

# *Temporal Dynamics of Surface Water and Its Coupling with Ecological Quality in a Semi-arid Region Using Google Earth Engine: A Case Study of Yuanzhou District, Guyuan City*

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**Abstract:** This study analyzes water–ecosystem coupling in Yuanzhou District, Guyuan City, using Google Earth Engine (GEE) and long-term Landsat data. MNDWI and RSEI reveal significant water body expansion and ecological quality improvement from 2000 to 2025, with strong interannual fluctuations driven by precipitation variability. Spatially, wetlands evolved from discrete patches to continuous networks, while ecological quality shifted from fragmented low-quality backgrounds to a dual-core high-quality pattern. Water–ecology coupling shows threshold effects: coupling strength weakened after major ecological engineering, indicating a shift from water-driven to multi-factor synergistic improvement.

## 1. Introduction

In Under the intensifying global climate change and the continuous impact of human activities, the vulnerability of semi-arid ecosystems is increasingly prominent<sup>[1,2]</sup>. Water resource scarcity, as a core factor restricting regional ecological security and sustainable development, not only serves as a key component of the hydrological cycle but also profoundly affects vegetation growth, soil moisture, and ecosystem functions through regulating local water and heat balance<sup>[3,4]</sup>. Therefore, long-term analysis of water body dynamics and their ecological effects is of great scientific value in revealing the ecological evolution mechanism of semi-arid regions.

The Loess Plateau, as a typical ecologically vulnerable area, has long been faced with the dual pressures of water resource scarcity and soil erosion. Since the implementation of ecological projects such as returning cultivated land to forests and grasslands since the late 1990s, the regional vegetation coverage and ecological quality have significantly improved<sup>[5,6]</sup>. However, existing research mainly focuses on vegetation restoration or land use change, with insufficient attention to the inherent dynamics of surface water bodies and their quantitative feedback mechanisms with

ecological quality, especially the lack of systematic characterization of the interdecadal evolution characteristics of water bodies.

Remote sensing technology provides key support for regional-scale water body and ecological monitoring. The improved normalized difference water index (MNDWI) proposed by Xu Wenxin<sup>[7]</sup> effectively inhibits soil and vegetation background interference through shortwave infrared bands, has high stability under complex underlying surface conditions, and has been widely used in water body identification and dynamic monitoring<sup>[8,9]</sup>; the remote sensing ecological index (RSEI) constructed by Xu Hanqiu<sup>[10]</sup> integrates multi-dimensional information such as vegetation, humidity, dryness, and temperature, can comprehensively reflect the regional ecological environment quality, and is widely used in ecological restoration assessment<sup>[11-13]</sup>. However, the systematic coupling analysis between the water body changes characterized by MNDWI and the ecological quality changes reflected by RSEI is still weak, especially in the ecological engineering background of semi-arid regions, and the stage characteristics of their response relationship have not been fully elucidated.

Based on this, this study takes the original district of Guyuan City, Ningxia as the study area, utilizes the Google Earth Engine (GEE) platform to construct a long-term surface water body and ecological environment quality dataset from 2000 to 2025, focusing on discussing: (1) the multi-year change characteristics of water body dynamics in semi-arid regions; (2) the temporal evolution law of regional ecological environment quality; (3) the coupling relationship between water body changes and ecological quality, and their stage characteristics. The aim is to provide a quantitative reference for the evaluation of ecological restoration effects and water resource management in semi-arid regions.

## 2. Study Area and Data

### 2.1. Study Area

Yuanzhou District of Guyuan City is located in the southern Ningxia Hui Autonomous Region (35° 14'-36° 18' N, 105° 20'-106° 58' E), in the heart of the Loess Plateau, a typical semi-arid ecologically fragile area (Figure 1). This study adopts an extended boundary of approximately 6,180 km<sup>2</sup>, covering the current Yuanzhou District (4,960 km<sup>2</sup>) and towns such as Sanhe, Qiyang, and Ganxiang in the lower Qinghe River Basin (currently administered by Haiyuan County of Zhongwei City), ensuring spatial continuity and watershed integrity for 2000 - 2025 remote sensing monitoring.

