# Evaluation of ecological environmental quality and its driving factors in a mountain basin: A case study of the Manas River Basin, China (Postprint)

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**Date:** 2026-04-16T10:08:48+00:00

## Abstract

In recent years, intensified land use change driven by climate change and human activities have markedly impacted the ecological environmental quality of the arid inland river basins. The implementation of forestry projects, coupled with continuous population growth, has increased the need for systematic assessments of ecological effects to ensure sustainable development in arid inland river basins. This study generated a 22-a (2000-2021) remote sensing ecological index (RSEI) data series for the Manas River Basin, a typical arid inland river basin in China, utilizing Moderate Resolution Imaging Spectroradiometer (MODIS) data and the Google Earth Engine (GEE) platform. We examined the spatiotemporal patterns of ecological environmental quality in the Manas River Basin through the Theil-Sen estimator, Mann-Kendall trend test, coefficient of variation (CV), and Hurst index. Furthermore, we employed the Optimal Parameter-based Geographical Detector (OPGD) method to quantify the influence of seven key drivers: elevation, slope, temperature, precipitation, gross domestic product (GDP), population density, and land use change. The key findings revealed that the basin' s ecological environmental quality showed significant improvement (mean RSEI of 0.38, with a range of 0.34-0.41), with areas exhibiting good and excellent grades increasing by 16.71%, particularly in the midstream oasis region and upstream mountainous region, while areas exhibiting poor and relatively poor grades decreased by 11.52% in the downstream desert region. Spatial heterogeneity of ecological environmental quality was pronounced, with 32.23% of the areas showing localized degradation, the midstream oasis region exhibiting sustainable recovery potential (Hurst index>0.50), and only 36.67% of the areas maintaining stable and highly stable conditions (primarily in the upstream mountainous region). The OPGD analysis revealed that temperature (q-value=0.496-0.780), land use change (q-value=0.705-0.782), and elevation (q-value=0.245-0.637) were dominant factors, with the influence of land use change increasing during 2000-2020. Strong interaction effects emerged between land use change and temperature (q-value>0.705) and between land use change and elevation (q-value=0.751 in 2020), highlighting intensified human-nature coupling. These findings provide vital perspectives for ecosystem management in arid inland river basins under both climate and anthropogenic pressures.

## Full Text

## Preamble

J Arid Land (2026) 18(4): 608-631 Evaluation of ecological environmental quality and its driving factors in a mountain basin: A case study of the Manas River Basin, China QI Wenwen , LI Yuanyuan , SHI Xiang [1] Department of Forestry and Ecological Environment, College of Urban and Environmental Sciences, Shihezi University, Shihezi 832000, China; Department of Forestry, Agricultural College, Shihezi University, Shihezi 832000, China

## Abstract

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2020. Strong interaction effects emerged between land use change and temperature ( -value>0.705) and between land use change and elevation ( 2020), highlighting intensified human-nature coupling. These findings provide vital perspectives for ecosystem management in arid inland river basins under both climate and anthropogenic pressures.

## Keywords

ecological environment quality; land use change; remote sensing ecological index (RSEI); Google Earth Engine (GEE); Optimal Parameter-based Geographical Detector (OPGD); mountain-oasis-desert system Citation:

QI Wenwen, LI Yuanyuan, SHI Xiang. 2026. Evaluation of ecological environmental quality and its driving factors in a mountain basin: A case study of the Manas River Basin, China. Journal of Arid Land, 18(4): 608-631.

## 1 Introduction

Ecological environmental quality serves as a comprehensive measure of an ecosystem' s structural and functional integrity, reflecting its state of health or degradation (Sowińska-Świerkosz, 2017).

As a sophisticated system that integrates economic, environmental, and social dimensions, ecological environmental quality is closely correlated with both sustainable societal development and human welfare (Xu and Zhou, 2003; Liang et al., 2019; Wang et al., 2019a; Yu, 2021).

However, population density and metropolitan expansion, in addition to rapid industrialization, have substantially intensified environmental pressure (Liang et al., 2019; Wang et al., 2019a; Yu, 2021), triggering a chain reaction of environmental pollution, resource scarcity, and ecosystem service degradation. These issues have become key bottlenecks restricting high-quality socioeconomic development (Lin and Yu, 2018; Ozcan et al., 2020; Nasir et al., 2021; An et al., 2022). Therefore, the foundation for formulating sustainable policies and executing ecological conservation efforts lies in the development of a robust system for quantitatively evaluating ecological environmental quality (Xu and Zhou, 2003; Peng et al., 2023).

The benefits of remote sensing technology, such as high periodicity, extensive coverage, and effective data collection, have made it a crucial technical instrument for ecological environmental quality monitoring (Aplin, 2005). Early studies mostly relied on single indicators (e.g., Rouse et al., 1974), such as the temperature vegetation drought index (TVDI) (Sandholt et al., 2002) and normalized difference built-up index (NDBI) (McFeeters, 1996), to evaluate specific surface features. However, single indicators are prone to uncertainty in evaluation results (Ding et al., 2020). As technology has developed, comprehensive evaluations that incorporate multiple indicators have taken center stage. The concept of the ecological index (EI) was first proposed in 2006, which laid the foundation for subsequent research (Lu and Chen, 2015). Xu (2008) built on this concept to create the remote sensing ecological index (RSEI), in which the Principal Component Analysis (PCA) method was used to independently determine the significance of four pivotal ecological parameters: greenness, humidity, dryness, and heat. This method greatly improved the scientific rigor and geographical explicitness of ecological assessments (Peng et al., 2023). RSEI has been broadly applied in many scientific fields (Cheng et al., 2015; Song and Xue, 2016), such as eco-watersheds (Zhou et al., 2024), mine monitoring (Tang et al., 2022), and urban environmental evaluation (Geng et al., 2022), because of its ease of operation and reliable results. However, the traditional RSEI method relies on Landsat data, and its temporal resolution and data continuity are difficult to satisfy when conducting large-scale, extended temporal sequence monitoring (Sun et al., 2023).

Owing to the strong data processing capabilities of the Google Earth Engine (GEE) platform and the high temporal resolution, multitemporal phases, and wide coverage of Moderate Resolution Imaging Spectroradiometer (MODIS) data, remote sensing technology advancements have enabled the use of MODIS data in the creation of a large-scale RSEI (Xiong et al., 2021; Zeng et al., 2021).

