

Research Paper

Spatiotemporal dynamics of groundwater storage inferred from MT-InSAR and hydraulic head data in Anyang–Puyang Plain

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ABSTRACT

Groundwater overexploitation in northern Henan Province has led to significant land subsidence and aquifer degradation. This methodologically driven study proposes a physically consistent framework that integrates Sentinel-1A-based Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) data (2017–2022) with long-term groundwater head observations to invert elastic and inelastic skeletal storage coefficients and assess total groundwater storage (TGWS) changes. The framework is applied to the Anyang–Puyang Plain as a representative case study. MT-InSAR deformation time series were combined with Multi-channel Singular Spectrum Analysis (MSSA) decomposition and polynomial fitting to extract seasonal and long-term trends, enabling spatially distributed inversion of aquifer parameters. Results show strong spatial coupling between land subsidence and hydraulic head decline (maximum Pearson r is 0.993), with deformation dominated by inelastic compaction. The elastic storativity ranges from 0.00093 to 0.01596, whereas the inelastic storativity, ranging from 0.0362 to 0.0457 indicates irreversible compaction processes associated with a cumulative groundwater loss of approximately $3.01 \times 10^8 \text{ m}^3$. Based on the long-term groundwater level observations collected in this study and the inferred assumption of preconsolidation head, the TGWS loss reached $-12.27 \times 10^9 \text{ m}^3$, with a mean annual rate of $-2.19 \times 10^9 \text{ m}^3/\text{yr}$ and pronounced depletion in northern areas. Standard deviational ellipse (SDE) analysis revealed a north-westward shift of the depletion centre and enhanced spatial clustering. These findings provide critical hydromechanical insights and quantitative constraints for future groundwater regulation and aquifer recovery strategies in overdrawn regions.

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1. Introduction

As one of China's major agricultural regions, Henan Province has long borne the strategic responsibility of safeguarding national food security. Agricultural production in this region is heavily reliant on

groundwater resources [1–3]. Over the past two decades, the intensification of agricultural irrigation, acceleration of industrialization, and the uneven spatiotemporal distribution of precipitation have led to groundwater extraction far exceeding its natural recharge capacity [4], resulting in an increasingly severe issue of groundwater overexploitation [5]. This long-term and unsustainable pattern of groundwater use has not only caused a substantial decline in groundwater storage, posing serious challenges to regional sustainable development, but has also had profound impacts on the stability of local ecosystems [6]. Ground subsidence induced by groundwater overexploitation is particularly prominent

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in Henan Province [7–10]. As groundwater levels continue to decline, irreversible land subsidence is triggered by inelastic compaction of the aquifer skeleton within confined aquifers [11,12]. This geological hazard threatens the structural integrity of critical infrastructure such as roads, bridges, and buildings, and may impair the operational efficiency of key systems, including urban drainage, flood control, and water supply. More critically, long-term damage to the aquifer structure significantly reduces its water storage capacity, leading to irreversible degradation of groundwater reserves. Similar challenges have been observed globally, including in California's Central Valley, USA [13,14], the Rafsanjan Plain in Iran [15–17] and northern India [18], where long-term overexploitation has resulted in a dual crisis of land subsidence and groundwater depletion. Therefore, typical regions in northern Henan, such as Anyang City and Puyang City, serve as critical case study areas for exploring the coupled mechanisms of groundwater overexploitation and land subsidence.

As the world's largest source of freshwater [19,20], groundwater plays an irreplaceable role in agriculture, industry, and domestic use. In regions such as northern Henan where groundwater depletion persists, accurately quantifying groundwater storage variations and identifying the spatiotemporal characteristics of its recoverable component are essential. Such insights support the optimization of water resource allocation, inform agricultural irrigation and industrial planning, and provide a scientific foundation for groundwater conservation, regulation, and disaster mitigation. At present, achieving high-resolution monitoring and precise estimation of groundwater storage changes has become a pressing scientific challenge for regional sustainable development [21,22].

In recent years, Interferometric Synthetic Aperture Radar (InSAR) technology has demonstrated remarkable advantages in ground subsidence monitoring and has gradually emerged as a valuable tool for aquifer parameter inversion. Galloway, Hoffmann, and others have systematically reviewed the potential of InSAR in hydrogeology, including delineation of aquifer boundaries, estimation of hydrogeological parameters, and constraint of numerical groundwater models [3,23–25]. Since Amelung et al. [26] first applied InSAR to reveal the relationship between land subsidence and groundwater dynamics in Las Vegas, the technique has been widely used to invert both elastic and inelastic skeletal specific storage coefficients [12,27,28]. For example, Hoffmann et al. [29] successfully estimated the inelastic skeletal specific storage and compression time constant in California's Antelope Valley by decomposing vertical and horizontal deformation fields using ascending and descending InSAR datasets. Numerous studies across North America, Europe, and Asia have since integrated InSAR with groundwater level measurements, gravity observations, and other datasets to provide robust support for groundwater storage inversion [30–34]. Among these techniques, MT-InSAR has become a critical method for indirect estimation of groundwater storage due to its high spatial and temporal resolution, wide coverage, and all-weather capability [35]. By analysing long-term surface deformation time series, MT-InSAR can effectively separate elastic and inelastic deformation components, enabling the quantification of recoverable and non-recoverable groundwater storage changes. When combined with ground-based hydraulic head measurements and geological hydrogeological data, InSAR demonstrates significant potential for skeletal storage coefficient inversion and regional hydrological response analysis.

Building on these advances, extending such integrated remote sensing-hydrogeological approaches to areas experiencing both severe overexploitation and complex subsidence dynamics is important. Similar to other groundwater-stressed regions worldwide—such as California's Antelope Valley and Iran's Rafsanjan

Plain—the Anyang-Puyang Plain in northern Henan Province has undergone prolonged groundwater extraction to support intensive agricultural and industrial development, leading to substantial groundwater level decline and widespread land subsidence. However, comprehensive studies that leverage InSAR data in combination with in-situ groundwater level observations to invert aquifer system parameters and track the evolution of groundwater storage remain limited for this region. To address this gap, this study focuses on the Anyang and Puyang areas (excluding the western mountainous zones; hereafter referred to as the Anyang Puyang Plain). We utilize Sentinel-1A SAR data acquired from March 2017 to November 2022 to generate high-resolution surface deformation time series. These data are integrated with multi year groundwater head measurements to invert both elastic and inelastic skeletal storage coefficients of the confined aquifer system, examine their spatial variability, and estimate total groundwater storage dynamics. Fundamentally, this study aims to develop a generalizable inversion framework based on remote sensing and hydrogeological data fusion, with the Anyang-Puyang Plain serving as a representative test site for validation under typical aquifer overexploitation conditions. The framework is designed to characterize spatiotemporal groundwater storage dynamics and quantify both recoverable and irreversible depletion in stressed aquifer systems of the North China Plain.

2. Study area and datasets

2.1. Study area

Located in northern Henan Province, China, the study area covers the plains of Anyang City and Puyang City (excluding the western mountainous areas), with a total area of approximately 9000 km². The region exhibits a general west-to-east descending topography and diverse geomorphological types, including piedmont alluvial-pluvial plains, lacustrine plains in the central part, and the eastern North China Plain. This stepped terrain and complex geological structures provide a varied geologic background for the formation and evolution of regional groundwater systems.

In terms of hydrogeology, the study area mainly lies within two geomorphic zones: the Yellow River alluvial plain and the piedmont alluvial-pluvial plain of the Taihang Mountains, with the former being predominant. The hydrogeological conditions are relatively complex. Groundwater exploitation is concentrated in the plains and transitional zones, especially within the Yellow River alluvial plain's low-lying, well-developed sedimentary zones, where water extraction intensity is the highest. The aquifer system in this region is structurally complex and can be categorized into major aquifer groups, with depths ranging from approximately 350 to 500 m. The shallow aquifers contain primarily fresh water and have favourable storage conditions. In contrast, the deep confined aquifers exhibit significant lithological variability, with a transition from medium-coarse sand to siltstone, reflecting a complex depositional environment and heterogeneity in aquifer media. Since the 1970s, long-term overexploitation of groundwater due to agricultural and industrial development has led to a persistent decline in deep confined water levels in northern Henan, forming typical groundwater depression cones [36–39]. According to documented hydrogeological surveys, the shallow groundwater level in northern Henan declined by up to approximately 20 m during the period from 1984 to 2003, primarily due to intensive agricultural water withdrawal and insufficient recharge [36].

This prolonged overexploitation has consequently resulted in increasingly severe land subsidence. Monitoring data indicate that by 2015, the maximum cumulative subsidence exceeded 1500 mm, and areas with more than 500 mm of subsidence

spanned approximately 3576 km², accounting for 47.5% of the total area [40]. Prolonged land subsidence increases the risk of geological hazards and poses significant threats to infrastructure, urban and rural development, and ecological security. To address the aforementioned challenges, northern Henan was designated in 2014 as a national pilot zone for integrated groundwater management. Since then, multiple measures have been gradually implemented, including groundwater extraction control and optimization of irrigation structures [40]. By the end of 2018, cumulative groundwater extraction in the region had been reduced by approximately 402 million cubic meters [41], laying the foundation for a regulatory and sustainable groundwater utilization framework.