The area is dominated by loess hilly and gully landforms, with elevations of 1,240 - 2,942 m, steep slopes, deeply incised valleys, and severe soil erosion. It has a temperate continental semi-arid climate, with annual precipitation of 400 - 600 mm (approximately 70% concentrated from July to September) and large interannual variability; evaporation exceeds precipitation, resulting in frequent droughts. The river system is mainly dominated by the Qinghe River and its tributaries, with seasonal (intermittent) flow characteristics. Numerous small and medium-sized reservoirs and check dams form an artificial-natural composite hydrological structure. Since 2000, the continuous implementation of the Grain for Green project has driven significant changes in land use and vegetation cover, providing an ideal site for studying water-ecosystem coupling relationships.

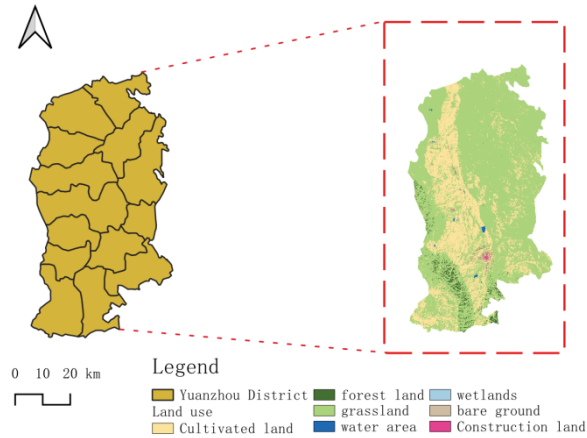


Figure 1: Location and land use characteristics of the study area.

## 2.2. Data Sources and Processing

This study uses USGS Landsat Collection 2 Level-2 Surface Reflectance (SR) products processed via Google Earth Engine (GEE) <sup>[13]</sup>, spanning 2000 – 2025. Sensors include Landsat 5 TM (2000 – 2011), 7 ETM+ (2000 – 2022), and 8/9 OLI (2013 – 2025), all at 30 m resolution.

To minimize seasonal and cloud effects, August – November images were selected (post-rainy season with stable hydrology). Cloud, shadow, and snow pixels were masked using the QA band, followed by median compositing to generate annual cloud-free images, reducing outliers and improving interannual comparability. Spectrally consistent bands were used across sensors to ensure radiometric and atmospheric comparability. This yielded a continuous 2000 – 2025 annual image sequence for water body dynamics and ecological quality analysis.

## 3. Research Methods

### 3.1. Water Body Extraction and Area Calculation Based on MNDWI

The Improved Normalized Difference Water Index (MNDWI) enhances the spectral separability between water and non-water surfaces, demonstrating a strong capability in identifying water bodies in complex backgrounds. The calculation formula is as follows:

$$MNDWI = \frac{Green - SWIR1}{Green + SWIR1} \quad (1)$$

Where Green represents the reflectance of the green band, and SWIR1 represents the reflectance of the shortwave infrared band. Water bodies exhibit strong absorption characteristics in the shortwave infrared band (reflectance close to 0), while showing relatively higher reflectance in the green band; therefore, healthy water bodies typically produce positive MNDWI values, while soil and vegetation typically produce negative values.

Based on the physical explanation of MNDWI and the actual surface characteristics of the study area, this study adopts a threshold method ( $MNDWI > 0$ ) to extract water pixels. This threshold has been widely validated in Xu's<sup>[7]</sup> original research and has been proven effective in distinguishing water from non-surface features through experiments in the study area: pixels with  $MNDWI > 0$  are classified as water, while pixels with  $MNDWI \leq 0$  are classified as non-water. To reduce noise interference, scattered patches smaller than 0.5 hectares (approximately 6 pixels at 30-meter resolution) are further eliminated.

Based on this, regional statistical values were calculated for the water body mask of each year, obtaining the annual total water area (Water\_Area, unit: km<sup>2</sup>); meanwhile, the average MNDWI value of all pixels in the study area was calculated to characterize the inter-annual changes of water body characteristics at the regional scale.

### 3.2. Construction of Remote Sensing Ecological Index (RSEI)

Remote Sensing Ecological Index (RSEI) integrates multi-dimensional ecological factors to comprehensively reflect regional eco-environmental quality<sup>[10]</sup>.

