Groundwater Storage Change and Population Exposure in the Yellow River Basin Based on GRACE Data (Postprint)

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Abstract

In recent years, the human-water conflict in the Yellow River Basin has intensified, with excessive depletion of groundwater storage emerging as a primary constraint on harmonious human-nature development in the region. Based on Gravity Recovery and Climate Experiment (GRACE) satellite data and Global Land Data Assimilation System (GLDAS) data, and according to the principles of watershed water cycle and water balance, this study quantifies variations in groundwater storage in the Yellow River Basin from 2003 to 2016, and identifies population exposure in areas with significant groundwater storage decline through investigation of its spatiotemporal variation characteristics. The results indicate that: (1) Spatially, groundwater storage in the Yellow River Basin is characterized by abundance in the west and scarcity in the east, with the magnitude of decline intensifying from west to east, and declining areas exhibiting a diffusion pattern from the lower reaches toward the middle and upper reaches. The declining areas are mainly concentrated in the central and eastern regions, with the magnitude of change primarily categorized as relatively severe and severe reduction. (2) Temporally, groundwater storage in the Yellow River Basin exhibited an overall declining trend from 2003 to 2016, with a mean annual decrease rate of 5.93 mm $\cdot$ a^{-1}. Specifically, 2004-2016 experienced continuous decline, with the most pronounced decrease occurring in 2015-2016; additionally, seasonal effects are evident in the temporal variation of groundwater storage, with the magnitude of decline being largest in spring, followed by winter, then autumn, and smallest in summer. (3) The population density of prefecture-level cities under groundwater exposure risk demonstrates an east-high-west-low pattern with interlaced distribution in the central region, with 16 prefecture-level cities exhibiting the highest population density under exposure risk; the cumulative percentage of population affected by groundwater storage decline shows a significant upward trend, reaching its maximum value in 2016. The research findings aim to provide scientific reference for sustainable utilization of groundwater resources in the Yellow River Basin.

Full Text

Groundwater Storage Changes and Population Exposure in the Yellow River Basin Based on GRACE Data

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Abstract: In recent years, the contradiction between humans and water resources in the Yellow River Basin has become increasingly prominent, particularly as excessive groundwater consumption has emerged as one of the primary constraints on harmonious human-nature development in the region. Based on Gravity Recovery and Climate Experiment (GRACE) satellite data and Global Land Data Assimilation System (GLDAS) data, this study calculated groundwater storage changes in the Yellow River Basin from 2003 to 2016. Building upon an analysis of spatiotemporal variation characteristics, we identified population exposure in areas experiencing significant groundwater decline. The results reveal three key findings: (1) Spatially, groundwater storage exhibits a pattern of abundance in the west and scarcity in the east, with the degree of depletion intensifying from west to east. The declining areas show a spreading trend from the lower reaches toward the middle and upper reaches, concentrated primarily in the central-eastern region where the decline rates are classified as relatively severe or severe. (2) Temporally, groundwater storage demonstrated an overall declining trend from 2003 to 2016, with an average annual decrease of 5.93 $\mathrm{mm} \cdot \mathrm{a}^{-1}$. This represents a continuous decline from 2004 to 2016, with the most significant drop occurring in 2015–2016. Additionally, seasonal effects are evident, with the largest declines in spring, followed by winter, autumn, and summer. (3) Regarding population exposure risk, prefecture-level city population densities under groundwater exposure risk show a pattern of high density in the east, low density in the west, and staggered distribution in the central region. The cumulative percentage of populations in areas exceeding various decline thresholds shows a clear upward trend, reaching its maximum in 2016. These findings provide a scientific reference for the sustainable utilization of groundwater resources in the Yellow River Basin.

