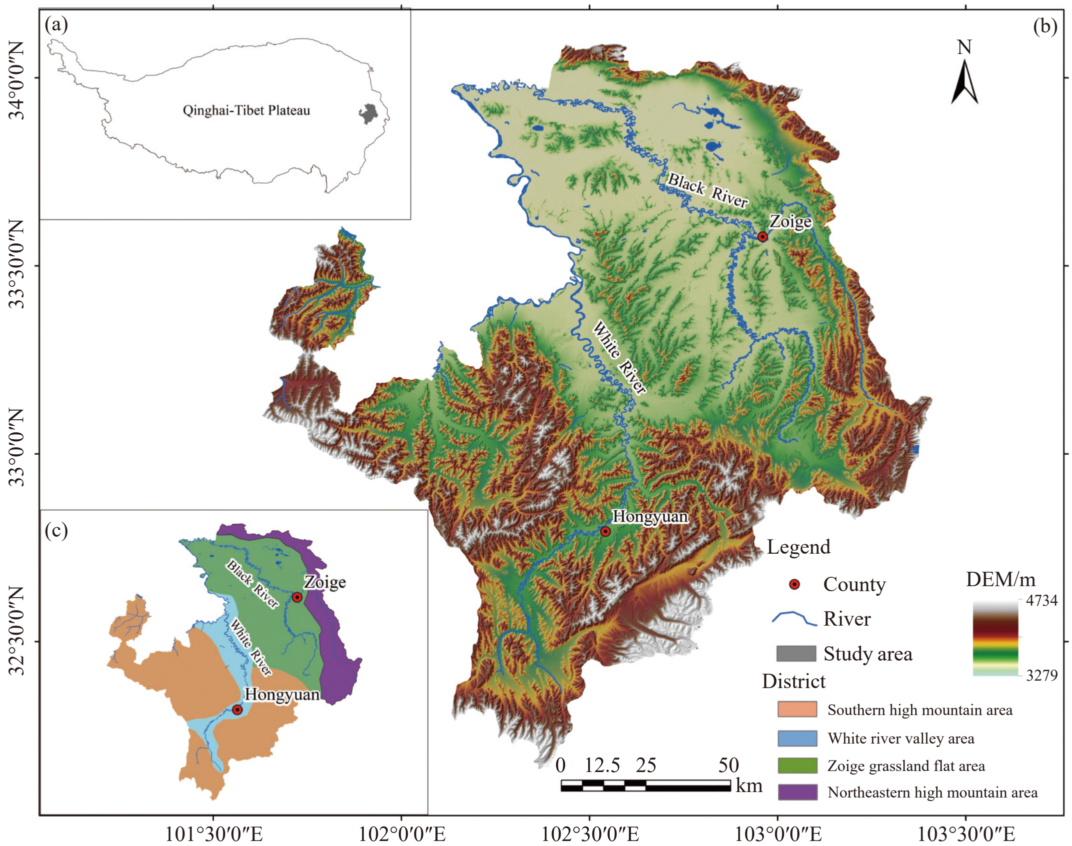


Fig. 1 (a) Location of the study area on the Qinghai-Tibet Plateau. (b) Topography and geomorphology of the study area. (c) Distribution of the four distinct areas within the study area

age remote sensing data were obtained from GRACE (Gravity Recovery and Climate Experiment) satellite data, which provides data on global gravity field changes since 2002. These data are widely used to estimate changes in terrestrial water storage, including groundwater, soil moisture, and snowmelt. This study used the CSR GRACE and GRACE-FO MASCON RL06 monthly time-varying equivalent water height change data, sourced from the Texas Center for Space Research (https://www2.csr.utexas.edu/grace/RL06_mascons.html). The data has a temporal resolution of one month, a spatial resolution of 0.25°, and spans from April 2002 to December 2023.

Hydrological Model Data: Hydrological model data were obtained from GLDAS (Global Land Data Assimilation System) model data, provided by NASA's Goddard Space Flight Center (GSFC). This high temporal resolution hydrological model uses near-real-time land surface and spatial data to constrain the model, resulting in near-real-time land surface change data (Rodell et al. 2004). This study used the GLDAS_NOAH025_M monthly model data from April 2002 to December 2023, with a data resolution of 0.25° × 0.25°, sourced from https://disc.gsfc.nasa.gov/datasets.

2.2 Research methods

Data Preprocessing: Prior to data analysis, the groundwater monitoring and remote sensing data underwent preprocessing to ensure data quality and reliability. Missing values in the time series were filled using linear interpolation. Specifically, for groundwater monitoring data, gaps in data (less than 10% missing in a given well's time series) were interpolated by linearly fitting the available data surrounding the missing values. Outliers were identified using the InterQuartile Range (IQR) method, where any data points outside the range of 1.5 times the IQR below the first quartile or above the third quartile were considered outliers and removed. For remote sensing data, anomalies or outliers that deviated significantly from expected physical values were flagged and excluded from further analysis. The cleaning of both groundwater and remote sensing datasets was critical for ensuring the accuracy of subsequent analysis.

Innovative Trend Analysis (ITA): This study introduced an innovative trend analysis method (ITA) to estimate groundwater level and storage changes. ITA is an improved non-parametric trend detection method that visually observes data series trends through graphical representation. It can observe whether trends are monotonic or non-monotonic, with five possible outcomes: monotonic increase, non-monotonic increase, monotonic decrease, non-monotonic decrease, and no trend. The method was proposed by Sen (2012) and has been widely applied in trend analysis of rainfall data. In recent years, it has also been applied to groundwater change detection with remarkable results (Chowdari et al. 2023; Minea et al. 2020; Seenu et al. 2021; Swain et al. 2022). Compared with the widely used M-K test and Linear Regression Analysis (LRA) in trend analysis, ITA provides a more intuitive, flexible, and accurate test for time series data.

The specific process of the ITA method is as follows: The data series is first divided into two equal parts, which are sorted in ascending order. Then, in a Cartesian coordinate system, the first part is used as the x-axis, and the corresponding second part is used as the y-axis to plot the scatter diagram. The scatter distribution is compared with the no-trend line (1:1 line). If the scatter points are above the 1:1 line, it indicates a monotonic increasing trend; if below, a monotonic decreasing trend; and if close to the line, no trend. The further the scatter points are from the 1:1 line, the more pronounced the trend. The ITA trend indicator factor is calculated using the following formula:

$$\text{ITA slope} = \frac{1}{n}\sum_{i=1}^{n}\frac{10\times(y_i - x_i)}{\bar{x}} \quad (1)$$

Where: x is the average value of the first half of the data, n is the number of data points, and x_i and y_i represent the corresponding data in the first and second halves, respectively. A positive ITA slope indicates an increasing trend, while a negative slope indicates a decreasing trend.