For instance, by utilizing MODIS data and the GEE platform, Peng et al. (2023) assessed the ecological environmental quality throughout the mid-lower Yangtze River Basin of China from 2000 to 2020 using the RSEI; Xiao et al. (2023) focused on the Muli coal field near the Qinghai Lake, China, to establish the RSEI across the preceding 21-a period, achieving an optimal evaluation. In the investigation of driving mechanisms, the incorporation of the Geodetector method (Wang and Xu, 2017) is highly significant, as demonstrated by Zhang et al. (2022), who accurately determined the evolution of ecological integrity within the Weihe River Basin of China by successfully merging the Geodetector technique with the Multiscale Geographically Weighted Regression (MGWR) model. Notably, the traditional Geodetector suffers from problems such as the strong subjectivity of the discretization method. Developed by Song et al. (2020), the Optimal Parameter-based Geographical Detector (OPGD) significantly improves reliability in driving factor analysis by automatically optimizing classification schemes. This advancement provides a more scientific tool for research using the RSEI (Zhao et al., 2024b).

Representing a characteristic “ mountain-oasis-desert’ ’ configuration within arid regions in

Northwest China (Wei et al., 2018), the Manas River Basin has long struggled with issues such as water scarcity, vegetation deterioration, and land use conflicts. Its ecological vulnerability is especially responsive to human activities and climate change. In addition to being an important ecological barrier, this representative watershed in the dryland regions of Northwest China has great scientific significance for understanding integrated water resources management and long-term ecological sustainability in water-scarce areas. However, a critical research gap persists. Although previous studies have applied remote sensing technology to analyze ecological environmental quality in the Manas River Basin and have preliminarily revealed its correlations with factors such as climate change or certain human activities (Zhang et al., 2010; Wang et al., 2019c), these investigations have often been constrained by shorter time series, a lack of systematic quantification of complex interactions among multiple drivers, and an inability to reliably forecast future trajectories on the basis of long-term data. Consequently, existing research has yet to provide a comprehensive, long-term ecological assessment that seamlessly combines high-temporal-resolution RSEI monitoring with advanced driver interaction diagnostics and robust forecasting of future trends. While recent studies have begun to leverage cloud platforms and remote sensing indices for ecological assessment in arid regions (Maimaitituersun et al., 2025) and to explore driving mechanisms with advanced analytical methods (Liu and Huang, 2025), a focused and integrative analysis addressing the specific “mountain-oasis-desert’’ system of the Manas River Basin over an extended period remains lacking. This study aims to address the following questions: (1) how have the spatiotemporal patterns of ecological environmental quality evolved over a 22-a period (2001–2022) under combined climatic and anthropogenic pressures? (2) what are the key drivers and their interactions in influencing ecological environmental quality in this complex system? and (3) what is the likely persistence of the current ecological trajectory and what are the implications for future management?

To answer these questions, we pursue three objectives: (1) reconstructing the 22-a spatiotemporal dynamics of ecological environmental quality in the Manas River Basin using a MODIS-based RSEI on the GEE platform; (2) quantifying the individual and interactive driving forces using the OPGD model; and (3) predicting the future persistence of ecological environmental quality changes using the Hurst index. Our approach will provide a novel framework that integrates continuous monitoring, interaction analysis, and persistence forecasting, offering a more dynamic and predictive understanding of ecological environmental quality in arid inland river basins than previous RSEI applications provide.
2 Materials and methods

## 2.1 Study area

Situated in Xinjiang Uygur Autonomous Region of China, the Manas River Basin encompasses both the Junggar Basin’ s southern periphery and the middle section along the northern slopes of the Tianshan Mountains. This typical inland river basin lies in China’ s arid northwestern regions (Fig. 1 [FIGURE:1]). The basin, which spans approximately 31,000.00 km from the northern boundary of the Gurbantunggut Desert to the glacial region of the Tianshan Mountains, runs north-south. Its administrative boundaries include five cities, four counties, and one district, including Hoboksar Mongolian Autonomous County, Baijiantan District, Karamay City, Hutubi County, Kuytun City, Shawan City, Shihezi City, Manas County, Wusu City, and Hejing County, from north to south.

The basin has characteristic temperate continental desert climate conditions, featuring mean annual temperatures ranging from 4.7°C to 5.8°C and mean annual precipitation levels between 110 and 200 mm. However, notable spatial variations exist, with the upstream mountainous region experiencing precipitation amounts of more than 300 mm. In contrast, the downstream desert region has less than 50 mm of annual precipitation. With a mean annual runoff of approximately 1.2$×$10 , 70% of the runoff is concentrated from June to August. The Manas River, originating the northern flank of the Eren Habirga Mountain in the Tianshan Mountains, serves as the

primary water source for the agricultural and ecological sustenance of the oasis. Water conservation occurs in the mountains, forests, and grasslands upstream of glaciers; fertile soil and flat terrain characterize the middle reaches of the midstream oasis region, which is centered in the basin that contains 80% of the population and arable land. Fragile and sensitive ecosystems are found downstream of the desert region. In dryland regions, this 〞mountain-oasis-desert’’ trinity of composite habitats is a typical example of an arid inland river basin.

Overview of the Manas River Basin. The image was accessed on 10 January 2024 from National Platform

## 2.2 Data sources and processing

In this study, MODIS series data products (MOD13A1 vegetation index, MOD11A2 land surface temperature (LST), and MOD09A1 surface reflectance) from 2000 to 2021 were used to construct the RSEI for the regional ecological environmental quality assessment, implemented on the GEE cloud platform. These MODIS products have been demonstrated to be reliable for deriving vegetation, moisture, and thermal metrics in arid regions of Central Asia (Wu et al., 2022; Gong et al., 2023), making them suitable for regional-scale ecological monitoring and trend analysis. The precise steps within the procedure are as follows: first, the data preprocessing step involved selecting plant growth period image data from June to August each year on the GEE platform, and

the annual composite image was developed via the maximum value composite (MVC) approach.

Then, atmospheric interference and water body pixels were removed through cloud mask processing, after which all the data were uniformly resampled to a spatial resolution of 500 m.

Second, the initial RSEI calculation included four principal ecological indicators —the normalized difference vegetation index (NDVI) for vegetation assessment, the wetness component (WET) for moisture analysis, the normalized difference bare soil index (NDBSI) for dryness evaluation, and the LST for thermal characteristics. To identify the first principal component (PC1) serving as the RSEI' s foundational index, we employed PCA following normalization of each index within the range of 0-1. This approach yielded the final RSEI output. Third, during the driving factor analysis, raster data from the study area were extracted and resampled to a 1000-m grid resolution using ArcGIS 10.8 software. RStudio 4.4.2 statistical software was used to read and prepare the data and the OPGD model was applied to determine the optimal parameter combination. Finally, statistical analysis was performed with RStudio 4.4.2 statistical software, with outcomes shown using Origin 2024 software. Tables 1 and 2 compile the investigation' s datasets with associated provenance details.

