

Dynamic Characteristics Analysis of Groundwater Level and Storage Variation in Minqin, 1985-2016: Postprint

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Abstract

Minqin is situated between two deserts, and the groundwater level has continued to decline in recent decades, with severe water resource shortages. To correctly guide the rational development and utilization of local groundwater and ecological restoration, analyzing the groundwater development and utilization process and the dynamic variation characteristics of groundwater over the years is particularly important. Based on collecting and analyzing water level data from 138 monitoring wells, the groundwater dynamic type zones in Minqin County were delineated, and Kriging interpolation was used to draw annual groundwater flow fields and water level amplitude maps for the Minqin Basin from 1985-2016. The grid method was employed to calculate multi-year groundwater storage variation. Simultaneously, the influencing factors of groundwater level in the Minqin Basin were investigated, regression equations were obtained, and exploitable groundwater resources were estimated. The results show: (1) The groundwater level dynamic types in Minqin County can be classified into exploitation type, irrigation infiltration-exploitation type, river infiltration-exploitation type, and runoff type. (2) The groundwater level in the Minqin Basin has generally declined over the years, with a significant decline in the irrigation area (maximum decline of 22 m) and a slight decline in the desert area. The cumulative multi-year groundwater deficit is $24.45 \times 10^8 \text{ m}^3$. (3) After the comprehensive management of the Shiyang River, the rate of water level decline has significantly decreased.

Full Text

Dynamic Characteristics of Groundwater Level and Storage Variables in Minqin from 1985 to 2016

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Abstract: Minqin County in Gansu Province is situated between the Badain Jaran and Tengger deserts in northern China. Over recent decades, the groundwater level in Minqin has experienced continuous decline, resulting in severe water resource shortages. Analyzing the historical process of groundwater development and utilization, along with the dynamic characteristics of groundwater changes, is crucial for guiding rational groundwater exploitation and ecological restoration efforts. Based on water level data from 138 monitoring wells, this study delineated groundwater dynamic type zones in Minqin County and employed Kriging interpolation to map annual groundwater flow fields and water level fluctuation patterns in the Minqin Basin from 1985 to 2016. The grid method was used to calculate multi-year groundwater storage variables. Additionally, the study explored influencing factors on groundwater levels, derived a regression equation, and estimated the recoverable groundwater volume. The results indicate: (1) Groundwater level dynamics in Minqin can be classified into four types: extraction-dominated, irrigation infiltration-extraction, river infiltration-extraction, and runoff. (2) The overall groundwater level has declined over the years, with a significant drop of up to 22 m in irrigation areas, while desert areas experienced slight declines. The cumulative groundwater loss reached $24.45 \times 10^8 \text{ m}^3$. (3) Following the comprehensive management of the Shiyang River, the rate of water level decline slowed markedly, with partial recovery observed and positive storage variables in some years. (4) The primary influencing factors are extraction volume and surface water diversion. The groundwater volume change process can be divided into four periods: rapid decline (1985-2000), stable decline (2001-2006), management implementation (2007-2009), and stabilization/recovery (2010-2016). (5) Under current surface water supply conditions, the recoverable groundwater volume in the Hongyashan Irrigation District is approximately $0.61 \times 10^8 \text{ m}^3$.

Keywords: groundwater level dynamics; groundwater storage variables; influencing factors; Minqin

Minqin is located in the lower reaches of the Shiyang River Basin, extending between the Tengger and Badain Jaran deserts, serving as a critical green barrier between these two vast desert regions. As an irrigation-dependent oasis, Minqin exemplifies the principle that “with water, there is fertile farmland; without water, there is desert” [?]. The importance of water resources cannot be overstated. Over recent decades, continuous groundwater level decline in the Minqin Basin has created numerous water use conflicts and triggered ecological problems including vegetation degradation, salinization, and desertification. To

curb ecological deterioration, the “Gansu Shiyang River Basin Key Management Plan” was implemented in 2007, which has played a positive role in restoring the local ecological environment.