2.2. Datasets

This study integrates Sentinel-1A-based InSAR observations and ground-based monitoring data to support the inversion of groundwater storage variations and the estimation of related hydrogeological parameters. A total of 66 ascending Sentinel-1A SAR scenes were utilized, spanning from March 14, 2017, to November 7, 2022. The Sentinel-1 data, operating in the C-band with VV polarization, have azimuth and range resolutions of approximately 20 m and 5 m, respectively. These images feature high spatial resolution and a short revisit interval of 12 days. Each original SAR frame covers an east west swath width of approximately 250 km, fully encompassing the study area in the Anyang Puyang plain of Henan Province. For time-series analysis, we selected Sentinel-1A swath 2 and swath 3 data covering an area of approximately 170 km × 130 km (as shown in Fig. 1). To eliminate topographic phase contributions and support geocoding, we employed the TanDEM-X DEM (https://download.geoservice.dlr.de/TDM30_EDEM/), which offers improved temporal relevance (produced in September 2016), higher absolute accuracy (vertical error <10 m), and moderate spatial resolution (30 m). The use of TanDEM-X DEM enhances the accuracy of surface deformation inversion across the study area.

In addition to the SAR dataset, groundwater level time series from observation wells serve as an essential supplementary data

source in this study. A total of 85 groundwater wells were selected across the study area based on data collected from the Henan Provincial Department of Water Resources. (Fig. 1). All wells have long-term water level observations covering two overlapping periods: from May 2011 to September 2020 and from May 2019 to December 2023. The groundwater levels were measured twice a year, in May (dry season) and September (wet season). To align with the SAR imaging frequency (every 24 days used in this study), we jointly applied cubic spline interpolation and third-order polynomial fitting to resample the two observational periods, ultimately generating 87 groundwater level snapshots spanning from March 2017 to November 2022. These interpolated time series effectively capture both seasonal fluctuations and long-term trends of the confined aquifer systems in the study area, providing critical constraints for aquifer system parameter inversion [42]. Additionally, we collected a large volume of auxiliary hydrogeological data within the study area, including aquifer lithology, thickness distribution, and the spatial extent of low-permeability layers, as well as regional precipitation records. The integration of these supplementary datasets provides essential background information and parameter support for the SAR-based inversion of groundwater storage changes and skeletal specific storage coefficients, ensuring the scientific robustness and reliability of the results.

Furthermore, a campaign conducted by the Henan Institute of Surveying and Mapping involves 19 CORS stations (red rectangles in Fig. 1) evenly distributed throughout the Anyang-Puyang plain, where observed displacements are used to validate the large-scale land deformation results derived by the MT-InSAR technique.

3. Methodology framework

To demonstrate the proposed approach, a comprehensive inversion framework was developed to integrate MT-InSAR-derived land deformation with multi-year groundwater head observations. This framework involves InSAR data processing, MSSA-based signal decomposition, estimation of elastic and inelastic skeletal storage coefficients, and spatiotemporal analysis of TGWS changes. Fig. 2 illustrates the conceptual workflow, highlighting

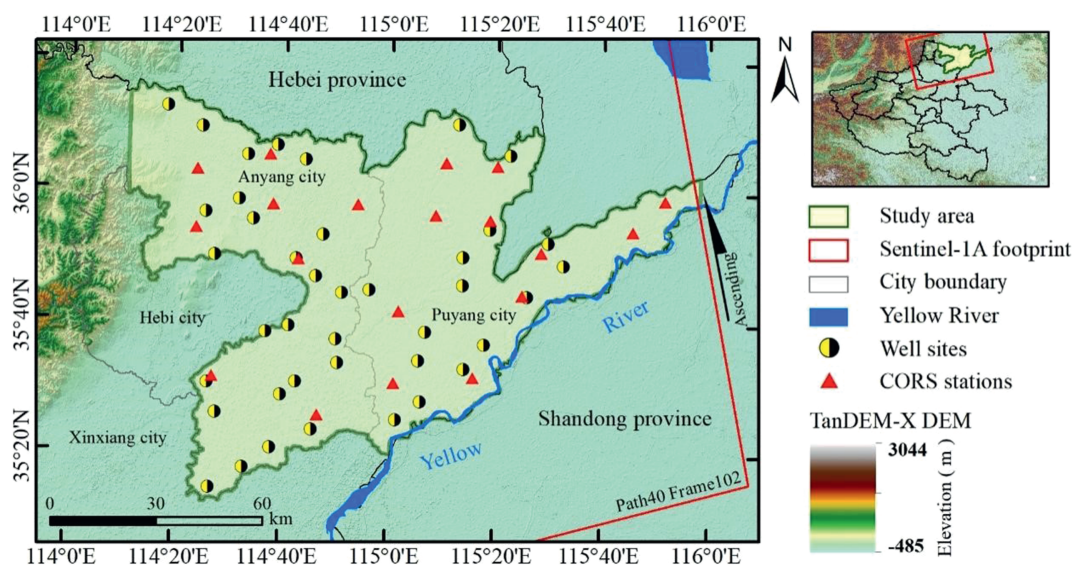


Fig. 1. Location and hydrogeological settings of the Anyang-Puyang Plain. The red rectangles represent five tracks of Sentinel-1A covering the entire study area. In-situ observations at wells and Continuously Operating Reference Station (CORS) are depicted by yellow-black circles and red triangles, respectively. The background is the TanDEM-X DEM. The inset map shows the location of the study area (light yellow) in China.

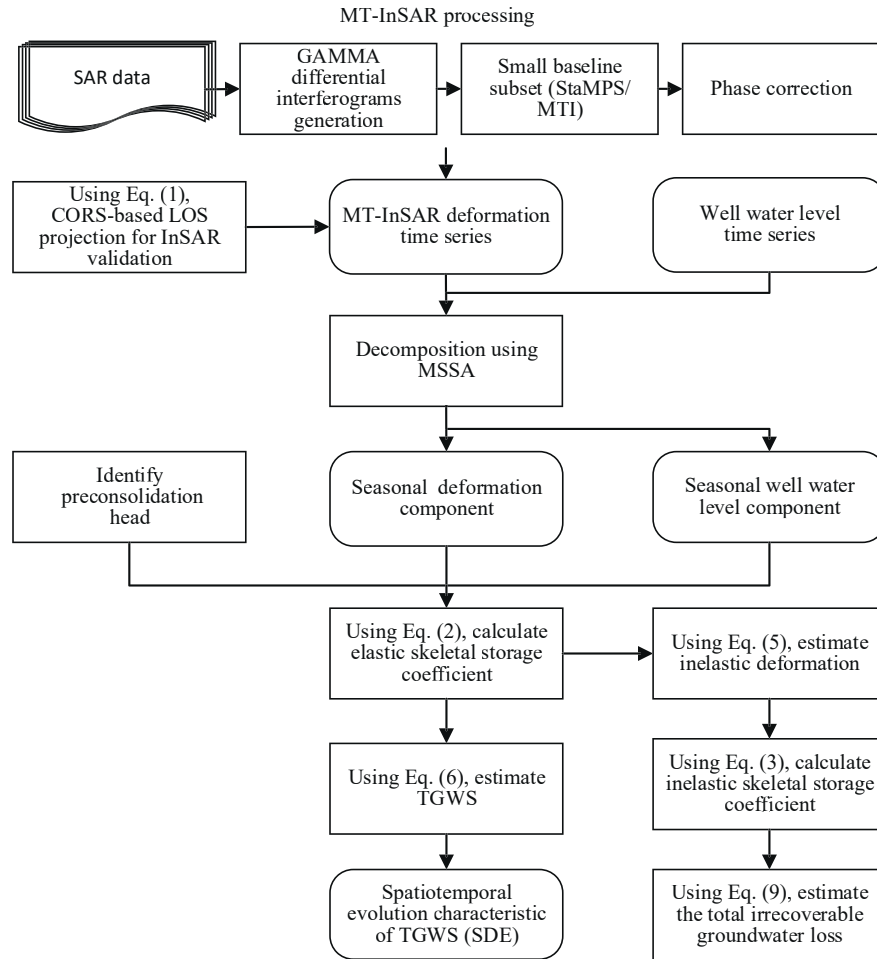


Fig. 2. Methodological workflow for groundwater storage inversion using InSAR and well observations.

the main data sources, computational steps, and analytical outputs used in this study. Each step is elaborated in the following subsections.

3.1. Time-series InSAR data processing

To demonstrate the generalizability of the proposed inversion framework, we apply it to the Anyang-Puyang Plain. To cover the entire Anyang-Puyang Plain from January 2017 to November 2022, a total of 66 SAR scenes acquired by the ascending Sentinel-1A satellite, along path 40-frames 112 with an average latency (time between acquisitions) of 30 days, were downloaded from the Alaska Satellite Facility. For the routine interferometric processing as co-registration, flattening, topographic phase computation based on TanDEM-X, interferogram generation, topographic phase removal and geocoding, etc., are performed by GAMMA software [43]. Due to the influence of Sentinel-1 TOPS imaging mode, the registration accuracy of the image azimuth needs to reach 0.001 pixels in order to avoid interference phase deviation of $>3^\circ$, therefore, the enhanced spectral diversity method [44] based on image information was used to refine the co-registration results on the basis of precision orbit and correlation alignment.

Subsequently, the small baseline subset processing implemented in StaMPS/MTI [45], was used to derive the spatial and temporal evolution of land deformation, which mainly includes the Stable Distributed Filtering Points (SDFPs) target points selection, spatial uncorrelated (correlated) look angle estimation, 3D

phase unwrapping, and master atmosphere and orbit error estimation. Additionally, when inspecting all interferograms individually, it was found that some neighbouring pairs connected to a particular SAR observation were severely contaminated by the long-wavelength phase ramp and short-wavelength turbulence [46,47]. Therefore, we first used a linear fitting to estimate the phase ramp attributable to orbital errors and the long-wave atmospheric phase disturbances, and then subtracted them from each unwrapped interferogram. Second, the Generic Atmospheric Correction Online Service for InSAR [48] was used to curb the negative effects of the stratified and turbulent atmospheric phase. Ultimately, a temporal baseline threshold of 90 days and a spatial baseline threshold of 150 m were applied, and low-quality interferograms exhibiting poor coherence or severe phase artefacts were visually identified and excluded. As a result, 115 single-master differential interferograms after removing various artefacts are obtained, from which we can derive the average deformation rate and cumulative displacement time series results for the study area over the observation period by least squares. Furthermore, the displacement time series and the mean deformation rates along the line-of-sight (LOS) direction were retrieved and converted into vertical deformation simply by dividing the cosine of the incidence angle, assuming the horizontal deformation is low in our study area.