Details of remote sensing data Remote sensing data Time resolution (d) Spatial resolution (m) Product level Variable Access to indicator MOD13A1 Greenness MOD11A2 MOD9A1 1-7 bands Wetness and dryness Note: L3, level 3 satellite data products; NDVI, normalized difference vegetation index; LST, land surface temperature.

Details of natural factor data and human factor data Data type Data name Data source Elevation ( Temperature ( Precipitation ( Natural factor Slope ( Elevation extraction Population density ( Human factor Land use change ( GDP ( Note: GDP, gross domestic product.

### 2.3.1 RSEI

The ecological environmental dynamics of the Manas River Basin (2000-2021) were evaluated using the RSEI (Xu, 2008), which was implemented on the cloud-based GEE platform. This index synthesizes four essential indicators that characterize the arid " mountain-oasis-desert'' system: the NDVI for greenness and productivity (Feng et al., 2009), the WET for soil or canopy moisture (Lobser and Cohen, 2007), the NDBSI for dryness (Xu, 2008), and the LST for surface heat (Rees et al., 2024). Detailed calculations are provided in Table 3 .

The four indicators were first normalized using the linear normalization method to eliminate scale effects (Yu et al., 2024). PCA was then employed for integration; this approach provides an objective, data-driven weighting mechanism by determining the weight of individual indicators through the principal component' s variance, which aligns with the model' s proven and widely adopted scheme (Wen et al., 2019; Gou and Zhao, 2020; Jing et al., 2020), thereby ensuring the comparability and consistency of our results.

where is the normalized value of the indicator; the original value of the indicator; are the maximum and minimum values of the indicator, respectively.

PCA combines four key indicators to create the RSEI, utilizing the PC1 according to the following formulas:

NDVI, WET, NDBSI, LST

− = − , (3)

normalized

Greenness (NDVI) ( ) ( ) NIR NIR red red NDVI $\rho$ $\rho$ $\rho$ $\rho$ = − +

green

= + + −

Wetness (WET) SWIR1 SWIR2 NDBSI

- − + = + + +

SWIR1 Dryness (NDBSI) SWIR1

## 2 IBI

Heat (LST) LST 0.02 273.15 DN = −

NDVI is the normalized difference vegetation index; represents the near-infrared band (nm); and represents the red-light band (nm).

WET is the wetness component; green SWIR1 , and SWIR2 denote the blue-light band (nm), green-light band (nm), short-wave infrared 1 band (nm), and short-wave infrared 2 band (nm), respectively.

NDBSI is the normalized difference bare soil index; SI denotes the soil index; and IBI denotes the index-based built-up index. where PC1 is the first principal component; NDVI is the normalized difference vegetation index; WET is the wetness component; NDBSI is the normalized difference bare soil index; LST is the land surface temperature (°C); RSEI normalized is the normalized RSEI, falling within the range of 0.00–1.00; RSEI is the initial RSEI; and RSEI represent the lower and upper bounds of the initial RSEI after normalization, respectively. A score of normalized RSEI approaching 1.00 denotes superior ecological environment quality, whereas a score far from 1.00 reflects inferior quality.

Ecological environmental quality levels were classified primarily using the natural breaks method (Xu, 2013). A sensitivity analysis, conducted by applying the equal interval method, confirmed that the identified spatiotemporal trends were highly consistent and robust regardless of the classification threshold used. This research classified the remotely sensed RSEI within the Manas River Basin into five distinct categories (Xu, 2008): poor (0.00–0.20), relatively poor (0.20–0.40), moderate (0.40–0.60), good (0.60–0.80), and excellent (0.80–1.00).

Formulas for the four indicators of the remote sensing ecological index (RSEI) Indicator Formula Clarification

- − + + + = + + + + +

green green SWIR1 SWIR1 SWIR1 green green SWIR1 SWIR1 SWIR1 LST is the land surface temperature (°C); and denotes the MOD11A2 image grayscale value.

Trend analysis combining Theil Sen median trend and Mann Kendall trend methods To assess the RSEI trends in the Manas River Basin (2000-2021), this study integrated Theil-Sen slope estimation and Mann-Kendall trend analysis. The Theil-Sen estimator, a distribution-free robust technique (Sen, 1968), determines time series trends by calculating median slopes from all possible data point pairs using the following formula (Yang et al., 2021):

RSEI RSEI Median j i j i $\beta -\quad = \quad -$ , (4)

where denotes the median trend magnitude; and RSEI and RSEI represent RSEI measurements at years , respectively. When <0, this suggests a decreasing pattern; when >0, it demonstrates an enhancing pattern.

Since this approach is not sensitive to outliers, it is appropriate for handling large time series data. Trend significance is typically evaluated using the Mann Kendall test—a nonparametric statistical approach that detects monotonic tendencies in temporal data by analyzing rank correlations between sequential observations (Kendall and Gibbons, 1990; Mann, 1945). The computational procedure is mathematically formulated as follows: sign RSEI

$= = + = - \sum\sum$ , (5)

$- \quad > \quad = \quad + \quad <$

where is the trend statistic that approximately follows a normal distribution; represents the number of temporal observations; sign() indicates the sign function; is the standardized test statistic; and var( ) represents the variance of . The specific meanings of each variable are detailed in Table 4 . When | |$ $1.96, this result is statistically significant at the 95% confidence threshold; conversely, if | |<1.96, the trend change is not significant.

Significance and trend test categories value Trend in RSEI value Trend in RSEI $ $0.0005 $ $1.96 Significant improvement < -0.0005 Slight degradation $ $0.0005 Slight improvement < -0.0005 < -1.96 Significant degradation Stable Note: RSEI is the remote sensing ecological index; is the trend statistic of RSEI that approximately follows a normal distribution; is the standardized test statistic.

