Postprint: Study on Ecological Base Flow in the Niya River Basin under Climate Change

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Abstract

Watershed ecological base flow is critical for the health and stability of river ecosystems. This study takes the Niya River Basin in Xinjiang as the research area, using meteorological data from the Minfeng County Meteorological Station from 1958 to 2018 and hydrological data from four hydrological monitoring sections of the Niya River from 1978 to 2018. Trend fitting, the Tennant method, correlation analysis, and regression models were employed to analyze watershed climate change, determine ecological base flow, investigate its spatiotemporal variation and assurance rate changes, and reveal the response of ecological base flow to climate change. The results indicate that over the past 61 years, watershed temperature increased at a rate of 0.22 ℃ $\cdot$ $(10a)^{-1}$, while annual precipitation increased at a rate of 3.8 mm $\cdot$ $(10a)^{-1}$. The recommended annual ecological base flow values for Niya Reservoir, Bayiba Headworks, Niya Hydrological Station, and Niya Headworks are 1.989 $m^3 \cdot s^{-1}$, 2.188 $m^3 \cdot s^{-1}$, 1.755 $m^3 \cdot s^{-1}$, and 1.702 $m^3 \cdot s^{-1}$, respectively. The interannual maximum ecological base flow occurred in 2010, the minimum in 1980; the intra-annual maximum occurred in July, and the minimum in January or December. Spatially, the distribution shows higher values in the upper reaches and lower values in the lower reaches, with the highest at Bayiba Headworks and the lowest at Niya Headworks. The multi-year average assurance rates of ecological base flow at each station are 50%, 45%, 50%, and 45%, respectively, exhibiting significantly higher values during the flood season than the non-flood season. Both annual and monthly ecological base flow values are significantly correlated with temperature and precipitation at the 0.01 level, showing sensitivity to temperature in spring and summer and to precipitation in autumn and winter. The coupling effects of regression models at each hydrological monitoring section are similar, with the overall watershed regression equation $R^2 = 0.365$, and the response of ecological base flow to climate change demonstrates integrity and attenuation characteristics. The research results can provide references for ecological water diversion and water ecological restoration in the Niya River Basin.

Full Text

Study on Ecological Base Flow in the Niya River Basin under Climate Change

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Abstract: Watershed ecological base flow is crucial for maintaining healthy and stable river ecosystems. This study examines the Niya River Basin in Xinjiang as the research area. Using meteorological data from the Minfeng meteorological station spanning 1958–2018 and hydrological data from four hydrological monitoring sections along the Niya River from 1978–2018, we employed trend analysis, correlation analysis, and regression modeling to investigate climate change trends, determine ecological base flow, explore its spatiotemporal variation and assurance rate changes, and reveal the response of ecological base flow to climate change. The results indicate that over the past 61 years, the basin's temperature has increased at a rate of 0.22 °C $\cdot$ $(10a)^{-1}$, while annual precipitation has increased at 3.8 mm $\cdot$ $(10a)^{-1}$. The recommended annual ecological base flow values are 1.989 $m^3 \cdot s^{-1}$ for Niya Reservoir, 2.188 $m^3 \cdot s^{-1}$ for the 818 Canal Head, 1.755 $m^3 \cdot s^{-1}$ for Niya Hydrological Station, and 1.702 $m^3 \cdot s^{-1}$ for the Niya Canal Head. Interannually, the maximum ecological base flow occurred in 2010 and the minimum in 1980; intra-annually, the maximum occurred in July and the minimum in January. Spatially, ecological base flow is higher in the upper reaches and lower in the lower reaches, peaking at the 818 Canal Head and reaching its lowest at the Niya Canal Head. The multi-year average assurance rates of ecological base flow at each station are 50%, 45%, 50%, and 45%, respectively, with flood season values significantly higher than non-flood season values. Both annual and monthly ecological base flow correlate significantly with temperature and precipitation at the 0.01 level, though base flow is sensitive to temperature in spring and summer and to precipitation in autumn and winter. The regression models for all hydrological monitoring sections show similar coupling effects, with the overall basin regression equation yielding $R^2 = 0.365$. The response of ecological base flow to climate change exhibits both integrity and attenuation characteristics. These findings provide scientific references for ecological water diversion and aquatic ecosystem restoration in the Niya River Basin.

Keywords: climate change; ecological base flow; hydrologic method; assurance rate; Niya River

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1 Introduction

Rapid socioeconomic development has led to excessive exploitation of water resources, threatening ecosystem stability. Riverine and riparian ecosystems have been particularly affected, exhibiting resource-based water scarcity, soil erosion, water quality deterioration, reduced river discharge, and biodiversity loss, all contributing to the continuous degradation of river ecosystems. Since the Industrial Revolution, extensive fossil fuel combustion has released large quantities of greenhouse gases, intensifying the greenhouse effect and causing global temperatures to undergo warming-dominated climate change. Precipitation has responded to this warming with spatiotemporal variability, though without showing a definitive trend. Consequently, river runoff has also changed in response to temperature and precipitation variations, altering hydrological elements such as discharge, water level, and flow velocity to varying degrees, thereby seriously impacting the stability of riverine and watershed ecosystems. Against this complex backdrop of climate change, how ecological base flow will respond remains unclear.

