Postprint: Sustainability Assessment of Groundwater Resources in the Northwestern Arid Region Based on GRACE and GLDAS

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Abstract

The northwestern arid region of China represents a typical groundwater-dependent ecosystem, where groundwater resources constitute strategic support for regional development. Real-time monitoring of groundwater dynamics is crucial for elucidating variation characteristics and informing regional economic development. Conventional manual groundwater monitoring approaches entail substantial costs and are impractical for large-scale, long-term time series analysis. The utilization of gravimetric satellites offers a viable solution to this challenge. Previous research has yet to quantitatively assess the sustainability of groundwater resources in this region. To address this gap, this study estimates 200 months of groundwater storage changes (April 2002–September 2020) in northwestern China' s arid region using GRACE satellite and GLDAS data, examines their temporal trends, computes a GRACE-based groundwater drought index to characterize drought conditions, and integrates GGDI with sustainability metrics to quantify groundwater reliability, resilience, and vulnerability, thereby evaluating recent groundwater resource sustainability. Results indicate significant groundwater storage decline and intensified drought from 2002 to 2020, with mean reliability of 0.495, resilience of 0.470, and vulnerability of 0.404. The regional groundwater sustainability index (SI) of 0.28 denotes a relatively low sustainability level. This research reveals spatiotemporal distribution patterns and evolution trends of groundwater sustainability, providing theoretical and data support for regional groundwater resource protection and management.

Full Text

Evaluation of Groundwater Resource Sustainability Based on GRACE and GLDAS in the Arid Region of Northwest China

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Abstract

The arid region of Northwest China is a typical groundwater-dependent ecosystem. Groundwater resources serve as strategic support for development in this region, and real-time monitoring of groundwater dynamics is crucial for revealing groundwater change characteristics and supporting regional economic development. Traditional groundwater monitoring based on manual methods is costly and difficult to implement at large scales over long time series. The application of gravity satellites provides an effective solution to this problem. Previous studies have not yet quantitatively evaluated the sustainability of groundwater resources in Northwest China. To investigate recent groundwater sustainability in this region, we used GRACE gravity satellite and GLDAS data to invert 200 months of groundwater storage changes from April 2002 to September 2020, analyzed trend variations, and calculated the groundwater drought index based on GRACE. Combined with the sustainability index, we quantified groundwater reliability, resilience, and vulnerability to evaluate the sustainability of groundwater resources in Northwest China. Results show that from 2002 to 2020, groundwater storage decreased significantly, groundwater drought intensified, average groundwater reliability was 0.495, vulnerability was 0.404, and the regional groundwater sustainability index was 0.28, indicating a low level of groundwater sustainability. This study reveals the spatiotemporal distribution patterns and evolution trends of groundwater resource sustainability in Northwest China, providing theoretical and data support for regional groundwater resource protection and management.

Keywords: Northwest China arid region; gravity satellite; groundwater drought index; groundwater resources; sustainability

Introduction

Groundwater, as an important component of water resources, is characterized by wide distribution, excellent water quality, and low development costs [**?**]. According to the 2020 China Water Resources Bulletin released by the Ministry of Water Resources of the People’ s Republic of China, the total national groundwater resources amount to 8553.5\$×10^{8}\$ m^3, with a groundwater supply of 892.5\$×10^{8}\$ m^3, accounting for 15.4% of the total water supply, demonstrating the extremely important role of groundwater resources in water supply [?]. With increasing water demand, groundwater exploitation in China has continuously exceeded 1000\$×10^{8}\$ m^3 since the 21st century, leading to reduced groundwater storage and declining water levels [?]. Groundwater over-exploitation may cause degradation of groundwater-dependent ecosystems and endanger regional ecological security. Arid and semi-arid regions are typical groundwater-dependent ecosystems, and only through sustainable groundwater utilization can the groundwater environment in these areas be alleviated [?].

