Postprint on the Evolution of Groundwater Resources in the Plain Area of the Kuitun River Basin, Xinjiang

Authors: Shen Ruixin, Lü Shuping, Du Mingliang, Wu Bin, Yang Pengnian, Wu Bin

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Abstract

This study focuses on the plain area of the Kuitun River Basin, systematically compiling data on precipitation, river runoff, and canal water diversion. Employing the extreme value ratio K, Mann-Kendall significance statistic Z, and Hurst exponent H derived from the R/S method, we analyze the evolutionary trends and persistence characteristics of each groundwater resource component, assess the evolution scenario of groundwater resources, and investigate its underlying causes. The results indicate: (1) Natural groundwater recharge exhibits a slight increasing trend; among transformed recharge components, river leakage recharge demonstrates an overall upward trend, while field infiltration recharge and canal system leakage recharge follow a pattern of initial increase followed by decrease, and reservoir leakage recharge remains relatively stable; (2) Groundwater resources in the Kuitun River Basin plain area experienced slow growth prior to 2008, with an accelerated growth rate thereafter. The significance test statistic Z and Hurst exponent H demonstrate that groundwater resources exhibit a statistically significant increasing trend with strong short-term persistence; (3) The increase in river leakage recharge constitutes the primary driver of groundwater resources augmentation.

Full Text

Analysis on the Evolvement of Groundwater Resources in the Plain Area of Kuytun River Basin

Shen Ruixin[1], **Lyu Shuping**[2], **Du Mingliang**[1], **Wu Bin**[1], **Yang Pengnian**[1] [1]College of Water Conservancy and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, China [2]Water Resources Bureau of Usu City, Usu 834700, Xinjiang, China

Abstract

This study examines the plain area of the Kuytun River Basin, compiling and analyzing data on precipitation, river runoff, and canal water diversion. Using the extreme value ratio (K), Mann-Kendall significance test (Z), and Hurst exponent (H) calculated via the Rescaled Range Analysis (R/S) method, we analyze the evolutionary trends and persistence of various groundwater resource components, assess the overall evolution of groundwater resources, and identify the underlying causes. The results indicate: (1) Natural groundwater recharge exhibits a slight increasing trend. Among transformed recharge components, river leakage recharge shows an overall upward trend, while field infiltration and canal leakage recharge initially increase then decrease, and reservoir leakage recharge remains stable. (2) Groundwater resources in the Kuytun River Basin plain area increased slowly before 2008, but the growth rate accelerated after 2008. Significance test values (Z) and Hurst exponent (H) demonstrate that groundwater resources show a significant increasing trend with strong short-term persistence. (3) The increase in river leakage recharge is the primary driver of groundwater resource growth.

Keywords: Xinjiang Kuytun River Basin; Groundwater; Water resources quantity; Groundwater recharge

Introduction

Against the backdrop of global warming and intensified human activities, changes in water resources have attracted widespread attention. Water resource security refers to a state where water quantity and quality can be continuously and stably maintained to meet human and social development needs while ensuring ecological water requirements [1]. China faces prominent water security challenges, with intertwined problems of water shortage, ecological damage, and environmental pollution that constrain sustainable socio-economic development and people' s production and livelihoods [2]. In arid and semi-arid regions, water scarcity has become a critical factor limiting regional economic development [3].

In recent years, with rapid economic development in the Kuytun River Basin plain area, water demand has surged, leading to excessive surface water diversion and groundwater over-exploitation. This has caused severe ecological and environmental problems, including downstream river channel drying, shrinkage of the Ganjia Lake wetland, natural vegetation degradation, and intensified land desertification. Studying the evolution of groundwater resources and analyzing the causes of change are crucial for improving water security systems and promoting sustainable socio-economic development and ecological civilization construction [4-5].

Numerous scholars have conducted extensive research on surface water resource evolution. Mu Minxia et al. [6] used hydrological station runoff data, selecting variation coefficients and concentration parameters to analyze that the Kuytun River Basin exhibits extremely uneven intra-annual runoff distribution, relatively stable inter-annual variation, and a weak increasing trend over multiple years. Muattar Saydi et al. [7] utilized various hydrological statistical models to analyze nearly 50 years of data, finding that the anomaly of multi-year average runoff showed large variation amplitude, particularly after 1990, with increased Cv values and more obvious runoff growth trends. Zhang Hui et al. [8] used remote sensing, meteorological, and hydrological data to conclude that glacier melting under climate influence leads to increased runoff.