Coefficient of variation (CV) This study employed the CV to evaluate the temporal stability of ecological environmental quality within the Manas River Basin between 2000 and 2021. The CV efficiently quantifies temporal and geographical variations in ecological environmental quality measures while serving as a crucial statistical tool for evaluating dispersion within temporal sequences (Ma et al., 2024). A negative relationship exists between its magnitude and environmental stability. More precisely, an area’ s ecological environment is less stable and exhibits greater temporal fluctuation when its CV value is greater. A lower

CV value, on the other hand, indicates that the ecosystem remains in a relatively stable state. Temporal stability of ecological environmental quality was classified into five levels using the spatial analysis functions of ArcGIS 10.8 software: stable (CV$ 0.10), $highlystable(0.10 < CV 0.20), relativelyunstable(0.20 < CV 0.25), highlyunstable(0.25 < CV 0.30), andextremelyunstable(CV$ $0.30) (He et al., 2023). The computational expression is provided below:

RSEI CV $\sigma$ $\mu$ = , (7)

where represents the standard deviation of the RSEI; and denotes the mean value of the RSEI. A larger CV value indicates greater data variability.

### 2.3.4 Hurst index

Our research utilized the Hurst index to evaluate the long-term persistence characteristics of ecological environmental quality of the Manas River Basin. The Hurst index, a crucial metric for nonlinear time series analysis (Hurst, 1951), may be used to efficiently elucidate the evolutionary trajectory of an ecosystem and forecast its future trend by assessing the long-term memory effect of RSEI fluctuations. Specifically, when the Hurst index=0.50, it signifies that the time series adheres to the random walk process, meaning that the current state does not substantially associate with its past trajectory, rendering future trends uncertain; when 0.50<Hurst index$ 1.00, itsignifiesthatthetimeseriesexhibitslong - termpersistence, withfuturetrendsaligningwithhistoricaltrajectories; andwhen0.00 $Hurst index<0.50, it denotes anti-persistence, suggesting that future changes may exhibit traits contrary to the historical patterns. On the basis of previous research (Li et al., 2024b), we further subdivided the intensities of persistence and anti-persistence into four levels. Specifically, the positive persistence (Hurst index>0.50) was classified as strong (0.75-1.00), stronger (0.65-0.75), weaker (0.55-0.65), and weak (0.50-0.55).

Conversely, the anti-persistence (Hurst index<0.50) was classified as strong (0.00-0.25), stronger (0.25-0.35), weaker (0.35-0.45), and weak (0.45-0.50).

In this study, we employed the OPGD model to measure the driving factors behind spatial heterogeneity of ecological environmental quality within the Manas River Basin. While the traditional Geodetector proposed by Wang and Xu (2017) is widely used, its reliance on subjective discretization methods (e.g., arbitrary classification thresholds) introduces bias and reduces reproducibility. To overcome this limitation, the OPGD systematically evaluates multiple classification strategies—including natural breaks, equal intervals, quantiles, standard deviation, and geometric intervals—across 3-10 categories. The optimal parameter combination is autonomously selected by maximizing the 90 percentile of the -value (where is the explanatory power indicator of the influencing factors on the ecological environmental quality), ensuring objective and stable results (Yang et al., 2024). Furthermore, the OPGD identifies interaction types (e.g., nonlinear enhancement and independent effects) through paired factor -value comparisons (Table 5 ).

Interaction types and their ecological interpretation in Optimal Parameter-based Geographical Detector (OPGD) analysis Interaction type Criteria Ecological interpretation The combined effect of two factors shows weaker explanatory power than either factor alone, indicating inhibitory or redundant effects.

Nonlinear attenuation q ( X 1 X 2 )<Min[ q ( X 1 ), q ( X 2 )]

The interaction is primarily driven by one dominant factor, with the second factor contributing minimally.

Unilinear attenuation )<Max[ Two-factor enhancement )>Max[ The combined effect exceeds individual factors but remains subadditive.

Independent Factors affect ecological processes independently without interaction.

Nonlinear enhancement Factors exhibit superadditive effects, dramatically amplifying ecological impacts.

Note: is the explanatory power indicator of the influencing factors on the ecological environmental quality; are the influencing factors of ecological environmental quality. 2.3.6 Land use data and classification system Land use data with 1000-m resolution were obtained from China' s Multiperiod Land Use Remote Sensing Monitoring Dataset (CNLUCC) in Resources and Environmental Science Data Platform utilized maps for 2000, 2005, 2010, 2015, and 2020. The CNLUCC data employ a two-tier

classification system with six first-level categories: farmland, forest, grassland, water body, built-up area, and unused land.

## 3 Results

3.1 Construction of composite indicators for RSEI modelling

### 3.1.1 PCA results

Greenness, wetness, dryness, and heat were the four primary parameters in this research's comprehensive PCA of ecological indicators in the Manas River Basin. According to the PCA results (Table 6 ), PC1 was significantly ecologically significant. It exhibited negative relationships with both temperature (LST) and dryness (NDBSI), but it had positive correlations with both greenness (NDVI) and wetness (WET). The biological conditions in the basin have been shown to improve as a result of precipitation and vegetation cover. However, they were damaged by heat and aridity, which is consistent with the characteristic " mountain-oasis-desert'' ecosystem structure of arid inland river basins.

During the study period of 2000-2021, the variance contribution of PC1 ranged from 52.02% to 64.37%, substantially higher than those of the second principial component (PC2; 26.80%-36.49%) and the third principial component (PC3; 5.43%-14.32%). These findings indicate that PC1 effectively captures the dominant ecological trends represented by the four indicators (cumulative explanatory power>50.00%), making it appropriate for constructing the RSEI model in this region. Thus, PC1 was selected to develop the RSEI for subsequent spatiotemporal analyses.

Changes in ecological environmental quality in the Manas River Basin The specific thresholds and indicative characteristics for each grade of RSEI are detailed in Table 7 .

The poor grade (0.00-0.20) predominantly represented the barren Gurbantunggut Desert, characterized by negligible vegetation, extreme dryness, and the highest surface temperatures, driven by natural aridity. The relatively poor grade (0.20-0.40) was typically associated with sparse grasslands in the desert-oasis ecotone, resulting in low biomass and susceptibility to water scarcity. The moderate grade (0.40-0.60) largely constituted the core oasis farmlands, where vegetation and soil moisture were managed by irrigation. High grades (0.60-0.80) were often linked to dense, well-irrigated farmlands or healthy natural vegetation in piedmont zones. An excellent grade (0.80-1.00), although rare, was found in mountainous headwaters with well-preserved forests, which exhibited the highest moisture and vegetation cover with minimal anthropogenic disturbance.