The concept of groundwater sustainability was first proposed by Alley et al. in 1999 and can be defined as the ability of groundwater systems to continuously provide sufficient quantity and good quality water resources for ecosystems and human society [?]. Numerous studies on groundwater sustainability have been conducted domestically and internationally, mainly including quantity-based, quality-based, and comprehensive evaluation methods. In terms of groundwater quantity evaluation, Thomas et al. [?] combined GRACE (Gravity Recovery and Climate Experiment) satellite data with GLDAS (Global Land Data Assimilation System) hydrological models to evaluate the sustainability of groundwater resources in 37 major aquifers. Groundwater quality evaluation mainly includes assessment through groundwater indices, groundwater vulnerability, and groundwater quality sustainability indicators. Comprehensive evaluation considers both groundwater quantity and quality, such as Singh et al. [?] who developed a groundwater sustainability index with 10 indicators to assess groundwater sustainability in the arid region of western Rajasthan, India. Jiang et al. [?] established a groundwater sustainability indicator system based on the Driver-Pressure-State-Impact-Response framework and reconstructed a groundwater sustainability evaluation method using analytic hierarchy process and information entropy theory.

Real-time dynamic monitoring of groundwater is crucial for sustainable utilization of groundwater resources. Traditional groundwater storage monitoring technology mainly relies on monitoring wells to measure groundwater level data to estimate groundwater storage. However, this method has significant limitations, including sparse wells, uneven distribution, and difficulty in monitoring large-scale regions [?]. With the continuous development of gravity satellite technology, an increasing number of researchers have used GRACE satellite data to better monitor groundwater storage in large-scale regions. Neves et al. [?] evaluated the performance of several different GRACE data sources in Iberia, showing that CSR Mascon data performed well in the region. Karunakalage et al. [?] used downscaled high-resolution GRACE data to monitor groundwater storage depletion in Gujarat, India, and verified GRACE’ s applicability in hydrological research. Shu et al. [?] used GRACE SH data to invert groundwater storage changes in the North China Plain and explore their spatiotemporal characteristics and driving mechanisms. Sun et al. [?] combined GRACE and GLDAS hydrological models to invert terrestrial water storage dynamics in the Keriya River Basin of Hotan region, simulated trends in groundwater equivalent water height changes, and validated the model with measured data, showing good applicability. Tao et al. [?] inverted the temporal variation sequence of groundwater storage in Anhui Province using GRACE and GLDAS, with a correlation coefficient of 89.62% with National Bureau of Statistics data. In summary, GRACE satellite data demonstrates high accuracy in inverting large-scale groundwater storage changes and can systematically and accurately obtain groundwater storage variations, with good performance in monitoring groundwater storage in China.

The arid region of Northwest China experiences scarce precipitation, strong evaporation, and water resource shortages. Natural lakes, wetlands, and native vegetation are strongly dependent on groundwater. In recent years, unreasonable groundwater resource development has led to declining water tables, desertification invasion, and groundwater 长期处于超采状态, posing a serious threat to groundwater resources [?]. Current research on groundwater in Northwest China mainly focuses on groundwater storage changes and water table depth analysis, with few studies on quantitative evaluation of groundwater resource sustainability. As groundwater is an extremely important resource for economic development in Northwest China, assessing regional groundwater sustainability levels is of great significance for regional development, groundwater protection, and sustainable utilization. This study aims to invert groundwater storage changes in Northwest China using GRACE and GLDAS hydrological models, combine the GRACE-based groundwater drought index with the sustainability index to quantify groundwater reliability, resilience, and vulnerability, evaluate the groundwater sustainability index in Northwest China, reveal the sustainability level of groundwater in the region, and provide important references for sustainable groundwater resource management in Northwest China.

1.1 Study Area Overview

The arid region of Northwest China is located in central Asia [?], geographically positioned between 73°~107°E and 35°~50°N, bounded by Helan Mountain in the east, extending south to the Kunlun, Altun, and Qilian Mountains, and bordered by national boundaries to the north and west (Figure 1). Administratively, it includes the entire Xinjiang Uygur Autonomous Region, the five cities of the Hexi Corridor in Gansu Province, and the Alxa League of Inner Mongolia. The total area is 2.09$×10^{6}$ km^{2}, accounting for approximately 21.5% of China's total area. The study area is deep inland, with annual precipitation less than 200 mm in most regions except for parts of Altay City, Tacheng area, Bole City, Kuytun City, Shawan County, the southern part of Manas County, Urumqi City, and the five cities of the Hexi Corridor. It is an extremely arid area with a typical continental climate. The terrain is dominated by plateaus, mountains, and basins with significant relief, including the Inner Mongolia Plateau, Altai Mountains, Tianshan Mountains, Kunlun Mountains, Altun Mountains, Qilian Mountains, Junggar Basin, Turpan Basin, and Tarim Basin.