In groundwater research, most studies have focused on groundwater quality and water level changes [9-10]. Due to the complex processes of groundwater resource changes under the combined effects of climate change and human activities, and the difficulty in collecting long-term series data, analysis of groundwater resource evolution trends remains limited. This study, integrated with Xinjiang’ s third water resources survey and evaluation project, analyzes the evolution process of each groundwater resource component in the Kuytun River Basin and provides projections for future groundwater resource trends.

1. Study Area Overview and Data Sources

1.1 Study Area Overview

The Kuytun River Basin plain area is located in the southwestern part of the Junggar Basin, characterized by an arid climate with an average annual precipitation of 257 mm and average annual evaporation of 1,830 mm. The main rivers in the basin originate from the northern slopes of the Yilianhabierga and Borokonu mountains in the Tianshan range. The multi-year average surface water resources amount to 1.643\$×10^{8}\$ m^3, with an available quantity of 1.319\$×10^{8}\$ m^3. The plain area groundwater recharge is 0.958\$×10^{8}\$ m^3, with an exploitable quantity of 0.406\$×10^{8}\$ m^3.

The “Golden Triangle” region formed by Kuytun City, Usu City, and the Dushanzi District of Karamay City within the basin represents a relatively developed and concentrated industrial area in Xinjiang, as well as a region with development potential receiving priority support for development [11-12]. The Ganjia Lake downstream of the Kuytun River Basin preserves natural landscapes formed at the end of the last glacial period, primarily protecting the desert white saxaul (*Haloxylon persicum*), a species 仅存于此地. This represents China’ s only temperate desert saxaul forest reserve, holding extremely high ecological protection value and environmental indicator significance [13].

The Kuytun River Basin plain area constitutes a complete hydrogeological unit [Figure 1: see original paper]. The southern piedmont alluvial-pluvial gravel plain serves as the main groundwater recharge and runoff area, while the central fine soil plain functions as the groundwater runoff and discharge area. From the southern and northern mountain fronts to the central plain area, groundwater types transition from single-layer unconfined water to multi-layer unconfined-confined water. Single-layer aquifers are mainly distributed in the northern part of Dushanzi District and urban areas of Kuytun and Usu cities, while confined water is primarily found in the area north of National Highway 312 and south of the northern Kuytun River channel. Groundwater level dynamics show an exploitation-type pattern, and based on multi-year observation well data, groundwater levels in the Kuytun River alluvial-pluvial plain and the Sikeshu River alluvial-pluvial fine soil plain continue to decline.

1.2 Data Sources and Analysis

Data sources are extensive. Piedmont lateral recharge, precipitation, surface water diversion, plain area surface runoff, canal diversion, and field irrigation data were obtained from Xinjiang' s second water resources assessment (1980-2000), data collected for Xinjiang' s third water resources assessment (2001-2016), and the *Usu City Surface Water Assessment Report* (2019). Piedmont lateral recharge and surface water diversion also referenced the *Usu Groundwater Resources Assessment Report* (2018) and the *Kuytun River Basin Planning Revision Groundwater Resources Investigation and Assessment Report* (2012). River runoff data came from hydrological station monitoring data, while river discharge data were derived from analysis of groundwater recharge characteristics in the Kuytun River Basin South Lowland (1972-2005) [14] and data from the Corps Design Institute for 2006-2018. Changes in reservoir numbers, canal seepage prevention, canal system effective utilization coefficients, and water-saving irrigation areas were based on the Xinjiang Water Conservancy Statistical Yearbook (2000-2018) and Water Resources Bulletins. Calculation parameters referenced the parameter tables in *Xinjiang Groundwater Resources* (2004).

2. Evolution of Groundwater Resource Components

Groundwater resources in the plain area are calculated using the recharge method, determined as total recharge minus well irrigation return flow, comprising natural recharge and surface water transformation recharge. Natural recharge primarily includes precipitation infiltration recharge and piedmont lateral recharge, while surface water transformation recharge mainly consists of river leakage, canal leakage, field infiltration, and reservoir leakage. Groundwater recharge evolution is influenced by natural factors (precipitation, temperature, etc.) and human factors (reservoirs, engineering construction, canal seepage prevention, and field water-saving irrigation technology) [15-16].

2.1.1 Evolution Analysis of Piedmont Lateral Recharge

Piedmont lateral recharge in the Kuytun River Basin mainly occurs in deeply incised valleys of the Kuytun, Sikeshu, Tewule, Mote, and Guertu rivers, replenishing the plain area through Quaternary loose deposits beneath the riverbed in the form of underflow. Valley underflow is calculated using Darcy' s law, with calculation sections selected at mountain pass outlets. Permeability coefficients, section widths, and aquifer thicknesses are obtained from engineering geological survey data at river outlet diversion gates, while hydraulic gradients are determined from river topographic slopes. The calculated valley underflow is 0.3147$×10^{8}$ m^3 .

