Research Article

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Spatiotemporal evolution of ecological environment quality in arid areas based on the remote sensing ecological distance index: A case study of Yuyang district in Yulin city, China

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Abstract: The ecological environment in arid areas of Northwest China has undergone considerable changes under the combined effects of climate change and human factors. Therefore, exploring the spatial and temporal evolution of the ecological environment quality is of great significance for the protection and management of the ecological environment in arid areas of Northwest China. This study adopted Yuyang district as the study area. Landsat Thematic Mapper/Operational Land Imager images from 1993 to 2018 were selected as the data source for the retrieval of important surface indicators and the construction of the remote sensing distance ecological index. The spatial distribution, trend, and grade classification of the ecological environment quality were monitored and analyzed. The results showed that (1) the ecological environment quality of Yuyang district from 1993 to 2018 showed an overall upward trend, mainly manifested as a sharp decline in the area of poor ecological environment from 84.81 to 53.36%. (2) The spatiotemporal changes in the ecological environment quality showed a downward trend in the central urban area and an upward trend in the noncentral urban area. (3) In general, rainfall and temperature had limited impact on the ecological environment quality. Urbanization seriously affected the local ecological environment quality and the implementation of the ecological restoration policies, regulations, and measures were the main drivers of the improvement to the ecological environment quality in other surrounding areas.

Keywords: Yuyang district, ecological environment quality, remote sensing ecological distance index, spatiotemporal evolution

1 Introduction

The rapid development of urbanization and overexploitation of resources since the 1980s have led to a series of ecological and environmental challenges, including vegetation degradation, land desertification, water shortages, and frequent extreme weather and natural disasters. These challenges have greatly hindered the attainment of the sustainable development of the society [1,2]. As the arid and semiarid regions of northwest China are characterized by scarce rainfall and low vegetation cover, the ecological environment of these regions shows obvious vulnerability [3]. Therefore, an improved understanding of the ecological health of ecologically fragile areas and clarifying the impacts of natural and social factors on the ecological environment quality can assist the management and restoration of the ecological environment in northwest China.

There are various advantages associated with the remote sensing technology, including a wide spatial monitoring range, a short revisit period, and low data cost. Remote-sensed data have been widely applied in ecology because these data provide an effective means of quantification, visualization, and evaluation of the ecological environment [4]. The application of remote-sensed data in earlier studies includes analyzing the response mechanisms of vegetation indices to human activities and climate change [5]; studying the spatiotemporal expansion

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and drivers of urban and rural construction land and analyzing the impact of urbanization on the ecological environment [6–8]; and assessing the urban heat island effect by analyzing changes in urban landscape patterns [9–11]. The study of changes in single indicators and their relationship with ecological response in the region has many limitations and is not able to provide a comprehensive evaluation of the regional ecological environment quality and a clarification of the ecological environment status of ecologically fragile areas [12]. Scholars have proposed a series of ecological environment comprehensive evaluation models to address this problem, including the "pressure-state-response" model [13], the remote-sensed ecological index (RSEI) model based on principle component analysis [14], and the ecological vulnerability evaluation model based on "cause–effect" indicators [15]. The use of a comprehensive evaluation model overcomes the challenge of the one-sidedness of a single-factor evaluation and provides a more comprehensive evaluation result. However, the identification of methods for determining the weights of multiple indicators has become a key and difficult challenge facing the ecological environmental evaluation research. In 2016, Zhang [16] adopted the Guazhou-Dunhuang as a study area and proposed a new system to evaluate the ecological environment quality based on the four-dimensional space remote-sensed ecological distance index (RSEDI). Shi et al. [17] affirmed the applicability and objectivity of RSEDI by its application to assess and monitor the ecological environmental quality of the oasis area in the Shiyang river basin. Huang et al. [12] used RSEDI to clarify the spatial and temporal changes in the ecological environment quality in Urumqi. The RSEDI has the advantages of objective weighting, simplicity, and speed. It also overcomes the challenge of one-sidedness of a single-factor evaluation and subjectivity in determining the weights of comprehensive evaluation indices. Therefore, the results of the RSEDI can objectively reflect the changes in the ecological environment in arid and semiarid areas over the long term.