The concept of ecological base flow emerged to reconcile the escalating conflict between water resource development and ecological protection, ensuring sustainable socioeconomic development by maintaining adequate instream flow to preserve river ecosystem stability. While meeting human water demands, ecological base flow also satisfies ecosystem water requirements, achieving a balance between the two. Although no universally standardized definition currently exists, the academic community broadly accepts ecological base flow as the minimum flow requirement for maintaining river health, particularly as conflicts between ecological and human water demands intensify.

International research on ecological base flow began relatively early, focusing primarily on developing water ecosystem service functions, securing agricultural ecosystem water supplies, protecting river biodiversity, and investigating calculation methods, forming a comprehensive framework spanning theoretical concepts, computational methods, and practical applications. Chinese research on river ecological base flow began in the 1990s, yielding substantial results through extensive studies and applications by scholars and managers. These efforts established an ecological base flow research indicator system adapted to China's natural environmental characteristics by examining ecological water demands across different times, spaces, and ecosystem types. Currently, few studies worldwide have linked climate change with ecological base flow, making research on ecological base flow responses under climate change highly significant.

Xinjiang, located in central Eurasia and northwestern China, experiences extreme water scarcity due to its inland location and mountain barriers, which create low precipitation and high evaporation. The Niya River, a tributary of the Tarim River, represents a typical arid region watershed with extremely tight ecological water availability. This study examines the Niya River Basin in Xinjiang using meteorological data from Minfeng County (1958–2018) and hydrological data from four monitoring sections (1978–2018). We analyze climate change trends, determine ecological base flow and its spatiotemporal variation, examine assurance rate changes, and reveal the response of ecological base flow to climate change, providing scientific references for rational ecological water allocation, comprehensive water resource utilization, and aquatic ecosystem restoration in the Niya River Basin.

[Figure 1: see original paper]

2 Data and Methods

The Niya River Basin lies in the central-western part of Minfeng County, Hotan Prefecture, Xinjiang, extending approximately 200 km north-south with an area of 10,160.96 km^2. Located between 82°36 –82°50 E and 36°12 –37°48 N, the Niya River is Minfeng County's largest river, flowing north-south from the Lüshitage Peak on the northern slope of the Kunlun Mountains. The river is seasonal, fed by snowmelt, seasonal snow cover, and valley glaciers. The Chakda tributary joins the main stream at the mountain pass, with no tributaries downstream. The upper reach features a dendritic drainage pattern with Gobi, pebble, and semi-consolidated sandy pebble channels, sparse riparian vegetation, and unstable conditions. The middle reach's alluvial plain constitutes the Niya Irrigation District, Minfeng County's largest agricultural area, spanning 75 km north-south with 33.34 km^2 of cultivated land. The lower reach's channel transitions from gravel to fine sand with gradually decreasing slope, flanked by natural forest reserves and oases dominated by Populus euphratica, Tamarix ramosissima, and Phragmites australis—natural barriers for oasis farmland. The river terminates deep in the Taklamakan Desert.

2.1 Data Sources

2.1.1 Hydrological Data We selected hydrological data from 1978–2018 for four sections along the Niya River mainstem: Niya Reservoir, 818 Canal Head, Niya Hydrological Station, and Niya Canal Head. Missing data for some years were estimated using regression replacement methods. Daily, monthly, and annual average flows and annual runoff volumes were obtained from the *Hydrological Data of the Tarim River Basin* in the People's Republic of China Hydrological Yearbook.

2.1.2 Meteorological Data We used measured meteorological data from 1958–2018 at the Minfeng meteorological station—the only station in the basin with long-term records—to analyze regional climate change. Data including daily, monthly, and annual temperature and precipitation were obtained from the China Meteorological Data Network (http://data.cma.cn/). Temperature was automatically recorded in standard Stevenson screens, while precipitation was manually measured using standard rain gauges.

2.2 Methods

2.2.1 Hydrological Methods Current ecological base flow calculation methods include hydrological, hydraulic, ecological simulation, and holistic analysis approaches. This study selected commonly used hydrological methods: the Tennant method, the guaranteed minimum monthly average flow method, and the multi-year average minimum monthly flow method.