To verify the reliability of the InSAR-derived deformation results, a cross-validation was conducted using vertical displacement data from 19 CORS distributed across the study area. CORS-

derived 3D displacement vectors were projected into the radar LOS direction to ensure consistency with InSAR geometry Eq. (1)

$$d_{\text{los}} = \begin{bmatrix} -\sin\theta\cos(\alpha_s - 3\pi/2) & -\sin\theta\sin(\alpha - 3\pi/2) & \cos\theta \end{bmatrix} \begin{bmatrix} d_{\text{North}} \\ d_{\text{East}} \\ d_{\text{Upside}} \end{bmatrix} \quad (1)$$

where d_{los} is the deformation of the radar LOS direction, d_{North} , d_{East} , d_{Upside} represent the local displacement components measured by Global Navigation Satellite System (GNSS) in the north, east, and vertical directions, respectively (in meters), θ is the radar incidence angle, α_s is the azimuth angle, $\alpha - 3\pi/2$ converts the satellite azimuth angle to the local East-North-Up coordinate frame. This transformation ensures that GNSS-derived displacement vectors are geometrically compatible with InSAR observations, enabling accurate and consistent validation of LOS deformation.

3.2. Aquifer parameters and storage inversion

3.2.1. Calculation of elastic skeletal storage coefficient

The skeletal storage coefficient is a key parameter representing the water-releasing capacity of an aquifer system. It is defined as the volume of water released or stored per unit area of the aquifer system due to compression or expansion of the aquifer skeleton, under a unit change in hydraulic head [49]. Therefore, the key to inverting groundwater storage changes based on MT-InSAR deformation time series and hydrogeological data lies in the accurate estimation of the skeletal storage coefficient of confined aquifers [50]. The skeletal storage coefficient exhibits significant differences before and after the effective stress exceeds the historical maximum effective stress. The water level corresponding to this “historical maximum effective stress” is referred to as the preconsolidation head [51]. For confined aquifers, when the current hydraulic head is above the preconsolidation head, both unconfined aquifers dominated by coarse-grained materials (sand, gravel, pebbles, grit) and weakly permeable layers composed of fine-grained materials (clay) primarily undergo elastic compression. This type of compression does not alter the structure of the sediment skeleton and is reversible with the recovery of the hydraulic head. The corresponding skeletal storage coefficient is relatively small.

Thus, accurate identification of the preconsolidation head is essential for determining the nature of surface deformation (elastic or inelastic) and for estimating the skeletal storage coefficient. However, this head is difficult to measure directly and tends to change gradually with ongoing groundwater extraction, making it challenging to distinguish the nature of deformation responses in practical applications. To address this, we utilized long-term and continuous observations of surface deformation and well water levels. Based on the historical groundwater extraction records in the study area, we identified well locations where the hydraulic head had fallen below the preconsolidation head. Data show that, since the 1970s, large-scale groundwater extraction for agricultural irrigation and industrial development has led to overall compaction of the aquifer system [39]. Accordingly, (1) we assumed that the groundwater levels in some wells in 1970 represent the natural condition of the aquifer system (i.e., before any major pumping commenced). Furthermore, (2) on the basis of (1), correlation analysis was performed between the long-term time series of cumulative surface displacement and the well water level time series, and those wells with a large correlation coefficient between head and InSAR deformation (>0.8) and small seasonal components were considered to reflect compression of

the weakly permeable layers more accurately. Therefore, the heads at these wells were deemed to be below the preconsolidation head, and these wells were used to invert the inelastic and elastic skeletal storage coefficients of the entire aquifer system.

Subsequently, for those wells where the current head is higher than the preconsolidation head, the total surface deformation observed by MT-InSAR consists of elastic deformation from unconfined aquifers dominated by coarse-grained materials and weakly permeable layers composed of fine-grained materials. We adopted a practical method proposed by Miller and Sgierzai [34], which assumes that the seasonal component of surface deformation is mainly caused by elastic compression, i.e., driven by the periodic variation of groundwater head. Based on this, the ratio of seasonal surface subsidence to the corresponding seasonal head change is used to estimate the elastic skeletal storage coefficient, and the calculation equation is as follows:

$$S_{\text{ke}} = \Delta d_s / \Delta h_s \quad (2)$$

where S_{ke} denotes the elastic skeletal storage coefficient; Δd_s and Δh_s represent the seasonal components of surface vertical displacement obtained from MT-InSAR and groundwater level variations observed in monitoring wells, respectively.

To address the challenge of extracting seasonal components from both deformation and groundwater level time series in Eq. (2), we employed the MSSA method. MSSA is a time series processing technique based on temporal and spatial covariance matrix decomposition. It does not require predefining periodicity or assuming sinusoidal waveforms, and it can stably extract quasi-periodic signals. This method is particularly suitable for identifying seasonal oscillations associated with periodic aquifer deformation and head variations. Therefore, in order to extract accurate seasonal signals of surface subsidence and groundwater head variation, we applied MSSA to the MT-InSAR deformation time series and the continuous well water level observations from March 2017 to November 2022. The seasonal and long-term trend components were decomposed from these data. On this basis, the elastic skeletal storage coefficient for each observation point or region was calculated using Eq. (2), providing a foundation for further distinguishing between recoverable and non-recoverable changes in groundwater storage.

3.2.2. Estimation of inelastic skeletal storage coefficient

When the current hydraulic head falls below the preconsolidation head, fine-grained soil layers (such as silt and clay) undergo inelastic compression, which manifests as permanent rearrangement of the skeletal structure and collapse of pore spaces. The irreversible compaction of the skeleton in weakly permeable layers becomes the dominant contributor to both surface subsidence and the non-recoverable portion of groundwater storage change. This process is typically accompanied by irreversible land subsidence and a permanent loss of storage capacity within the aquifer system. The groundwater released during this process thus becomes a “non-renewable resource” that is extremely difficult to replenish. For this irreversible compaction process, which primarily originates from the skeletal structure of weakly permeable layers (i.e., inelastic compression), we follow the relationship that can be used as proposed by Hoffmann in 2003 [29]:

$$\Delta d_{\text{inelastic}} / \Delta h = S_{\text{kv}} \left(1 - \frac{8}{\pi^2} e^{-\frac{\pi^2 t}{4\tau_0}} \right) \quad (3)$$

where $\Delta d_{\text{inelastic}}$ denotes the inelastic deformation; Δh is the cumulative change in the hydraulic head; S_{kv} is the inelastic skeletal storage coefficient; τ_0 is the compaction time constant,

representing a temporal lag caused by delayed equilibration of aquitard head levels to neighbouring aquifer head levels [52]. The term Δh in Eq. (3) is derived from historical groundwater level data provided by the Water Resources Department. $\Delta d_{\text{inelastic}}$ represents the inelastic deformation, which, together with the elastic deformation $\Delta d_{\text{elastic}}$, constitutes the total surface deformation observed by $\Delta d_{\text{MT-InSAR}}$. Based on the discussion above, we know that at those well locations where the current water head is lower than the preconsolidation head, the compression in weakly permeable layers is mainly governed by inelastic deformation of the aquifer skeleton (the magnitude of inelastic compaction can be 10 to 100 times that of elastic compaction). In contrast, in other cases where the water head is higher than or close to the preconsolidation head, both the aquifer and the weakly permeable layers predominantly undergo elastic compression. Therefore, using the elastic skeletal storage coefficient S_{ke} obtained from Eq. (2) in Section 3.2.1 and the observed head change Δh , the corresponding elastic deformation $\Delta d_{\text{elastic}}$ can be calculated by Eq. (4):

$$\Delta d_{\text{elastic}} = S_{\text{ke}} \Delta h \quad (4)$$

For those well locations where the current water level is lower than the preconsolidation head, the total deformation observed by $\Delta d_{\text{MT-InSAR}}$ includes both the elastic deformation of unconfined aquifers and the inelastic deformation of weakly permeable layers (confined aquifer). Therefore, by subtracting the elastic deformation $\Delta d_{\text{elastic}}$ from the total deformation $\Delta d_{\text{MT-InSAR}}$, the inelastic deformation $\Delta d_{\text{inelastic}}$ can be obtained:

$$\Delta d_{\text{inelastic}} = \Delta d_{\text{MT-InSAR}} - \Delta d_{\text{elastic}} = \Delta d_{\text{MT-InSAR}} - S_{\text{ke}} \Delta h \quad (5)$$

Once $\Delta d_{\text{inelastic}}$ and Δh observations are determined, this study uses the least-squares fitting method to invert Eq. (3), yielding the corresponding inelastic skeletal storage coefficient S_{kv} and compaction time constant τ_0 .

3.2.3. Estimation of groundwater storage change

When deep confined groundwater is extracted, the contribution of deep groundwater storage to the total extracted volume originates from: (1) the elastic expansion of water volume caused by the reduction of pore pressure; (2) the compression of the confined aquifer skeleton caused by the increase in effective stress.

Since the compressibility of water is much smaller than that of the aquifer skeleton, the water volume released due to elastic expansion can be neglected. Therefore, the change in deep groundwater storage is approximately equal to the compression of the aquifer skeleton, which corresponds to the total volume of surface deformation, namely:

$$\Delta V = \Delta d_{\text{MT-InSAR}} \cdot \text{Area} \quad (6)$$

where ΔV represents the total change in groundwater storage during the observation period, $\Delta d_{\text{MT-InSAR}}$ is the cumulative surface subsidence derived from MT-InSAR, and Area is the spatial extent over which the deformation is calculated.