In addition to valley underflow, west of the Sikeshu River, the direct contact between mountainous Paleozoic Carboniferous bedrock and plain area Quaternary deposits allows small amounts of bedrock fissure water to laterally recharge the plain area. Bedrock fissure water lateral recharge can be approximated using the mountainous groundwater balance method: mountainous precipitation infiltration recharge minus base flow at mountain outlets minus valley underflow. Base flow can be determined using the cutting method or baseflow-index method. The calculated bedrock fissure water lateral recharge is 0.3577$×10^{8}$ m^3. Combined, the Kuytun River Basin piedmont lateral recharge totals 0.6724$×10^{8}$ m^3 .

Piedmont lateral recharge changes positively correlate with mountainous precipitation. To obtain long-term series data, Xinjiang' s third groundwater resources assessment calculated the 1956-2016 series by multiplying the change rate of multi-year surface water resources by the multi-year average lateral outflow from mountainous areas (i.e., plain area piedmont lateral recharge) and adding the multi-year average lateral outflow. Overall, piedmont lateral recharge in the Kuytun River Basin shows a slight increasing trend over the past 60 years [Figure 2: see original paper].

2.1.2 Evolution of Plain Rainfall Infiltration Recharge

According to Xinjiang' s third groundwater resources assessment, precipitation in the Kuytun River Basin plain area from 1956-2018 ranged from a maximum of 486.8 mm to a minimum of 80.3 mm. Precipitation infiltration recharge ranged from a maximum of 0.70$×10^{8}$ m^3 to a minimum of 0.13$×10^{8}$ m^3, averaging 0.39$×10^{8}$ m^3. Precipitation infiltration recharge depends on effective precipitation (events >10 mm), precipitation infiltration coefficients (ranging 0.04-0.20 based on different unconfined water depths, lithologies, and precipitation amounts), and calculation areas (based on different calculation units, unconfined water depths, and vadose zone lithology zones). Precipitation changes affect groundwater recharge [18]. In recent years, plain area precipitation has gradually increased, with the 2000-2016 average of 257.16 mm being 76.12 mm higher than the 1956-2000 average.

However, increasing groundwater exploitation (from 0.54$×10^{8}$ m^3 in 1980 to 5.14$×10^{8}$ m^3 in 2018) has caused groundwater depth to increase. In 2000, areas with groundwater depth <6 m accounted for 67.45% of the total, but by 2016, this proportion had decreased to 11.64%. Despite slightly increasing precipitation trends and greater groundwater depths, precipitation infiltration recharge has only increased slightly overall [Figure 3: see original paper].

2.2.1 Evolution of River Leakage Recharge

River leakage recharge is calculated using the following formula:

$$Q_{river} = (Q_{runoff} - Q_{diversion} - Q_{out}) \times (1 - \lambda_1 - \lambda_2) \quad (1)$$

where Q_{river} is river leakage recharge; Q_{runoff} is average runoff at the hydrological station (mountain outlet); Q_{out} is river terminal discharge (inflow to terminal lake); $Q_{diversion}$ is canal diversion under current water conservancy conditions; λ_1 is river surface evaporation coefficient; and λ_2 is river bank infiltration loss coefficient.

River leakage recharge is primarily affected by annual runoff, diversion, and discharge. According to Jilede Hydrological Station monitoring, runoff from 1956-2016 increased with a dry-wet cycle of approximately 20 years and a growth rate of 189$×10^{4}$ m^3·10a^{-1}. From 1997-2018, years with positive anomalies increased, showing an overall increasing trend. The Kuytun River Basin' s 60-year runoff shows a stable increasing trend [Figure 4: see original paper] with a growth rate of 1,325$×10^{4}$ m^3 · 10a^{-1} and approximately 20-year cyclical oscillations. Runoff increased significantly after 1997, with more years exceeding the average.