Groundwater Storage Calculation: GRACE gravity satellite data was used to calculate changes in terrestrial water storage in the study area, including groundwater, surface water, and soil moisture. To extract groundwater changes, this study used GLDAS data to estimate canopy water, snow water storage, and soil moisture, and calculated groundwater storage changes using the following formula:

$$\begin{aligned} GWS = {} & TWS(GRACE) - (WCAN(GLDAS) + \\ & WSWE(GLDAS) + WQS(GLDAS) + \\ & WSOIL(GLDAS)) \end{aligned} \quad (2)$$

Where: GWS represents groundwater storage changes, TWS(GRACE) represents total terrestrial water storage estimated by GRACE, and WCAN, WSWE, WQS, and WSOIL represent canopy water, snow water, surface water, and soil moisture storage estimated by GLDAS, respectively.

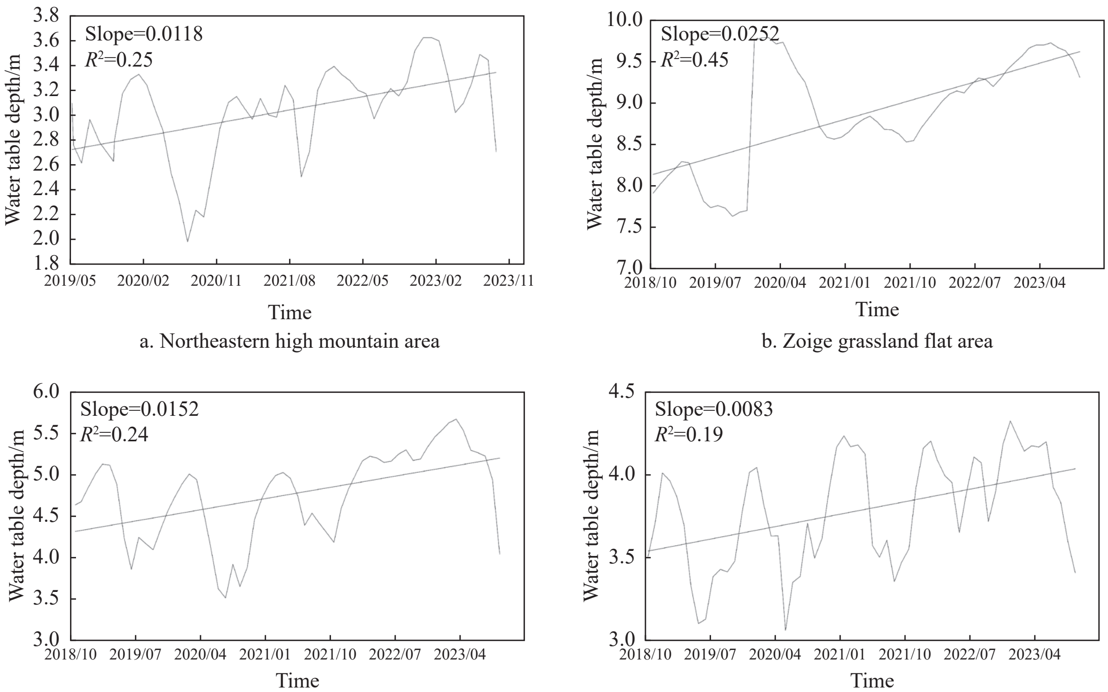
Spatial Interpolation and Trend Analysis: Spatial interpolation techniques were used to spatially extend groundwater monitoring data to obtain the spatial distribution characteristics of groundwater changes in the study area. In addition, the results of GRACE and GLDAS were combined for trend analysis to further verify the dynamic characteristics of groundwater storage in different regions.

Comparative Analysis: To verify the effectiveness of the ITA method, the Mann-Kendall test and Sen's slope estimate were used to conduct a comparative analysis of groundwater change trends to evaluate the accuracy and consistency of different methods in trend identification.

3 Results and discussion

3.1 Groundwater depth dynamics

To investigate the temporal behavior of groundwater across the study area, we analyzed typical monitoring data of groundwater depth from four distinct areas, as presented in Fig. 2. In the Northeastern high mountain area (Fig. 2a), groundwater depth varied from 1.9 m to 3.7 m between April 2019 and October 2023, showing a slight increasing trend (slope = 0.0118, R^2 = 0.25) with marked seasonal fluctuations, likely influenced by precipitation cycles. In the Zoige grassland flat area (Fig. 2b), groundwater depth increased steadily from 7.5 m to 9.8 m between September 2018 and October 2023 (slope = 0.0252, R^2 = 0.45), indicating a significant decline in water levels, possibly due to reduced recharge or heightened extraction. The Southern high mountain area (Fig. 2c) exhibited groundwater depths between 3.5 m and 5.8 m over the same period, with a moderate increasing trend (slope = 0.0152, R^2 = 0.24), reflecting seasonal variability and a gradual decline in water levels. Finally, the White River valley area (Fig. 2d) showed stable groundwater depths ranging from 3.0 m to 4.3 m, with a minimal increasing trend (slope = 0.0083, R^2 = 0.19), suggesting a near-balanced recharge-discharge system. Overall, the Zoige grassland flat area exhibited the most significant increase in groundwater depth (highest slope and R^2), indicating a pronounced decline in water levels, while the other three areas displayed relatively stable conditions with weaker increasing trends (slopes ranging from 0.0083 to 0.0152),



a. Northeastern high mountain area

b. Zoige grassland flat area

c. Southern high mountain area

d. White River valley area

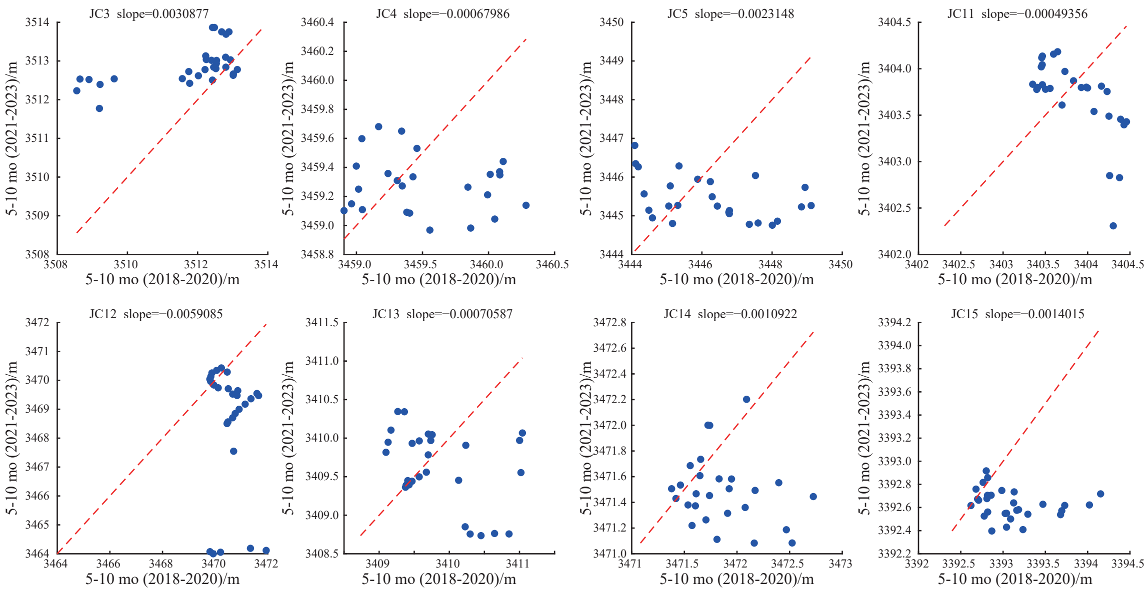
Fig. 2 Typical Groundwater Monitoring Data Distribution Curves

highlighting the influence of regional hydrogeological settings, climate variability, and anthropogenic activities on groundwater dynamics.

