

Postprint: Impacts of NDVI and Land Use on Spatiotemporal Variation of Evapotranspiration in the Yellow River Basin

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Abstract

Based on evapotranspiration (ET), Normalized Difference Vegetation Index (NDVI), and land use data, this study employs the Mann-Kendall (M-K) test, Sen's trend analysis, and other methods to investigate the spatiotemporal distribution of ET and its variation patterns under different vegetation cover and land use conditions in the Yellow River Basin from 2001 to 2015. The results indicate: (1) The mean annual ET in the Yellow River Basin exhibits a spatial distribution pattern characterized by high values in the southeast and low values in the northwest, demonstrating good consistency with vegetation cover and land use patterns; (2) Both ET and NDVI in the Yellow River Basin show a fluctuating increasing trend, while land use areas of all types except grassland have increased, with significant differences observed among the upper, middle, and lower reaches; (3) ET is positively correlated with vegetation in most areas of the basin, and vegetation change constitutes one of the primary factors influencing ET; (4) The spatiotemporal differences in how land use types respond to ET are notably pronounced in the Yellow River Basin.

Full Text

Effects of NDVI/Land-Use on Spatiotemporal Changes of Evapotranspiration in the Yellow River Basin

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Abstract: The Yellow River Basin is primarily distributed across arid, semi-arid, and semi-humid regions with a fragile ecological environment, representing one of the most severely soil-eroded areas in China and globally. Evapotranspiration (ET) constitutes an essential component of the terrestrial water and energy cycle, playing a vital role in global ecosystem regulation and hydrological processes. ET mainly comprises vegetation transpiration and soil water evaporation, exhibiting distinct spatiotemporal distribution characteristics under different vegetation cover or land-use types. Accurate characterization of ET's spatiotemporal patterns and its response relationships is crucial for understanding regional surface water and heat balance regimes. Remote sensing has been widely employed for dynamic ET monitoring at global and regional scales. Analyzing ET spatiotemporal variations in the Yellow River Basin enhances understanding of how vegetation and land-use changes impact the water cycle and facilitates rational water resource allocation.

Based on MODIS ET data, Normalized Difference Vegetation Index (NDVI), and land-use products as data sources, we investigated ET spatiotemporal change patterns in the Yellow River Basin from 2001 to 2015 using the Mann-Kendall test and Sen's trend analysis. We examined ET impacts and different change characteristics under varying NDVI conditions and land-use types. The results revealed: (1) The ET distribution pattern in the Yellow River Basin shows a clear gradient, gradually decreasing from southeast to northwest. The average ET value in the study area is 319.24 mm, with an average NDVI of 0.59. High ET and NDVI values concentrate in downstream areas, and their spatial distributions exhibit strong consistency. (2) Both ET and NDVI time series in the Yellow River Basin displayed fluctuating growth trends from 2001 to 2015, with significant differences among river segments. In interannual variations, ET and NDVI trends align, showing significantly increased levels in the middle reaches. (3) Vegetation change represents the primary factor affecting ET, positively correlating with ET across most of the Yellow River Basin. (4) From 2001 to 2015, all land cover types except grassland showed increasing trends, with ET responses varying among different river reaches. The spatiotemporal differences in land-use types' responses to ET are pronounced. Comprehensive analysis of evaporation variation patterns in the upper, middle, and lower reaches of the Yellow River Basin holds great significance for ecosystem protection and water resources management, providing references for promoting sustainable regional economic and social development.

Key words: evapotranspiration; vegetation cover; NDVI; land use; Yellow River Basin

1.1 Study Area Overview

The Yellow River Basin is located between 96°-119°E and 32°-42°N, covering a drainage area of 79.5×10^4 km². The basin spans arid, semi-arid, and semi-humid zones across China. The terrain is high in the west and low in the east, with the section from the river source to Hekou Town in Inner Mongolia constituting the upper reaches characterized by large elevation drops. The middle reaches extend from Hekou Town to Taohuayu in Henan Province, featuring loess landforms with severe soil erosion. The lower reaches below Taohuayu consist primarily of alluvial plains formed by loess deposition [Figure 1: see original paper].