The study documented a clear positive trend in ecological conditions across the basin (mean RSEI of 0.38, ranging from 0.34 to 0.41). As shown in Figure 2 [FIGURE:2], the annual average RSEI of the Manas River Basin exhibited a distinct oscillatory increase, reaching the lowest point of 0.34 in 2000 and peaking at 0.41 in 2010, suggesting an overall increase of 18.64%, according to a review of temporal sequence datasets from 2000 to 2021. Specifically: (1) areas classified as having poor and relatively poor grades exhibited a continuous decrease, declining from 18,636.44 (59.27%) in 2000 to 15,012.11 km (47.75%) in 2021, resulting in a net decrease of 3624.33 (11.52%); (2) areas classified as having moderate grade showed considerable stability, varying between 23.91% and 29.09%; and (3) areas classified as having good and excellent grades experienced substantial expansion, increasing from 3660.10 km (11.64%) in 2000 to 8912.38 km (28.35%) in 2021, yielding a net increase of 5252.28 km (16.71%). The pattern of ＂two decreases and one increase'' (a reduction in poor and relatively poor grades, stabilization of intermediate rating, and an increase in good and excellent grades) signifies an improvement in the ecological environmental quality of the Manas River Basin throughout the observation period.

The spatial distribution of the areas designated as having good and excellent grades of RSEI was mostly located in the midstream oasis region, including Shawan City, Kuytun City, Manas County, and Shihezi City, in addition to throughout the southern part of the upstream

Figure 3

Figure 1: Figure 3

Principial Component Analysis (PCA) results for the four ecological indicators in the Manas River Basin during 2000-2021 Eigenvalue Eigenvalue contribution (%) NDBSI Eigenvalue Eigenvalue contribution (%) NDBSI Eigenvalue Eigenvalue contribution (%) Note: WET, wetness component; NDBSI, normalized difference bare soil index; PC1-PC4, the first to fourth principal components, respectively. mountainous region (Fig. 3

). The moderate ecological zone was primarily situated in the upstream mountainous region, whereas it was occasionally found in the midstream oasis region, including Shihezi City and Manas County. In 2000, the moderate ecological area covered 9145.50 , accounting for 29.09% of the entire land area, but the area decreased to 7353.83 km

2021, representing 21.38% of the total region. Conversely, areas designated as having poor and relatively poor grades of RSEI were predominantly located within the downstream desert region and upstream mountainous region.

The watershed was largely characterized by poor to moderate grades, with an overall average percentage of 58.62%, and this area was mostly situated in the upstream mountainous region and middle oasis region. Areas designated as having relatively poor grade of RSEI, which accounted for an average percentage of 19.52%, were mostly situated within the ecotone separating the upstream mountainous region and midstream oasis region.

Ecological characteristics of each RSEI grade in the Manas River Basin RSEI grade Land cover type Spatial zone and key characteristics Relatively poor (0.20-0.40) Moderate (0.40-0.60) Farmland and high-coverage grassland (0.60-0.80) Excellent (0.80-1.00) Core area in the downstream desert region: sparse vegetation surface temperatures Midstream alluvial plain and upstream slopes: including natural grassland and irrigated farmland with moderate ecological function Upstream water source area: dominated by forests and glaciers, ensuring high soil moisture and stable ecological function (0.00-0.20) Gobi and sandy land 0.29$±0.030.17±0.040.87±0.04*Low* − *coveragegrassland*0.40±0.060.19±0.030.72±0.07*Oasis*–*desertecotone* : *fragileecosystemvulnerabletodisturbanceModerate*–*coveragegrassland*0.51±0.160.27±0.050.62±0.150.70±0 *ThevaluesfortheNDVI*, *WET*, *andLSTpresentedinthistablewerenormalizedtobedimensionlessandderivedf* deviation.

Interannual variation in the remote sensing ecological index (RSEI) and area for each RSEI grade in the Manas River Basin during 2000-2021 3.2 Trend analysis of ecological environmental quality changes in the Manas River Basin For a comprehensive assessment of spatiotemporal patterns and potential trends in terms of ecological environmental conditions within the Manas River Basin, this research combined the Hurst index with Theil-Sen slope estimation and

Figure 4

Figure 2: Figure 4

Mann Kendall trend analyses. The ecological environmental quality of the basin displayed significant spatial differentiation between 2000 and

Spatial distribution of RSEI grade within the Manas River Basin in 2000 (a), 2005 (b), 2010 (c), 2015 (d), 2020 (e), and 2021 (f) 2021, as the improved areas (38.61%) were scattered primarily throughout the basin’ s central sector and the transition zone, with slightly improved areas (10.82%) situated within the medium- high-elevation areas of the upstream mountainous region and the oasis–mountain transition zone in the midstream oasis region, and significantly improved areas (27.79%) scattered around urban areas in the midstream oasis region (Fig. 4

). Areas with slight degradation in ecological environmental quality accounted for 32.23% of the basin and were sporadically distributed in the upstream mountainous region and the fringes of the downstream desert region. Significantly degraded areas (15.89%) were mainly concentrated throughout the high-elevation areas in the upstream mountainous region and the edges of the desert areas in the downstream desert region, as well as in the plain areas of the midstream oasis region (Shihezi City, Manas County, and Shawan City).

Furthermore, covering 13.27% of the basin, the stable areas were predominantly located in the desert zone of the downstream desert region.

Hurst index analysis revealed that 78.22% of the basin area (24,594.61 km ) will demonstrate anti-persistence characteristics in the future (Hurst index<0.50), which are predominantly located in the upstream mountainous region and midstream oasis region, with sporadic occurrences in the downstream desert region, implying the potential reversibility of ecological changes in these regions. Conversely, 21.78% of the study area (6847.39 km ) will exhibit persistent characteristics (Hurst index>0.50), primarily concentrated in the core irrigation zones of the midstream oasis region and the desert–oasis transition zone of the downstream desert region (notably around Karamay City), with scattered distributions along the southwestern periphery of the upstream mountainous region, suggesting that the current trends of ecological environmental quality in these areas may endure over the long term. A thorough investigation indicated that while the majority of

the Manas River Basin (78.22%) may display anti-persistence characteristics in the future, the midstream oasis region demonstrates notable sustainable attributes, with its ecological improvement tendencies reflecting robust sustainability.

Change trend (a) and future spatial distribution (b) of ecological environmental quality in the Manas River Basin On the ArcGIS 10.8 platform, based on the comprehensive Theil–Sen slope trend analysis and the continuous assessment of the Hurst index, we classified the ecological environmental quality change patterns of the Manas River Basin into six typical types (Table 8 ): strong anti-persistent degradation, weak anti-persistent degradation, weak anti-persistent stability, weak anti-persistent improvement, weak persistent improvement, and strong persistent improvement. As shown in There are also areas with weak anti-persistent degradation and strong anti-persistent degradation (totally accounting for 46.30%); although historically degraded, these areas are projected to subsequently recover. Their primary distribution encompasses the downstream desert region, in addition to high-elevation zones within the upstream mountainous region (excluding forests).