3.2 Application of ITA method in groundwater analysis

Based on the observed seasonal variations in groundwater levels across the study area, the ITA method was applied to analyze groundwater changes during the wet season (May-October) and dry season (November-April) in each subregion (Figs. 3 and 4).

The results indicated that, in the northeastern high mountain area, seven of the monitored points had a negative ITA trend indicator value during the wet season (87.5% of the total) and five had a negative value during the dry season (62.5% of the total). This indicates a decreasing trend in groundwater levels during both the wet and dry seasons in this area. In the Zoige grassland flat area, seven points had a negative ITA trend indicator value during the wet season (87.5% of the total), and six



a. Northeastern high mountain area

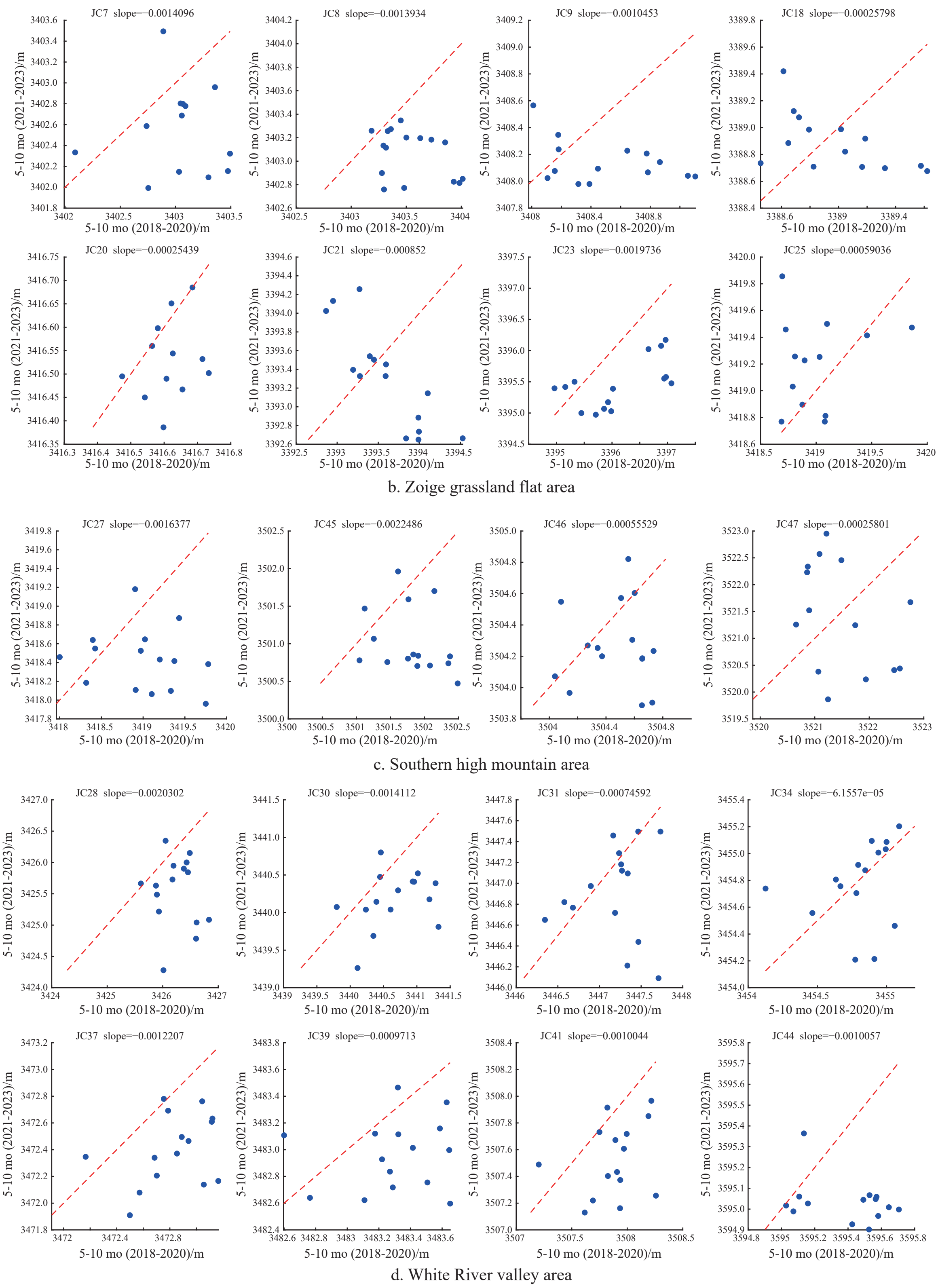
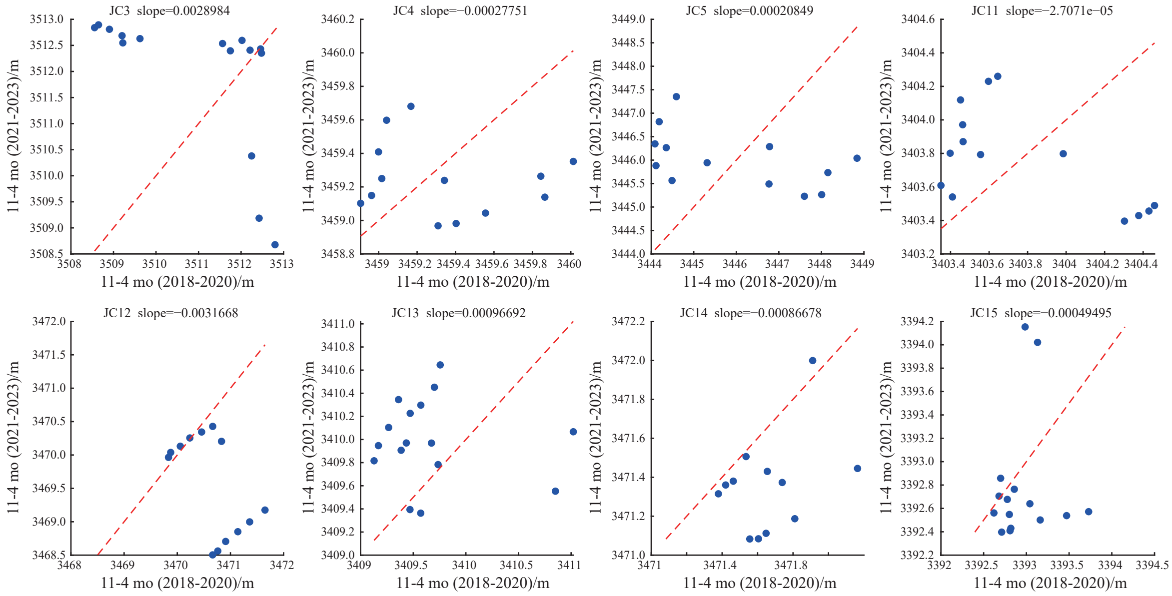