The basin exhibits a continental climate transitioning from semi-humid in the southeast to semi-arid and arid in the northwest. Annual temperature variations are pronounced, with average precipitation ranging from 200-600 mm. The basin contains diverse landform types, with vegetation cover showing a spatial pattern of high values in the southeast and low values in the northwest. The primary land-use types are forestland, grassland, and cropland.

1.2 Data Sources and Processing

The MODIS data used in this study were obtained from the U.S. National Aeronautics and Space Administration (NASA) website. This dataset features complete characteristic parameters and high temporal resolution, making it advantageous for monitoring regional spatiotemporal distribution patterns. The ET data were derived from the MOD16A2 product with a spatial resolution of 500 m and temporal resolution of 8 days. NDVI data were obtained from the MOD13Q1 product with a spatial resolution of 250 m and temporal resolution of 16 days. Land-use data were sourced from the MCD12Q1 product with a spatial resolution of 500 m and temporal resolution of 1 year. The global vegetation classification includes 17 land-use types. For analyzing major land-use type changes in the Yellow River Basin, the land cover data were reclassified into forestland, grassland, permanent wetland, cropland, built-up land, and water bodies.

1.3 Methodology

1.3.1 Mann-Kendall Test In the Mann-Kendall test, the null hypothesis states that the time series data (X_1, X_2, \dots, X_n) are n independent and identically distributed random variables. The alternative hypothesis assumes that for all k and j ($k, j \leq n$), the distributions of X_k and X_j are not identical. The test statistic S is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(X_j - X_k)$$

where the sign function is defined as:

$$\text{sgn}(X_j - X_k) = \begin{cases} +1 & \text{if } X_j - X_k > 0 \\ 0 & \text{if } X_j - X_k = 0 \\ -1 & \text{if } X_j - X_k < 0 \end{cases}$$

When $n \geq 8$, the statistic S approximately follows a normal distribution with mean $E[S] = 0$ and variance:

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

The standardized test statistic Z is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

In a two-tailed trend test at a given confidence level α , if $|Z| \geq Z_{1-\alpha/2}$, the time series exhibits a significant upward or downward trend. For the standardized statistic Z , $Z > 0$ indicates an upward trend, while $Z < 0$ indicates a downward trend.

1.3.2 Sen' s Trend Analysis Sen' s trend analysis quantifies the change magnitude, representing the change per unit time. The slope β is calculated as:

$$\beta = \text{median} \left(\frac{X_i - X_j}{i - j} \right), \quad 1 < j < i < n$$

When $\beta > 0$, the time series shows an upward trend; conversely, $\beta < 0$ indicates a downward trend.

2.1 Spatial Characteristics of ET and NDVI/Land-Use

The spatial distributions of multi-year average ET and land-use status in 2015 are shown in [Figure 2: see original paper]. High evapotranspiration areas concentrate in the Yellow River source region, upper Weihe River, Jinghe River, Beiluo River, and Yanhe River basins, while evaporation is relatively low in wind-sand areas. Vegetation spatial distribution varies significantly across the Yellow River Basin, showing a gradual decreasing trend from southeast to northwest.

Regions with higher NDVI values concentrate in the Yellow River source area and the middle-lower reaches, while vegetation cover is lower in wind-sand areas,

the northern Hetao Irrigation District, and the Shida Kongdui region. Grassland is the primary land-use type in the Yellow River Basin, distributed across the upper reaches, northern Jinghe River, northern Qingjian River, and north-western Fenhe River regions. The Jingwei River Plain and Fenhe River Plain are suitable for crop growth. Overall, ET shows certain correlations with vegetation cover and land-use types.