1.2 Data and Processing

1.2.1 GRACE Data

The Gravity Recovery and Climate Experiment (GRACE) satellite, launched in March 2002, monitored global gravity fields for over 15 years until GRACE-FO was successfully launched in May 2018 to continue the mission [?]. This study used the 0.5°$×$0.5° RL06-level2 Mascon data model released by the Jet Propulsion Laboratory (JPL) [?] and the China regional Mascon data from the land water storage change dataset based on precipitation reconstruction released by the National Tibetan Plateau Science Data Center [?]. All data 扣除 2004-2009 年间的平均值, representing monthly data as mass changes relative to the average, converted to equivalent water column height.

The study period spans April 2002 to September 2020 (200 months), with some missing months. The 11-month data gap during the GRACE/GRACE-FO transition period was filled using the China regional land water storage change dataset based on precipitation reconstruction, with the remaining data being GRACE/GRACE-FO data.

1.2.2 GLDAS Data

The Global Land Data Assimilation System (GLDAS) is jointly developed by NASA Goddard Space Flight Center and the National Centers for Environmental Prediction, including four land surface process models (Noah, CLM, VIC, Mosaic) [?]. The data includes surface runoff, temperature, canopy water, evapotranspiration, soil moisture, and snow water from 2000 to present, simulated by four models with spatial resolutions of 1°$×1°*or*0.25°×0.25°*andmonthlytemporalresolution.ThisstudyusedtheNoahlandsurfaceprocessmodelfrom*

1.2.3 Rainfall Data

Rainfall data were obtained from the National Meteorological Information Center' s China Surface Climate Data Daily Value Dataset (V3.0), including annual, monthly, and daily average precipitation data from 2002 to 2020, with cumulative rainfall units of 0.1 mm.

1.2.4 Land Use Data

Globeland 30 is a high-resolution land cover product developed by the National Geomatics Center of China, with a spatial resolution of 30 m, classification accuracy exceeding 85%, and strong consistency in quality and space [?]. It includes ten categories: cultivated land, forest, grassland, wetland, water bodies, tundra, shrubland, artificial surfaces (urban and residential areas), bare land, and glaciers/permanent snow. Globeland 30 data from 2000 and 2020 were processed through mosaicking, masking, and vector-raster conversion to analyze the impact of land use change on groundwater resources in Northwest China.

1.3 Methods

1.3.1 Groundwater Storage Estimation

Groundwater storage changes were obtained through GRACE data products as terrestrial water storage anomalies (TWSA), which include aboveground components (plant canopy surface water, soil water, and snow water) and underground components (groundwater). The aboveground components need to be obtained through GLDAS data.

The groundwater storage change (GWS) is calculated as:

$$\mathrm{GWS} = \mathrm{TWS} - (\Delta\mathrm{can} + \Delta\mathrm{soil} + \Delta\mathrm{snow})$$

where Δcan is canopy surface water change, Δsoil is soil water change, and Δsnow is snow water change. Groundwater storage changes were obtained by combining GRACE and GLDAS data.

1.3.2 GRACE-Based Groundwater Drought Index

The GRACE Groundwater Drought Index (GGDI) is a normalized groundwater storage indicator for assessing aquifer system drought. Its novelty lies in combining groundwater storage deficits and surpluses to evaluate groundwater drought, where GGDI > 0 indicates surplus status and GGDI < 0 indicates deficit [**?**].

First, monthly climatology (Ci) is calculated to eliminate the impact of monthly variation factors on groundwater storage:

$$C_i = \frac{1}{n}\sum_{j=0}^{n-1} \mathrm{GWSA}_{i+12j}, \quad i = 1, \cdots, 12$$

Monthly groundwater storage anomalies (GWSA) are subtracted from monthly climatology to obtain groundwater storage deviation (GSD):

$$\mathrm{GSD}_t = \mathrm{GWSA}_t - C_t$$

Finally, GGDI is obtained by subtracting the mean and dividing by the standard deviation of GSD:

$$\mathrm{GGDI} = \frac{\mathrm{GSD}_t - \overline{\mathrm{GSD}}}{\sigma_{\mathrm{GSD}}}$$

where GWSA is the groundwater storage anomaly time series extracted from GRACE data after removing monthly climate fluctuations; $\overline{X}$ and σ are the mean and standard deviation of the time series.