Keywords: GRACE; groundwater storage change; spatiotemporal characteristics; population exposure risk; Yellow River Basin

Introduction

As human activities intensify, water resource consumption continues to escalate, making the human-water contradiction increasingly prominent. Groundwater, as a crucial component of water resources, is essential for human survival and development due to its stable reserves, good water quality, and direct usability across various sectors. However, unsustainable utilization in some regions has exacerbated water resource problems, triggering environmental issues such as land subsidence, seawater intrusion, and groundwater depletion, particularly in arid and semi-arid areas. Traditional groundwater monitoring methods are time-consuming, labor-intensive, and create monitoring blind spots beyond observation points, making it difficult to track groundwater storage changes in a timely manner. GRACE (Gravity Recovery and Climate Experiment) satellite data provides an effective approach for monitoring large-scale regional groundwater storage changes. Numerous scholars have used this data for extensive research, primarily focusing on groundwater storage change monitoring, with some conducting studies on technical method improvements, accuracy verification, and spatial resolution downscaling. While these studies have yielded rich results in quantifying dynamic groundwater storage changes, few have examined the relationship between groundwater storage changes and population exposure risk—a critical basis for scientifically formulating water resource policies.

Against this background, President Xi Jinping chaired a symposium on ecological protection and high-quality development of the Yellow River Basin in Zhengzhou, Henan Province in September 2019, making major deployments to strengthen Yellow River governance and protection and promote high-quality development in the basin. The Yellow River Basin covers an area of 75.24$×10^{4}$ km^2, flowing through nine provinces and regions. With only about 2% of the nation’ s runoff, it supports 12% of the national population and 15% of the country’ s cultivated land (including irrigation areas within and outside the basin). Consequently, the basin holds significant importance in China’ s socioeconomic development and ecological security. However, its main runoff generation zone lies in arid and semi-arid regions with an average annual precipitation of approximately 450 mm, resulting in scarce water resources with uneven spatiotemporal distribution. As socioeconomic development continues, water withdrawal has remained high, intensifying the contradiction between water supply and demand. Therefore, studying long-term groundwater storage changes in the Yellow River Basin is scientifically significant for sustainable water resource utilization in the region.

This study takes the Yellow River Basin as the research area, calculating long-term groundwater storage changes based on GLDAS data and GRACE remote sensing data, combined with LandScan population grid data. We explore the relationship between groundwater storage changes and population exposure, focusing on analyzing spatiotemporal variation characteristics of groundwater storage, identifying areas with persistent groundwater decline, and analyzing population exposure risks in these areas. The findings aim to provide scientific references for sustainable groundwater resource utilization in the Yellow River Basin.

1 Study Area Overview

The Yellow River originates from the Qinghai-Tibet Plateau and flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong provinces and autonomous regions [Figure 1: see original paper]. The basin is situated primarily in arid and semi-arid regions, where water resources are the constraining factor for production and life. The climate type is predominantly arid and semi-arid, making the relationship between groundwater storage and vegetation ecology more critical than in other climatic zones.

2 Data and Methods

2.1 Data Sources and Preprocessing

GRACE Data: The GRACE satellite carries precise ranging instruments that can detect changes in local gravity by measuring distance variations between twin satellites, thereby deriving total terrestrial water storage changes in the monitoring area. Previous studies have shown that groundwater storage derived from GRACE satellite data is consistent with monitoring well data, making it suitable for groundwater storage research in China. GRACE data processing, distribution, and management are jointly undertaken by the Jet Propulsion Laboratory (JPL), the German Research Centre for Geosciences (GFZ), and the Center for Space Research at the University of Texas (CSR). These institutions provide monthly Earth gravity field models to the public after validation. While GRACE data products include Level-0, Level-1A, Level-1B, and Level-2, Level-2 data products are not freely available. To facilitate research on mass anomalies (such as water layers), some teams have generated Level-3 data products based on Level-2 data after geophysical corrections. These are stored in NetCDF format, conveniently accessible and freely downloadable from https://disc.gsfc.nasa.gov/datasets/GLDAS_{{{CLSM025}}*{{DA1}}}*{D_2}.2/summary?keywords=CLSM

Soil Moisture Data: Soil moisture data were obtained from the Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov/datasets/GLDAS_{{{NOAH This study selected monthly soil moisture data from the GLDAS-2.1 model for 2003-2016. The data include four soil layers (0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm). Monthly soil moisture for each layer was summed to obtain soil moisture content below 200 cm. The multi-year monthly average was subtracted from each year' s monthly soil moisture to obtain soil moisture anomalies, representing monthly soil moisture changes.