Analysis of Kuytun River Basin water resource utilization shows diversion changes in four phases: (1) 1980-2000: steady growth with irrigation area expansion at 0.094$×10^{8}$ m^3 · a^{-1}; (2) 2001-2007: rapid growth at 0.217$×10^{8}$ m^3 · a^{-1}; (3) 2008-2010: sharp decrease from 11.69$×10^{8}$ m^3 (2008) to 7.64$×10^{8}$ m^3 (2010) due to low water availability in the dry year of 2009; (4) 2011-2018: slight decreasing trend at 7.83-8.15$×10^{8}$ m^3 [Figure 5: see original paper]. During this phase, cultivated land increased from 905.79 hm^2 (2011) to 1,892.94 hm^2 (2018), yet surface diversion did not increase, instead decreasing slightly. This occurred because expanded cultivated land relied primarily on groundwater irrigation (groundwater exploitation increased from 4.94$×10^{8}$ m^3 in 2011 to 6.94$×10^{8}$ m^3 in 2018), and efficient water-saving irrigation reduced irrigation quotas (efficient water-saving irrigation area increased 40.1% from 716.36 hm^2 in 2011 to 1,003.84 hm^2 in 2018).

River terminal discharge, influenced by inflow and human regulation, shows a slight overall increasing trend. From 1972-1997, despite extreme fluctuations, discharge remained stable at approximately 2.09$×10^{8}$ m^3. From 1997-2018, discharge showed a slight upward trend, averaging 2.94$×10^{8}$ m^3.

Consequently, calculated river leakage recharge shows an overall increasing trend with a growth rate of 140$×10^{4}$ m$^3 \cdot a^{-1}$ and 15-20 year cyclical oscillations. Changes are primarily influenced by runoff and diversion variations [Figure 6: see original paper]. The 2001 wet year (runoff: 20.7$×10^{8}$ m^3; diversion: 10.38$×10^{8}$ m^3) produced a peak leakage recharge, while the 2009 and 2014 dry years (runoff: 11.03$×10^{8}$ m^3 and 12.99$×10^{8}$ m^3; diversion: ~8.5$×10^{8}$ m^3) produced low values. From 1980-2018, increasing runoff and initially increasing then decreasing diversion caused river leakage recharge to show an overall upward trend.

2.2.2 Evolution of Canal and Field Leakage Recharge

Canal leakage recharge changes divide into three phases: (1) 1980-2007: continuous growth. Rapid farmland water conservancy development began in 1985, focusing on canal seepage prevention and constructing new and renovated facilities. Increasing surface diversion caused canal leakage recharge to rise from 1.02$×10^{8}$ m^3 to 1.70$×10^{8}$ m^3, with slowed growth during 1990-2000 due to improved canal seepage prevention rates. The 2001-2002 decrease from 1.57$×10^{8}$ m^3 to 1.46$×10^{8}$ m^3 resulted from reduced diversion in the 2002 dry year. (2) 2008-2010: decreasing phase, with reduced canal diversion and increased groundwater exploitation causing canal leakage recharge to drop from 1.68$×10^{8}$ m^3 to 1.26$×10^{8}$ m^3. (3) 2011-2018: stable phase, with canal leakage recharge at 1.20-1.27$×10^{8}$ m^3 [Figure 7: see original paper]. Changes are primarily influenced by diversion and canal system utilization coefficients. Before 2008, diversion increased; after 2008, it decreased. By 2014, the Kuytun River plain area had 28 main diversion canals (total length 480.9 km), with 345.4 km seepage-proofed (72% of main conveyance canals). By 2018, main canal seepage prevention reached 100%, with main and branch canal utilization coefficients reaching 0.79, reducing canal leakage recharge over the past decade. Overall, canal leakage recharge shows an initial increase followed by a decrease.

Field infiltration recharge trends closely follow canal infiltration recharge. Field infiltration recharge increased from 0.3185$×10^{8}$ m^3 in 1980 to 0.923$×10^{8}$ m^3 in 2000, decreased to 0.81$×10^{8}$ m^3 in 2002, gradually increased to 1.08$×10^{8}$ m^3 in 2007, then decreased to 0.87-0.81$×10^{8}$ m^3 after 2010 [Figure 8: see original paper]. Field infiltration recharge is primarily influenced by irrigation methods and field water application. After 2008, rapid expansion of under-film drip irrigation (from 840.42 hm^2 in 2008 to 1,287.31 hm^2 in 2018) increased water-saving irrigation rates from 45% to 68%. Although increased cultivated land raised field water application, improved water-saving irrigation rates and field water use efficiency reduced field infiltration recharge over the past decade. Both canal leakage and field infiltration recharge increased before 2008 but decreased in the past decade.

2.2.3 Evolution of Reservoir Leakage Recharge

Reservoir leakage recharge is calculated using:

$$Q_{reservoir} = Q_{capacity} \times \alpha \quad (2)$$

where $Q_{reservoir}$ is reservoir leakage recharge; $Q_{capacity}$ is reservoir storage capacity; and α is reservoir leakage recharge coefficient.