1.3.3 Groundwater Resource Sustainability Evaluation and Indicators

The Sustainability Index (SI) combines reliability (REL), resilience (RES), and vulnerability (VUL) to assess large-scale groundwater resource sustainability [**?**]:

$$\mathrm{SI} = \mathrm{REL} \times \mathrm{RES} \times (1 - \mathrm{VUL})$$

Reliability is defined as the frequency of system failure. For groundwater, reliability is the historical probability of aquifer storage being below normal conditions, i.e., the proportion of time GGDI is at reliable levels. Northwest China groundwater reliability is classified into five levels: low reliability (0<REL\$ 0.25), $lowerreliability(0.25 < REL\ 0.40), mediumreliability(0.4 < REL\ 0.60), highreliability(0.6 < REL\ 0.75), andveryhighreliability(0.75 < REL$ \$1).

Resilience represents the speed of recovery from unsatisfactory to satisfactory conditions. For groundwater, resilience is the probability of recovery from negative to positive states. Northwest China groundwater resilience is classified into five levels: low resilience (0<RES\$ 0.2), $lowerresilience(0.2 < RES\ 0.3), mediumresilience(0.3 < RES\ 0.5), highresilience(0.5 < RES\ 0.75), andveryhighresilience(0.75 < RES$ \$1).

Vulnerability is a measure of the severity and probability of unsatisfactory conditions. For regional groundwater systems, severity and probability are represented by the groundwater drought index value (s_j) and its occurrence probability (e_j):

$$\mathrm{VUL} = \sum_{j=1}^{n} s_j e_j$$

Northwest China groundwater vulnerability is classified into five levels: low vulnerability (0<VUL\$ 0.1), $lowervulnerability(0.1 < VUL\ 0.4), mediumvulnerability(0.4 < VUL\ 0.6), highvulnerability(0.6 < VUL\ 0.75), andveryhighvulnerability(0.75 < VUL$ \$1).

Based on Thomas et al.' s classification standards, Northwest China groundwater sustainability is divided into five levels: low sustainability (0<SI\$ 0.2), $lowersustainability(0.2 < SI\ 0.3), mediumsustainability(0.3 < SI\ 0.5), highsustainability(0.5 < SI\ 0.75), andveryhighsustainability(0.75 < SI$ \$1).

1.3.4 Trend Analysis with Theil-Sen and Mann-Kendall Significance Test

The Theil-Sen median trend analysis and Mann-Kendall significance test are non-parametric methods that do not require normal distribution or serial correlation assumptions and are insensitive to outliers, effectively handling small outliers and missing values [?]. The formula is:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \quad \forall i < j$$

where β is the median slope of all data pairs, with sign indicating trend direction (positive for increasing, negative for decreasing). This study used this method with confidence level $\alpha = 0.01$ to analyze spatiotemporal trends in groundwater storage changes.

1.3.5 Maximal Information Coefficient

Reshef et al. [?] proposed the Maximal Information Coefficient (MIC) to mine potential relationships between variable objects, measuring both linear and non-linear relationships. For two-dimensional random variables (X, Y) with sample set D = {1,2,3, ,n} and sample size N, X and Y values are divided into m and n intervals respectively, creating an m×n grid G. Under specified grids, mutual information I can be estimated:

$$I(D|G) = \sum_{x,y} p(x,y|G) \log_2 \frac{p(x,y|G)}{p(x|G)p(y|G)}$$

where p(x|G) and p(y|G) are empirical marginal densities, and p(x,y|G) is empirical joint probability density. The maximum mutual information over all possible grids G is:

$$I^*(D) = \text{Max}_G I(D|G)$$

The MIC is:

$$\text{MIC} = \frac{I^*(D)}{\log_2 \min(m,n)}$$

where B is typically set as B(N) = N^{0.6} [?]. Larger values indicate stronger linear/non-linear relationships.

2 Results

2.1.1 Terrestrial Water and Groundwater Storage Changes

Based on monthly terrestrial water storage anomalies (TWSA) and inverted groundwater storage anomalies (GWSA) (Figure 2), TWSA in Northwest China shows large seasonal variation, with maximum equivalent water height of 3.96 cm in July and minimum of -4.42 cm in January, showing a periodic but downward trend. GWSA also shows a clear, continuous decreasing trend, with maximum of 3.06 cm in July and minimum of -6.52 cm in January. After 2012, the decreasing trend slowed and began to show periodic fluctuations, with cumulative equivalent water height decrease of 6.52 cm during the study period.