This study constructs RSEI based on four indicators: greenness, humidity, dryness, and heat.

Greenness Index: uses the Normalized Difference Vegetation Index (NDVI) to characterize vegetation coverage status;

Wetness Indicator: The calculation formula is based on the wetness component derived from the Tasseled Cap Transformation (TCT).

$$WET=0.1511\times Blue+0.1973\times Green+0.3283\times Red+0.3407\times NIR-0.7117\times SWIR1-0.4559\times SWIR2 \quad (2)$$

Drought Indicator: Uses the Normalized Difference Bare Soil Index (NDBSI) to characterize the degree of surface bareness.

$$NDBSI=\frac{(SWIR1+Red)-(NIR+Blue)}{(SWIR1+Red)+(NIR+Blue)} \quad (3)$$

Thermal Index: Land Surface Temperature (LST) is derived from the thermal infrared band using the single-window algorithm.

After calculating these four indicators, they are normalized to the 0-1 range, and principal component analysis (PCA) is applied to extract the first principal component (PC1). PC1 usually explains most of the variance, and its loading characteristics conform to ecological interpretations: greenness and humidity are positively correlated, while dryness and heat are negatively correlated. Therefore, PC1 is adopted as the RSEI value. To enhance interannual comparability, RSEI is finally renormalized to the [0,1] interval.

### 3.3. Coupling Relationship Analysis Method

To quantitatively characterize the coupling relationship between water body dynamics and ecological environment quality, this study analyzes from two dimensions: trend analysis and correlation analysis. First, a linear regression model is used to examine the long-term trends of MNDWI (Normalized Difference Water Index), water area, and RSEI (Remote Sensing Ecological Index):

$$Index_t=Slope\times Year+Intercept \quad (4)$$

Subsequently, the Pearson correlation coefficient was used to assess the linear correlation degree between MNDWI and RSEI, as well as between water body area and RSEI. Additionally, a linear regression model was established to quantify the coupling relationship:

$$RSEI=a\times MNDWI+b \quad (5)$$

$$RSEI=c\times Water\_Area+d \quad (6)$$

Considering that the implementation of ecological engineering may have phased impacts on water ecological relationships, the study period was divided into two phases: the early phase (2000-2012, n=13) and the late phase (2013-2025, n=13). Regression models were established for each phase respectively to compare the changes in coupling relationship strength (R<sup>2</sup>) and sensitivity

(slope) between different phases. The significance level for all statistical analyses is set to  $\alpha = 0.05$ , and all analyses are performed using the SciPy library in Python 3.9.

## 4. Results

### 4.1. Dynamic Changes of Water Bodies and Temporal Evolution of Eco-environmental Quality

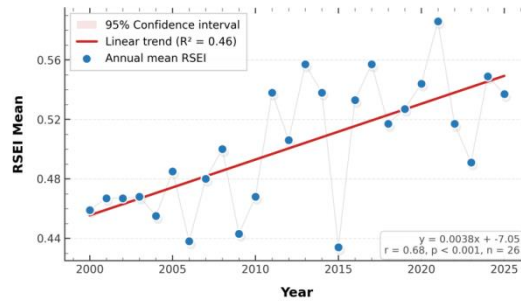


Figure 2: Temporal variation of annual mean RSEI in Yuanzhou District from 2000 to 2025.

From 2000 to 2025, RSEI shows a significant growth trend (Figure 2), with an annual average increase of 0.0038 ( $R^2 = 0.459$ ,  $p < 0.001$ ), rising from 0.459 to 0.537. However, significant interannual fluctuations are evident ( $CV = 8.3\%$ ). The troughs occurred in 2006 (0.438) and 2015 (0.434), corresponding to severe regional drought events, while the peak occurred in 2021 (0.586), which is associated with years of abundant precipitation.