2.2 Temporal Series Analysis of ET and NDVI/Land-Use

Interannual variations of ET and NDVI in the Yellow River Basin and its upper, middle, and lower reaches from 2001 to 2015 are shown in [Figure 3: see original paper]. The entire basin experienced growth in ET, with accelerated growth after 2010 due to higher-than-normal temperatures. The upper, middle, and lower reaches all showed increasing ET, with the lower reaches exhibiting the most dramatic fluctuations. ET in the lower reaches was highest throughout the study period, followed by the upper and middle reaches. After 2010, ET growth in the middle reaches became more significant, while the lower reaches showed the lowest ET levels at 377.35 mm.

NDVI in the Yellow River Basin remained above 0.5 on average, showing an increasing trend. The minimum and maximum values occurred in 2001 (0.48) and 2015 (0.62), respectively. Vegetation growth was most vigorous in the lower reaches, with NDVI consistently above 0.55 and a relatively stable trend. The middle reaches showed steady and significant vegetation growth, while NDVI in the upper reaches fluctuated between 0.45-0.55, consistent with the overall basin pattern.

Land-use type area changes from 2001 to 2015 are shown in [Figure 4: see original paper] and [Figure 5: see original paper]. Cropland area increased significantly while grassland decreased markedly. From 2001-2010, forestland, cropland, and built-up land areas rose steadily while grassland declined at a stable rate. During 2010-2015, cropland and water body areas stabilized while grassland reduction slowed. Forestland area growth rates were relatively stable in the upper and middle reaches but more variable in the lower reaches. Grassland area consistently decreased, with notable variation among river segments. Upper reach grassland decreased from $44.91 \times 10^4 \text{ km}^2$ to $44.12 \times 10^4 \text{ km}^2$, stabilizing after 2010. Middle reach grassland decreased at $0.076 \times 10^4 \text{ km}^2$ annually, stabilizing after 2010. Lower reach grassland showed fluctuating changes without clear trends. Wetland areas in all reaches increased slowly with minor fluctuations, while cropland, built-up land, and water body areas remained stable.

2.3 Impact of NDVI Changes on Evapotranspiration

The study area's multi-year average NDVI and ET values and their grade proportions are shown in and . NDVI values between 0.4-0.6 account for 59.88% of the basin, while $\text{NDVI} > 0.8$ represents only 0.30% of the area. The propor-

tion of NDVI > 0.6 regions increases from upstream to downstream, indicating higher vegetation coverage from east to west. The lower reaches show the highest proportion of NDVI > 0.6 at 44.30%.

ET values of 200–400 mm dominate the basin at 51.55%, while only 0.30% of areas exceed 800 mm. The proportion of 600–800 mm ET areas increases progressively from upstream to downstream, indicating more intense evapotranspiration from east to west. The lower reaches concentrate high ET values, with 95.40% of areas exceeding 200 mm. Overall, ET magnitude corresponds well with vegetation cover spatial distribution, demonstrating strong correlation between ET and vegetation cover.

Using trend analysis, we calculated pixel-by-pixel Z_c values and interannual change rates (β) for NDVI and ET, classifying their trends and proportions, . The middle reaches showed the largest NDVI change rate ($\beta = 0.008$), with $Z_c = 2.53$ ($P < 0.05$), indicating significant increase. The lower reaches showed $Z_c = 1.73$, reaching significant increase levels, while the upper reaches ($Z_c = 0.82$) showed non-significant increase. Basin-wide NDVI showed non-significant increasing trends.

NDVI change rates primarily fell between 0–0.005 (69.54% of area), with rates < -0.005 and > 0.01 accounting for 15.14% and 15.32%, respectively. Upper reach vegetation showed slowly decreasing trends in 47.96% of areas. Basin-wide ET change rates mainly ranged 0–12 $\text{mm} \cdot \text{a}^{-1}$ (30.41% of area), with rates < 0 $\text{mm} \cdot \text{a}^{-1}$ and > 12 $\text{mm} \cdot \text{a}^{-1}$ accounting for 72.57% and 14.93%, respectively. The middle reaches were the fastest increasing region, with 63.02% of areas showing rates > 4 $\text{mm} \cdot \text{a}^{-1}$. Upper and lower reaches showed increasing trends but with relatively smaller magnitudes.