The Yuyang district of Yulin city is the center of modern agriculture in the agro-pastoral transition zone of northern China and an example of sustainable development within the Loess Plateau. At the same time, Yuyang district, as an influential city, located on the border between Shaanxi, Gansu, Ningxia, Mongolia, and Shanxi, acts as a base of national energy and chemical production in northern Shaanxi. Natural factors such as climate change and human activities such as agricultural development, energy development and utilization, and implementation of ecological projects have had certain impacts on the local ecological environment in recent decades. Therefore, the study of the process of ecological change and factors influencing Yuyang district is of practical significance for the ecological management of the area. The present study used Landsat Thematic Mapper (TM)/Operational Land Imager (OLI) image data, integrated the topography and geomorphology of the study area, combined the RSEI, and constructed a four-dimensional RSEDI based on the distance function. This index was used to analyze the ecological environment change process in Yuyang district and to explore the driving factors. The results of the present study can provide a scientific basis for achieving sustainable development of the Yuyang district.

2 Study area, materials, and methods

2.1 Study area

Yuyang district is located within the municipal district of Yulin city, Shaanxi Province, and is the political, economic, and cultural center of Yulin city (Figure 1). The elevation of Yuyang district generally decreases from the northeast to the southcentral area. The study area is roughly bounded by the Great Wall of Ming and consists of two major types of landforms: (1) wind-sand and grassland area in the north accounting for ~75% of the total area and (2) hilly and gully area in the south accounting for ~25% of the total area [18]. Yuyang district is located in a typical continental marginal monsoon climate zone characterized by four distinct seasons. The average annual rainfall and temperature of the study area are 412.2 mm and 8.8°C, respectively [19].

2.2 Data sources

The Landsat program of the United States National Aeronautics and Space Administration has launched eight satellites since 23 July, 1972. The data collected by these satellites can be downloaded from the United States Geological Survey website (https://earthexplorer.usgs.gov/). Landsat data are long-term and large-scale ecological environmental monitoring data [20]. The spatial resolution of the Landsat data was 30 m, and they underwent system radiation and geometric correction. The dataset used in the present study was provided by the Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The present study maximized the accuracy of the surface information of the study area and ensured that image cloud cover

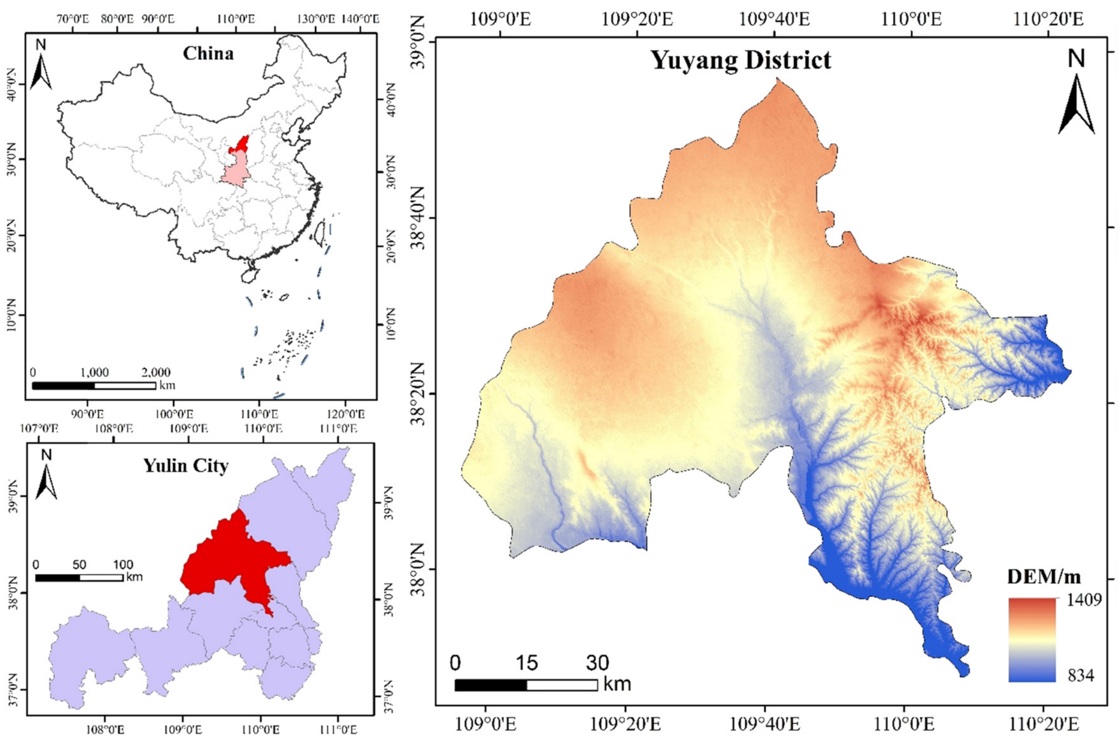

Figure 1: Location and digital elevation map of Yuyang district in Yulin city, China.