Due to its typical water resource and ecological challenges, Minqin has been the subject of extensive research by scholars both domestically and internationally. Current research findings primarily focus on water resource development and utilization management systems [?], ecological water demand [?], and groundwater ecology studies [?]. Numerous scholars have also investigated groundwater dynamics in the Minqin Basin. For instance, E Youhao et al. [?] systematically studied groundwater dynamics in the Shajingzi area of Minqin and predicted water level trends. Liu Wenjie et al. [?] used statistical methods to examine changes in groundwater mineralization in the Minqin Basin from 1985 to 2005. Song Dongmei et al. [?] conducted spatial interpolation of groundwater to obtain spatiotemporal variations in depth and mineralization. Ma Jinhui et al. [?] analyzed the spatial and temporal characteristics of groundwater depth using geostatistical techniques based on annual observation data.

Existing research has primarily focused on typical observation wells, with limited analysis of regional overall water level changes, particularly long-term variations in the groundwater flow field. Furthermore, studies on multi-year groundwater volume change processes are insufficient. To meet current management needs for dual control of water level and volume, an integrated approach examining both aspects is necessary to more clearly describe groundwater dynamic processes. This paper investigates groundwater depletion in the Minqin Basin by calculating multi-year groundwater storage variables. Currently, two main methods are used to calculate groundwater storage variables: the grid method for areas with uniformly distributed monitoring wells and abundant water level data [?], and the Thiessen polygon method for areas with insufficient water level data [?].

To address Minqin’s current water resource challenges, studying the historical process of groundwater development and utilization and its dynamic changes is essential. This paper classifies groundwater dynamic types in Minqin, analyzes 31 years of groundwater level change characteristics, calculates groundwater storage variables, examines their spatiotemporal distribution and evolution trends, and provides a theoretical basis for rational groundwater development and ecological restoration.

1 Study Area Overview

Minqin experiences a continental arid climate with perennial drought and low rainfall. The overall terrain slopes gently from southwest to northeast. Groundwater primarily consists of unconsolidated rock pore water (Figure 1). Within 130 m depth lies the phreatic aquifer, composed of interbedded gravel, sand, and sub-clay, underlain by a continuous clay layer forming a weakly permeable barrier, with a confined aquifer beneath. Agricultural extraction concentrates almost entirely in the phreatic aquifer, which is the focus of this study. Ground-

water recharge sources include agricultural irrigation infiltration, canal seepage, atmospheric precipitation, and lateral runoff. The main discharge pathway is groundwater extraction, accounting for approximately 94.5% of total discharge, with the remainder through evaporation. Agriculture forms the pillar industry in Minqin, with major irrigation districts including Hongyashan, Huanhe, Nanhu, and Changning. Hongyashan is a mixed surface-groundwater irrigation district, while the others rely primarily on groundwater.

Since the 1960s, extensive water resource use for socioeconomic development in the upper Shiyang River Basin has substantially reduced surface water inflow to Minqin, forcing excessive groundwater extraction to meet agricultural and industrial demands. In the 1970s, annual groundwater extraction in the Minqin Basin was $2.5 \times 10^8 \text{ m}^3$, exceeding $2.8 \times 10^8 \text{ m}^3$ by the early 1980s. By 2000, groundwater levels had dropped 10–15 m compared to the 1960s, with an average annual decline of $0.38 \text{ m} \cdot \text{a}^{-1}$. This caused progressive groundwater resource depletion, vegetation degradation, and desert encroachment. According to the latest over-exploitation zone designation [?], the Minqin Basin is classified as the “Wuwei City Minqin Shallow Large General Over-exploitation Zone,” covering 1785.78 km^2 . Implementation of the “Gansu Shiyang River Basin Key Management Plan” in 2007 enabled unified water resource management and scheduling across the basin, with surface inflow increasing annually at a rate of $2.0 \times 10^7 \text{ m}^3 \cdot \text{a}^{-1}$, effectively curbing water level decline. Desert and desertified areas decreased from 94.5% to 89.8% of the total area, while forest coverage increased from 10.86% to 17.91% [?], demonstrating ecological improvement.