2.1.2 Groundwater Storage Change Validation

Validation was performed for Xinjiang, which accounts for the largest area proportion. Using groundwater reserve data from Xinjiang Water Resources Bulletins as reference (Figure 3), the GRACE-inverted GWSA shows consistent variation trends. Groundwater reserves were lowest in 2013 at 443.9$×10^{8}$ m^3, corresponding to the minimum GWSA in September 2013. In 2016, continuous rainstorm and flood disasters in Xinjiang led to increased groundwater reserves [?], with GWSA also showing an upward trend.

2.1.3 Spatial Trend Analysis of Groundwater Storage Changes

Using the Theil-Sen median method combined with Mann-Kendall significance testing, spatial trends in groundwater storage changes in Northwest China were obtained (Figure 4). At the 95% confidence level ($\alpha \leq 0.01$), approximately 19.3% of the region shows significant positive changes (groundwater increase), while 80.7% shows significant negative changes (groundwater decrease). The overall spatial trend shows banded distribution from north to south: the northernmost band shows slight increase; the middle band shows obvious groundwater decrease with the largest east-west span; the southern band shows relatively obvious increase. Most regions show decreasing trends, most significantly at the intersection of Awati County, Korla City, and Yining County, while the most significant increase occurs in Hotan City.

2.2 Groundwater Drought Index GGDI

Based on time series groundwater storage changes, monthly climatology values were removed to obtain groundwater storage deviations (GSD), which were then normalized to obtain the GRACE-based GGDI (Figure 5). GGDI > 0 indicates groundwater storage surplus, while GGDI < 0 indicates deficit. Before August 2008, Northwest China groundwater was in surplus with stable conditions, with the highest GGDI value in July 2003. After August 2008, GGDI began fluctuating around zero. Since October 2012, GGDI has been consistently negative with a decreasing trend, indicating deepening groundwater deficits and intensifying drought.

2.3.1 Reliability

Reliability represents the proportion of surplus months during the study period. Quantification of Northwest China groundwater reliability (Figure 6) shows a regional average of 0.495, reaching medium reliability level. Medium reliability areas account for the largest proportion at 89.8%, widely distributed. Lower reliability areas (7.27%) are distributed in Alxa Left Banner in the eastern study area and southeast of Korla City and northeast of Hotan. Very few high reliability areas exist, with no low or very high reliability areas (Table 1).

2.3.2 Resilience

Resilience represents the ability to recover from deficit to surplus states. Quantification shows a regional average of 0.470, at medium resilience level. Medium resilience areas have the highest proportion at 72.8%, distributed in central regions. High resilience areas account for 27.2%, mainly distributed along the southern boundary and northern parts of Northwest China. No low, lower, or very high resilience areas exist (Table 2).

2.3.3 Vulnerability

Vulnerability refers to the degree and probability of groundwater deficit. The regional average vulnerability is 0.404. Vulnerability results show mainly lower and medium vulnerability areas, accounting for 60.49% and 32.47% respectively. A small portion (7.03%) are high vulnerability areas, with no low or very high vulnerability areas. The most vulnerable areas are at the intersection of Awati County and Korla City (Table 3).

2.3.4 Groundwater Resource Sustainability

Based on reliability (REL), resilience (RES), and vulnerability (VUL), the regional groundwater resource sustainability was obtained (Figure 9). The minimum value among the three indicators has the greatest impact on the index; when any indicator is 0, the region is unsustainable. The regional average sustainability index (SI) is 0.28, indicating low groundwater sustainability. Spatially, sustainability shows high levels in northern and southern areas and low levels in central areas. Lower sustainability areas account for the largest proportion at 53.69%, distributed in southeastern and northwestern regions including Alxa Left Banner, Hami City, and Turpan City. Medium sustainability areas account for 42.2%, distributed in southwestern and northern regions including Hotan City, Artux City, Kashgar City, and Altay City. Low sustainability areas account for 4.11%, mostly in Awati County and scattered in central Northwest China. No high or very high sustainability areas exist (Table 4).

2.4 Correlation Analysis

Using MIC and Pearson correlation coefficients, relationships between reliability, vulnerability, resilience, and sustainability in Northwest China from 2002-2020 were analyzed (Table 5). Reliability and resilience show positive correlations with sustainability, while vulnerability shows negative correlation. The absolute MIC value between vulnerability and sustainability (0.91) is the largest, indicating vulnerability has the greatest impact on groundwater sustainability.