was less than 3% by selecting three phases of satellite images with strip numbers (127, 33) and (127, 34) for 18 June, 1993, 16 June, 2004, and 23 June, 2018. Remote sensing images need to be subjected to a series of preprocessing steps before they can be used for quantitative research. The ENVI 5.3 software was used to preprocess the images, including strip repair, image registration, radiometric calibration, atmospheric correction, cloud detection, image mosaic, and cropping. The temperature and rainfall data of Yuyang district were obtained from the China Meteorological Data Network (http://data.cma.cn/). The land use type data were obtained from the Global Geo-information Public Product (http://www.globallandcover.com/).

2.3 Research method

2.3.1 Humidity index

The humidity index indicates the degree of wetness of soil. The present study used the wetness index (WI) of the tassel cap transformation to reveal soil drought variability. The wetness component equation is as follows:

$$\mathrm{WI} = c1B_1 + c2B_2 + c3B_3 + c4B_4 + c5B_5 + c6B_6. \quad (1)$$

In equation (1), B_1–B_6 represent blue, green, red, near red, mid-infrared 1, and mid-infrared 2 bands, respectively, and $c1$–$c6$ are the sensor parameters. The humidity component calculation parameters for the TM and OLI sensors differ due to the different satellite sensor types. In the case of the TM sensor, the values of $c1$–$c6$ are 0.0315, 0.2021, 0.3012, 0.1594, −0.6806, and −0.6109, respectively [21], whereas they are 0.1511, 0.1973, 0.3283, 0.3407, −0.7117, and −0.4559, respectively, for the TM sensor [22].

2.3.2 Greenness index

The greenness index is expressed through vegetation indices, among which the remote sensing-based normalized difference vegetation index (NDVI) better reflects the vegetation growth status, vegetation biomass, and other parameters, and is widely used in the study of the spatial and temporal changes of vegetation cover and in the monitoring of crop growth status. Therefore, the present study used NDVI as the greenness index based on the environmental characteristics of the study area. The NDVI can be calculated as follows [23]:

$$\mathrm{NDVI} = (B_{\mathrm{NIR}} - B_{\mathrm{R}})/(B_{\mathrm{NIR}} + B_{\mathrm{R}}). \quad (2)$$

In equation (2), B_{NIR} and B_R represent the near red and red bands, respectively.

2.3.3 Dryness index

The dryness index is used to reflect the degree of dryness of the land surface, with both bare land and built-up land increasing land surface "dryness." The brightness values of the surface types of built-up and bare soil are higher than those of other land types. Therefore, the brightness value of the land surface can act as an indicator of bare surfaces and can represent the spatial distribution of built-up land. The ecological environment is influenced by the spatial distributions of both bare surfaces and built-up land [14]. Therefore, the index-based built-up index (IBI) and the soil index (SI) can be used to construct a normalized differential build-up and bare soil index (NDSI) to represent the dryness of the RSEI. This is calculated as follows [24]:

$$SI = [(B_5 + B_3) - (B_4 + B_1)]/[(B_5 + B_3) + (B_4 + B_1)], \quad (3)$$

$$IBI = \frac{\{2B_5/(B_5 + B_3) - [B_4/(B_4 + B_3) + B_2/(B_2 + B_5)]\}}{\{2B_5/(B_5 + B_3) + [B_4/(B_4 + B_3) + B_2/(B_2 + B_5)]\}}, \quad (4)$$

$$NDSI = \frac{SI + IBI}{2}. \quad (5)$$

2.3.4 Heat index

The heat index is reflected through the land surface temperature (LST). As the Landsat TM data only include one thermal infrared band, the present study selected a single-channel algorithm to invert the LST [25]:

$$LST = T/[1 + (\lambda T/\rho)\ln \varepsilon], \quad (6)$$

$$T = K_2/\ln(K_1/B_{TIR} + 1). \quad (7)$$

In equations (6) and (7), B_{TIR} is the thermal infrared band radiation, obtained from the sixth and tenth bands of the TM and OLI sensors, respectively, T is the brightness temperature at the sensor, and K_1 and K_2 are the sensor calibration parameters. For the sixth band of the Landsat-5 TM, $K_1 = 607.76\,\mathrm{W/(m^2\,sr\,\mu m)}$ and $K_2 = 1260.56\,\mathrm{K}$. For the tenth band of Landsat-8 OLI/TIR, $K_1 = 774.89\,\mathrm{W/(m^2\,sr\,\mu m)}$ and $K_2 = 1321.08\,\mathrm{K}$. λ is the central wavelength of the thermal infrared band, $\rho = 1.438 \times 10^{-2}\,(\mathrm{m\,K})$, and ε is the specific emissivity of the feature.