Population and Vegetation Data: Population data were derived from LandScan population grid data (https://landscan.ornl.gov) with a spatial resolution of 1 km^2, which has been widely used and validated by numerous scholars for research in China. Vegetation coverage data were obtained from the website https://landweb.nascom.nasa.gov/ with a spatial resolution of 250 m. The maximum value composite method was first used to synthesize annual NDVI data, then vegetation coverage was calculated using established formulas.

Data Preprocessing: All raw raster data were first reprojected to the WGS84 geographic coordinate system. Second, masking was performed based on the Yellow River Basin vector boundary. Finally, resampling was conducted to the smallest grid resolution (0.25°) to maintain consistent pixel sizes across raster datasets, with temporal resolution matched at the monthly scale.

2.2 Methods

Groundwater Storage Calculation: According to the water balance principle, the annual average change in groundwater storage in the Yellow River Basin from 2003 to 2016 was calculated. Terrestrial water storage changes are caused by variations in soil water, surface water, snowmelt water, and groundwater storage. At long time scales, soil moisture and groundwater storage changes are the main contributors to terrestrial water storage changes, while snow water equivalent and surface water storage changes can be neglected. Therefore, groundwater storage changes were obtained by subtracting soil moisture changes from GRACE-derived terrestrial water storage changes:

$$GWS_i = TWS_i - SMS_i$$

where GWS_i represents the annual average change in groundwater storage for year i (mm), TWS_i represents the annual average change in terrestrial water storage for year i (mm), and SMS_i represents the annual average change in soil moisture for year i (mm).

Theil-Sen Median Trend Analysis: The Theil-Sen Median trend analysis is a robust non-parametric statistical trend calculation method used to reflect the long-term evolution trend of groundwater storage in the Yellow River Basin:

$$S = \text{Median}\left(\frac{W_j - W_i}{j - i}\right), \quad 2003 \leq i < j \leq 2016$$

where W_j and W_i represent the equivalent water heights of groundwater storage in years j and i, respectively. The median of all $(n(n-1)/2)$ data combination slopes is calculated. When $S > 0$, groundwater storage shows an increasing trend; when $S < 0$, it shows a decreasing trend.

Mann-Kendall Significance Test: The Mann-Kendall method was used to test the significance of temporal trends in groundwater storage. For time series $\{W_i\}, i = 2003, 2004, ..., 2016$, the Z-statistic is defined as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & S < 0 \end{cases}$$

where $\mathrm{Var}(S)$ is the variance of S and n is the length of the time series. When $|Z| > 1.96$, significant change exists at the $\alpha = 0.05$ level. The test results were classified into four categories: extremely significant change ($|Z| > 2.58$), significant change ($1.96 < |Z| \leq 2.58$), weakly significant change ($1.65 < |Z| \leq 1.96$), and no significant change ($|Z| \leq 1.65$).

Groundwater Storage Change Classification: Following previous research, the standard deviation classification method was used to categorize groundwater storage equivalent water height into five levels based on the mean and standard deviation of annual changes: increase, stable, decrease, relatively severe decrease, and severe decrease .

3 Results

3.1 Spatial Variation Characteristics of Groundwater Storage

From 2003 to 2016, the annual average equivalent water height of groundwater storage in the Yellow River Basin showed significant east-west differences, with increases in the west and decreases in the east. The multi-year average equivalent water height was -22.62 $\mathrm{mm} \cdot \mathrm{a}^{-1}$, with the degree of depletion intensifying from west to east. The declining areas exhibited a spreading trend from the lower reaches to the middle and upper reaches [Figure 2: see original paper]. The declining regions were concentrated mainly in the central-eastern areas, with change levels classified as relatively severe decrease and severe decrease. Initially, severely declining areas included cities such as Xi' an, Luoyang, Sanmenxia, and Zhengzhou; by the end of the study period, most cities in the middle and lower reaches were included, and even cities in the upper reaches such as Yushu Tibetan Autonomous Prefecture, Golog Tibetan Autonomous Prefecture, and Hainan Tibetan Autonomous Prefecture became severely declining areas. This pattern reflects that rapid economic growth and strong population aggregation in the middle and lower reaches have increased agricultural, industrial, and domestic water consumption, while groundwater recharge rates are far lower than consumption rates. In contrast, groundwater storage in the southwestern region continues to increase due to the Qinghai-Tibet Plateau and Loess Plateau topography with average elevations above 2000 m, sparse populations, underdeveloped agriculture and industry, and increased glacier meltwater from global climate change, resulting in groundwater recharge rates exceeding consumption rates.