Correlation analysis between ET and NDVI time series [Figure 6: see original paper] revealed positive correlations across most of the Yellow River Basin, with strong correlations concentrated in the Huangqiu area of the Helong section, upper Jingwei River, and northeastern Inner Mongolia reaches. The southern middle reaches, with abundant rainfall and dense vegetation, showed consistent ET and NDVI trends. Weaker correlations occurred in the Yellow River source region, where high altitude and low vegetation cover contrasted with relatively high ET. Cropland areas showed lower correlations. Overall, ET variations correlate with vegetation growth status, making vegetation a key influencing factor.

2.4 Impact of Land-Use Changes on Evapotranspiration

[Figure 7: see original paper] shows land-use types and ET changes across river sections. Basin-wide ET change rates primarily ranged 0–12 $\text{mm} \cdot \text{a}^{-1}$, with grassland as the main land-use type showing decreasing area over time while other types increased. All land-use types exhibited increasing ET trends. Over 60% of grassland is located in the upper reaches, where land-use area changes and ET increases aligned with basin-wide patterns. Forestland and cropland

are mainly distributed in the middle reaches, with both land-use types showing consistent ET increases over time. The lower reaches are dominated by cropland, with all land-use types showing greater ET than middle and upper reaches, particularly wetland and forestland.

In typical sub-basins, the Hun River lower reaches are dominated by cropland with high ET. The Qingjian River, Yanhe River, Shida Kongdui, Huangfuchuan, Kuye River, Tuwei River, and Wuding River are primarily grassland-dominated. The Jinghe River, Beiluo River, and Weihe River are forestland-dominated, with ET increasing from northwest to southeast. Land-use is thus an important factor affecting ET, with pronounced spatiotemporal differences in how land-use types respond to ET across the Yellow River Basin. Understanding actual ET spatiotemporal patterns is crucial for rational water resource allocation and improving water use efficiency.

3 Conclusions

Current research on ET in the Yellow River Basin has primarily utilized MODIS products or remote sensing estimation models to analyze spatiotemporal variation characteristics, often focusing on small scales. Studies on the entire Yellow River Basin remain limited. The MODIS ET dataset, which comprehensively considers vegetation transpiration, canopy interception evaporation, and soil moisture evaporation, meets regional-scale research requirements. The MOD16A2 product effectively reflects ET conditions, promoting regional ecological protection and rational water resource allocation.

Based on MODIS ET, NDVI, and land-use data from 2001-2015, this study investigated ET spatiotemporal variation characteristics in the Yellow River Basin, using trend and correlation analyses to explore ET-NDVI relationships and statistical analysis of ET variation patterns across different land-use types. The main conclusions are:

- 1) The Yellow River Basin ET distribution shows a southeast-high, northwest-low pattern, with average ET of 319.24 mm and average NDVI of 0.59. High ET and NDVI values concentrate in downstream areas, showing strong spatial consistency. ET and NDVI time series exhibit fluctuating growth, with significant interannual fluctuations, particularly dramatic in the lower reaches.
- 2) Vegetation change is a primary factor affecting ET, positively correlating with ET across most basin areas. Most regions show significantly increasing ET trends, with vegetation and ET trends being consistent.
- 3) From 2001-2015, all land-use types except grassland showed increasing trends with distinct stage characteristics. Different river reaches exhibited varying land-use area change trends, but overall, Yellow River Basin land-use is developing favorably.

- 4) Different river reaches show varying land-use type impacts on ET, with lower reach evapotranspiration significantly greater than middle and upper reaches. Land-use is a crucial factor influencing ET, with pronounced spatiotemporal differences in responses.

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