Additionally, they are sporadically distributed in the western part of the midstream oasis region.

Areas with weak anti-persistent stability (18.28%) are concentrated in the downstream desert region (such as Hoboksar Mongolian Autonomous County), indicating that the past stable state may change in the future.

While the continuous degraded areas in the high-elevation zone of the upstream mountainous region and the desert edge zone in the downstream desert region pose major threats to the basin’ s overall ecological security, spatial pattern analysis reveals that the oasis area in the midstream oasis region constitutes the basin’ s continuous core of ecological improvement. This spatial trend of “ improvement–degradation’ ’ shows how delicate the ecological conditions are in the Manas River Basin. 3.3 Stability analysis of ecological environmental quality in the Manas River Basin The stability of the spatial distribution of ecological environmental quality in the study area

percentage (%) Strong anti-persistent degradation Significantly degraded in the past and may be improved in the future Weak anti-persistent degradation Slightly degraded in the past and may be improved in the future Weak anti-persistent stability Slightly stable in the past and may be changed in the future Weak anti-persistent improvement Slightly improved in the past and may be degraded in the future Weak persistent improvement Slightly improved in the past and may be continuously improved in the future Strong persistent improvement Significantly improved in the past and may be continuously improved in the future Spatial distribution of integrated future trend (a) and coefficient of variation (CV; b) for ecological environmental quality in the Manas River Basin between 2000 and 2021 was assessed using the CV approach. Significant geographical variations in the stability of ecological environmental quality were noted during this period throughout the Manas River Basin, as presented in Figure 5b [FIGURE:5]. The region, spanning 19,913.63 km (63.33% of the study area), was notably dominated by unstable ecological environmental quality levels, which included relatively unstable, highly unstable, and extremely unstable grades. The downstream desert region and the transition zone between the upstream mountainous region and the midstream oasis region were the main locations of these unstable zones, with isolated incidents occurring in the downstream desert region near Hutubi County. Especially, the extremely unstable grade, covering 6722.90 km (21.38% of the total area), was predominantly found in the northern part of Kuytun City in the midstream oasis region and downstream desert region, such as the Hoboksar Mongolian Autonomous County. This indicates that the spatial stability of ecological environmental quality is most compromised in these areas.

In contrast, the stable grade (including stable and highly stable grades) accounted for 36.67% of the total area, amounting to 11,528.37 km . This stable ecological environmental quality was predominantly distributed in strip-like patterns across the upstream mountainous region and the transition ecotone between the midstream oasis region and the upstream mountainous region, indicating relatively good spatial stability of the ecological environment in these locations.

Overall, the ecological environmental quality was relatively unstable in most regions of the Manas River Basin from 2000 to 2021, with the upstream mountainous region being the most stable.

3.4 Driving mechanisms of ecological environmental quality in the Manas River Basin In this study, elevation, slope, and climatic conditions (temperature and precipitation) were selected to represent natural factors, while land use change, GDP, and population density were considered human factors. Five data periods –2000, 2005, 2010, 2015, and 2020–were chosen due to data availability, and key determinants of ecological environmental quality across the Manas River Basin during 2000-2020 were investigated using the OPDG. The results of single-factor detection (Table 9 ) indicated that the influence of the driving factors on the RSEI across the Manas River Basin during 2000-2020 exhibited a marked pattern of fluctuation ( $<0.001$), specifically characterized by the following order: land use change>temperature>elevation>precipitation> GDP>slope>population density. Throughout the study period, land use change and temperature consistently exhibited the greatest explanatory capacity, with -values ranging from 0.705 to 0.782 and from 0.496 to 0.780, respectively, although a general decline was observed. The impact of natural factors such as elevation, precipitation, and slope progressively diminished, with -values decreasing from 0.637, 0.624, and 0.464 in 2000 to 0.245, 0.046, and 0.021 in 2020, respectively.

Conversely, the greatest explanatory capacity of human factors, particularly population density, notably increased from 0.064 in 2000 to 0.316 in 2020, while the influence of GDP remained largely constant, with -values oscillating between 0.227 and 0.315. This trend signified a notable transformation in the primary determinants of spatial differentiation in the study area from 2000 to 2020: the initial period (2000-2005) was influenced primarily by natural and human factors (land use change, temperature, and elevation), whereas the final phase (2015-2020) increasingly transitioned to human factors, indicating the growing influence of human activities on the spatial pattern of ecological environmental quality in the Manas River Basin.

The interaction detection findings (Fig. 6 [FIGURE:6]) indicated that the interplay between land use change and temperature was the most important, with the -value declining from 0.859 in 2000 to 0.751 in 2020, although it still retained the greatest interpretative value. The interaction strength among natural factors typically surpassed that among natural-human factor combinations. Specifically, -value for the interplay between elevation and temperature ranged from 0.793 to 0.797 during 2000-2005, before decreasing to 0.694 in 2010. In contrast, the interaction between GDP and temperature showed a pattern of initial increase and subsequent decline, with -values of 0.813 in 2000, 0.831 in 2005, and 0.717 in 2010. Particularly during the latter period (2015-2020), as the single-factor explanatory capacity decreased markedly, the interaction between slope and land use change exhibited high -values of 0.736 and 0.725, respectively.

Single-factor detection results of the influencing factors on the ecological environmental quality in the Manas River Basin during 2000-2020 Project Natural factor Human factor -value -value sorting -value -value sorting -value -value sorting -value -value sorting -value -value sorting Note: 1, elevation; 2, GDP; 3, land use change; 4, slope; 5, population density; 6, precipitation; 7, temperature.

Heatmap of interaction -values among driving factors of ecological environmental quality in the Manas River Basin in 2000 (a), 2005 (b), 2010 (c), 2015 (d), and 2020 (e). 1, elevation; 2, gross domestic production (GDP); 3, land use change; 4, slope; 5, population density; 6, precipitation; 7, temperature. is the explanatory power indicator of the influencing factors on the ecological environmental quality.

Moreover, the value for the interaction between land use change and population density remained stable between 0.731 and 0.851 during 2000-2020, suggesting that spatial distribution patterns are consistently impacted by the synergistic effect of land use change and population density. According to a detailed investigation, the spatial differentiation mechanism in the study area is characterized by interactive features of " two-factor enhancement'' and " nonlinear enhancement'' . Although the interplay between human drivers and important natural elements is gradually becoming more intense, the synergistic effect among natural components is still prevalent, albeit weakened.