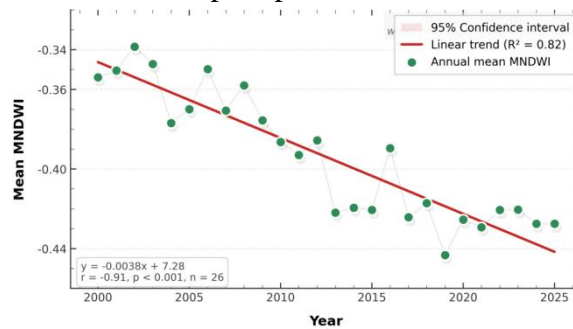


Figure 3: Temporal dynamics of mean MNDWI in Yuanzhou District from 2000 to 2025.

MNDWI shows a highly significant decreasing trend (Figure 3), with an average annual reduction of 0.0038 ( $R^2 = 0.824$ ,  $p < 0.001$ ), decreasing from -0.354 to -0.443, indicating a continuous enhancement of water body characteristics. The interannual fluctuation of MNDWI is relatively small (coefficient of variation is 6.4%), and it shows a mirror-symmetric change pattern with RSEI.

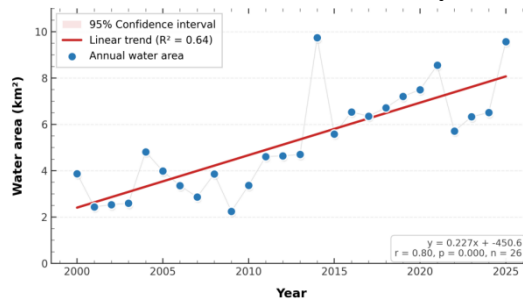


Figure 4: Temporal variation of surface water area in Yuanzhou District from 2000 to 2025.

The water area extracted based on MNDWI shows significant expansion (Figure 4), with an annual average increase of 0.227 km<sup>2</sup> ( $R^2=0.638$ ,  $p<0.001$ ), growing from 3.87 km<sup>2</sup> to 9.57 km<sup>2</sup>; an increase of 147%. Significant interannual fluctuations are observed (CV=35.2%), with peaks occurring in 2014 (9.74 km<sup>2</sup>) and 2021 (8.55 km<sup>2</sup>), and troughs in 2006 (3.35 km<sup>2</sup>) and 2009 (2.25 km<sup>2</sup>). The trend strength of MNDWI ( $R^2=0.824$ ) was significantly higher than that of water area ( $R^2=0.638$ ) and RSEI ( $R^2=0.459$ ).

#### 4.2. Spatial Distribution Characteristics

The spatial distribution of MNDWI (Figure 5) shows that water bodies are mainly concentrated in the central and southern parts of the study area, and the wetland area has expanded significantly over time. Between 2000 and 2025, areas with high MNDWI values (dry land) have gradually decreased, while areas with low MNDWI values (water bodies and wetlands) have continued to expand.

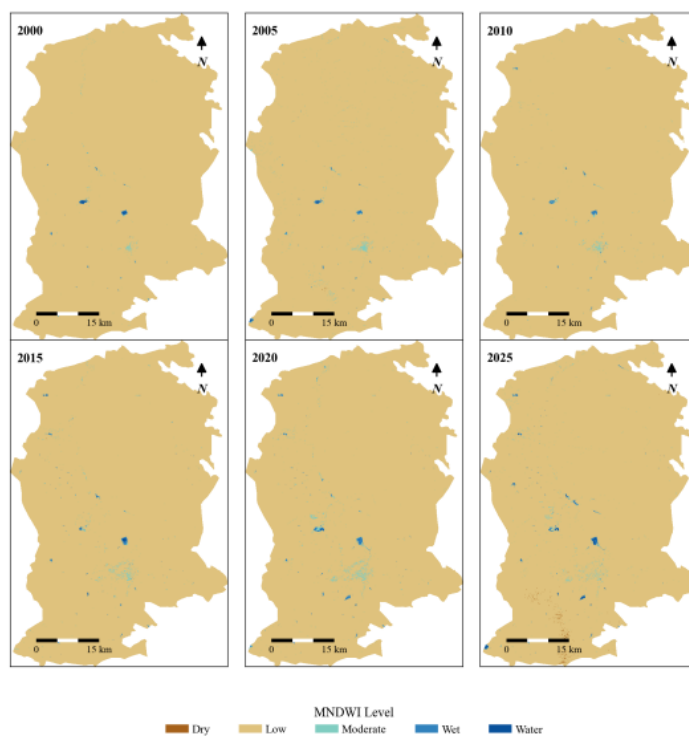


Figure 5: Spatial distribution of MNDWI levels in Yuanzhou District for selected years (2000, 2005, 2010, 2015, 2020, 2025).