3.3. Extraction of spatiotemporal evolution characteristic of TGWS

To further quantify and characterize the spatiotemporal evolution of TGWS change in the study area during 2017–2022, this study introduces the SDE method to comprehensively describe their spatial clustering, primary dispersion direction, and degree of dispersion. This method constructs elliptical representations of the spatial distribution of groundwater storage change by calculating the geometric centre of TGWS points at each time step, along with the standard deviations along the major and minor

axes. The SDE method not only reveals the spatial pattern of groundwater storage change—including the degree of spatial concentration or dispersion—but also delineates the dominant orientation and spatial heterogeneity of the distribution. By calculating parameters such as the ellipse centre, the lengths of the major and minor axes, and the azimuth angle of the ellipse, the spatial distribution trends and evolution pathways of TGWS can be quantitatively analysed from multiple dimensions.

In this study, groundwater storage change results inverted from March 2017 to November 2022 were used to construct standard deviational ellipses for three time periods, aiming to visualize and compare the spatial migration trends and dominant directions of TGWS. Specifically, the calculation equations are presented in Eq. (7) and Eq. (8), which define the key geometric parameters, including the centre coordinates, lengths of the major and minor axes, and orientation angles of the ellipses. The introduction of this method effectively supplements conventional point-based analytical approaches. Through spatial statistical analysis reveals regional differences and evolution trends in groundwater storage change, providing theoretical support and methodological foundation for a better understanding of the spatial response mechanisms of groundwater systems in northern Henan.

$$\text{SDE}_x = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n}}, \text{SDE}_y = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{Y})^2}{n}} \quad (7)$$

$$\tan \theta = \frac{A+B}{C} = \frac{(\sum_{i=1}^n \tilde{x}_i^2 - \sum_{i=1}^n \tilde{y}_i^2) + \sqrt{(\sum_{i=1}^n \tilde{x}_i^2 - \sum_{i=1}^n \tilde{y}_i^2)^2 + 4 \times (\sum_{i=1}^n \tilde{x}_i \tilde{y}_i)^2}}{2 \times \sum_{i=1}^n \tilde{x}_i \tilde{y}_i} \quad (8)$$

where x_i and y_i are the coordinates of SDFPs pixels corresponding to the arithmetic mean centre of $\bar{X}$ and $\bar{Y}$, their deviations are $\tilde{x}_i$ and $\tilde{y}_i$, and n is the total number of pixels in SDFPs.

4. Results and discussion

4.1. Land deformation and its response to hydraulic head changes

Vertical deformation rate map of the Anyang-Puyang Plain was obtained through multi temporal InSAR processing (Fig. 3), from which a total of 225793 SDFPs were extracted, with an average point density of approximately 20 points per km². The results indicate that surface deformation in the study area exhibits significant heterogeneity across both spatial and temporal scales. Overall, the ground surface remains relatively stable, but notable subsidence or uplift phenomena are observed in certain localized regions.

In the northern part of the study area, a pronounced subsidence centre has developed from the urban area of Anyang City (Adjacent to the east of zone 1 in Fig. 3). The maximum annual deformation rate in this zone reaches −73 mm/year, making it the area with the greatest and most spatially continuous deformation, covering 602.25 km² (zone 1 in Fig. 3). In the southern boundary region between Huaxian County and Fengqiu County (In the area between well 27 and well 28), significant subsidence is also observed, with most deformation rates ranging from −30 to −15 mm/year. This deformation zone covers 266.86 km² (zone 2 in Fig. 3) and exhibits relatively poor surface stability. In contrast to the subsiding areas, several uplift zones are also present in the study area. These are mainly located near the Yuecheng Reservoir in Anyang City (zone 3

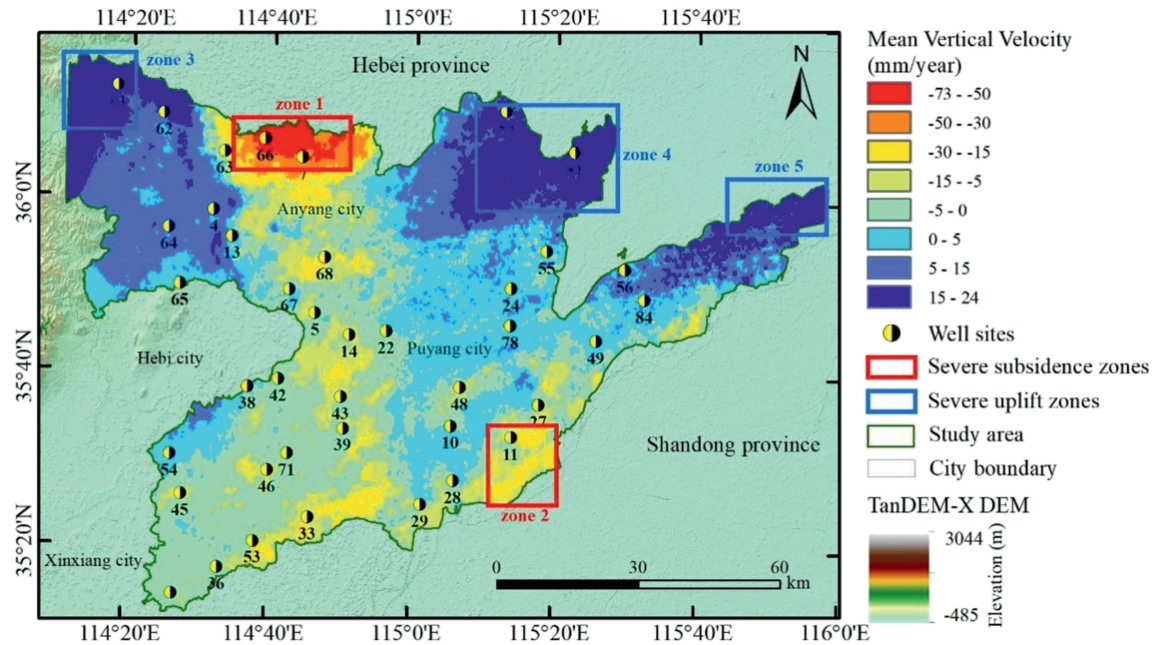


Fig. 3. Spatial distribution of average vertical surface deformation rates derived from InSAR observations from March 2017 to November 2022. Negative values indicate ground subsidence, while positive values represent uplift.

in Fig. 3), in the eastern part of Nanle County (zone 4 in Fig. 3), and the eastern part of Taiqian County (zone 5 in Fig. 3). The maximum annual uplift rate reaches 23 mm/year. The upward surface trends in these areas stand in sharp contrast to the surrounding subsiding regions, indicating localized differentiation in the groundwater surface system responses. Fig. 4 presents the cumulative deformation from December 2017 to November 2022, revealing the progressive intensification of subsidence across key regions, particularly in the northern part of the study area.

Cross-validation between MT-InSAR results and CORS measurements showed strong consistency across the study area. The regression analysis yielded an R^2 of 0.974 and RMSE of 7.2 mm, confirming the accuracy and reliability of the InSAR-derived deformation time series (Fig. 5).

To further quantify the coupling characteristics between groundwater head and surface subsidence, a fuzzy matching approach was applied between InSAR deformation targets and well locations. Specifically, for each observation well located in typical subsidence zones, all InSAR deformation points within a 500-m radius were selected as reference points. The average of their deformation time series was computed to represent the surface deformation behaviour at the well location. Subsequently, dual-axis scatter plots were generated to visualize the relationship between the calibrated displacement and groundwater level time series. Pearson correlation coefficients and corresponding p-values were calculated to quantify the correlation between the two time-series, as seen in Fig. 6.

The resulting time series comparisons between average cumulative surface subsidence (red dots) and groundwater level variations (blue curves) for nine representative monitoring wells (7, 27, 33, 43, 46, 53, 63, 66, and 68) are presented in Fig. 6, covering the period from March 2017 to November 2022. The results show that the temporal evolution of ground deformation and groundwater levels at most wells exhibit strong consistency, with clear linear responses. Among them, wells 7, 63, and 66 are located in the northern subsidence centre of the study area (seen in Fig. 6(j)), where groundwater

levels dropped by more than 5 m over six years, and cumulative surface subsidence reached approximately 400 mm, 150 mm, and 450 mm, respectively. The corresponding deformation and water level time series show a high linear correlation, with Pearson coefficients of 0.993, 0.980, and 0.981, respectively (seen in Fig. 6(a), (f), and (g)). These wells represent typical inelastic compaction behaviour in deep confined aquifers, where the aquifer skeleton is loosely structured and highly compressible, resulting in rapid subsidence responses with minimal time lag. In the southern subsidence zone, wells 33, 53, and 46 show groundwater level declines of 2–3 m, with cumulative subsidence ranging from 90 to 160 mm (seen in Fig. 6(a), (f), and (g)). Although the overall trends are consistent, the subsidence continued to accumulate even after groundwater levels began to recover in 2020, indicating a temporal lag. This reflects the slow drainage rate of aquitards, where compaction processes persist after head recovery, a typical manifestation of lagged subsidence under low-permeability aquitard control. Well 27 (in the central region in Fig. 6(a)), and wells 43 and 68 (in the southeastern subsidence area in Fig. 6(d) and (e)), show moderate subsidence (80–140 mm) and groundwater level declines of 2–4 m. Despite smaller magnitudes, their time series exhibit stable and synchronized responses.