Fig. 3 Wet season (May-October) groundwater level ITA analysis

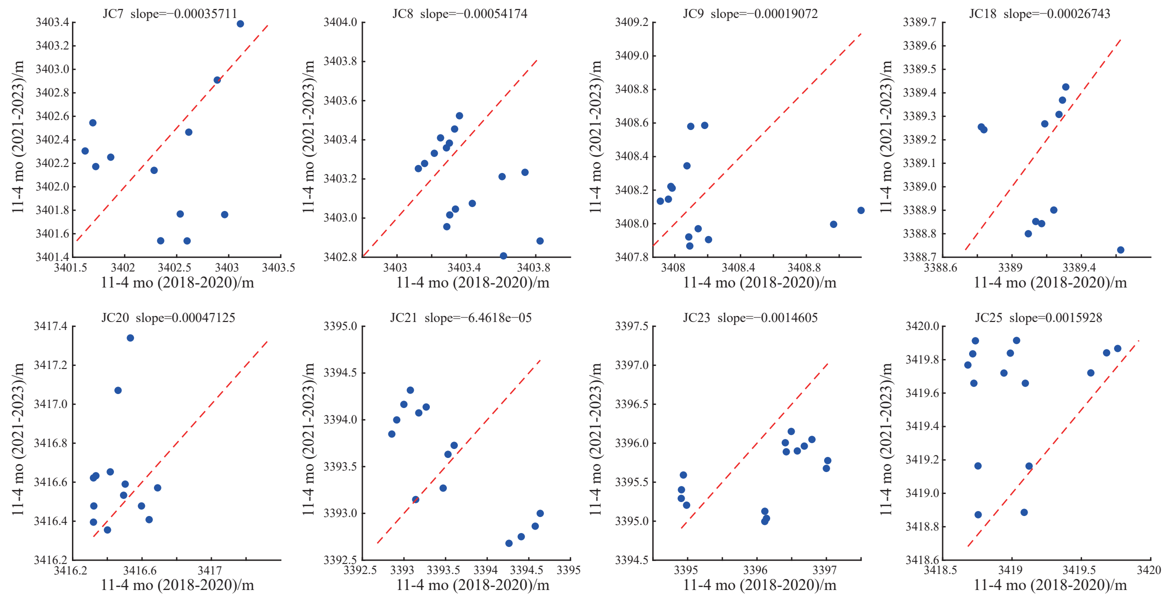
during the dry season (75% of the total), suggesting a decreasing trend in groundwater levels during both seasons. In the southern high mountain area, four points showed a negative trend during the wet season (100% of the total), and three during the dry season (75% of the total), indicating a decreasing trend in both seasons. In the White River valley area, all eight points had a negative trend during the wet season (100% of the total), while four points had a negative trend during the dry season (50% of the total), indicating a decreasing trend during the wet season and relatively stable conditions during the dry season. Overall, groundwater levels decreased during the wet season in all areas, but the decline rate was relatively small, while during the dry season, all areas except the White River valley showed a decreasing trend.

To verify the accuracy of the ITA method, the Mann-Kendall test and Sen's slope estimation were used to further analyze groundwater level trends. The results are summarized in Table 1.

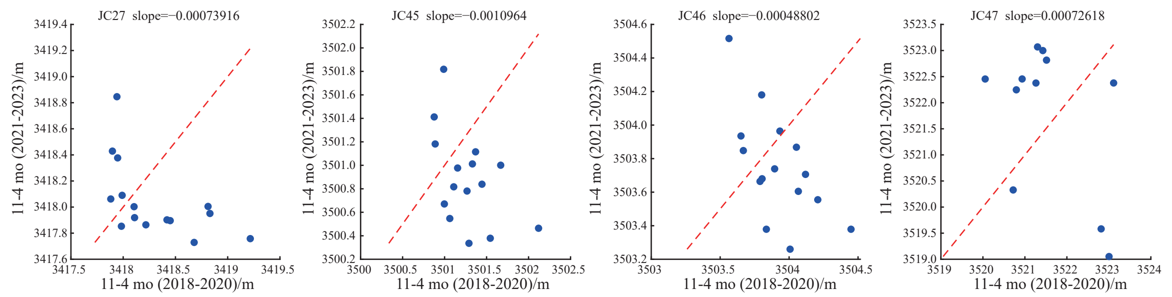
The Mann-Kendall, LRM, and ITA trend test results showed that groundwater levels in the northeastern high mountain area, Zoige grassland