3 Discussion

Human activities are considered the main drivers of groundwater sustainability changes, including groundwater extraction, irrigation, urban expansion, and afforestation projects. Toksun County in southwest Turpan, located in a low sustainability area, experienced the largest groundwater decline of 7.49 m during 2002-2017 due to extraction and agricultural irrigation [?]. Oases occupy only 4-5% of the arid region area but concentrate over 90% of the wealth [?], with agriculture almost entirely dependent on groundwater irrigation, leading to low oasis groundwater sustainability. The Chahaertan Oasis has SI of 0.23 (lower sustainability), with groundwater levels declining 0.2-0.3 m annually due to large-scale irrigation [?]. Similar conclusions were reached in Minqin Oasis and Dunhuang Oasis studies [?, ?].

Land use changes significantly impact groundwater sustainability. From 2000-2020, artificial surface (construction land) area in Northwest China increased by 21.5% (8755 km^2), and cultivated land increased by 14.5% (34,490 km^2) (Table 6). Urban expansion inevitably causes groundwater sustainability decline [?]. Large-scale afforestation also affects groundwater sustainability; vegetation restoration projects in the Mu Us Sandy Land since 2000 have significantly improved vegetation coverage, but groundwater storage shows significant negative correlation with NDVI [?], and increasing cultivated land area inevitably leads to more agricultural irrigation, reducing regional groundwater sustainability.

Climate factors including precipitation and evapotranspiration also affect groundwater storage. At annual scale, precipitation and groundwater storage equivalent water height show similar fluctuations: in 2002-2003, groundwater storage increased with annual precipitation; in 2007-2008, it decreased with precipitation. However, at interannual scale, groundwater storage did not always follow precipitation changes, indicating other driving factors (Figure 10). Zhang et al. [?] found that socioeconomic indicator combinations explained 87.7% of groundwater sustainability variance, while climate precipitation indicators explained only 13.3%, with population factors, GDP, and fertilizer usage showing negative correlations with groundwater sustainability. Urbanization level improvement also contributes to groundwater sustainability decline.

For medium-high sustainability areas in Northwest China, conservation measures should focus on water saving: implementing total groundwater extraction and water level control systems; promoting advanced water-saving technologies; strengthening economic instruments including groundwater resource taxes; and detailing protection measures. For low sustainability areas, stricter measures should be combined with new water source development, including water transfer projects, to curb declining groundwater sustainability. Given the current low groundwater sustainability level in Northwest China, accelerated implementation of regulations and effective groundwater protection management models are needed to promote stable improvement.

Study limitations include not quantifying all influencing factors (natural climate, rainfall, evapotranspiration, and human activities such as mining, grazing, urban expansion, and shelterbelt construction), which will be addressed in future research. Additionally, subjectivity in quantifying reliability, resilience, and vulnerability, and alternating different data versions due to data gaps, may affect results.

4 Conclusions

This study inverted groundwater storage changes in Northwest China using GRACE and GLDAS hydrological models, combined with the GRACE-based groundwater drought index and sustainability index to evaluate groundwater sustainability. The following conclusions were obtained:

1) From 2002-2020, Northwest China groundwater storage showed an overall decreasing trend, with cumulative equivalent water height decrease of 6.52 cm. Spatially, 19.3% of the region showed positive changes while 80.7% showed negative changes, with banded distribution from north to south. The middle belt showed the most significant decrease, while the southern belt showed an increasing trend.

2) Based on GGDI, the trend can be divided into three stages: April 2002-August 2008 with GGDI > 0, indicating surplus; August 2008-October 2012 with GGDI fluctuating around zero; and after October 2012 with GGDI consistently negative and decreasing, indicating deepening deficit and intensifying drought.

3) Northwest China groundwater reliability, resilience, and vulnerability averages are 0.495, 0.470, and 0.404 respectively, all at medium levels. The regional groundwater sustainability index is 0.28, indicating low sustainability. Spatially, sustainability shows high levels in north and south, low in central areas.

4) Correlation analysis shows vulnerability has the greatest impact on groundwater sustainability (MIC = 0.91). Human activities are the main drivers of groundwater sustainability decline, including extraction, irrigation, urban expansion, and afforestation. Climate factors have relatively smaller influence.

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Note: Figure translations are in progress. See original paper for figures.