2.1 Monitoring Well Data

Groundwater monitoring data used in this study were obtained from the Minqin County Water Affairs Bureau (1985–2005) and the Second Hydrogeological and Engineering Geological Team of the Gansu Provincial Bureau of Geology and Mineral Resources (2006–2016), comprising 85 monitoring wells from the Water Affairs Bureau and 53 from the Second Hydrogeological Team (Figure 3). Meteorological data, groundwater extraction volumes, and surface water diversion volumes were provided by the Gansu Provincial Hydrology and Water Resources Bureau.

This study employs the grid method to calculate shallow groundwater storage variables in the Minqin Basin from 1985 to 2016. The methodology involves: (1) subdividing the study area into $400 \text{ m} \times 400 \text{ m}$ grids, totaling 29,100 grid points; (2) using Kriging interpolation [?] to spatially interpolate monitoring well water level data and obtain end-of-year water level values $h_{k(i,j)}$ for each grid point from 1985 to 2016 (where i, j are grid numbers and $k = 1985, \dots, 2016$); (3) discretizing aquifer specific yield $\mu_{i,j}$ to each grid point based on shallow aquifer specific yield zones (Figure 4); and (4) calculating annual storage variables for the study area using the following formula:

$$Q_k = \sum [\alpha_{i,j} \times (h_{k,i,j} - h_{k-1,i,j}) \times A_{i,j}]$$

where Q_k represents groundwater storage variable in year k (10^8 m^3); $h_{k,i,j}$ is the end-of-year water level value at grid point (i,j) in year k (m); $h_{k-1,i,j}$ is the end-of-year water level value at grid point (i,j) in year $k-1$ (m); $\alpha_{i,j}$ is the aquifer specific yield at grid point (i,j) ; and $A_{i,j}$ is the grid area (m^2).

3.1 Groundwater Dynamic Types and Characteristics in Minqin County

The main factors influencing groundwater dynamics in the study area include artificial groundwater extraction, river and canal seepage, field irrigation infiltration, and atmospheric precipitation, with groundwater extraction being the primary driver of water level changes. Based on the main influencing factors and dynamic characteristics, shallow groundwater levels in Minqin County can be classified into four dynamic types: extraction-dominated, irrigation infiltration-extraction, river infiltration-extraction, and runoff (Figure 5).

The extraction-dominated type is mainly distributed in Nanhu and Changning townships, which lack surface water irrigation and experience intense groundwater extraction. Using the Nanhu Gancao well as an example, the multi-year average monthly water level dynamics show that agricultural extraction begins in March, causing water levels to decline; May–July represents the peak water use period with continued decline; after October, agricultural activities weaken, extraction decreases, and water levels slowly recover. This area experiences large intra-annual water level fluctuations with a maximum amplitude of 13.15 m. Since 1985, the average annual water level decline in this type has been $6.76 \text{ m} \cdot \text{a}^{-1}$.

The irrigation infiltration-extraction type is distributed in the Hongyashan Irrigation District, the main body of the Minqin Basin with the densest population and most intense agricultural activities. As a mixed surface-groundwater irrigation district, its groundwater dynamics are influenced by both groundwater extraction and surface water irrigation. Using the Quanshan No. 3 well as an example, the multi-year average monthly water level variation shows: January–February with no extraction, water levels slowly rise; March–July with extraction, water levels rapidly decline; August–September with reduced agricultural activity, the decline rate slows; October–December with widespread surface water winter irrigation, water levels partially recover. This area exhibits large intra-annual groundwater level fluctuations with a maximum amplitude of 2.11 m, and year-end water levels are approximately 0.55 m lower than year-beginning levels. Since 1985, the average annual water level decline in this type has been $0.55 \text{ m} \cdot \text{a}^{-1}$.

The river infiltration-extraction type is distributed near the Shiyang River channel and downstream of the Hongyashan Reservoir, where surface water bodies provide continuous recharge to groundwater. Using the Xia’ an Sheshe monitoring well as an example, the multi-year average monthly water level variation

shows: January–February with no extraction but river lateral recharge, water levels continuously rise; March–July when extraction exceeds river recharge, water levels decline; after October, water levels gradually recover. This area has minimal extraction while receiving river recharge, resulting in stable intra-annual water levels with a maximum amplitude of 0.2 m.