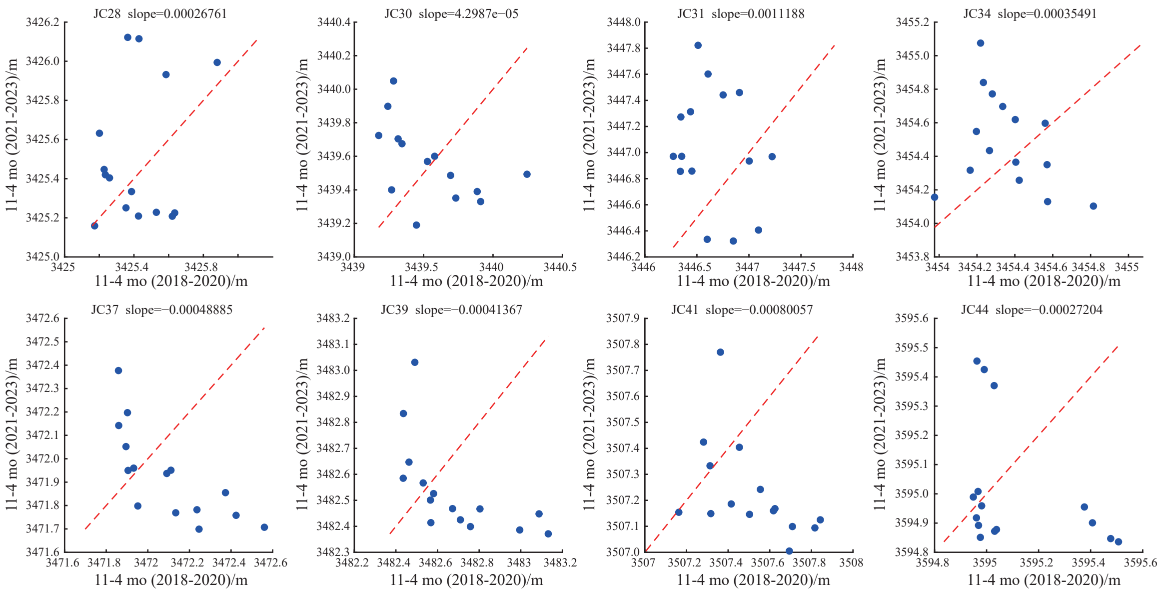
a. Northeastern high mountain area



b. Zoige grassland flat area



c. Southern high mountain area



d. White River valley area

Fig. 4 Dry season (November-April) groundwater level ITA analysis

Table 1 Mann-Kendall, Linear regression (LRM), and ITA trend test results

Area	**Monitoring point**	**b**	**z**	**ITA slope**		
				Wet season	**Dry season**	**Entire year**
Northeastern high mountain area	JC03	−0.02277	−0.03453	0.00137	0.00290	0.00211
	JC04	−0.00655	−0.00566	−0.00131	−0.00028	−0.00068
	JC05	−0.01452	0.01140	−0.00376	0.00021	−0.00231
	JC11	−0.00590	−0.00521	−0.00065	−0.00003	−0.00049
	JC12	−0.06105	−0.08020	−0.00806	−0.00317	−0.00591
	JC13	0.00689	−0.00550	−0.00180	0.00097	−0.00071
	JC14	−0.01140	−0.01177	−0.00127	−0.00087	−0.00109
	JC15	−0.00738	−0.00913	−0.00132	−0.00049	−0.00140
Zoige grassland flat area	JC07	−0.00979	−0.00769	−0.00141	−0.00036	−0.00106
	JC08	−0.01227	−0.00978	−0.00139	−0.00054	−0.00108
	JC09	−0.00509	−0.00699	−0.00105	−0.00019	−0.00072
	JC18	−0.00633	−0.00404	−0.00026	−0.00027	−0.00023
	JC20	−0.00226	−0.00365	−0.00025	0.00047	0.00013
	JC21	−0.00682	−0.00525	−0.00085	−0.00006	−0.00050
	JC23	0.02906	0.02519	−0.00020	−0.00146	−0.00174
	JC25	−0.01300	−0.01246	0.00059	0.00159	0.00054
Southern high mountain area	JC27	−0.00693	−0.00801	−0.00164	−0.00074	−0.00089
	JC45	−0.01602	−0.01501	−0.00225	−0.00110	−0.00152
	JC46	−0.00171	−0.00161	−0.00056	−0.00049	−0.00015
	JC47	−0.00404	0.00251	−0.00026	0.00073	−0.00011
White River valley area	JC28	−0.00296	0.00423	−0.00203	0.00027	−0.00048
	JC30	−0.00121	0.00300	−0.00141	0.00004	−0.00026
	JC31	−0.00283	−0.00263	−0.00075	0.00112	0.00040
	JC34	−0.00103	−0.00114	−0.00006	0.00035	0.00036
	JC37	−0.00468	−0.00529	−0.00122	−0.00049	−0.00048
	JC39	−0.00331	−0.00417	−0.00097	−0.00041	−0.00038
	JC41	−0.00862	−0.00834	−0.00100	−0.00080	−0.00064
	JC44	0.00253	−0.00394	−0.00101	−0.00027	−0.00054

Note: In the table, b represents the Sen's slope estimate derived from the M-K test, z denotes the slope value from linear regression (LRM). Cells shaded in gray indicate negative values (i.e. declining trends).

flat area, and southern high mountain area were mainly decreasing during the wet season, dry season, and annually. In the White River valley area, groundwater levels showed no significant trend during the dry season according to the ITA method, while other methods indicated a decreasing trend during both the wet season and annually.

In conclusion, the study area exhibited distinct seasonal variations in groundwater levels, with higher levels during the wet season (May-October) and lower levels during the dry season (November-April). From January 2018 to October 2023, groundwater storage in the study area generally showed a decreasing trend, with a relatively small rate of decline.

3.3 Inversion analysis of regional groundwater storage

(1) Spatial distribution characteristics of groundwater storage

Based on the CSR_GRACE_GRACE-FO_RL0602_Mascons_all-corrections data (April 2002-September 2023), spatial distribution maps of terrestrial water storage changes were produced for the winter (January), summer (July), and autumn (September/October) seasons in the study area from 2019 to 2023 (Fig. 5).

The spatial distribution of Terrestrial Water Storage (TWS) changes (Fig. 5) reveals pronounced seasonal variability and spatial heterogeneity across the study region from 2019 to 2023. In winter (January), TWS changes exhibited a relatively uniform spatial pattern, with magnitudes at moderate annual levels. In contrast, summer (July) showed significant TWS increases, characterized by a distinct northeast-to-southwest decreasing gradient, with the northeastern sector experiencing the most substantial increases. TWS began to decline in autumn (September/October) following the summer peak. During the study period, the highest TWS levels occurred between July and October 2019, particularly in the northeastern region, where the most significant increases were