2.3.5 Construction of the RSEDI

Four remote sensing ecological indicators, namely WI, NDVI, NDSI, and LST, were selected to form a four-dimensional space (Figure 2). Here, the minimum values of WI and NDVI and the maximum values of NDSI and LST represented the least desired ecological environment quality. The distance from all pixel points in the space to the worst point of the ecological environment quality was used as the RSEDI to assess the ecological environment quality in the study area [16]. The value of the RSEDI was proportional to the ecological environment quality.

$$RSEDI = \sqrt{\begin{array}{l}(WI - WI_{min})^2 + (NDVI - NDVI_{min})^2 \\ + (NDSI - NDSI_{max})^2 + (LST - LST_{max})^2\end{array}}. \quad (8)$$

In equation (8), WI_{min} and $NDVI_{min}$ are the minimum values of the humidity index and the NDVI in the study area, respectively, $NDSI_{max}$ and LST_{max} represent the maximum values of the dryness index and surface temperature, respectively. The calculated RSEDI was normalized to [0, 1] according to a 99.5% confidence interval, after which the RSEDI was classified into five ecological environmental quality classes based on the equal spacing

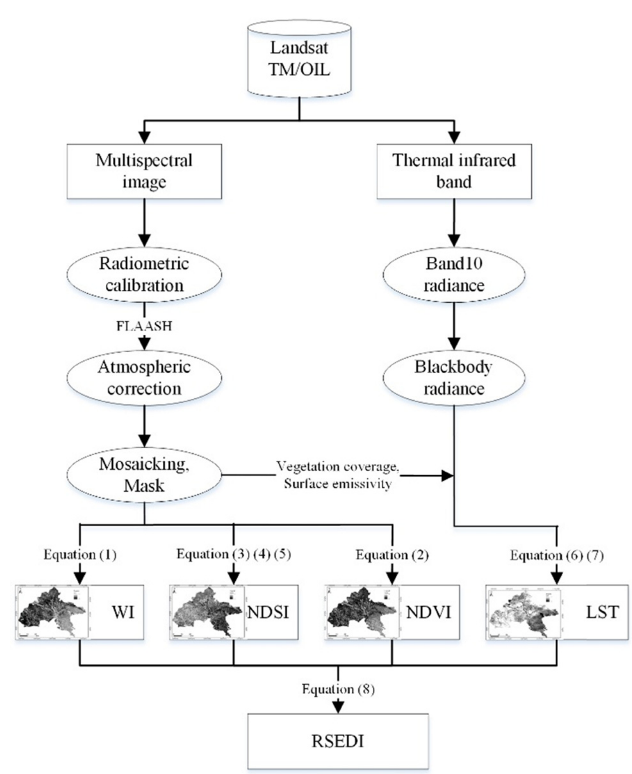

Figure 2: Technique flow chart.

method: (1) poor (0.0–0.2), (2) fair (0.2–0.4), (3) moderate (0.4–0.6), (4) good (0.6–0.8), and (5) excellent (0.8–1.0).

3 Results

3.1 Overall evaluation of ecological environment quality of Yuyang district

Table 1 shows the mean values of each indicator and RSEDI in Yuyang district of Yulin city for 1993, 2004, and 2018. The trends of each indicator show that the mean LST decreased between 1993 and 2018, indicating a decreasing trend in heat in the study area. However, the rate of decrease during 2004–2018 was significantly lower than that during 1993–2004. Both the NDVI and WI showed increasing trends and larger increases during 1993–2018, indicating that the vegetation cover and soil moisture in Yuyang district have increased. The ecological environment quality of Yuyang district improved significantly from 1993 to 2018, with the mean RSEDI increasing from 0.27 in 1993 to 0.33 in 2004 and further to 0.42 in 2018, an overall increase of 55.03%. Considered together, the ecological environment quality of Yuyang district showed an overall upward trend during the 25 year study period.