Specifically, In 2000, arid land dominated, with only 2–3 small isolated water patches in the south; wetlands showed a point-like scattered pattern. During 2005–2010, water patches slightly expanded and humid areas extended finger-like along low-lying terrain, yet the arid matrix remained dominant. After 2015, wetland expansion accelerated: central-southern humid areas doubled, and isolated water bodies achieved connectivity through transition zones. By 2025, a sharp contrast emerged between the northern high-value background and the central-southern low-value concentration: arid land retreated northward and peripherally in a "C"-shaped enclosure, while central-southern wetlands formed a continuous areal distribution with water and humid areas almost fully covering the region; additionally, new wetland patches appeared in the southeast, indicating multi-center expansion.

This spatial evolution indicates significant wetland succession (swampification) with enhanced

landscape heterogeneity. Wetlands transformed from discrete patches into a network-like continuous structure, substantially improving ecosystem connectivity and integrity.

The spatial distribution of RSEI (Figure 6) shows that from 2000 to 2005, Poor and Fair grades were dominant, while Good/Excellent grades were limited to local areas. During the 2010-2015 period, Moderate grade became the main category. By 2020-2025, the Good/Excellent grade has significantly expanded, especially in the northern and western regions.

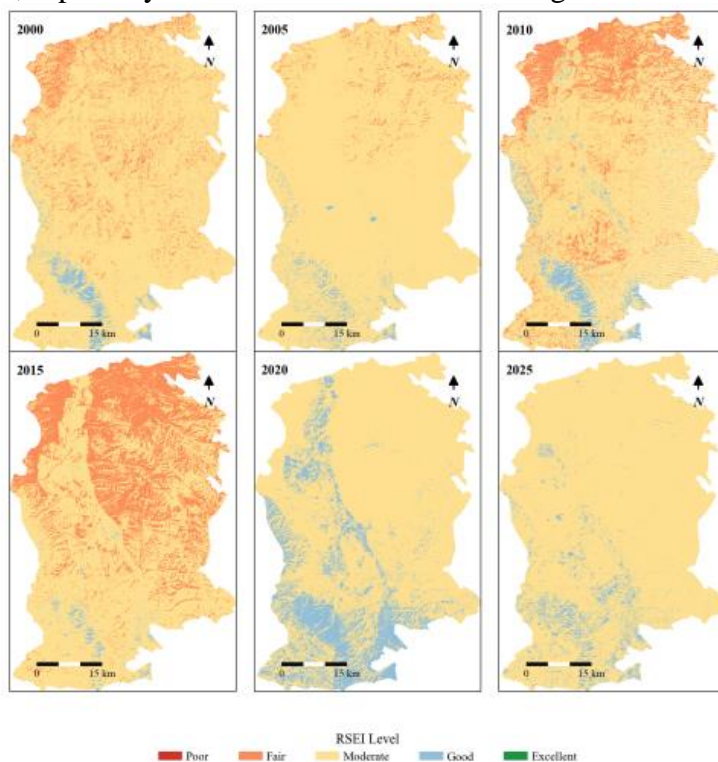


Figure 6: RSEI spatial distribution in Yuanzhou Region (Selected years: 2000, 2005, 2010, 2015, 2020, 2025)

In 2000, the study area showed a yellow medium-level matrix with poor-level red patches widely distributed in the north, while good-level light blue areas were only sporadically embedded around water bodies in the central-south, forming isolated point-like distributions. By 2005, this pattern remained largely unchanged. In 2010, northern areas transformed into orange medium-low level, poor-level red areas significantly decreased, and good-level areas in the central-south extended along wetland expansion. By 2015, a "north-high, south-low" pattern formed, with some excellent-level green patches. After 2020, improvement accelerated; by 2025, good-level areas in the northwest showed continuous distribution, while central-southern excellent-level areas doubled and merged with good-level areas, forming a "dual-core north-south with westward expansion" structure, with only narrow medium to medium-low strips along the eastern edge.