Overall, the Pearson correlation coefficients between corrected displacement and groundwater level time series at the nine well locations range from 0.0111 to 0.9960, with an average value of 0.8270. These results indicate significant spatial heterogeneity in the deformation–head coupling across the study area. In core subsidence zones, synchronous and direct compaction responses dominate, while in marginal and transitional zones, lagged deformation and complex hydromechanical behaviours are more common, reflecting the joint control of stratigraphic structure, hydraulic conductivity, and aquifer composition. These findings confirm that in most cases, surface subsidence is strongly correlated with groundwater level decline, supporting the conclusion that excessive groundwater extraction for irrigation in the Anyang Puyang plain leads to significant head decline, which in turn induces surface deformation.

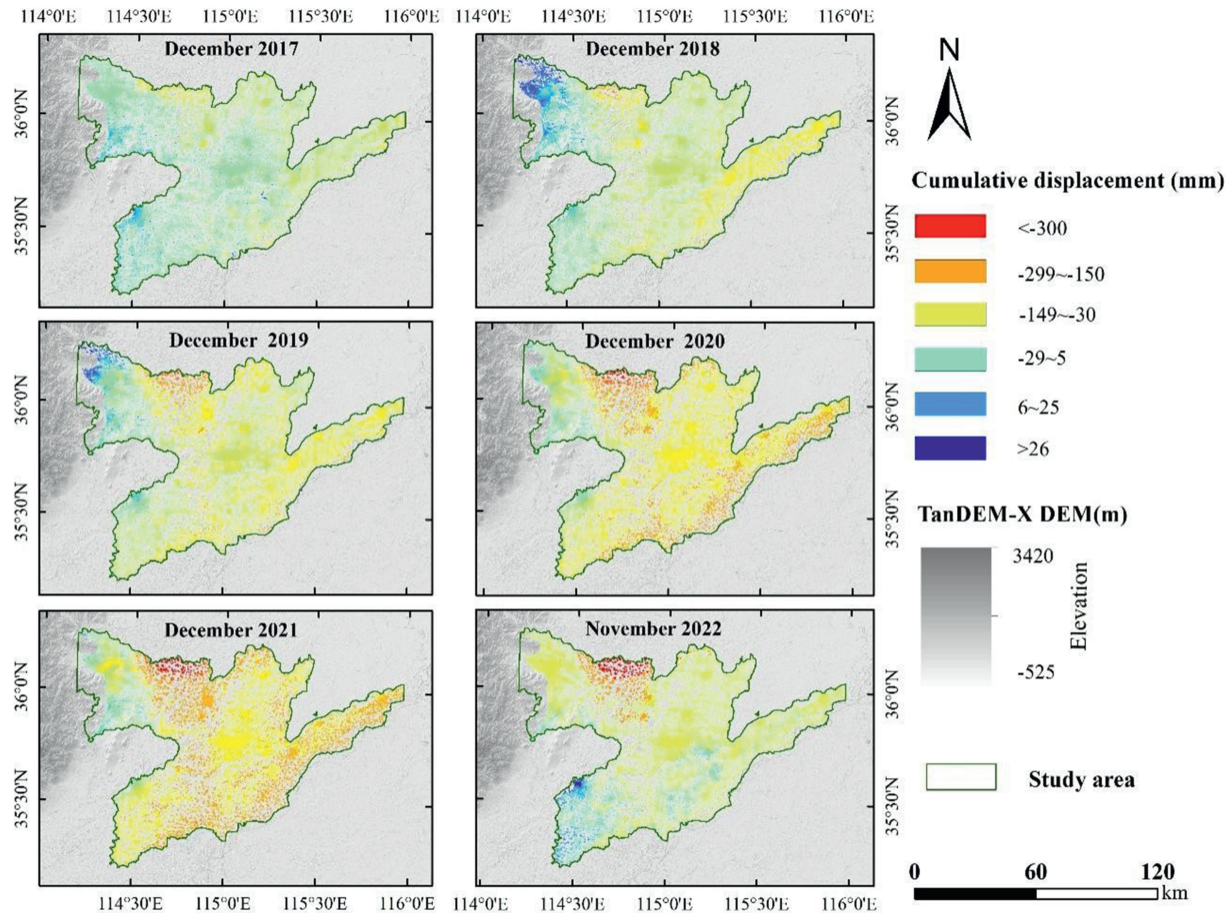


Fig. 4. Spatial distribution of cumulative surface deformation across the Anyang-Puyang Plain. Each panel represents cumulative displacement for the respective year-end. Displacement values are classified into six categories, with red indicating severe subsidence (>300 mm) and blue indicating uplift.

4.2. Skeletal storativity inversion and TGWS variations

4.2.1. Elastic skeletal storativity inversion

After obtaining a high-precision cumulative surface deformation time series, the skeletal storage coefficients of the confined

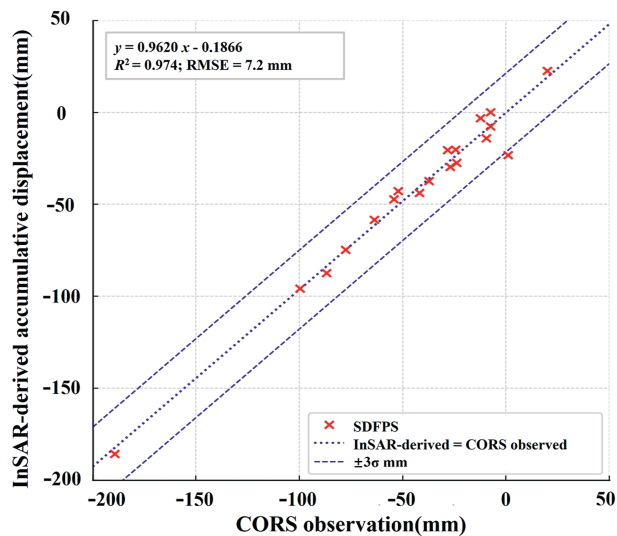


Fig. 5. Regression between the accumulative vertical displacement of Sentinel-1A and the CORS observed results in the Anyang-Puyang Plain. The two sets of results were resampled to a grid of $500 \text{ m} \times 500 \text{ m}$.

aquifer system in the region were estimated based on the method described in Section 3.2.1. To achieve this, the extraction of seasonal deformation components from the MT-InSAR displacement and groundwater level observation time series in the Anyang-Puyang Plain is a necessary prerequisite. Accordingly, the seasonal amplitudes of surface deformation and groundwater level change Δd_s and Δh_s from March 2017 to November 2022 were calculated, as shown in Fig. 7(a) and (b).

Fig. 7 illustrates the spatial distribution of seasonal amplitudes of surface deformation in the Anyang Puyang plain from March 2017 to November 2022, reflecting the degree of periodic response of surface deformation to intra-annual groundwater head fluctuations. The amplitude values range from approximately 2–42 mm, with colours transitioning from blue to red, indicating increasing deformation magnitude from weak to significant. Overall, the seasonal deformation response in this region shows pronounced spatial variability. Higher deformation amplitudes (orange-red to red areas) are observed in the urban area of Puyang City, northern Puyang City, and northern Anyang City, while lower amplitudes (blue-green areas) are found in the southern parts, such as Taiqian County and Huaxian County.

In areas with strong seasonal deformation, the intra-annual surface deformation amplitudes generally exceed 25 mm, with maximum values surpassing 40 mm. This indicates that the groundwater system exhibits strong elastic or delayed responses to water head fluctuations caused by precipitation and pumping-recharge cycles. This behaviour may be attributed to loosely structured aquifers, active confined systems, and evident extraction-