The runoff type is mainly distributed in desert areas where human activities have minimal impact on groundwater levels. Using the 1985 data from Desert Area Well No. 2 as an example, this area is primarily influenced by natural groundwater runoff, with small intra-annual water level fluctuations and a maximum amplitude of 0.2 m. Year-end water levels are essentially equivalent to year-beginning levels.

3.2 Groundwater Level Change Characteristics in the Minqin Basin

Focusing on the Hongyashan Irrigation District and its periphery, this study collected shallow phreatic water level data from the Minqin Basin for 1985–2016. Monitoring wells with continuous, complete records were selected while ensuring relatively uniform spatial distribution, ultimately yielding 138 wells to produce annual average water level contour maps for 1985–2016 and specific contour maps for 1985, 2000, 2007, and 2016 (Figure 6). Groundwater levels decrease from southwest to northeast across the Minqin Basin, indicating an overall flow direction from southwest to northeast. Compared with 1985, water levels throughout the basin had declined by 2000, with three major depression centers near east Suwu Town, Datang Town, and Shoucheng Town. By 2007, water levels continued to decline. Following comprehensive Shiyang River management, the rate of decline slowed significantly by 2016, with slight declines near Qinfeng Farm and east Hongshaliang Town, while water level recovery occurred in some areas like Donghu Town, with a maximum recovery rate of $0.2 \text{ m} \cdot \text{a}^{-1}$.

Subtracting the 1985 flow field from the 2016 flow field yields the groundwater level amplitude variation map for 1985–2016 (Figure 7). Overall, water levels declined throughout the Minqin Basin during this period. In intensively cultivated areas south of Minqin County seat, south of Quanshan, and in Donghu, declines reached 22 m, 18 m, and 16 m, respectively. Agricultural extraction around Minqin County seat is minimal, with groundwater supplying only small industrial and domestic uses, resulting in a multi-year water level decline of approximately 0.2 m. Desert areas on both sides of the Minqin Basin showed smaller changes compared to the central oasis, with only slight declines.

3.3 Spatiotemporal Distribution Characteristics of Groundwater Storage Variables in the Minqin Basin

Annual and cumulative shallow groundwater storage variables in the Minqin Basin for 1985–2016 are shown in Figure 8. The cumulative storage variable

for 1985–2016 was $-24.45 \times 10^8 \text{ m}^3$, indicating overall negative equilibrium. After 2007, annual storage variables alternated between positive and negative values, but cumulative storage variables continued to decline. Table 1 presents groundwater storage variables for the Hongyashan Irrigation District and peripheral desert areas. Due to large groundwater extraction volumes in the Hongyashan Irrigation District, a regional groundwater depression cone formed, yielding an average annual storage variable of $-2.86 \times 10^8 \text{ m}^3$. Although desert areas have no groundwater extraction, groundwater levels continued to decline due to radial flow toward the Hongyashan Irrigation District, producing an average annual storage variable of $-0.33 \times 10^8 \text{ m}^3$.

3.4 Trend Analysis of Groundwater Storage Variables in the Minqin Basin

The significant groundwater level decline in the Minqin Basin since the 1960s results from both natural and human factors. The basin's arid climate yields average annual precipitation of only 113 mm, producing minimal infiltration recharge. Correlation analysis between multi-year groundwater storage variables and rainfall shows a weak Pearson correlation coefficient of just 0.001. Evaporation is intense in the Minqin Basin, but groundwater depth exceeds 4 m in most areas, reaching maximum depths of 30 m—far greater than the evaporation limit depth—making phreatic evaporation negligible [?]. Surface water inflow to the basin is regulated by the Hongyashan Reservoir and is essentially independent of natural upstream snowmelt recharge. Human activities affecting groundwater primarily involve extraction and irrigation. The Pearson correlation coefficient between groundwater extraction volume and storage variables is -0.86 , indicating high correlation, while that between surface water diversion volume and storage variables is 0.61 , indicating moderate correlation. These results demonstrate that extraction volume is the key factor determining storage variable magnitude in the Minqin Basin, followed by surface water diversion volume.