## 3.5 Analysis of land use dynamics

In this study, land use changes across five study periods (2000, 2005, 2010, 2015, and 2020) were systematically analyzed. The change results are shown in Figure 7 [FIGURE:7] and Table 10 , revealing three dominant land cover types—farmland (18.77%), grassland (30.67%), and unused land (42.76%)—which collectively constitute 92.20% of the basin' s total area. The most significant transformation was a 9.69% expansion of farmland, concentrated primarily in the midstream oasis region, with conversion sources dominated by grassland (59.34%) and unused land (29.60%) according to transfer matrix analysis (Fig. 8 [FIGURE:8]). In contrast, the forest cover in the upstream mountainous region remained remarkably stable, showing only a 2.32% variation throughout the study period. These patterns demonstrated intensive agricultural development in the midstream oasis region, creating a potential balance with respect to food production and grassland ecosystem services, which requires further investigation (see Table 11 ).

## 4 Discussion

4.1 Spatiotemporal evolution of ecological environmental quality and its driving factors in the Manas River Basin Using the GEE platform, we reported that the ecological environmental quality in the Manas River Basin improved overall between 2001 and 2022 (16.71% of the area increased), although

Land cover types of the Manas River Basin in 2000 (a), 2005 (b), 2010 (c), 2015 (d), and 2020 (e) Grassland 11,380.47 11,005.52 10,127.56 10,044.77 Unused land 14,453.74 14,434.74 14,730.45 14,648.33 14,536.07 +0.24 with fluctuations, a trend that aligns with the findings of previous studies (Wang et al., 2019b; Wang et al., 2019c). This recovery was stronger than that in the Tabu River Basin, China (2.62% of the area increased; Zhang et al., 2024). The ecological environmental recovery in the Manas River Basin is markedly more pronounced, attributable to the synergistic effects of ongoing glacier meltwater ablation (Wang et al., 2024) and water-saving irrigation technology (Zhang et al., 2012); nonetheless, it remains inferior to the substantial improvement of 71.60% observed in the Yellow River Basin, China (Li et al., 2024a). This result is primarily due to: (1) disparities in water availability, as the Yellow River Basin benefits from consistent precipitation whereas the Manas River Basin relies on seasonal glacier meltwater and faces competing demands for oasis

Spatial distribution of land use change in the Manas River Basin from 2000 to 2020. ’ ‘-’’ means the transition from one land cover type to another land cover type.

Transition matrix of farmland with other land cover types during 2000–2020 Direction of conversion Land cover type transition Area (km Area percentage (%) Grassland–farmland Built-up area–farmland Forest–farmland Conversion to farmland Water body–farmland Unused land–farmland Total Farmland–grassland Farmland–built-up area Farmland–forest Conversion from farmland Farmland water body Farmland–unused land Total Note: ’ ‘-’’ means the transition from one land cover type to another land cover type. agriculture; and (2) time-lagged policy implementation, as the “ Grain for Green Project” initiative in the Yellow River Basin (Chen et al., 2023) commenced five years prior to its counterpart in the Manas River Basin. These findings offer valuable comparative insights for ecological restoration in dryland areas.

Between 2000 and 2005, areas exhibiting good and excellent ecological environmental quality in the Manas River Basin have expanded. After 2005, the execution of the Natural Forest Protection Program (Zhang et al., 2021) and the water-saving irrigation project (Zhang et al., 2012) caused the areas classified as good and excellent ecological environmental quality to expand from 3660.12 to 5950.55 km , significantly enhancing the ecological conditions in the midstream oasis region. The significant increase in ecological environmental quality from 2005 to 2010 can be ascribed to climate warming (Lee et al., 2020), which resulted in increased precipitation and intensified glacier and ice melt, thereby improving vegetation cover. Additionally, energy-saving and emission-reduction policies (Wang et al., 2015) incentivize local environmental protection

measures. From 2010 to 2015, slight degradation occurred, potentially linked to land use intensification in the core area of the midstream oasis region and the spatial concentration of areas classified as good and excellent ecological environmental quality. From 2015 to 2020, ecological environmental quality showed variable trends, possibly because of unsustainable water extraction practices, including illegal well construction. However, the downstream desert region remained at risk of further degradation because of desertification pressure.

The ecological environmental quality of the Manas River Basin exhibited a distinct south north gradient, corresponding to the mountain–oasis–desert transition. The upstream mountainous region, with high precipitation and dense vegetation, maintains moderate to good ecological environmental quality. The midstream oasis region, supported by irrigation infrastructure, hosts intensive agriculture activities and urban development but retains good excellent ratings because of managed water inputs. In contrast, the downstream desert region, with sparse vegetation and arid climate conditions, displays fragile ecological environmental quality, except for wetlands near the Manas Lake. This tripartite ecosystem structure underscores the need for region-specific restoration strategies (Wei et al., 2018).

This study provides new insights into long-term ecological environmental changes across arid inland river basins by integrating the RSEI analysis with interaction diagnostics and persistence forecasting—an approach not previously applied in the Manas River Basin. While prior studies (e.g., Yang et al., 2016) have documented the ecological vulnerability of the basin, our findings specifically quantified the spatiotemporal patterns and driver interactions behind the observed fluctuations. Notably, the Hurst index-based persistence analysis reveals distinct future trajectories: the upstream mountainous region shows strong anti-persistent degradation, indicating high sensitivity and potential reversals under future climate change, which contrasts with the widespread degradation trends reported in similar arid inland river basins such as the Tarim River Basin, China (Tang et al., 2025). Conversely, the midstream oasis region has experienced persistent improvement, a pattern also observed in other managed oasis ecosystems because of sustained water inputs (Yuan et al., 2021; Xu et al., 2023). 4.2 Driving factors and the masking effect of ecological environmental quality in the Manas River Basin In this study, the primary determinants of ecological environmental quality within the Manas River Basin and their interactions were investigated. A noticeable decrease in the explanatory power ( -value) of natural factors such as precipitation does not indicate a diminished ecological role. Instead, we argue that this is largely a consequence of rapid irrigated farmland expansion.

The conversion of native desert or steppe to high-biomass farmland artificially elevated the NDVI, a core component of the RSEI. Since the OPGD model attributes this dramatic land cover change to human factors (e.g., land use change), the relative statistical contribution of climatic variables appears to decline—a "masking effect". This phenomenon, where agricultural intensification obscures the statistical role of climate, is increasingly recognized in arid zone studies (Cao et al., 2025). Crucially, climate, particularly water availability from precipitation and glacier melt, remains the ultimate constraint of the ecosystem. This interpretation implies that the observed RSEI gains are partially tied to unsustainable water inputs and that future water scarcity or policy shifts could quickly re-expose the basin to its fundamental climatic constraints, potentially reversing the positive trajectory.