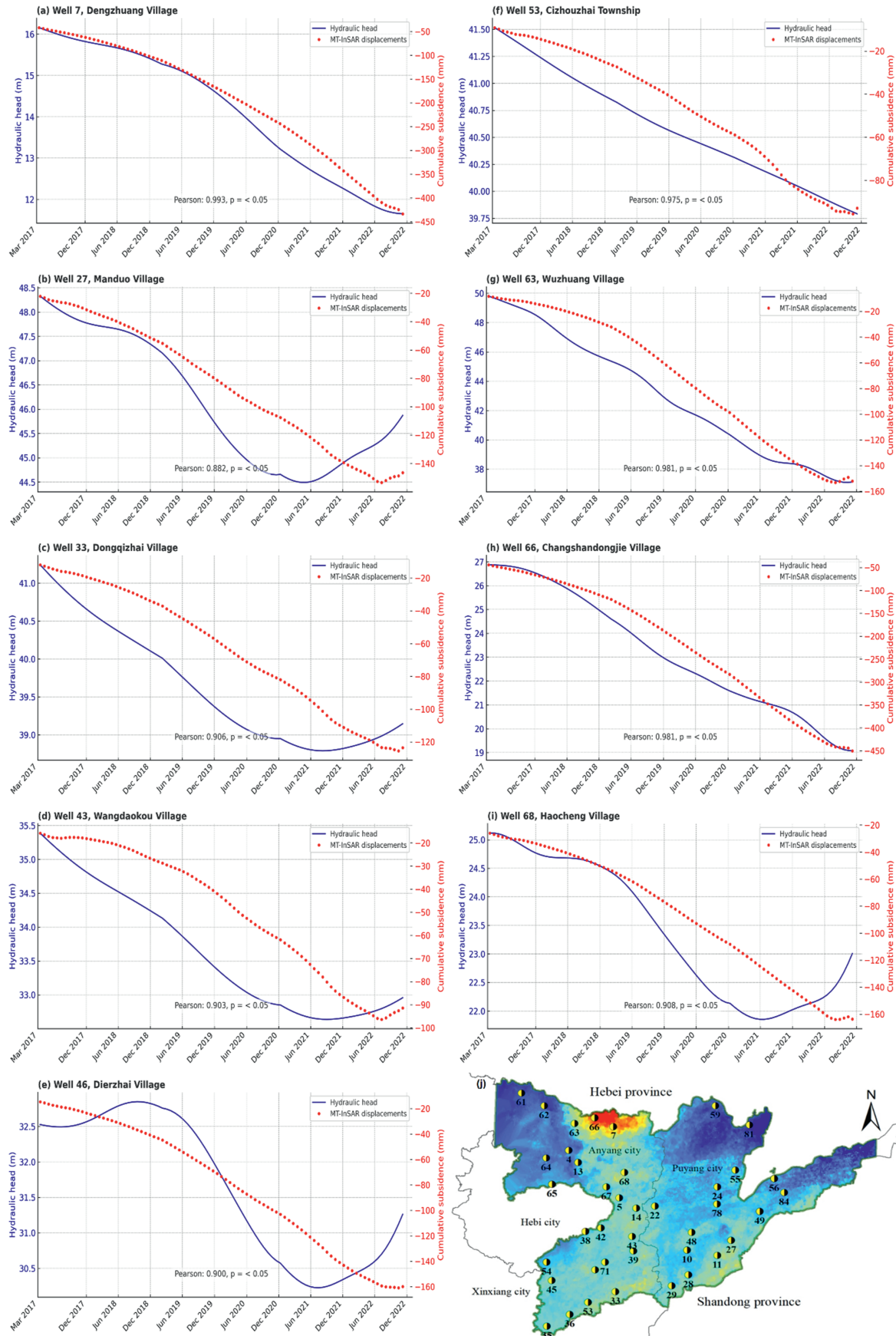


Fig. 6. Time-series subsidence versus hydraulic head changes at wells 7, 27, 33, 43, 46, 53, 63, 66, 68 in confined aquifer. Pearson correlation coefficients and p-values are shown to quantify the linear relationship between the two variables.

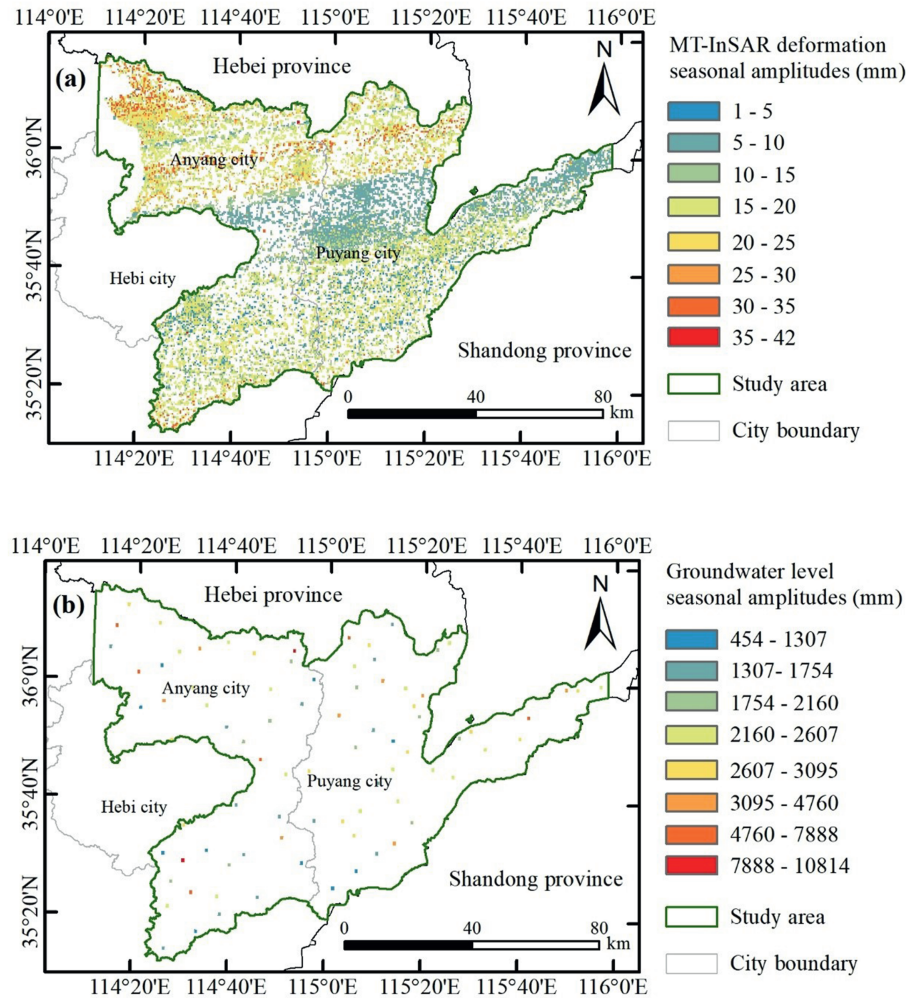


Fig. 7. (a) Seasonal amplitude of surface deformation (mm); (b) Seasonal amplitude of observed groundwater levels (mm) at 85 well locations.

recharge periodicity. In contrast, regions with low deformation amplitudes show minimal surface response despite groundwater head fluctuations of 0.2–1 m within the year. This may result from irreversible compaction of the strata, leading to a weakened storage deformation mechanism.

The elastic (or inelastic) skeletal storage coefficient is a key parameter that characterizes the volume of water released or stored by the deformation of confined aquifer systems and weakly permeable layers under unit hydraulic head change, and serves as an important indicator for evaluating recoverable groundwater storage. Therefore, in this study, we further estimated the elastic skeletal storage coefficient S_{ke} by combining the seasonal amplitudes of MT-InSAR deformation and head measurements at 85 observation wells, following Eq. (2) (see Table S1). Furthermore, the point-based estimates at the 85 wells were interpolated using the IDW method to derive the regional-scale distribution of elastic skeletal storage coefficients across the Anyang-Puyang Plain (Fig. 8). The resulting spatial pattern reveals significant heterogeneity, with values ranging from 9.3×10^{-3} to 1.596×10^{-2} . The highest coefficients are observed in the northern part of Anyang City, while the lowest values are concentrated in the central and southern parts of Puyang City. Regionally, low values of the elastic coefficient appear in western Anyang City, northern Puyang City, and along the Yellow River floodplain, likely due to densely

layered, low-permeability aquitards or relatively consolidated formations. In contrast, eastern Puyang City and northeastern Anyang City exhibit higher coefficients, suggesting these areas consist of loosely structured aquifers with a more active hydraulic exchange, where deformation is more sensitive to head variations.

4.2.2. Inelastic skeletal storativity inversion

To further evaluate the irrecoverable groundwater loss caused by the inelastic compaction of confined aquifers during the observation period, we applied the method described in Section 3.2.2. Specifically, 30 observation wells (Table 1) were selected based on criteria including long-term groundwater level decline since the large-scale groundwater abstraction in the 1970s, small seasonal head fluctuation, and a clear correlation between deformation and head variation. For these wells, the inelastic skeletal storage coefficient (S_{kv}) and the compaction time constant (τ_0) were estimated through curve fitting based on Eq. (3). The results show that S_{kv} ranges from 3.62×10^{-2} to 4.57×10^{-2} (see Table S1), which is generally consistent with pumping test results in regions with similar hydrogeological and climatic conditions in northern China (1.0×10^{-3} to 8.0×10^{-3}) [36].

At typical sites such as well 5 (see Table 1), the inelastic skeletal storage coefficient is approximately 12.63 times greater than the elastic coefficient, indicating that the observed deformation is

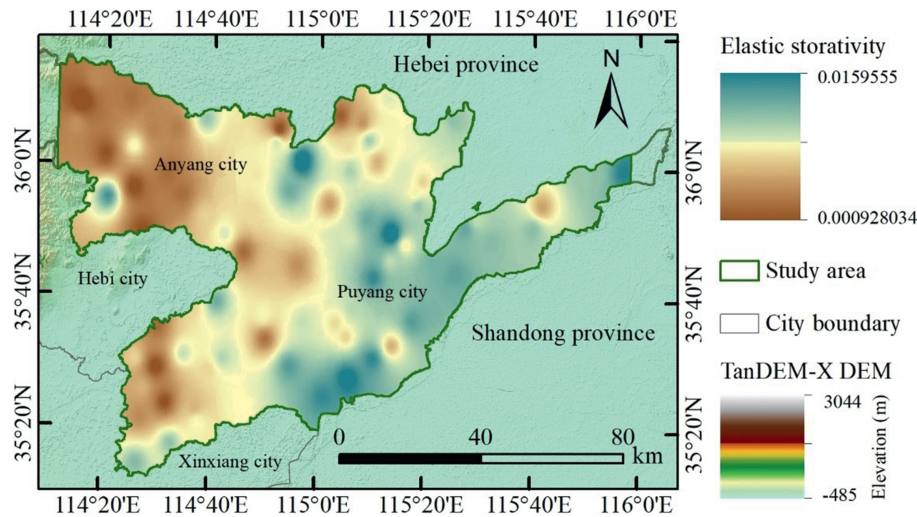


Fig. 8. Spatial distribution of the elastic skeletal storage coefficient in the Anyang-Puyang Plain.

primarily governed by irreversible inelastic compaction, with the inelastic component accounting for over 90% of the total groundwater loss. The estimated compaction time constants at wells 4, 7, and 10 are range from 1.3×10^{-2} to 2.3×10^{-2} years, while that of well 66 exceeds 1.3 years, suggesting spatial heterogeneity in aquifer response. This discrepancy may be attributed to variations in local hydrogeological structures or time-lag effects in the deformation head relationship.

Finally, the estimated values of S_{kv} from the 30 selected wells were interpolated using the IDW method to generate the spatial distribution map of inelastic skeletal storage coefficients (Fig. 9), providing a crucial basis for assessing irrecoverable groundwater loss across the study area.

Table 1
Elastic and inelastic skeletal storage coefficients and compaction time constants (τ_0) for the 30 selected observation wells used in inelastic parameter estimation.