3.2 Spatiotemporal distribution of ecological environment quality

The present study graded the RSEDI values according to the equal interval method using an interval of 0.2. The RSEDI values were assigned to five grades from high to low: (1) excellent, (2) good, (3) medium, (4) fair, and (5) poor. Figure 3 shows the spatiotemporal distribution of RSEDI in Yuyang district in 1993, 2004, and 2018, and Table 2 shows the percentages corresponding to each grade. The ecological environment of Yuyang district generally showed a spatial distribution pattern of the ecological environment quality decreasing from the east to the west. Areas with an excellent ecological environment quality in the study area from 1993 to 2018 showed a V-shaped change in the ecological environment quality over time, whereas those with a good ecological environment quality experienced an almost constant ecological environment quality during 1993–2004, following which the ecological environment quality increased dramatically during 2004–2018 from 2.65 to 14.07%. Areas with a medium ecological environment quality showed a continuous upward trend in the ecological environment quality from 10.89% in 1993 to 30.03% in 2018. The regions with fair ecological environment quality showed an inverted V-shaped change in the ecological environment quality. Regions with a poor ecological environment quality showed significant decreasing trends in the ecological environment quality and accounted for 39.63 and 8.03% of the total land area in 1993 and 2018, respectively, a decrease of 31.60%. Overall, the ecological environment quality of Yuyang district from 1993 to 2018 showed an increasing trend, and the proportions of areas with excellent and good grades in the study area continued to increase from 4.30% in 1993 to 16.62% in 2018. The areas with poor and fair ecological environment qualities continued to decrease from 84.81% in 1993 to 53.36% in 2018.

Table 1 : Average values of the RSEDI and indicators in Yuyang district, Shaanxi Province, China in 1993, 2004, and 2018

Year	Index				
	LST	NDSI	NDVI	WI	RSEDI
1993	0.85	0.52	0.18	0.27	0.27
2004	0.76	0.42	0.23	0.39	0.33
2018	0.75	0.40	0.35	0.50	0.42

3.3 Spatiotemporal evolution of ecological environment quality

This study used the difference method to detect changes in the RSDEI in Yuyang district in 1993 and 2018 to identify the spatiotemporal changes to the ecological environment quality in Yuyang district from 1993 to 2018. The areas experiencing change were classified into five classes: (1) drastically degraded (≤−2), (2) mildly degraded (−1), (3) largely unchanged (0), (4) mildly improved (1), and (5) drastically improved (≥2). Figure 4 and Table 3 show the areas of the different classes as a proportion of total area. As shown in Table 3, the area of improved ecological environment quality between 1993 and 2018 accounted for 63.81% of Yuyang district. Over the 25 year study period, the ecological environment quality in Yuyang district mainly improved or remained unchanged. Of the total area of Yuyang district, 31.75, 48.29, and 15.52% fell into the largely unchanged, mildly improved, and drastically improved