3.2 Temporal Variation Characteristics of Groundwater Storage

Interannual Trends: Groundwater storage in the Yellow River Basin showed an overall declining trend from 2003 to 2016, with the highest equivalent water height of 10.32 mm and the lowest of -75.56 mm. The average annual decrease was 5.93 $\mathrm{mm} \cdot \mathrm{a}^{-1}$. The change amplitude was relatively small from 2003 to 2004, but the main characteristic shifted from increase to decrease after 2004, showing a continuous declining trend from 2004 to 2016. The largest decline occurred in 2015, decreasing by 24.41 mm.

Seasonal Patterns: Comparing multi-year monthly averages revealed significant seasonal variation, with the largest declines in spring, followed by winter, autumn, and summer. Specifically, the mean equivalent water height in spring was -58.92 mm, in winter -54.12 mm, in autumn -47.81 mm, and in summer -38.02 mm. This pattern occurs because the Yellow River Basin is influenced by monsoon climate, with summer and autumn being rainy seasons when surface runoff recharges groundwater, while winter and spring are dry seasons when groundwater supplies surface water.

Linear Trend Significance: To further characterize the linear trend, Theil-Sen Median and Mann-Kendall methods were combined to analyze significance [Figure 5: see original paper]. The linear significance trends were divided into seven categories: weakly significant decrease, significant decrease, extremely significant decrease, weakly significant increase, significant increase, extremely significant increase, and no significant change . The results show that decreasing trends dominate, with extremely significant decreases covering 50.62$×10^{4}$ km^2 (63.60% of the basin area), primarily distributed in the middle and lower reaches including central-northern Shaanxi, most of Shanxi, and Yellow River coastal areas of Henan and Shandong. Significant decreases covered 2.36$×10^{4}$ km^2 (2.96% of the basin area) in Haibei Tibetan Autonomous Prefecture and Xining City, Qinghai Province.

Relationship with Vegetation Coverage: Analysis of vegetation coverage from 2003 to 2016 showed a significant increasing trend, opposite to the interannual groundwater storage trend. At the $P < 0.01$ level, the Pearson correlation coefficient was -0.47, indicating a significant negative correlation. The increasing vegetation coverage consumes substantial water resources, primarily groundwater, demonstrating that vegetation changes profoundly impact local groundwater storage.

3.3 Population Exposure Risk Analysis

Population Distribution Under Exposure Risk: To accurately identify groundwater exposure risk areas, regions with significant and extremely significant decreasing trends were defined as groundwater exposure risk zones. Population density in these risk zones showed an east-high, west-low, and centrally staggered distribution [Figure 6: see original paper]. Sixteen prefecture-level cities had the highest exposure risk population density (>200 $\text{persons} \cdot \mathrm{km}^{-2}$), including Lanzhou, Yinchuan, Xi' an, Weinan, Jinzhong, Yuncheng, Linfen, Jiyuan, Anyang, Puyang, Jiaozuo, Xinxiang, Zhengzhou, Heze, Tai' an, and Jinan. Cities with exposure risk population density of 101-200 persons $\cdot$ km^{-2} included Linxia Hui Autonomous Prefecture, Ulanqab, Jincheng, and Lüliang. Cities with 51-100 persons $\cdot$ km^{-2} included Baiyin, Pingliang, and Baotou. Cities with 21-50 persons $\cdot$ km^{-2} were interspersed throughout the region.

Cumulative Population Percentage: For analysis, groundwater storage equivalent water height decline amplitude was divided into five unequal intervals, and the cumulative population percentage exceeding each threshold was calculated [Figure 7: see original paper]. The results show that the cumulative percentage curve shifts rightward with a clear upward trend. Areas with equivalent water height < -15 mm accounted for 48.26% of the total basin population in 2003, rising to 60.72% in 2016. Areas with < -35 mm accounted for 34.17% in 2003, rising to 57.44% in 2016. Areas with < -55 mm accounted for 25.80% in 2003, rising to 61.54% in 2016. Areas with < -65 mm accounted for 0.28% in 2003, rising to 63.12% in 2016, reaching 3908.94\$×10^{4}\$ persons (82.55% of the basin population). This indicates that population exposure risk in declining groundwater storage areas is intensifying, with human-water conflicts becoming increasingly prominent.