Well number	Elastic stroavity	Inelastic storativity	τ_0 (year)
5	0.003092361	0.039041708	0.008
7	0.007073468	0.021152541	0.013
10	0.006692352	0.017415126	0.023
11	0.005696095	0.06154638	0.957
14	0.006110187	0.049735187	0.940
22	0.004627144	0.045235664	1.015
24	0.015987288	0.039389243	0.973
27	0.012217008	0.036074974	0.975
29	0.013197706	0.032429551	1.050
33	0.00789328	0.029341522	1.020
35	0.010835254	0.026728866	1.072
36	0.010486584	0.0245823	1.093
38	0.006724329	0.021034118	0.852
39	0.003372006	0.019111879	1.293
42	0.011508732	0.01779562	1.085
43	0.007789444	0.016917477	1.203
45	0.005755597	0.016997862	1.235
48	0.009482184	0.016208411	1.087
49	0.011979488	0.014088018	1.142
53	0.007939632	0.01352275	1.146
54	0.006833623	0.012957409	1.144
59	0.008459279	0.011501319	1.230
62	0.003356935	0.010969032	1.226
63	0.003840361	0.010634341	1.237
64	0.001521672	0.010218093	1.241
66	0.010333204	0.009789588	1.306
67	0.008642033	0.009527607	1.289
68	0.006866243	0.0088744	1.277
81	0.009283187	0.015619627	1.266
84	0.010800757	0.037695262	1.280

*Wells were selected based on long-term head decline since the 1970s, minimal seasonal fluctuations, and strong correlation with InSAR-derived deformation.

Based on the estimated S_{kv} , we further calculated the irrecoverable groundwater loss in the confined aquifers of the Anyang Puyang plain during the period March 2017 to November 2022. The calculation followed the equation below:

$$\Delta V_{\text{confined}}^{\text{loss}} = S_{kv} \cdot \Delta h \cdot \text{Area} \tag{9}$$

where Δh represents the cumulative head decline at each observation well, and Area denotes the corresponding spatial extent. To obtain high-resolution spatially distributed loss estimates, we first interpolated the Δh values from 30 typical observation wells using the IDW method. The resulting surface was then clipped to match the extent of the skeletal storage coefficient grid. Subsequently, pixel-wise calculations were performed using raster multiplication for pixels with $\Delta h < 0$ excluding areas where no head decline or even water table rise occurred, i.e., regions without inelastic compaction or recharge-driven uplift.

The final result shows that from March 2017 to November 2022, the total irrecoverable groundwater loss in the study area was approximately $3.01 \times 10^8 \text{ m}^3$. The severely affected regions are primarily concentrated in northern Anyang City, northern Neihuang County, southwestern Huaxian County, and southern parts of Puyang City. These results indicate that continuous groundwater overexploitation has led to significant inelastic compaction in weakly permeable layers across the affected zones.

4.2.3. TGWS variations in the confined aquifer

Since cumulative surface subsidence can, under certain conditions, be approximately equivalent to the water volume released due to aquifer system compaction, we used the total deformation volume derived from MT-InSAR and Eq. (6) to estimate the groundwater storage changes for each grid cell. On this basis, to further quantify the temporal trend of groundwater storage variation, we introduced the concept of Equivalent Water Thickness (EWT) to represent the change in groundwater storage per unit area. Specifically, the cumulative deformation volume was first standardized to a uniform spatial resolution grid. The TGWS of the study area was then estimated by summing the deformation volume across all grid cells (i.e., the total pixel area).

Taking March 2017 as the reference date, we calculated the cumulative groundwater storage change at the end of each year relative to the starting time. The conversion from mass to thickness was carried out using the following mass thickness relationship: $1 \text{ kg/m}^2 \text{ water} = 0.1 \text{ cm EWT}$.

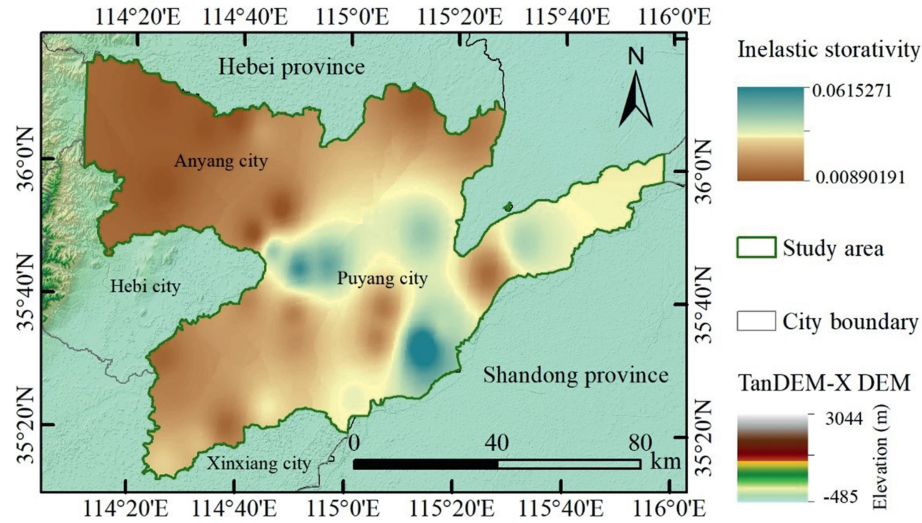


Fig. 9. Spatial distribution of the inelastic skeletal storage coefficient in the Anyang-Puyang Plain.

By converting the groundwater storage change from mass units to equivalent water thickness, the spatially explicit visualization of groundwater storage variations in the Anyang-Puyang Plain from March 2017 to November 2022 was achieved (see Fig. 10).

As seen in Fig. 10, during the study period from March 2017 to November 2022, the TGWS in the Anyang-Puyang Plain exhibited a continuous declining trend. Over this period, the average EWT deficit across the study area reached -73 mm, corresponding to a

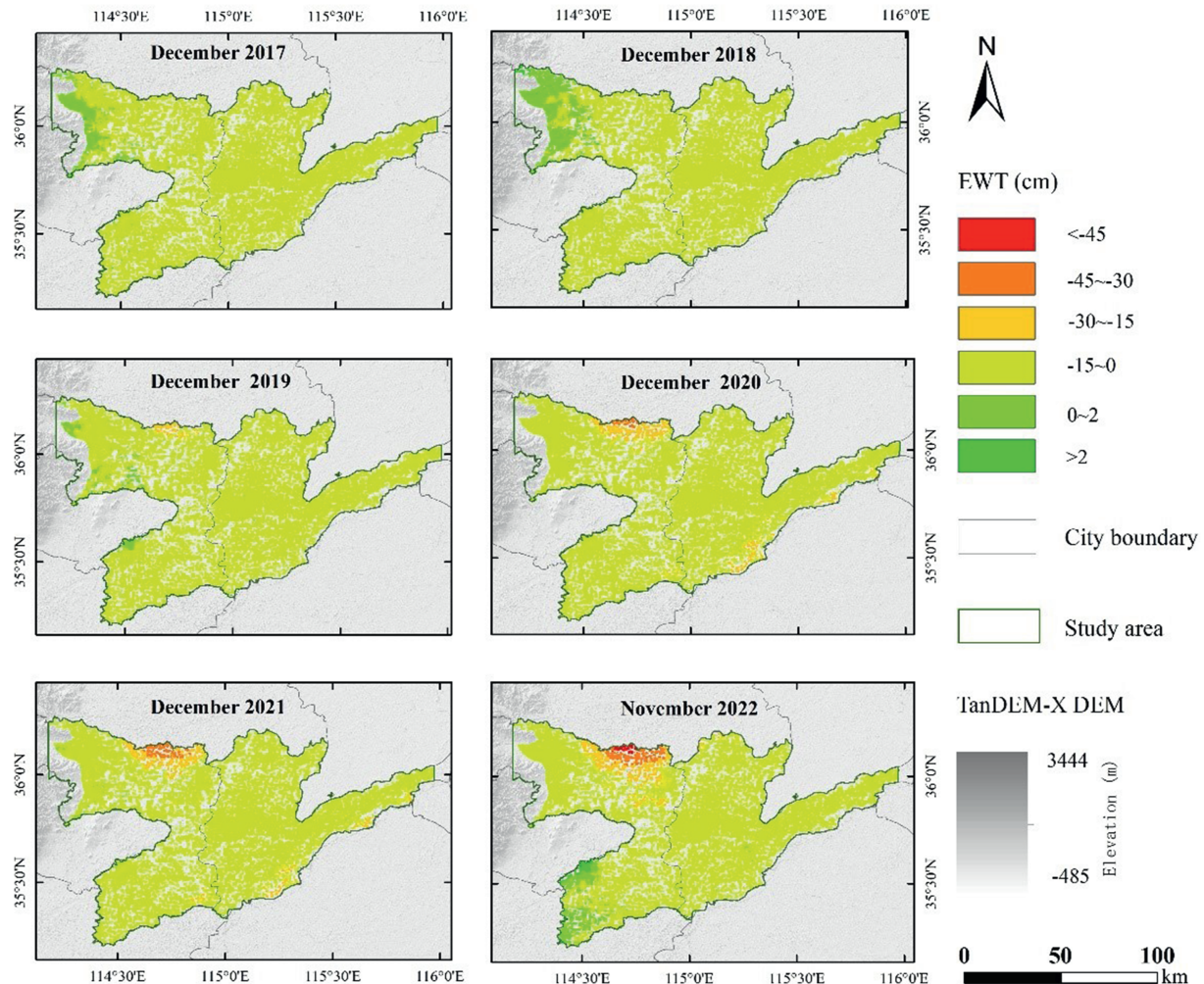


Fig. 10. Spatiotemporal evolutions of the TGWS in Anyang-Puyang Plain from March 2017 to November 2022, expressed as EWT. Each panel shows the cumulative change in groundwater storage relative to March 2017.

cumulative groundwater storage loss of $-12.27 \times 10^9 \text{ m}^3$. On an annual basis, this equates to an average storage loss rate of $-2.19 \times 10^9 \text{ m}^3/\text{year}$, and an average EWT decline rate of $-12.92 \text{ mm}/\text{year}$, indicating that the regional groundwater system is undergoing a marked depletion under the persistent high-intensity extraction regime. Unlike other typical subsidence areas such as the Beijing Tianjin Hebei region, where groundwater depletion has shown signs of stabilization—particularly following the operation of the South-to-North Water Transfer Project Middle Route [53,54]—the groundwater storage in the Anyang Puyang plain has not shown clear signs of stabilization during the study period. The region remains in a state of sustained overexploitation, predominantly driven by agricultural irrigation demand.