This observed masking effect is further substantiated by interaction effects. Interaction effects revealed that human–nature synergies dominated after 2005, which aligns with the results of studies in arid regions (Wang et al., 2019c; Lee et al., 2023), particularly the work of Tang et al. (2025) in the Tarim River Basin. This finding supports the emerging paradigm that synergistic human–nature interactions are primary drivers of ecological environmental quality change in managed drylands (Shen et al., 2025). However, our analysis provides a more pronounced spatial understanding. In the core area of the midstream oasis region, human activities (e.g., irrigation and land levelling) temporarily override natural constraints, leading to strong nonlinear

enhancements in the RSEI. In contrast, in the downstream desert region and upstream mountainous region, the interactions are weaker, and the system remains predominantly under natural climatic and topographic control. This spatial heterogeneity in human–nature interactions is a key finding that was not fully captured in previous basin-wide studies.

These human activities are directly supported by land cover dynamics, such as farmland expansion and stabilized forest cover (Du et al., 2022; Li et al., 2025), primarily in the midstream oasis region and upstream mountainous region. The adoption of drip irrigation has enabled farmland expansion (Ling et al., 2019), while the Natural Forest Protection Project has stabilized mountain forests. The expansion of built-up area is positively correlated with increasing -values between GDP and population density, suggesting that economic growth exacerbates water stress and environmental pollution. Groundwater depletion in the downstream of the basin exemplifies these pressures and underscores the potential vulnerability of the current ecological trajectory (Wei et al., 2018). 4.3 Management recommendations for the ecological environmental quality in the Manas River Basin based on spatial zoning Building on our findings regarding driving forces and persistence forecasting, we propose the following spatially explicit management strategies to guide ecological environmental governance in the Manas River Basin. (I) High-recovery potential areas (midstream oasis region). These areas show persistent improvement in ecological environmental quality. Recommendations include: (1) optimizing irrigation efficiency by transitioning to precision irrigation scheduling and promoting water- saving crops to consolidate ecological gains while mitigating groundwater depletion; and (2) strictly regulating urban sprawl and farmland encroachment into ecologically sensitive transition zones. (II) Critical conservation hotspots (oasis–desert ecotone). These hotspots are areas of intense human–nature interactions and are highly vulnerable. Actions should focus on: (1) establishing ecological buffers by planting native, drought-tolerant vegetation to halt desertification; and (2) enforcing land use regulations to prevent further conversion of natural landscapes. (III) Climate-sensitive areas (upstream mountainous region). These areas exhibit an anti-persistence signal, calling for proactive adaptation. Management should include: (1) strengthening monitoring of glacier retreat and precipitation patterns to inform adaptive water resource allocation; and (2) enhancing the Natural Forest Protection Project and similar conservation policies to preserve forest cover and water retention capacity. (IV) Vulnerable restoration areas (downstream desert region and wetlands). These areas require targeted restoration efforts due to their ecological fragility. It is critical to: (1) implement dedicated ecological water transfers to ensure minimum water levels in the Manas Lake and associated wetlands; and (2) restore native vegetation in degraded areas to enhance ecosystem resilience and counter degradation trends in these vulnerable restoration areas.

## 4.4 Limitations and future work

This investigation has certain limitations that merit attention. First, the 500-m pixel size of the MODIS imagery could obscure the landscape' s ecological environmental variability, especially across the patchy oasis–desert transition zones, possibly averaging out localized dynamics.

Second, despite its integrative nature, the RSEI might introduce distortions; the substantial contribution of NDVI implies that " greenness'' increases because farmland expansion is counted as an ecological gain, a representation that might not accurately capture the condition of native ecosystems. Third, the OPGD analysis is inherently correlative and cannot establish definitive causal relationships between the identified drivers and RSEI changes.

Future research should focus on integrating higher-resolution imagery (e.g., Sentinel-2) to better characterize landscape heterogeneity. A modified RSEI that can better distinguish between natural vegetation and farmland would provide a more accurate assessment of genuine ecological environmental quality. Furthermore, employing causal inference methods or process-based

ecosystem models would help validate the interactions identified here and move from correlation to causation in understanding the driving mechanisms.

## 5 Conclusions

In this research, the spatial and temporal dynamics of ecological environmental quality and underlying driving factors in the Manas River Basin were investigated using the RSEI (2000–2021), yielding the following conclusions. (1) The basin’ s mean annual RSEI (0.38) fluctuated but significantly increased. The areas characterized by poor and relatively poor ecological environmental quality decreased by 11.52%, while the areas with good and excellent ecological environmental quality increased by 16.71%.

Spatially, improvements were concentrated in the midstream oasis region and upstream mountainous region, whereas degradations were predominantly observed across the downstream desert region, in addition to the upstream ecotone areas.

Notably, 58.62% of the total basin consistently had poor to moderate ecological environmental quality grades, highlighting persistent ecological fragility. (2) Trend analysis revealed complex dynamics: 32.23% of the basin experienced slight degradation, but 38.61% showed improvement (especially in the midstream oasis region). The Hurst index suggested a potential but unstable future recovery in the midstream oasis region, in contrast to the ongoing degradation in the upstream mountainous region and downstream desert region. Only 36.67% of the basin (mainly in the upstream mountainous region) exhibited stable and highly stable conditions, underscoring widespread ecological environmental vulnerability. (3) After 2005, drivers shifted from nature-dominated (temperature and elevation) to human-dominated (land use change). The factor interactions revealed that land use change and temperature were historically strongest ( -value>0.859). The interactions between land use change and elevation became dominant by 2020 ( “ human–nature’’ synergistic regulation.

These findings call for differentiated management: optimization of water use in the downstream oasis region, conservation in the upstream mountainous region, and desertification control in the downstream desert region.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements This research was supported by the National Natural Science Foundation of China (32360084).

Author contributions QI Wenwen: conceptualization, methodology, formal analysis, writing - original draft preparation, writing - review and editing, resources; Li Yuanyuan: writing - review and editing, funding acquisition, supervision; Shi Xiang: funding acquisition, supervision. All authors approved the manuscript.

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Figure 9

Figure 3: Figure 9

Figure 20

Figure 4: Figure 20

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## Figures

*Source: ChinaXiv —Machine translation. Verify with original.*

Figure 21

Figure 5: Figure 21