Based on calculated storage variables and multi-year changes in extraction and diversion volumes, groundwater volume changes in the Minqin Basin since the 1980s can be divided into four stages: (1) Rapid decline period (1985–2000): Groundwater extraction exceeded $2.5 \times 10^8 \text{ m}^3$, surface inflow remained below $2.0 \times 10^8 \text{ m}^3$, and annual groundwater deficits fluctuated significantly around $-1 \times 10^8 \text{ m}^3$. (2) Stable decline period (2001–2006): Groundwater extraction stabilized around $2.8 \times 10^8 \text{ m}^3$ and surface diversion around $2.0 \times 10^8 \text{ m}^3$, with storage variables fluctuating between $-0.1 \times 10^8 \text{ m}^3$ and $-0.6 \times 10^8 \text{ m}^3$. (3) Management period (2007–2009): Comprehensive Shiyang River management began, reducing groundwater extraction while significantly increasing upstream inflow. Storage variables fluctuated between $-0.1 \times 10^8 \text{ m}^3$ and $0.5 \times 10^8 \text{ m}^3$, with positive equilibrium achieved in 2010. The groundwater level decline rate slowed substantially, with localized recovery (Figure 6). (4) Stabilization/recovery period (2010–2016): Groundwater

extraction stabilized at $1.8 \times 10^8 \text{ m}^3$ and surface diversion at $3.0 \times 10^8 \text{ m}^3$, with storage variables alternating between positive and negative values.

Linear regression fitting of the data yields the following regression equation for the irrigation infiltration-extraction dynamic zone in the Minqin Basin:

$$Q = -0.361 \times Q_D + 0.001 \times Q_I + 0.218$$

where Q is groundwater storage variable (10^8 m^3), Q_D is groundwater extraction volume (10^8 m^3), and Q_I is surface water irrigation volume (10^8 m^3). According to this equation, to achieve zero storage variable (i.e., stable groundwater levels) with a surface diversion volume of $3.0 \times 10^8 \text{ m}^3$, groundwater extraction should be $0.61 \times 10^8 \text{ m}^3$, which can be considered the recoverable groundwater volume.

4 Conclusions

This study thoroughly analyzed extensive groundwater level data since 1985, classified groundwater dynamic types in Minqin County, mapped flow fields to examine 31 years of groundwater level changes, calculated annual groundwater storage variables using the grid method, and analyzed their spatiotemporal distribution characteristics and evolution trends. The main conclusions are:

- (1) Groundwater dynamics in Minqin include four types: extraction-dominated, irrigation infiltration-extraction, river infiltration-extraction, and runoff. Their intra-annual and inter-annual variation characteristics differ: extraction-dominated and irrigation infiltration-extraction types show large intra-annual water level fluctuations with average multi-year declines of $6.76 \text{ m} \cdot \text{a}^{-1}$ and $13.15 \text{ m} \cdot \text{a}^{-1}$, respectively. River infiltration-extraction and runoff types exhibit stable intra-annual water levels, with year-end levels essentially equivalent to year-beginning levels.
- (2) Groundwater in the Minqin Basin flows from southwest to northeast. Before comprehensive Shiyang River management, water levels declined rapidly throughout the basin; after management implementation, the decline rate decreased significantly, with water level recovery occurring in localized areas such as Donghu Town at a maximum rate of $0.2 \text{ m} \cdot \text{a}^{-1}$, demonstrating the effectiveness of integrated management in curbing groundwater level decline.
- (3) Influenced by comprehensive management, annual storage variables in the Minqin Basin have alternated between positive and negative values since 2007. From the mid-1980s to 2016, irrigation areas experienced significant water level declines up to 22 m, with cumulative groundwater depletion of $24.45 \times 10^8 \text{ m}^3$. The storage variable modulus and extraction modulus for the irrigation infiltration-extraction type were $-1.04 \times 10^8 \text{ m}^3$ and $1.76 \times 10^8 \text{ m}^3$, respectively. Desert areas and the county seat experienced only slight water level declines.

- (4) Groundwater storage variables in the Minqin Basin are primarily influenced by extraction and surface water irrigation. To alleviate water resource shortages, groundwater extraction should be further restricted while increasing surface water imports. Under current surface water supply conditions, groundwater extraction in the Minqin Basin should not exceed $0.61 \times 10^8 \text{ m}^3$.

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