The **Tennant method**, also known as the Montana method, was proposed by Tennant in 1976. It uses a percentage of the long-term average natural flow as ecological base flow, making it the most commonly used method for rivers with extensive hydrological records. Given the Niya River's seasonal nature, we modified the method by designating the flood season as June–September. The recommended ecological base flow standards are shown in Table 1.

Guaranteed minimum monthly average flow method organizes and statistically analyzes over 30 years of hydrological observations. We performed frequency analysis on monthly average runoff for each section, using the 90% guarantee rate to determine ecological base flow.

Multi-year average minimum monthly flow method uses the multi-year average of minimum monthly flows as the ecological base flow. Though requiring shorter observation series, we applied it for comparative analysis.

The Tennant method formula for calculating monthly ecological base flow is:

$$Q_i = M_i \times N_i, \quad i = 1, 2, \dots, 12$$

where Q_i is the ecological base flow for month i ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), M_i is the average flow for month i ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), and N_i is the ecological base flow percentage for month i.

The ecological base flow assurance rate formula is:

$$P_i = \frac{D}{12} \times 100\%, \quad i = 1, 2, \dots, 41; \quad k = 1, 2, \dots, 12$$

where P_i is the annual ecological base flow assurance rate (%), Q_k is the monthly average runoff for year i ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), Q_j is the ecological base flow for month j ($\mathrm{m}^3 \cdot \mathrm{s}^{-1}$), and D is the number of months satisfying $Q_k \geq Q_j$.

2.2.2 Statistical Methods We applied F-tests, trend analysis, correlation analysis, and regression analysis. To quantify relationships between climate change and ecological base flow, we used a binary linear regression model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon$$

where y is the dependent variable (ecological base flow), x_1 is annual precipitation, x_2 is average annual temperature, β values are regression coefficients, and ε is the error term.

3 Results and Analysis

3.1 Climate Change Analysis

3.1.1 Temperature Variations Linear trend analysis of temperature data revealed that the Niya River Basin warmed at a rate of 0.22 $°\mathrm{C} \cdot (10\mathrm{a})^{-1}$ from 1958–2018, consistent with Jiao et al.'s finding that temperature extremes in Xinjiang increased at 0.5 $°\mathrm{C} \cdot (10\mathrm{a})^{-1}$. The basin's annual average temperature showed a fluctuating upward trend: a slow warming phase from 1958–1990 with a 0.40 °C increase, followed by a relatively rapid warming phase from 1990–2018 with a 1.14 °C increase.

[Figure 2: see original paper]

3.1.2 Precipitation Variations Linear trend analysis of precipitation data showed that annual precipitation increased at 3.8 $\mathrm{mm} \cdot (10\mathrm{a})^{-1}$, consistent with Shi et al.'s conclusion that southern Xinjiang precipitation increased by 23.2% after 1987. Annual precipitation fluctuated with several abrupt increases and decreases (exceeding 100 mm before dropping below 50 mm the following year), though most years showed minor oscillations.

[Figure 3: see original paper]

Table 2 summarizes temperature, precipitation, and anomalies across different decades.

3.2 Ecological Base Flow Determination and Characteristics

3.2.1 Ecological Base Flow Calculation We calculated ecological base flow using the Tennant method, guaranteed minimum monthly average flow method, and multi-year average minimum monthly flow method. All three methods effectively captured flood and non-flood season variations (Fig. 4). However, the guaranteed minimum monthly and multi-year average minimum monthly methods yielded significantly higher values than the Tennant method, with the latter producing the highest estimates. Considering the Niya River's status as a water-scarce seasonal river in an arid region and the conceptual definition of ecological base flow as the minimum water volume required for stable ecosystem function, we adopted the Tennant method results as our recommended values (Table 3).

The monthly ecological base flow maxima occurred in July and minima in January across all sections, showing dramatically higher values during the flood season than the non-flood season. Based on monthly recommendations, the annual ecological base flow values are 1.989 $m^3 \cdot s^{-1}$ for Niya Reservoir, 2.188 $m^3 \cdot s^{-1}$ for 818 Canal Head, 1.755 $m^3 \cdot s^{-1}$ for Niya Hydrological Station, and 1.702 $m^3 \cdot s^{-1}$ for Niya Canal Head, peaking at 818 Canal Head and bottoming at Niya Canal Head.

[Figure 4: see original paper]

3.2.2 Spatiotemporal Variation Characteristics Temporally, annual ecological base flow peaked in 2010 and reached its minimum in 1980 across all sections, with pronounced interannual fluctuations. The largest increase occurred at 818 Canal Head (from 26.70 to 34.16 $m^3 \cdot s^{-1}$), while the smallest occurred at Niya Canal Head (from 15.72 to 20.11 $m^3 \cdot s^{-1}$). Intra-annual variation was also substantial, with flood season base flow accounting for over 90% of annual totals, reflecting the river's seasonal nature and snow-ice meltwater dominance.

