RESEARCH ARTICLE

Impacts of water surge from mountain railroad tunnels on ecological environments based on the RSEI model

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Abstract

Tunnels play a significant role in mountain railroad routes and increase the efficiency of railroad traffic. However, water surge from tunnels can seriously impact the ecological environment during the construction period. This study selected a typical mountain railroad tunnel in southwest China and used the remote sensing ecological index (RSEI) to evaluate the changes in the ecological environment along the tunnel surge water path and relate the impacts to the main influencing factors throughout the whole tunnel construction cycle. The following conclusions were obtained: (1) The RSEI from 2005 to 2020 mostly ranged within 0.25–0.75. The most severe ecological disturbances occurred in areas directly affected by tunnel construction and along the water surge path. (2) In addition to affecting the surrounding ecological environment during the construction period, tunnel surge water continued to adversely affect the environment during the post-construction period. (3) In the post-construction period, the areas 300–450 m and 750–850 m from the tunnel exit had the largest changes in RSEI. This study provides scientific evidence to support environmental planning for mountain railroad tunnel construction, which is necessary to achieve both efficient tunnel construction and environmental protection.

Keywords Mountain railroad tunnels · Water surge · Ecological environment · Vegetation cover · Spatial and temporal evolution · Ecological restoration

Introduction

With the rapid development of global transportation and communication, there is an increasing demand for infrastructure projects such as railroads in many developing countries and regions (Ai et al. 2014; Hodgson 2018; Pang et al. 2023). As a common large-scale accessory project during mountain railroad construction, tunnels can greatly improve railroad traffic efficiency (Xiao et al. 2019). They play important roles in improving route alignment, shortening track length, and increasing the operational efficiencies of railroads (Komu et al. 2020). However, mountain tunnels are commonly constructed in areas with poor geological structures and hydrological conditions, where groundwater resources are particularly plentiful. The complexity of the construction environment and technical limitations of the tunneling operation will inevitably change the flow of groundwater resources during the boring process (Amaranthus et al. 1985; Said et al. 2019; Pang et al. 2023). Therefore, problems due to underground water surge during tunneling are common (Sharifzadeh et al. 2013; Li et al. 2018). Water surge not only increases the difficulty and hazards associated with the tunnel construction itself but can also disturb and damage the local natural environment at the tunnel construction site (Li et al. 2012; Qiu et al. 2020; Li et al. 2021). Tunnel problems are not conducive to the coordinated and sustainable development of railroad tunnels and

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ecological environmental protection. The hazards caused by water surge in tunnels have caused concern worldwide.

Recently, studies on the impacts of water surge in tunnels have been relatively fruitful. Scholars have studied the impact of tunnel water surge on the engineered tunnel structures themselves as well as the ecological environment around the tunnel. This is important because, due to uncertainties during construction and the complexity of the strata, compared to the effects caused by hydrostatic pressure, the local water dynamics that influence tunnel water can produce very large pressures (Chen et al. 2021b). Focusing on physical structures, the force of tunnel water not only affects the construction of the tunnel but can also have a continuous impact on the operation and maintenance of tunnels (Kang et al. 2019). Furthermore, water surge will also affect soil wetness, penetrating to a certain range into the surrounding soil and rock (Muxart et al. 1995; Lai et al. 2017; Wang et al. 2020b). Therefore, on the one hand, water pressure can act directly on the surrounding rock, increasing the load of the tunnel structure. On the other hand, water can penetrate into the surrounding rock and damage the soil structure, potentially leading to deformations in the overall tunnel structure (Li et al. 2019). Through the joint action of these two mechanisms, water surge can easily damage mountain tunnels (Zhang et al. 2012; Hou et al. 2015; Zhang et al. 2021). In addition, preexisting underground facilities and infrastructure can be impacted by tunnel excavation. For example, sewage pipes can be ruptured during tunnel excavation, so the water surge discharge can carry large amounts of sewage (Hou et al. 2015; David et al. 2018).