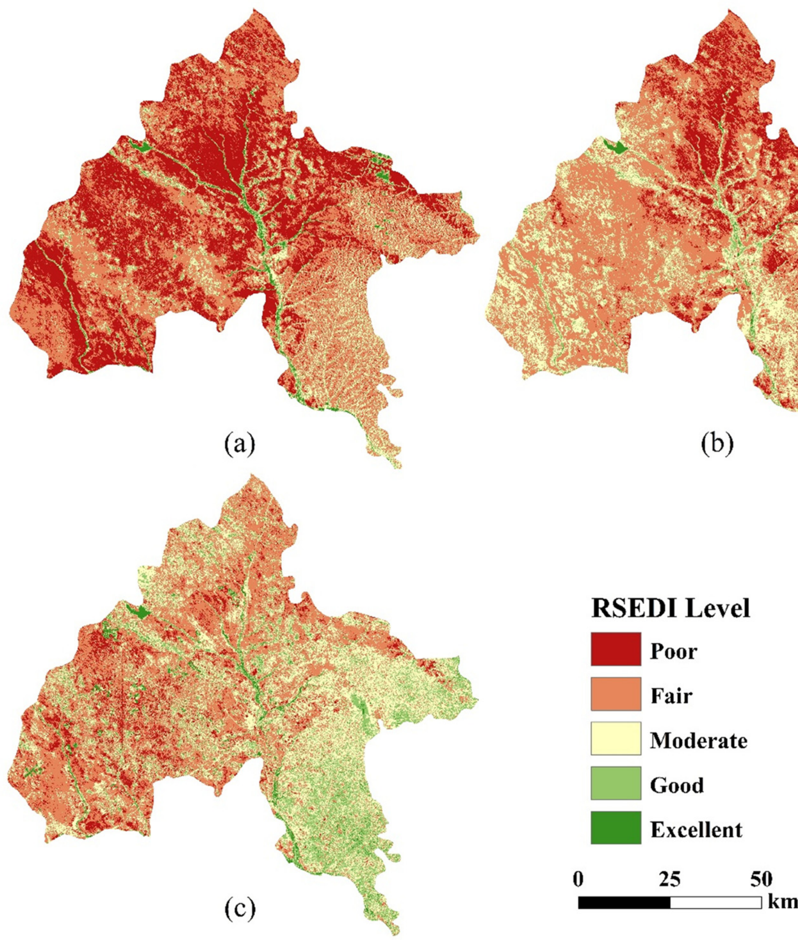

Figure 3: Spatiotemporal distribution of ecological environment quality in Yuyang district, China. (a) 1993, (b) 2004, and (c) 2018.

classes, respectively. The area showing a degraded ecological environment quality in Yuyang district was relatively small, accounting for only 4.44% of the total area. As shown in Figure 4, areas showing an improved ecological environment quality in Yuyang district had a scattered distribution. Areas falling into the largely unchanged class showed a scattered distribution in the western part of the study area.

Table 2 : Proportions of total land area (%) of Yuyang district, Shaanxi Province, China showing different grades of RSEDI from 1993 to 2018

Level	Grading standards	Percentage		
		1993	2004	2018
Poor	[0.0, 0.2]	39.63	15.93	8.03
Fair	(0.2, 0.4]	45.18	57.02	45.33
Moderate	(0.4, 0.6]	10.89	23.96	30.03
Good	(0.6, 0.8]	2.79	2.65	14.07
Excellent	(0.8, 1.0]	1.51	0.44	2.55

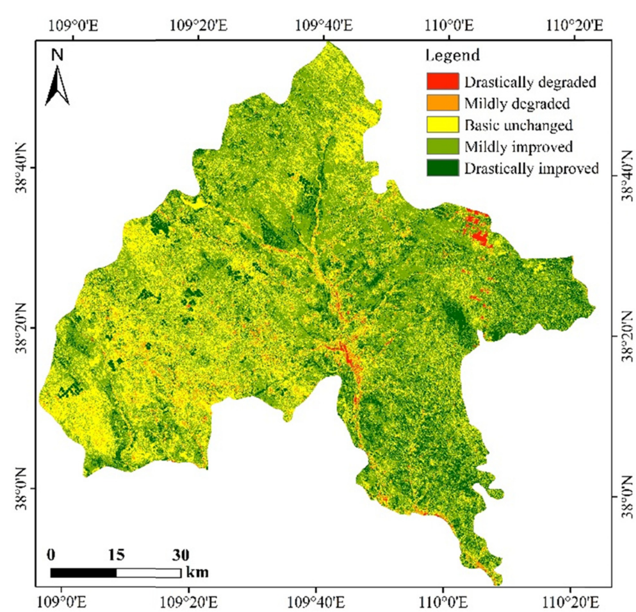

Figure 4: Spatial distribution in changes to ecological environment quality in Yuyang district, Shaanxi Province, China from 1993 to 2018.

Table 3 : Percentage change in RSEDI in Yuyang district, Shaanxi Province, China from 1993 to 2018

Type	Level	Variation type	Level percent
Degraded	≤−2	Drastically degraded	0.79
	−1	Mildly degraded	3.65
Unchanged	0	Basic unchanged	31.75
Improved	1	Mildly improved	48.29
	≥2	Drastically improved	15.52

Areas showing a degraded ecological environment quality were mainly distributed in urban areas and in the western and northeastern parts, distributed in a strip, point, and block pattern, respectively. The spatiotemporal change in the ecological environment quality in Yuyang district during 1993–2018 generally showed a declining trend in urban areas and an increasing trend in the surrounding areas.