Spatially, ecological base flow showed higher values upstream and lower downstream, with significant seasonal differences. The 818 Canal Head maintained the highest values year-round, followed by Niya Reservoir, Niya Hydrological Station, and Niya Canal Head. This pattern corresponds to oasis water demand, decreasing from upstream to downstream with diminishing oasis scale. Two primary factors explain spatial differences: (1) decreasing runoff from the Kunlun Mountains toward the Taklamakan Desert (except at 818 Canal Head where the Chakda tributary increases flow), and (2) agricultural, industrial, and domestic water consumption. Paradoxically, downstream ecological base flow should theoretically be larger, but measured flows decrease along the channel.

[Figure 5: see original paper] [Figure 6: see original paper]

3.2.3 Assurance Rate Analysis Annual ecological base flow assurance rates for the four sections (Fig. 7) yielded multi-year averages of 50% for Niya Reservoir, 45% for 818 Canal Head, 50% for Niya Hydrological Station, and 45% for Niya Canal Head. Flood season flows consistently met ecological base flow requirements, while non-flood season flows often failed to do so. Three main factors explain non-flood season shortfalls: (1) the basin's arid inland location concentrates 90% of annual runoff in the flood season, with low non-flood season flows, early channel drying, and prolonged dry periods; (2) water storage and irrigation projects further reduce ecological water volumes, particularly during spring agricultural peaks; and (3) increasing domestic water consumption increasingly competes with instream ecological water needs during non-flood periods.

[Figure 7: see original paper]

3.3 Ecological Base Flow Response to Climate Change

We calculated basin-wide annual ecological base flow by weight-averaging values from the four sections and correlated these with annual average temperature and precipitation. Results show significant correlations ($p < 0.01$) between ecological base flow and both climate variables at annual and monthly scales. The annual ecological base flow correlation coefficient is $r = 0.593$ with temperature and $r = 0.257$ with precipitation. The relatively low temperature correlation stems from high interannual temperature variability and low warming rates (0.022 $°C \cdot a^{-1}$). Monthly correlations are stronger ($r = 0.758$ with temperature, $r = 0.862$ with precipitation) because snowmelt and rainfall are key runoff drivers, and ecological base flow derives from measured discharge.

Sensitivity analysis reveals that ecological base flow responds to temperature in spring-summer and to precipitation in autumn-winter, consistent with the Niya River's glacier-snowmelt-fed nature in an arid region. Regression analysis yielded the following relationships (Table 4):

All hydrological sections show similar model coupling effects, with the overall basin regression equation:

$$y = 0.11x_1 + 0.298x_2, \quad R^2 = 0.365$$

where y is annual ecological base flow, x_1 is annual precipitation, and x_2 is average annual temperature. This indicates that ecological base flow responds to climate change not through abrupt local changes but through gradual, basin-wide attenuation along the river course.

4 Conclusions

1. From 1958–2018, the Niya River Basin showed fluctuating increases in annual average temperature and precipitation, exhibiting a warming-wetting trend. Temperature increased at 0.22 $°C \cdot (10a)^{-1}$ and precipitation at 3.8 $mm \cdot (10a)^{-1}$.
2. Based on 1978–2018 hydrological data from four Niya River sections, we calculated monthly ecological base flow using three hydrological methods. The recommended annual values are 1.989 $m^3 \cdot s^{-1}$ for Niya Reservoir, 2.188 $m^3 \cdot s^{-1}$ for 818 Canal Head, 1.755 $m^3 \cdot s^{-1}$ for Niya Hydrological Station, and 1.702 $m^3 \cdot s^{-1}$ for Niya Canal Head.
3. Temporally, ecological base flow shows fluctuating upward trends with pronounced interannual and intra-annual variability, peaking in 2010 and bottoming in 1980. Flood season values exceed non-flood season values dramatically, with flood season flows comprising over 90% of annual totals. Spatially, base flow is higher upstream and lower downstream, with maximum values at 818 Canal Head and minimum values at Niya Canal Head.
4. Assurance rate variations are similar across sections, with multi-year averages of 50% for Niya Reservoir and Niya Hydrological Station, and 45% for 818 Canal Head and Niya Canal Head. Maximum annual assurance

rates reach 58.33%, while non-flood season base flow is often not guaranteed due to low flows, early channel drying, frequent irrigation project operation, and increasing domestic water consumption.

5. Correlation analysis shows significant relationships ($p < 0.01$) between ecological base flow and temperature/precipitation at annual and monthly scales. Base flow is temperature-sensitive in spring-summer and precipitation-sensitive in autumn-winter. Regression models show similar coupling effects across sections, with the basin-wide equation $R^2 = 0.365$. The response to climate change is integrated and attenuated along the river course, particularly pronounced in wet years.

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