Like the tunnel structure and maintenance, high tunnel water flows will also continuously impact the ecological environment of the surrounding area, including the water environment, vegetation environment, and biological habitat environment (Taylor and Dykstra 2005; Wang et al. 2022). In terms of the water environment, tunnel excavation will disturb the original hydrological balance, destroy parts of the groundwater recharge, runoff, and drainage systems, and lower the local groundwater level in both the short and long terms. This can result in wasted water resources, local depletion of water resources, and water deficits for domestic, industrial, and agricultural use (Jin et al. 2012; Qingqing et al. 2014; Ding et al. 2021). Therefore, many scholars have attempted to predict how tunnel water surge will affect the groundwater environment using groundwater modeling and simulation techniques before tunnel excavation begins (Chiu and Chia 2012; Xiao et al. 2019; Chen et al. 2021a). This can provide effective strategies for anticipating and reducing the impacts of tunnel water surge on water resources. Preset drainages, sludge sedimentation and retardation ponds, and wastewater treatment facilities can all partially mitigate the impacts of tunnel water surge on the water environment (Zhang and Franklin 1993).

Furthermore, many studies have shown that natural vegetation growth and the moisture and salinity of soil are closely related to groundwater depth (Ma 1997; Zhang et al. 2022). It will also affect the water level, the depth of groundwater, groundwater mineralized degree, suspended moisture content and salt content, etc. Natural vegetation ecosystem mostly depended on groundwater. The research results showed that groundwater level directly influenced vegetation's growth and its variety; these phenomena depended on the changeable of soil water content (Xu 2019; Zhu et al. 2020). When groundwater level was above 3.5 m, it influenced surface soil water content through evaporation and capillary action, and the proportion of vegetation coverage and species was vividly high; when groundwater level was below 4.0 m, it can hardly effected surface soil water, so herbaceous vegetation disappeared gradually. When groundwater was lower than 5.0 m, most trees and shrubs died from lack of water, then vegetation species tended to be simple, the vegetation coverage would decrease, and the trees growth appeared downfall. Therefore, after a large amount of water is discharged and the groundwater level decreases, the soil water content can be reduced, and there may even be a water shortage, increasing the distance between the plant root and groundwater depths. This will reduce the ability of groundwater to supply moisture to vegetation, which can severely affect the growth and survival of numerous species. When the hydrology of a region is out of balance, the ecological balance is also disrupted. Regional water storage contributes to the reproduction and growth of phytoplankton (Guo et al. 2021; Zhang et al. 2020a). The growth of phytoplankton is significantly reduced in watersheds with reduced water compared to other regions, and the growth of bait organisms also receives an impact. In addition, the water from some mountain tunnels can be high-temperature, influenced by geological conditions (Osborne et al. 2004; Xia et al. 2022). This can further increase the impact of surge water on vegetation and natural ecosystems (Cheng et al. 2011; Yuan et al. 2019).

The above research results on the impact of tunnel water influx are very fruitful. Some scholars have used simulation techniques such as groundwater modeling to predict the impact of tunnel water influx on the groundwater environment. These research results do reduce the environmental damage to some extent. However, most simulation-based studies have been conducted under various assumptions in simplified environments, while in the actual tunnel construction process, adverse and complex geological and hydrological conditions are common. This makes it difficult to predict sudden water surges with complete accuracy and limits the strategies available to circumvent the effects of water surge. Other scholars have addressed the impact of tunnel water surges on a single aspect of the environment. There is an abundance of related studies, but they rarely represent the

overall impact of water surge on the surface environment. In general, there are few studies on the impacts of tunnel gushing water on the surface environment flowing along the route after gushing, and the impacts of tunnel gushing water on the surrounding environment are obvious, and few have examined the whole tunnel construction cycle (pre-construction, construction period, and post-construction) to make a comparative analysis of ecological environment disturbance from tunnel water surge. The shortage of research in this part of the study does not allow us to have a more comprehensive understanding of the environmental impacts of water surges in tunnels. Therefore, there is an urgent need to carry out research.