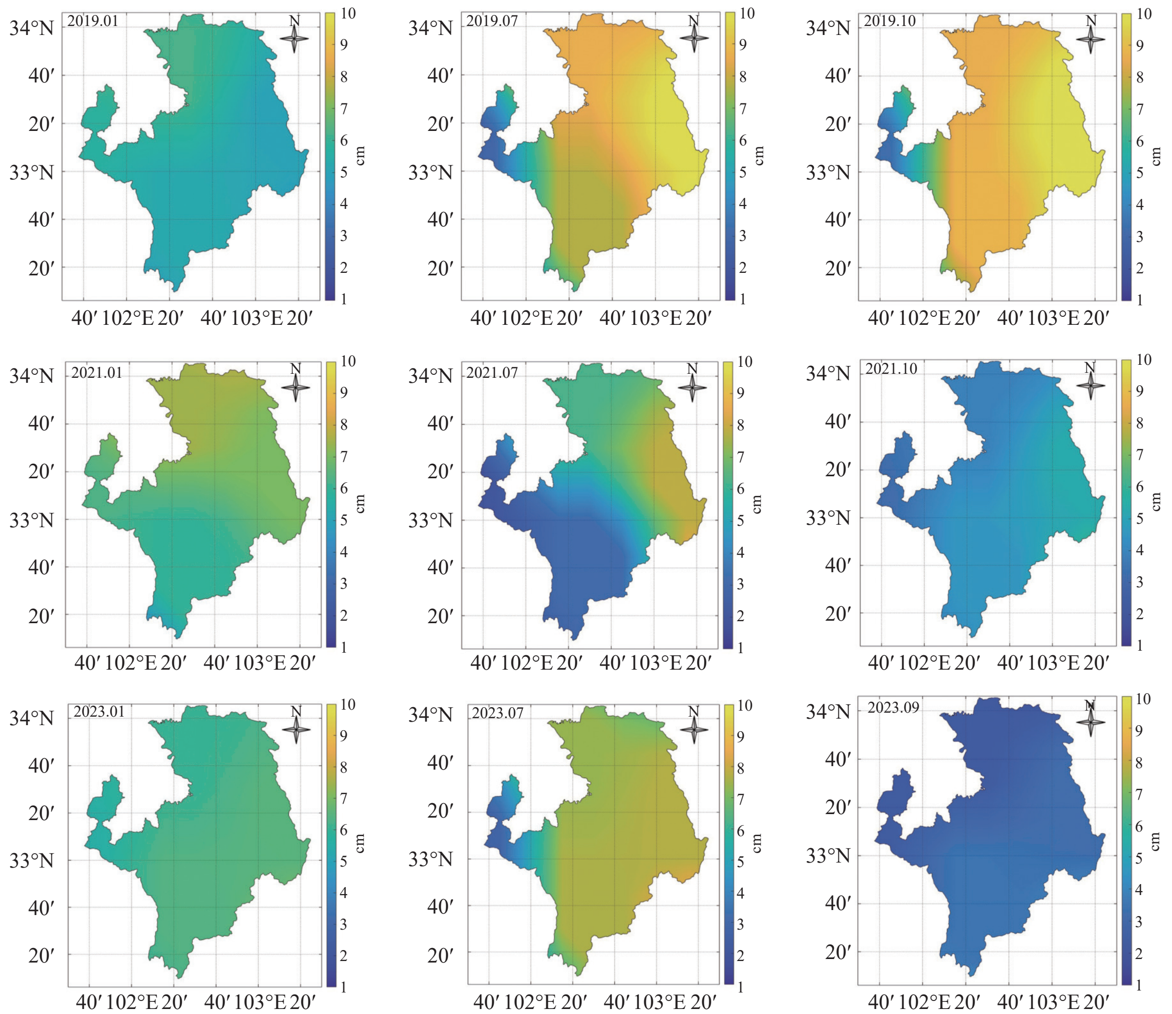


Fig. 5 Spatial distribution maps of terrestrial water storage changes (2019–2023)

observed, followed by a subsequent decreasing trend. These patterns reflect the combined influence of seasonal climatic variability and regional hydrogeological characteristics on TWS dynamics.

The spatial distribution of Groundwater Storage (GWS) Changes, derived from GRACE and GLDAS data (Fig. 6), reveals pronounced seasonal and spatial variability across the study area from 2019 to 2023. In winter (January), the southeastern piedmont valley area exhibits the most significant GWS increase, reaching up to 11.4 cm in Equivalent Water Height (EWH), while the northwestern sector experiences a notable decline of up to 10 cm EWH. This spatial heterogeneity is driven by distinct hydrological processes: (1) In the southwestern mountainous area, winter snow accumulation, coupled with temperature fluctuations (e.g. episodic warming or diurnal freeze-thaw cycles), promotes snowmelt infiltration, recharging groundwater in the piedmont valleys; (2) along the northwestern margin near the Yellow River's main channel, low winter river stages create a hydraulic gradient that induces groundwater discharge into the river (termed stream capture), reducing GWS in riparian area (Gleeson et al. 2020).

In summer (July), rising temperatures and

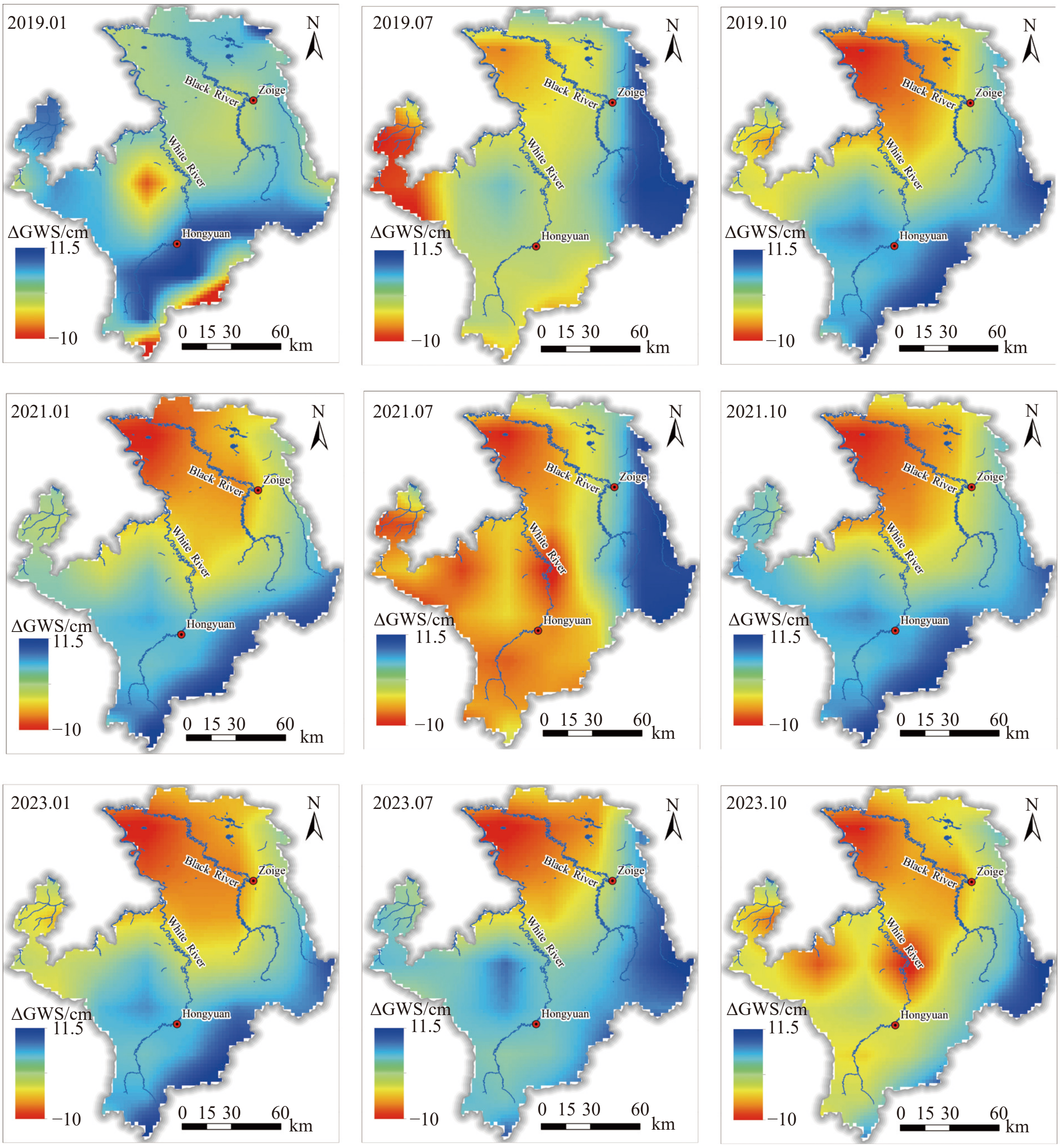


Fig. 6 Spatial distribution maps of groundwater storage changes (2019–2023)

substantial precipitation facilitate groundwater recovery, particularly in the eastern high-elevation areas, where enhanced runoff drives rapid recharge. However, in the western grassland-wetland region, localized GWS declines are observed, likely due to increased Evapotranspiration (ET) under elevated temperatures, as supported by recent studies (Maxwell and Condon, 2016). Additionally, the fine-textured soils prevalent in this area may enhance capillary rise, further promoting direct evaporation and exacerbating water loss. In autumn (October), reduced precipitation leads to a progressive decline in GWS, signaling the onset of seasonal depletion. These patterns highlight the interplay of seasonal climatic variations, hydrological processes, and regional soil characteristics in shaping GWS dynamics.