4 Discussion

Rapid groundwater depletion not only threatens urban water security but also causes land subsidence, becoming a major hazard to regional urban development and resident safety. Currently, few studies have examined long-term, macro-scale groundwater storage in arid and semi-arid regions due to China' s complex geological structure and high costs and difficulties associated with manual groundwater monitoring. This study integrated multiple remote sensing datasets including GRACE and GLDAS data, calculating Yellow River Basin groundwater storage from 2003 to 2016 based on basin water cycle and water balance principles to identify spatiotemporal trends and analyze population exposure under different decline levels.

The results show that Yellow River Basin groundwater storage is declining annually while population exposure percentages continue rising. Compared with existing studies, our conclusions are consistent with research on the North China Plain, Haihe River Basin, and Guanzhong area. For instance, Feng et al. (2017) found that the North China Plain experienced groundwater mass depletion of 7.58\$±0.9$Gt \cdot a$^{-1}\$ from 2003 to 2014, while Li et al. (2018) reported groundwater loss in the Haihe River Basin of 10.2\$±0.9$mm \cdot a^{\{-1\}.Yang(2017)demonstratedthatGuanzhongareaexperiencedlong-termgroundwaterdepletionatarateof-3.70mm \cdot a}\{$- 1}\$. These findings underscore that groundwater resources security should be prioritized alongside food security in the context of ecological protection and high-quality development in the Yellow River Basin. Measures such as developing water-saving agriculture and implementing freshwater recharge in key areas should be adopted to ensure groundwater storage safety.

However, this study has several limitations. First, data availability restricted us to first-generation GRACE data (2003–2016), limiting the study' s timeliness. Additionally, GRACE data, despite calibration and geographic processing, still contain uncertainties due to spatiotemporal resolution limitations. Some studies have used three-point moving averages to eliminate intra-seasonal random fluctuations in GRACE time series. Furthermore, soil moisture data processing involves unavoidable uncertainties because surface hydrological processes are complex and surface water data are lacking in many regions. The GLDAS model used in this study only considers four soil layers (0–3.43 m), which may not fully capture soil water content. Although we referenced previous studies and selected GLDAS-2.1 soil moisture data including 0–3.50 m soil water content, uncertainties remain. Second, while soil moisture and groundwater storage changes are considered the main contributors to terrestrial water storage changes in the middle and lower reaches (where snow water equivalent and surface water storage changes can be neglected), this assumption may not fully apply to the upper reaches. For upper basin areas, snow water, plant root zone water, and canopy water impacts on groundwater storage should be considered. Third, the relationship between groundwater storage changes and human economic activities warrants further investigation.

Future research should focus on three aspects. First, combine GRACE data with groundwater observation station data to retrieve higher spatiotemporal resolution groundwater storage data for China, filling gaps between the two GRACE satellite generations to more accurately investigate spatiotemporal dynamics and influencing mechanisms in arid and semi-arid regions. Second, supplement calculations with snow water and plant water changes to refine groundwater storage estimates, particularly for the upper basin. Third, integrate portable absolute gravimeter and groundwater monitoring well data to validate and analyze spatial distribution and change trends of groundwater storage in areas with prominent human-water conflicts, providing scientific references for future economic development and sustainable resource utilization in the Yellow River Basin.

5 Conclusions

This study reveals three major findings about groundwater storage changes and population exposure in the Yellow River Basin:

(1) **Spatial characteristics:** Groundwater storage changes show clear east-west differences, with increases in the west and decreases in the east. The multi-year average equivalent water height is -22.62 $\mathrm{mm} \cdot \mathrm{a}^{-1}$, with depletion intensity increasing from west to east. Declining areas spread from lower to middle and upper reaches, concentrated in the central-eastern region with predominantly severe and extremely severe decline rates. Initially, severely declining areas included cities like Xi' an, Luoyang, Sanmenxia, and Zhengzhou; by the study' s end, most cities in the middle and lower reaches were included, along with upper-reach areas like Yushu,

Golog, and Hainan Tibetan Autonomous Prefectures. This indicates increasingly prominent human-water conflicts, with regional economic development partially dependent on excessive groundwater exploitation.