Recently, satellite remote sensing has become one of the most effective and important methods for monitoring and assessing regional environmental changes and as such has been applied to evaluate certain ecological indicators of the impacts of water surge (Xiong et al. 2021). Remote sensing can measure changes in radiation that reflect the characteristics of ground targets which, when processed, can simplify and comprehensively express different aspects of complex ecological environments (Piao et al. 2011; Garg et al. 2020; Chaudhary et al. 2022). These indicators include the NDVI, used to investigate changes in vegetation; land surface temperature, used to characterize the urban heat island effect; and land surface moisture, used to characterize the response of local climates to environmental changes. However, these indices are each specifically suited to explain specific ecological characteristics and cannot comprehensively, accurately, and objectively evaluate changes in complex ecological environments (Hang et al. 2020; Zhang et al. 2020b). The remote sensing-based ecological index (RSEI) is a novel remote sensing comprehensive ecological index that considers indicators of greenness, heat, dryness, and humidity in natural environments (Xu et al. 2019). RSEI is widely used in various ecological investigations and studies, such as environmental salinization (Chen et al. 2023; Xia et al. 2022) and environmental changes around lakes (Xiong et al. 2021). It can objectively and quantitatively evaluate the regional ecological quality, generalize the environmental situation at different periods, and intuitively and spatially analyze regional ecological evolution, which meets the needs for comprehensive assessments of ecological environments in long-term series (Xu et al. 2018; Hu and Xu 2019).

To assess the full impact of tunnel water surge on the surface environment, a comprehensive indicator that can encompass the full construction cycle study period of the case study tunnel should be selected. Furthermore, we should not restrict our investigation to the disturbance factors that directly affect the ecological environment, such as the water environment, vegetation, and temperature. Studies should include the impact of tunnel construction on the environment, as well as factors that are affected by water surge at the treatment site. Therefore, this study selected a tunnel with frequent water surge in the karst region of southwest China as a case study. To meet the established analytical requirements, the RSEI was used as the response index to assess the ecological environment of the tunnel surge area. This approach visualized the direct and indirect effects of tunnel water surge on the surface ecological environment. It also allowed for a better understanding of the impact of tunnel water surge on the overall surface ecology throughout all tunnel construction periods.

This study provides a valuable overall assessment of the ecological impact of tunnel water surge. It analyzes the spatial and temporal changes in the RSEI along the buffer zone of the water flow of the case study tunnel during the entire construction cycle (pre-construction, construction period and post-construction). Moreover, this paper analyzes the influencing factors that cause changes in RSEI in order to distinguish the effects of water surges in different periods during tunnel construction. This paper provides an accurate and effective method to study the ecological environment changes in the whole life cycle and provides a reference for enriching the theory of green management of tunnel surge water. It is hoped that the conclusions of this paper provide a valuable reference for future research regarding the impact of water surge on ecological environments surrounding railway tunnels in mountainous areas. And the results will have a profound and positive impact on improving the harmony between tunnel construction and environmental protection.

The rest of the article is organized as follows: the "Methodology" section introduces the study framework, the study area, methodology, and data sources. The results are presented in the "Results" section. The results of this study are discussed and analyzed in the "Discussion" section, at which point the limitations of this study are introduced. Finally, the "Conclusions and suggestions" section presents the conclusions of this study and gives feasible suggestions for mitigating the effects of water surge during tunnel construction.