(2) Temporal distribution characteristics of groundwater storage

The collected groundwater monitoring data, spanning only from January 2018 to October 2023, are insufficient for accurately assessing long-term trends in groundwater dynamics. To address this limitation, we derived mean Groundwater Storage (GWS) changes for each subregion from April 2002 to February 2024 using GRACE and GLDAS model data, generating time-series curves (Fig. 7). These time-series curves reveal distinct seasonal and periodic fluctuations in GWS across all subregions, reflecting the seasonal regulation of precipitation (primarily concentrated in summer) and evaporation. Over the 2002–2024 period, GWS in all subregions exhibits an overall declining trend, with annual decline rates ranging from 0.1 cm/a in the northeastern high mountain area to 0.4 cm/a in the Zoige grassland area. The slowest decline rate in the mountain areas (0.1 cm/a) is attributed to enhanced topographic precipitation effects (Bookhagen and Burbank, 2010) and the water retention capacity of vegetation (Deng et al. 2019), coupled with minimal human interference. In contrast, the Zoige grassland area experiences the most rapid decline (0.4 cm/a), driven by wetland degradation (Shen et al. 2019) and intense evaporation, which collectively exacerbate groundwater system imbalance.

3.4 Comparative analysis of groundwater changes using ground-based monitoring and GRACE remote sensing

To validate the reliability of the groundwater inversion method employing CSR GRACE and GRACE-FO MASCON RL06 data combined with the GLDAS_NOAH025_M.2.1 hydrological model, this study conducted a cross-validation using satellite data from the German Research

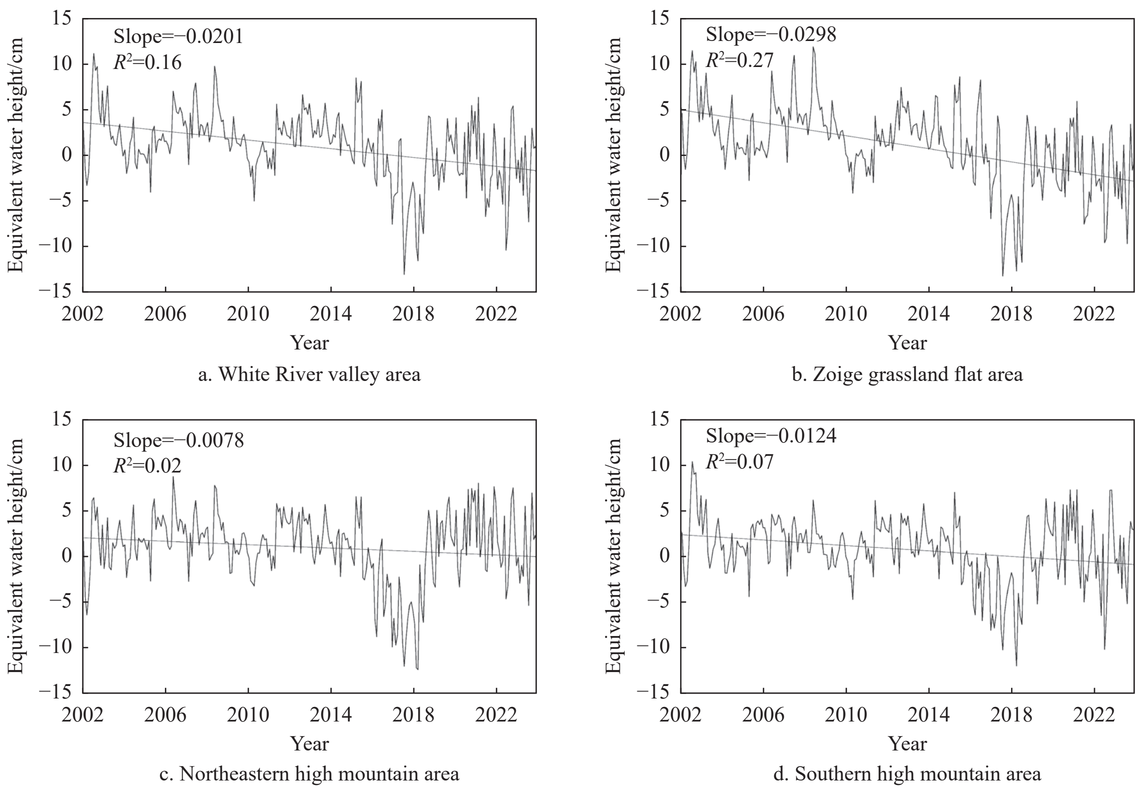


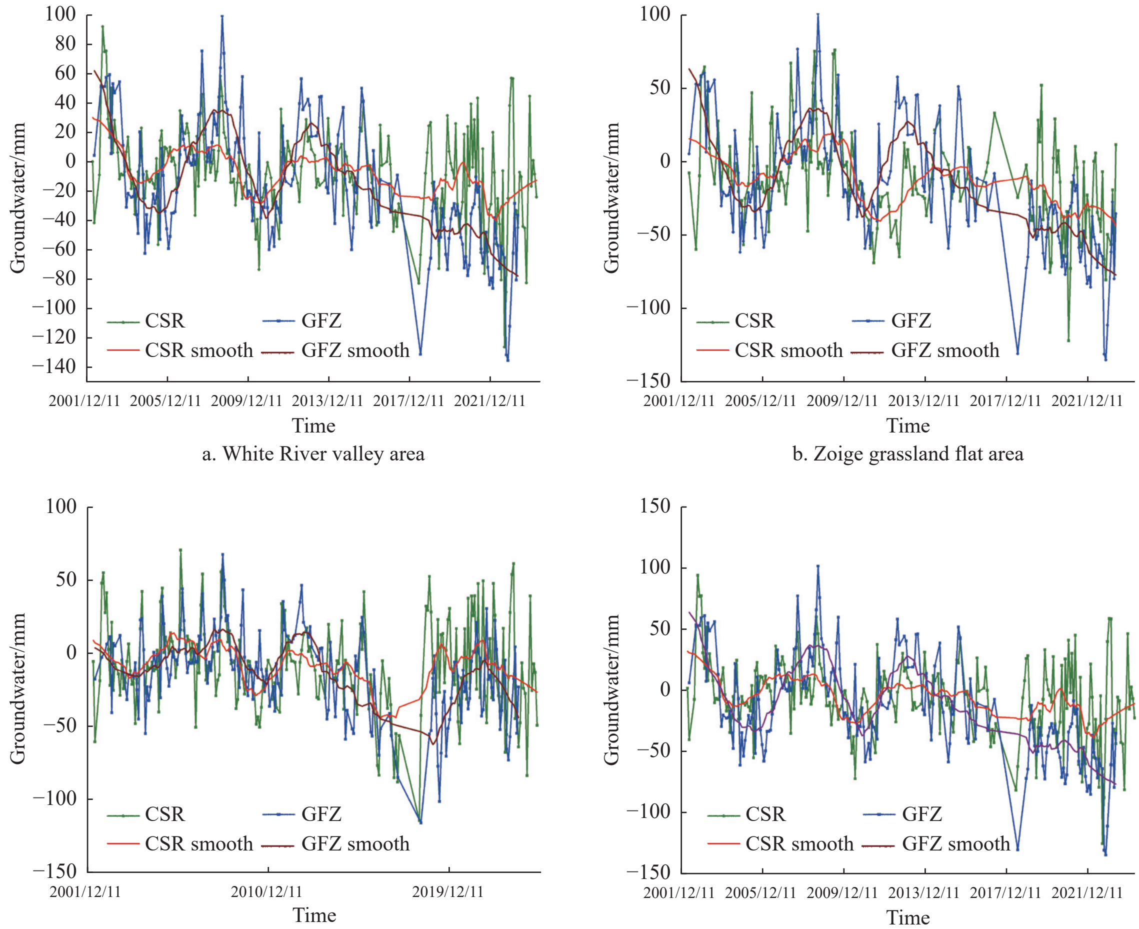
Fig. 7 Time series distribution curves of groundwater storage changes