(2) **Temporal characteristics:** Groundwater storage showed an overall declining trend from 2003 to 2016, with an average annual decrease of 5.93 $\mathrm{mm} \cdot \mathrm{a}^{-1}$. The highest equivalent water height was 10.32 mm and the lowest was -75.56 mm, with the maximum decline of 24.41 mm occurring in 2015. Seasonal effects are evident, with the largest declines in spring (-58.92 mm), followed by winter (-54.12 mm), autumn (-47.81 mm), and summer (-38.02 mm). Theil-Sen Median and Mann-Kendall analyses show decreasing trends dominate, with extremely significant decreases covering 63.60% of the basin area.

(3) **Population exposure risk:** Prefecture-level city population densities under groundwater exposure risk show an east-high, west-low, and centrally staggered distribution. Sixteen cities have the highest exposure risk population density (>200 $\text{persons} \cdot \mathrm{km}^{-2}$). The cumulative percentage of populations in areas exceeding various decline thresholds continuously increased, reaching maximum values in 2016, indicating prominent human-water contradictions.

References

[1] Gong Huili, Li Xiaojuan, Pan Yun, et al. Groundwater depletion and regional land subsidence of the Beijing Tianjin Hebei area[J]. Bulletin of National Natural Science Foundation of China, 2017, 31(1): 72-77.

[2] Yang Yang. Monitoring and analysis of temporal and spatial variation of groundwater reserves in Guanzhong area[D]. Lanzhou: Lanzhou Jiaotong University, 2017.

[3] Tao Zhengguang, Tao Tingye, Ding Xin, et al. Groundwater storage changes in Anhui Province derived from GRACE and GLDAS hydrological model[J]. Progress in Geophysics, 2021, 36(4): 1456-1463.

[4] Tu Mengzhao, Liu Zhifeng, He Chunyang, et al. Research progress of groundwater storage changes monitoring in China based on GRACE satellite data[J]. Advances in Earth Science, 2020, 35(6): 643-656.

[5] Zhao Zhenzhen, Feng Jiandi. Investigation of water storage variation in Horqin Sandy Land based on multi source data[J]. Bulletin of Soil and Water Conservation, 2019, 39(3): 119-125, 131.

[6] Howard K W F. Sustainable cities and the groundwater governance challenge[J]. Environmental Earth Sciences, 2015, 73(6): 2543-2554.

[7] Li Jia, Tang He, Rao Weilong, et al. Influence of South North Water Transfer Project on the changes of terrestrial water storage in North China Plain[J]. Journal of University of Chinese Academy of Sciences, 2020, 37(6): 775-783.

[8] Long D, Pan Y, Zhou J, et al. Global analysis of spatiotemporal variability in merged total water storage changes using multiple GRACE products and global hydrological models[J]. Remote Sensing of Environment, 2017(192): 198-216.

[9] Hu Pengfei, Li Jing, Zhang Yanli, et al. Temporal and spatial variation and influencing factors of water storage on the Loess Plateau[J]. Remote Sensing Technology and Application, 2019, 34(1): 176-186.

[10] Xu Zijun, Yi Lihe, Hu Fusheng, et al. Spatial and temporal variations of terrestrial water storage in northwest China during 2002–2015[J]. Journal of China Institute of Water Resources and Hydropower Research, 2018, 16(4): 314-320.

[11] Cao Yanping, Nan Zhuotong, Hu Xinglin. Changes of groundwater storage in the Heihe River Basin derived from GRACE gravity satellite data[J]. Journal of Glaciology and Geocryology, 2012, 34(3): 680-689.

[12] Zhong Y, Zhong M, Feng W, et al. Groundwater depletion in the west Liaohe River Basin, China and its implications revealed by GRACE and in situ measurements[J]. Remote Sensing, 2018, 10(4): 493, doi: 10.3390/rs10040493.