It is worth noting that the decline in the spatial pattern of groundwater storage shows considerable heterogeneity. The most severe reductions are concentrated in northern Anyang City, the Nanle Qingfeng area, and eastern Puyang City, indicating poor recoverability of the groundwater systems in these zones and prolonged irrecoverable groundwater withdrawal.

4.3. Spatiotemporal variations of TGWS

To further reveal the spatial evolution characteristics of TGWS changes in the Anyang Puyang plain, we performed a spatial trend analysis based on annual EWT data from March 2017 to November 2022 using the SDE method as described in Eq. (7) and Eq. (8). To focus on groundwater depletion zones, all positive EWT values were excluded prior to calculation, and the remaining negative values were converted to absolute values, allowing EWT to represent the groundwater depletion magnitude—larger values indicating more severe loss. The results are shown in Fig. 11.

From March 2017 to November 2022, standard deviational ellipses derived from annual TGWS variations revealed a clear north-westward migration of groundwater depletion centers across the Anyang-Puyang Plain. As shown in Table 2, the ellipse centroids shifted from 115.1156°E , 35.7808°N in 2017 (eastern Hualong District, Puyang City) to 114.8896°E , 35.9218°N in 2022 (northeastern Neihuang County, Anyang City), indicating a progressive convergence of depletion toward the boundary region between northeastern Anyang and northern Puyang. Accompanying this spatial shift, the geometry of the ellipses exhibited notable evolution: the major axis grew from 89.1 km to a peak of 95.8 km in 2019 before reaching 97.5 km in 2022, which corresponded to the

most widespread groundwater depletion observed during the study period. Meanwhile, the minor axis contracted from 67.3 km to 58.8 km, and the ellipse shape became increasingly elongated, reflecting enhanced spatial concentration in the vertical direction and stronger anisotropy. By 2022, the ellipse rotation angle reached 110.6° , suggesting an increasingly directional depletion pattern aligned toward the northeast. The areal extent of depletion, as captured by the ellipses, also followed a dynamic trajectory: it expanded to a maximum of 5650 km^2 in 2019, then gradually contracted to 4499 km^2 in 2022, indicating a staged process of groundwater loss with an initial phase of expansion followed by spatial consolidation. Together, these changes reflect a coherent spatiotemporal pattern characterized by north-westward migration, increased directional clustering, and the transition from dispersed multi-centre depletion to a concentrated dominant zone, underscoring the evolving structural response of the aquifer system to prolonged groundwater overexploitation.

5. Conclusion

Based on MT-InSAR-derived surface deformation time series (2017–2022) and multi-year groundwater head observations, this methodologically driven study develops and validates a generalizable inversion framework that integrates remote sensing and hydrogeological data to estimate the skeletal storage coefficients and quantify groundwater storage changes in the Anyang Puyang plain. Results indicate a strong coupling between land subsidence and water level decline, with pronounced spatial heterogeneity. Significant subsidence was observed in urban Anyang and Huaxian Taiqian regions, with rates up to $-72.53 \text{ mm}/\text{yr}$ and a maximum Pearson correlation of 0.993, confirming that confined aquifer drawdown—particularly inelastic compaction—is the primary driver. The elastic skeletal storage coefficients, ranging from 9.3×10^{-4} to 1.596×10^{-2} , exhibit clear spatial variability, with higher values in northern and border areas and lower values in central zones. In contrast, inelastic coefficients, estimated from 30 wells, range from 3.62×10^{-2} to 4.57×10^{-2} —5 to 12 times greater—and are concentrated in northeastern Anyang, Neihuang, and southwestern Huaxian, suggesting widespread irreversible compaction and an estimated cumulative irrecoverable groundwater loss of about $3.01 \times 10^8 \text{ m}^3$ during 2017–2022. TGWS, expressed via EWT, declined by $-12.27 \times 10^9 \text{ m}^3$, averaging $-2.19 \times 10^9 \text{ m}^3/\text{yr}$, forming a pronounced north south

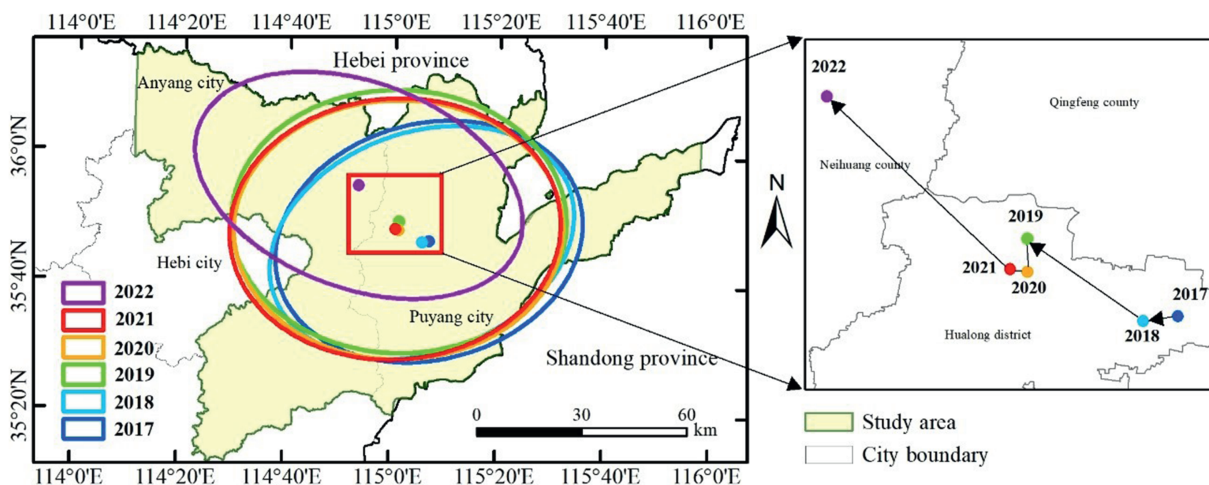


Fig. 11. EWT SDEs and centroid migration trajectories of groundwater storage depletion areas. Each ellipse represents the spatial distribution pattern and directional trend of annual groundwater depletion, while the dots indicate the centroid positions for each year.

Table 2

Spatiotemporal parameters of the standard deviational ellipses of TGWS (2017–2022) derived from EWT distribution.

Year	X-axis coordinate (°E)	Y-axis coordinate (°N)	Major axis (km)	Minor axis (km)	Rotation angle θ (°)	Shape Area (km ²)
2017	115.1156	35.7808	89.1135	67.3095	74.8267	4710.694953
2018	115.0931	35.7778	89.6416	62.7929	69.9129	4420.620718
2019	115.0186	35.8307	95.8121	75.0925	90.9821	5650.442139
2020	115.0185	35.8091	94.1099	73.8896	89.4709	5461.158721
2021	115.0075	35.8111	94.7023	74.4636	85.9071	5538.224474
2022	114.8896	35.9218	97.4771	58.7763	110.5925	4499.488734

gradient of depletion, with more severe losses in the north. Spatial analysis using SDE revealed a clear north-westward shift in the depletion centre, with the ellipse centroid moving from Puyang to northeastern Anyang, the major axis lengthening to 97.5 km, and the rotation angle increasing from 74.8° to 110.6°, indicating enhanced spatial convergence and directionality. Collectively, the results highlight severe structural degradation of the aquifer system under long-term overexploitation, characterized by reduced elastic response, intensified inelastic compaction, and continued storage loss. These findings offer critical parameters and spatial insights for guiding groundwater regulation, recovery planning, and future analysis of aquifer compaction mechanisms in over-drawn regions. It should be noted that the proposed framework assumes vertical deformation as the dominant displacement component and adopts a regional generalization of storage coefficients based on available well data. While these assumptions are supported by the confined aquifer characteristics of the study area, they may introduce uncertainties in settings with significant lateral heterogeneity or fault-controlled deformation.

CRedit authorship contribution statement

Zheng Zhou: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jie Meng:** Resources, Investigation, Formal analysis. **Jiyuan Hu:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Deng Pan:** Validation, Resources. **Menglei Xie:** Visualization, Data curation. **Jiayao Wang:** Supervision, Funding acquisition. **Jiabei Wang:** Validation, Data curation. **Chenxiang Wang:** Writing – review & editing, Formal analysis.

Data availability statement

The TanDEM-X Digital Elevation Model was obtained from https://download.geoservice.dlr.de/TDM30_EDEM/. Sentinel-1A SAR data were freely accessible from ESA portals, and reanalysis atmospheric data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI, <https://www.ncei.noaa.gov>). Groundwater level time series from 85 observation wells were obtained from the Henan Provincial Department of Water Resources and were not publicly available due to institutional restrictions; access may be granted upon reasonable request. Additional hydrogeological data (e.g., aquifer lithology, thickness, and low-permeability layer distributions) were also used in this study. CORS monitoring data were provided by the Henan Remote Sensing Institute and were not publicly available; access must be formally requested from the data-providing institution.

Declaration of competing interest

The authors declare that there is no conflicts of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geog.2025.09.004>.

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