3.4 Responsive relationship between ecological environment quality and land use type

Figure 5 shows the spatial distribution of land use types in Yuyang district. Superposition analysis was used to identify the RSEDI of different land use types in Yuyang district in 2018 (Table 4). The results showed that the land use types in Yuyang district are mainly grassland, cropland, and bare land, accounting for 62.56, 19.91, and 12.44% of the area of Yuyang district, respectively, among which grassland was spread all over Yuyang district and cropland and bare land were distributed between grassland in blocks. There was clear variability in the RSEDI among different land use types. Water and wetland were the two land use types with the highest ecological environment quality in the study area, with RSEDI values of 0.91 and 0.70, falling in the excellent and good ecological grades, respectively. Cropland, woodland, and grassland followed with RSEDI values of 0.55, 0.53, and 0.50, respectively, and all falling in the medium ecological grade. Built-up land and bare land showed the lowest RSEDI values of 0.37 and 0.26, respectively.

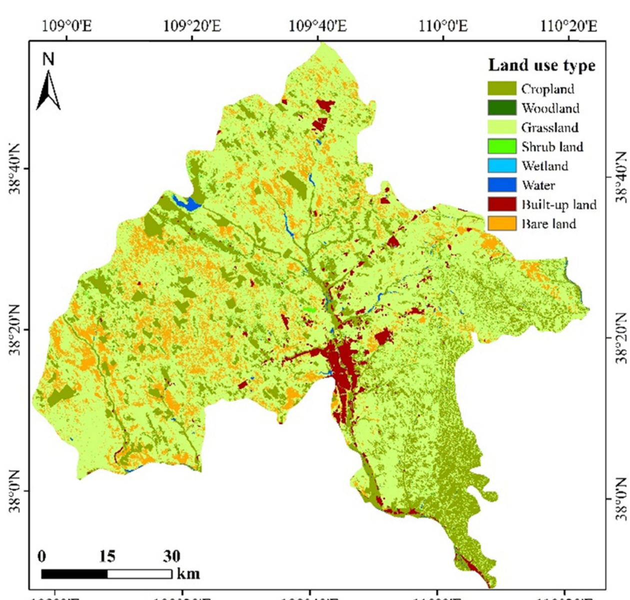

Figure 5: Spatial distribution of land use types in Yuyang district, Shaanxi Province, China.

Table 4 : RSEDI of different land use types in Yuyang district, Shaanxi Province, China in 2018

Land use type	Area (km^2)	Percent	RSEDI	Ecological rating
Cropland	1402.44	19.91	0.55	Moderate
Woodland	20.22	0.29	0.53	Moderate
Grassland	4406.12	62.56	0.41	Moderate
Shrub land	98.50	1.40	0.50	Moderate
Wetland	0.69	0.01	0.70	Good
Water	32.16	0.46	0.91	Excellent
Built-up land	206.68	2.93	0.37	Fair
Bare land	875.87	12.44	0.26	Fair

3.5 Responsive relationship between ecological environment quality and hydrothermal conditions

Figure 6 shows the annual rainfall and average annual temperature of Yuyang district from 1991 to 2018. As shown in Figure 5, there was an increasing trend in the average temperature during the study period, with a rate of 0.0434°C/a, indicating a pronounced warming trend in Yuyang district. The study area showing a fluctuating increasing trend in annual rainfall at a rate of 9.213 mm/a, indicating a rising trend in air humidity in Yuyang district from 1991 to 2018.

4 Discussion

The present study exploring the factors influencing the ecological environment quality in Yuyang district. The results showed that climate change is resulting in trends of increasing temperature and rainfall in Yuyang district, consistent with the results of other studies [26,27]. Water

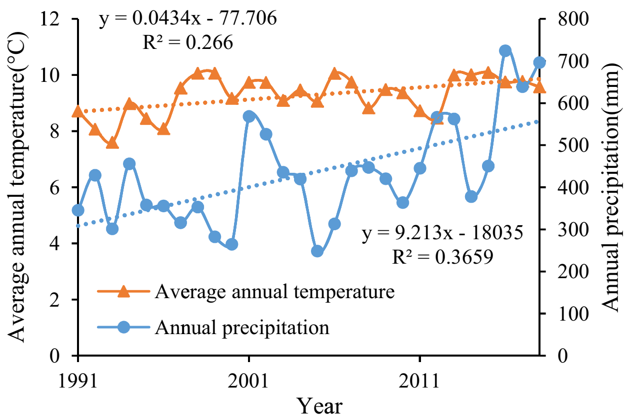

Figure 6: Variations in annual rainfall and temperature in Yuyang district, Shaanxi Province, China from 1991 to 2018.

and heat conditions are the two most important natural conditions for promoting the vegetation growth and vegetation cover, thereby improving the quality of the local ecological environment. Therefore, water and heat conditions play an important role in the process of improving the ecological environment in Yuyang district. However, significant variability in the trends of the heat and dryness indices, as indicators of temperature and rainfall, respectively, was evident in the study area. The heat and dryness indices continued to decline despite rising temperature and rainfall. This result indicates the existence of other factors contributing to the trends in the heat and dryness indices.