[13] Zhang Kaili, Feng Rongrong, Liu Tan, et al. Coordination and obstacle factors of urbanization and ecosystem service value in the Yellow River Basin[J]. Arid Land Geography, 2022, 45(4): 1254-1267.

[14] Yuan Lei, Han Shuangbao, Li Fucheng, et al. Evolution of irrigation development in the Yellow River Basin and its impact on groundwater resources[J]. Yellow River, 2022, 44(4): 80-84.

[15] Tapley B D, Bettadpur S, Ries J C, et al. GRACE measurements of mass variability in the earth system[J]. Science, 2004, 305(5683): 503-505.

[16] Xu Houze. Satellite gravity missions–New hotpoint in geodesy[J]. Science of Surveying and Mapping, 2001, 26(3): 1-3.

[17] Lu Dadao, Sun Dongqi. Comprehensive management and sustainable development of the Yellow River Basin[J]. Acta Geographica Sinica, 2019, 74(12): 2431-2436.

[18] Wang Xuemei, Li Xin, Ma Mingguo. Advance and case analysis of population spatial distribution based on remote sensing and GIS[J]. Remote Sensing Technology and Application, 2004, 19(5): 320-327.

[19] Feng Wei, Wang Changqing, Mu Dapeng, et al. Groundwater storage variations in the North China Plain from GRACE with spatial constraints[J]. Chinese Journal of Geophysics, 2017, 60(5): 1630-1642.

[20] Feng W, Zhong M, Lemoine J M, et al. Evaluation of groundwater depletion in north China using the gravity recovery and climate experiment (GRACE) data and ground based measurements[J]. Water Resources Research, 2013, 49(4): 2110-2118.

[21] Yi S, Wang Q, Sun W. Basin mass dynamic changes in China from GRACE based on a multibasin inversion method[J]. Journal of Geophysical Research: Solid Earth, 2016, 121(5): 3782-3803.

[22] Sen P K. Estimates of the regressions coefficient based on Kendall' s Tau[J]. Journal of the American Statistical Association, 1968, 63(324): 1379-1389.

[23] Li Wanqiu, Wang Wei, Zhang Chuanyin, et al. Monitoring groundwater storage variations in the Guanzhong area using GRACE satellite gravity data[J]. Chinese Journal of Geophysics, 2018, 61(6): 2237-2245.

[24] Huang Xiaojun, Qi Mingyue, Li Yanyu, et al. Spatio-temporal evolution and population exposure risk to PM2.5 in the Guanzhong area[J]. Environmental Science, 2020, 41(12): 5245-5255.

[25] Chen Yongjin, Abula Aikeremu, Zhang Tianju, et al. Effects of ecological water conveyance on groundwater depth in the lower reaches of Tarim River[J]. Arid Land Geography, 2021, 44(3): 651-658.

[26] Li Jie, Fan Dongming, You Wei. Using GRACE to monitor regional drought in China and its influencing factors[J]. Journal of Geodesy and Geodynamics, 2019, 39(6): 587-595.

[27] Wei Shiyu, Guo Yuntong, Cui Yali, et al. Dynamic characteristics of groundwater level and storage variables in Minqin from 1985 to 2016[J]. Arid Land Geography, 2021, 44(5): 1272-1280.

[28] Sun Qian, Baidourela Aliya. Mathematical fitting of influencing factors and measured groundwater level: Take Keriya River Basin in Hetian area as an example[J]. Advances in Earth Science, 2018, 37(7): 50-60.

[29] He C, Ma Q, Li T, et al. Spatiotemporal dynamics of electric power consumption in Chinese Mainland from 1995 to 2008 modeled using DMSP/OLS stable nighttime lights data[J]. Journal of Geographical Sciences, 2012, 22(1): 125-136.

[30] Zhou F, Bo Y, Ciais P, et al. Deceleration of China' s human water use and its key drivers[J]. Proceedings of the National Academy of Sciences, 2020, 117(14): 7702-7711.

[31] Zhang Lianglin, Pan Jinghu. Spatial-temporal pattern of population exposure risk to PM2.5 in China[J]. China Environmental Science, 2020, 40(1): 1-12.

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