Reservoir leakage recharge is closely related to new water conservancy projects. Reservoir construction began in the early 1950s, reaching 21 reservoirs by 1980 with leakage recharge of 0.4469\$×10^{8}\$ m^3, and 23 reservoirs by 1990 with leakage recharge of 0.4571\$×10^{8}\$ m^3. Currently, the Kuytun River plain area has 24 reservoirs of various sizes, with multi-year average reservoir leakage recharge of 0.4473\$×10^{8}\$ m^3.

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3. Evolution Situation of Groundwater Resources

Kuytun River Basin groundwater resources show an overall increasing trend from 1980-2018 [Figure 8: see original paper]. The 2001 value of 0.965\$×10^{8}\$ m^3 represents the maximum in 38 years, while 2009 and 2014 represent two lower values at 0.373\$×10^{8}\$ m^3 and 0.462\$×10^{8}\$ m^3, respectively. These extremes result from wet and dry years affecting natural recharge and river leakage recharge, which account for 16.4% and 46.1% of groundwater resources, respectively, exerting substantial influence on groundwater resource variations.

Groundwater resource recharge components include precipitation infiltration, piedmont lateral recharge, river leakage, canal leakage, field infiltration, and reservoir leakage. Based on 1980-2018 data series, extreme value ratios, Mann-Kendall tests, and R/S analysis Hurst exponents were used to evaluate stability, trend significance, and persistence of each component . Extreme value ratios K<2, 2<K<4, and K>4 indicate stable, unstable, and extremely unstable conditions, respectively. Mann-Kendall test values |Z|>1.28, 1.64, and 2.32 indicate significance at 90%, 95%, and 99% confidence levels, respectively (Z>0: increasing trend; Z<0: decreasing trend). Hurst exponents 0<H<0.5 and 0.5<H<1 represent anti-persistence and persistence, respectively, with values approaching 0 indicating stronger anti-persistence and values approaching 1 indicating stronger persistence [20-21].

Results show precipitation infiltration and river leakage are extremely unstable, piedmont lateral recharge and canal leakage are stable, and field infiltration recharge is unstable. Precipitation infiltration and river leakage show significant increasing trends, piedmont lateral recharge shows non-significant increase, while canal leakage and field infiltration show non-significant decreases. Piedmont lateral recharge exhibits weak persistence, while other components show strong persistence.

The Kuytun River Basin groundwater resource evolution shows an unstable but significant increasing trend. Statistical measures from Hurst analysis indicate that the effective influence time of past conditions on future trends reaches 8 years, suggesting that short-term groundwater resource changes will continue the 38-year increasing trend without reversal. In groundwater resource calculations, natural recharge (16.4%) and river leakage recharge (46.3%) show significant increasing trends with strong persistence, with river leakage recharge changes dominating regional groundwater resource evolution. The primary cause of increased river leakage recharge is increased runoff [22-23] combined with reduced diversion. Piedmont lateral recharge, canal leakage, and field infiltration show non-significant increasing or decreasing trends with relatively minor impacts on groundwater resources. Precipitation, river diversion, cultivated land changes, water conservancy construction, canal seepage prevention improvements, and irrigation method changes all influence component variations, with their combined effects ultimately producing the observed increasing trend in regional groundwater resources.

TABLE:2 shows the evaluation results for each component.

Conclusions

(1) Natural recharge (precipitation and piedmont lateral recharge) shows slight increasing trends. Among transformed recharge components, river leakage shows a clear increasing trend; canal and field leakage recharge increased then decreased after 2008, showing regular patterns; reservoir leakage recharge remains stable at an average of 0.45$×10^{8}$ m^3. Natural recharge is affected by increasing precipitation, while transformed recharge is influenced by comprehensive factors including controlled diversion, canal construction, cultivated land expansion, increased field water application, irrigation methods, and water conservancy projects.

(2) Kuytun River Basin plain area groundwater resources show an unstable but significant increasing trend from 1980-2018, with strong short-term persistence continuing this trend. Groundwater resource increases primarily result from increased runoff and decreased diversion, leading to increased river leakage recharge.

(3) Over the next several decades, Kuytun River Basin plain area groundwater resources will show a slow growth trend. Implementation of the strictest water resources management system, including total water use control, improved farmland water conservancy facilities, closure of some wells, and reduced water allocation, will enable groundwater resources to

support regional socio-economic development, ensure ecological security, and maintain water resource security.

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