There is an obvious correlation between the ecological environment index and land use types in Yuyang district, with the two factors showing coinciding spatial distributions. This result indicates that the greenness and dryness indices contribute the most to the evaluation of the ecological environment quality, consistent with the findings of Wang and Dai [28]. The effects of changes in land use type on the ecological environment quality can be both positive or negative, with water bodies, wetland, woodland, grassland, and shrubland contributing to an increased ecological environment quality. Therefore, these land use types can be collectively called "ecological land." An increase in the vegetation cover has a positive effect on the ecological environment quality. Built-up land and bare land decrease the ecological environment quality. These results are consistent with those of Qiu [29].

The "Land-to-Household" policy implemented in China in 1983 greatly encouraged the reclaiming of arable land by local people and ultimately resulted in the areas of cropland and bare land increasing and decreasing, respectively, between 1980 and 1998 [30]. The policy "Taking Farmland Returning to Forest or Grassland" was implemented in 1998. Yuyang district took the lead in implementing the pilot project of "Return Cropland to Woodland," resulting in 1.11 m mu of other land use types being converted to woodland between 1999 to 2008, including 272,300 mu of cropland, 827,700 mu of bare land suitable for afforestation, and 10,000 mu of mountain area. The area of afforestation and conservation over the entire district reached 4.517 m mu, including 374,000 mu of arbor woodland and 121,000 mu of economic woodland [31]. The area of bare land continued to decrease from 1999 to 2018, thereby explaining the difference between the heat index and dryness index and hydrothermal conditions. The increase in woodland area and the trends of increasing temperature and rainfall explain the increasing greenness and humidity indices. The above analysis confirms that the implementation of ecological projects in China has promoted changes in land use types, thereby improving the ecological environment quality in Yuyang district, Yulin city.

The evaluation of the ecological environment is currently a popular research topic. The dynamic monitoring of the ecological environment based on long-term remote sensing data provides a new platform and perspective for regional ecological environment evaluation [32,33]. The present study used the humidity (WI), dryness (NDSI), greenness (NDVI), and heat (LST) indices to represent ecological environment quality of Yuyang district. The minimum values of the WI and NDVI and the maximum values of sandiness and salinity were taken to represent the least desirable ecological environment quality in the study area to construct the RSEDI. The RSEDI was then used to monitor the ecological environment quality. The results showed an increasing trend in the ecological environment quality of Yuyang district from 1993 to 2018, mainly influenced by the combination of national reforestation, wind and sand control, and other ecological projects and changes in hydrothermal conditions, consistent with the results of existing related studies [34–36]. However, the present study only analyzed changes in land use types and hydrothermal conditions relating to changes in the ecological and environmental quality. Other factors contribute to changes to environmental quality, such as population changes and industrial structure. Future research on the ecological and environment quality changes should integrate natural conditions and social and economic factors.

5 Conclusions

The present study constructed the RSEDI by integrating various indicators to enhance its applicability and to simplify the calculation method. The spatiotemporal evolution of the ecological environment quality of Yuyang district from 1993 to 2018 was quantitatively and objectively analyzed. The driving forces behind the spatiotemporal evolution of the ecological environment quality were also described from two perspectives, namely water and heat conditions and ecological policies implemented in China. The result showed that the ecological environment quality in Yuyang district from 1993 to 2018 fell in the fair or moderate categories and showed an improving trend over time. The evolution of the ecological environment quality of Yuyang district is the result of the combined effects of changes in water and heat conditions and implementation of ecological policies in China, with the latter being the dominant driving force. Urbanization had negative impacts on the ecological environment of Yuyang district, whereas the increase in rainfall and implementation of ecological policies had positive impacts on the ecological environment. Therefore, future restoration of the ecological environment of Yuyang district should focus on implementation of ecological policies and further greening of the city. These approaches can increase vegetation coverage and control the speed of expansion and development of built-up area.

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