This evolution indicates the spatial pattern evolved from "isolated high-quality islands in a homogeneous low-quality background," through a "north-south differentiation gradient," to "large-area continuous high-quality regions interspersed with residual low-quality patches," significantly enhancing overall ecosystem service function.

### 4.3. Water-Ecology Coupling Relationship

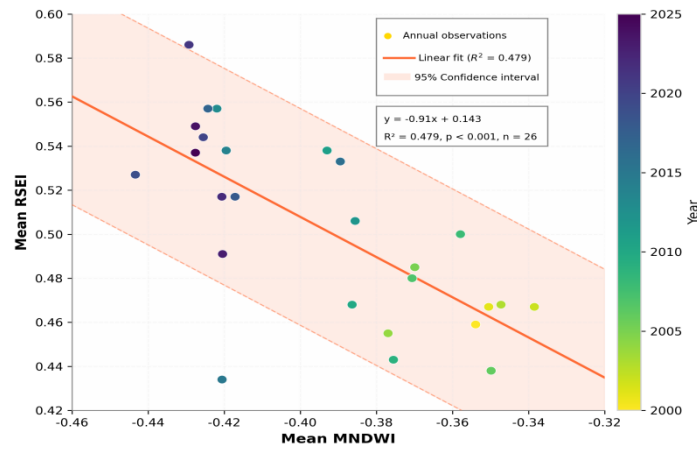


Figure 7: Correlation between MNDWI and RSEI in Yuanzhou District (2000–2025).

MNDWI showed a significant negative correlation with RSEI (Fig. 7,  $R^2 = 0.479$ ,  $p < 0.001$ ,  $n = 26$ ), and the regression equation was:  $RSEI = -0.912 \times MNDWI + 0.143$ . Specifically, for every 0.1 unit decrease in MNDWI, RSEI increased by an average of 0.091.

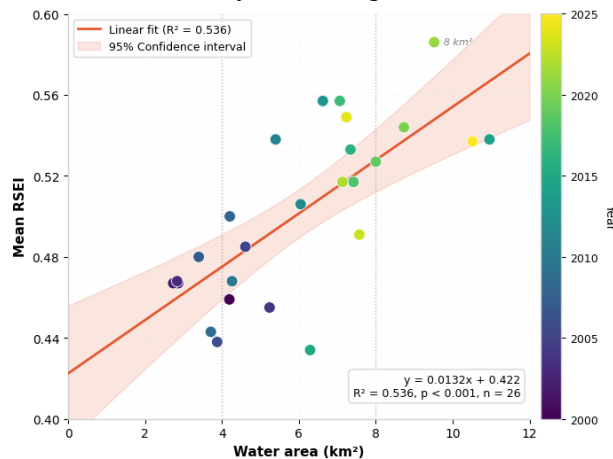


Figure 8: Correlation between surface water area and RSEI in the study area (2000 – 2025).

The water body area is significantly positively correlated with the RSEI (Figure 8,  $R^2 = 0.536$ ,  $p < 0.001$ ,  $n = 26$ ), with the regression equation:  $RSEI = 0.0132 \times \text{water body area} + 0.422$ . For each  $1 \text{ km}^2$  increase in water body area, the regional average RSEI increases by approximately 0.013. Over 26 years, the theoretical increase in RSEI caused by water body expansion is 0.083, which closely matches the observed total increase in RSEI (0.078).

A clear threshold effect is observed: when the water body area is less than  $4 \text{ km}^2$ , RSEI mainly ranges from approximately 0.44 to 0.50; when it exceeds  $8 \text{ km}^2$ , RSEI is generally greater than 0.54.

## 5. Conclusions

- (1) Water bodies expanded significantly but with high interannual variability, sensitive to drought and precipitation.
- (2) Ecological quality improved overall yet remains vulnerable to climate fluctuations.

(3) Coupling exhibits threshold effects; post-engineering weakening suggests shifting from water-driven to multi-factor synergy.

(4) Spatial patterns evolved from fragmentation to connectivity, enhancing ecosystem integrity.

These findings support water resource management and ecological restoration in semi-arid regions.

## Acknowledgements

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