Centre for Geosciences (GFZ) (GRACE_GFZOP_BA01_0600_LND_v04, GRFO_GFZOP_BA01_0601_LND_v04) integrated with the GLDAS-NOAH_1deg_tws_anomaly_monthly hydrological model. Typical monitoring sites were selected in each of the four subregions for comparison, and the time-series curves of Groundwater Storage (GWS) derived from the inversion data at these sites are presented in Fig. 8. Overall, both CSR and GFZ datasets exhibit consistent long-term trends across all subregions, although the GFZ data display more pronounced fluctuations. After applying smoothing and denoising techniques, the data reveal long-term GWS trends, notably a significant decline after 2015, likely associated with climate change and shifts in precipitation patterns. The consistency between the two datasets confirms the reliability of the different data sources, providing robust support for further investigations into groundwater dynamics.

Ground monitoring data and GRACE remote sensing inversion analysis generally showed consistency, but differences were also observed, primarily in the following aspects:

Consistency in Seasonal and Long-Term Trends: Ground-based monitoring data and GRACE-derived Groundwater Storage (GWS) estimates generally exhibit strong agreement in seasonal variability, with both datasets indicating increases in GWS during the wet season and decreases during the dry season. From 2018 to 2023, groundwater levels at several monitoring sites in the study area show a notable declining trend, particularly pronounced in the Zoige grassland flat area (Fig. 2). Similarly, GRACE-derived data reveal a gradual reduction in terrestrial water storage in the study area, with GWS decline rates across subregions being comparable (Fig. 7). These trends reflect the impact of climate change on regional water resources, including altered precipitation patterns and increased water loss. Overall, the long-term trends derived from both data sources demonstrate strong consistency, validating the reliability of GRACE inversions for capturing regional groundwater dynamics.

Differences in Spatial Distribution: Ground monitoring data reflect local groundwater level changes but are limited by the distribution of



a. White River valley area

b. Zoige grassland flat area

c. Northeastern high mountain area

d. Southern high mountain area

Fig. 8 Time series curves of groundwater changes based on CSR and GFZ inversion data monitoring points, especially within specific geomorphological units (e.g. high mountains, flat areas, and valleys), where variations can be significantly depending on monitoring site locations. GRACE data provide large-scale (approximately 28 km resolution) information on overall water storage changes, making it challenging to capture detailed local changes like ground monitoring but effectively characterizing regional dynamics. Thus, GRACE data offer broad spatial coverage for overall trend assessment, while ground monitoring provides finer details for localized areas. Spatial consistency between the two data sources is generally good at the regional scale, though local differences may persist.

Data Accuracy and Uncertainty: Ground monitoring data offer high temporal resolution and accuracy, effectively capturing specific point-level changes in groundwater, particularly during transitions between wet and dry seasons. In contrast, GRACE inversion data have limited accuracy due to satellite gravity measurement resolution and complex data processing algorithms, resulting in higher uncertainty, particularly in complex plateau terrain. GRACE is sensitive to large-scale water storage changes but less effective at resolving small-scale variations. Therefore, although both data types differ in accuracy and spatial resolution, GRACE is well suited for general, regional assessments, whereas ground monitoring is preferable for detailed local analysis.

4 Conclusion

The comprehensive analysis of groundwater dynamics in the Zoige Plateau from 2018 to 2023 reveals significant spatial and temporal variability influenced by regional hydrogeological settings, seasonal climatic patterns, and anthropogenic activities. Groundwater depth trends, assessed through ground-based monitoring, indicate a pronounced decline in the Zoige grassland flat area, with depths increasing from 7.5 m to 9.8 m (slope = 0.0252, R^2 = 0.45), driven by reduced recharge and potential over-extraction. In contrast, the Northeastern and Southern high mountain areas exhibit moderate declines (slopes of 0.0118 and 0.0152, respectively), while the White River valley maintains relative stability (slope = 0.0083, R^2 = 0.19), reflecting a balanced recharge-discharge system. Seasonal analysis using the ITA method further confirms consistent groundwater level decreases during the wet season across all subregions, with the White River valley showing relative stability in the dry season. These trends are corroborated by Mann-Kendall and Sen's slope analyses, highlighting a region-wide decline in groundwater levels, particularly pronounced in the grassland flat area.

Spatially, GRACE and GLDAS-derived groundwater storage (GWS) data reveal significant heterogeneity, with the southeastern piedmont valley experiencing substantial winter recharge (up to 11.4 cm EWH) due to snowmelt infiltration, while the northwestern margin near the Yellow River shows GWS declines (up to 10 cm EWH) due to stream capture. Summer recharge is prominent in eastern high elevation areas, driven by enhanced runoff, whereas the western grassland-wetland region experiences localized GWS losses due to high evapotranspiration and soil-driven evaporation. Temporally, GWS across all subregions exhibits a long-term decline from 2002 to 2024, with the Zoige grassland area showing the steepest annual decline (0.4 cm/a) due to wetland degradation and intense evaporation, compared to slower declines in mountainous areas (0.1 cm/a) attributed to topographic precipitation and vegetation retention.

Cross-validation of ground-based monitoring and GRACE remote sensing data confirms strong consistency in seasonal and long-term GWS trends, particularly the region-wide decline post-2015, likely linked to climate-driven precipitation shifts. However, differences arise in spatial resolution, with ground data offering high-precision local insights and GRACE providing broader regional trends but limited by lower resolution (approximately 28 km) and higher uncertainty in complex terrain. These complementary datasets underscore the interplay of climatic variability, hydrological processes, and human impacts in shaping the Zoige Plateau's groundwater dynamics.

In conclusion, the Zoige Plateau's groundwater system is undergoing a significant decline, most notably in the grassland flat area, driven by reduced recharge, high evapotranspiration, and anthropogenic pressures. The integrated use of ground-based monitoring and GRACE remote sensing provides a robust framework for understanding these dynamics, offering critical insights for sustainable water resource management in this ecologically sensitive region.

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