Methodology

Research framework

This study assesses the impact of water surge during mountain railway tunnel construction on the surrounding ecological environment. In order to simultaneously consider the high-temperature properties of tunnel water, the changes in soil moisture content, vegetation growth, and the changes in land use around tunnel site and other construction lands, this study used the RSEI model to monitor changes in the ecological environment of the area along the water flow path from the case study tunnel (Fig. 1).
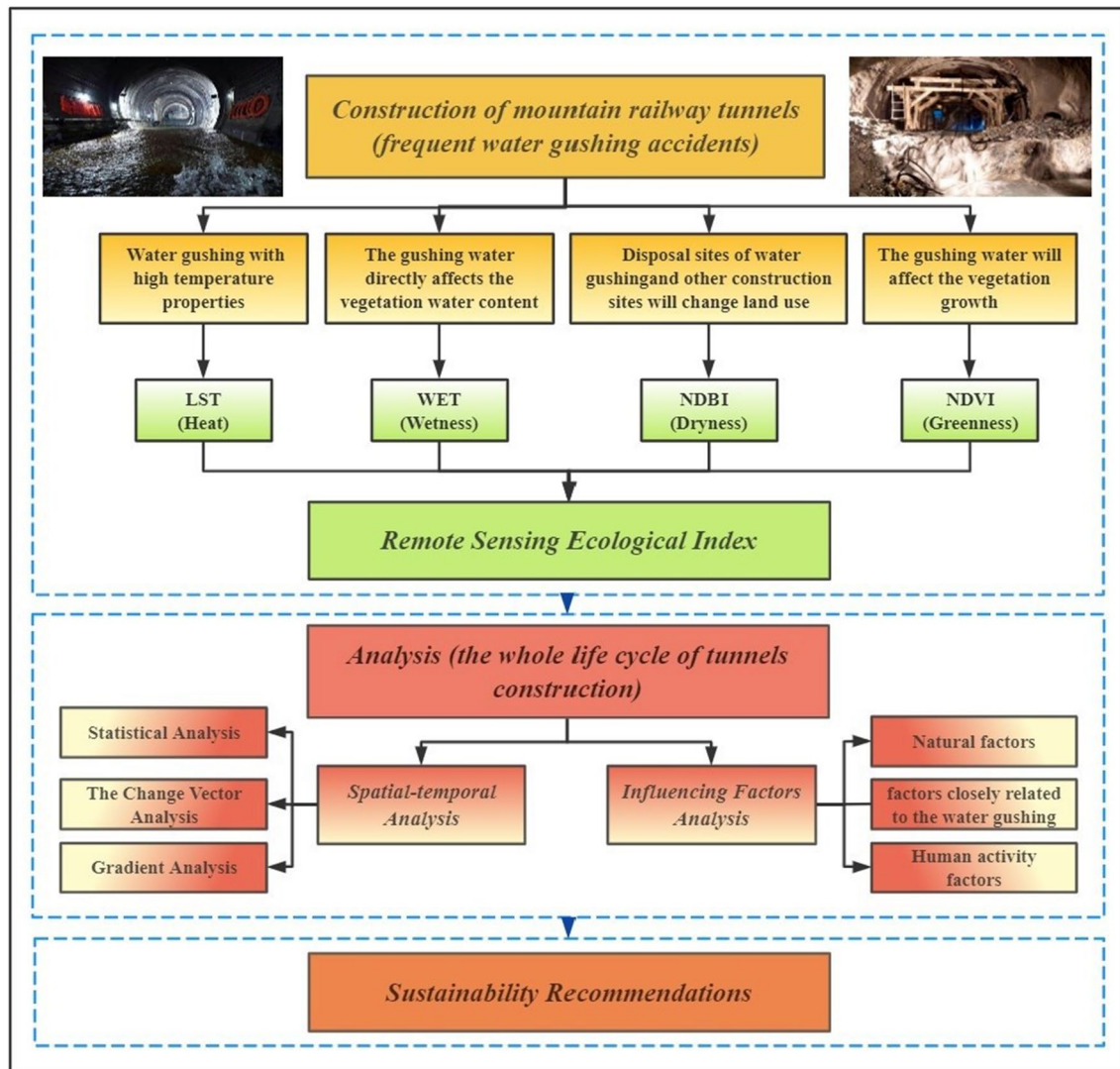
Fig. 1 Research framework

The research objectives of this study were as follows: (1) analyze the spatial and temporal changes in the RSEI along the buffer zone of the water flow of the case study tunnel during the entire construction cycle (pre-construction, construction period, and post-construction) and (2) analyze the factors influencing the RSEI of the buffer zone of the water path from the case study tunnel throughout the construction cycle (pre-construction, construction period, and post-construction).

Study area

The case study tunnel (Fig. 2) is in Baoshan City, Yunnan Province, China, at 99° 18′ E and 25° 12′ N in a low-latitude, high-altitude karst region with highly undulating terrain. Groundwater sources are plentiful, and the distribution of aquifers is relatively complex. The average annual temperature is about 15.8°C and the average annual rainfall is 1092 mm. Tunnel elevation is about 1700 m. And the longitudinal slope of the tunnel is designed as double spur grade, which means that the elevation will affect the direction of water flow to a certain extent when water surges in the tunnel.

Dazhu Mountain Tunnel traverses a total of 6 geological fracture zones, and water surges occur frequently. Among them, the first water surge occurred on August 5, 2009, when the tunnel boring through the Yanziwuo fracture zone, located in the tunnel flat guide PDK111+860-947 section. The surge was extremely high, with a flow of about 5,300 cubic meters at final stabilization, and an average surge of about 950 cubic meters per hour, with a maximum of 12,180 cubic meters per hour. The construction could only continue to advance after utilizing the accumulation of materials to close the solidified exit and carry out grouting; the
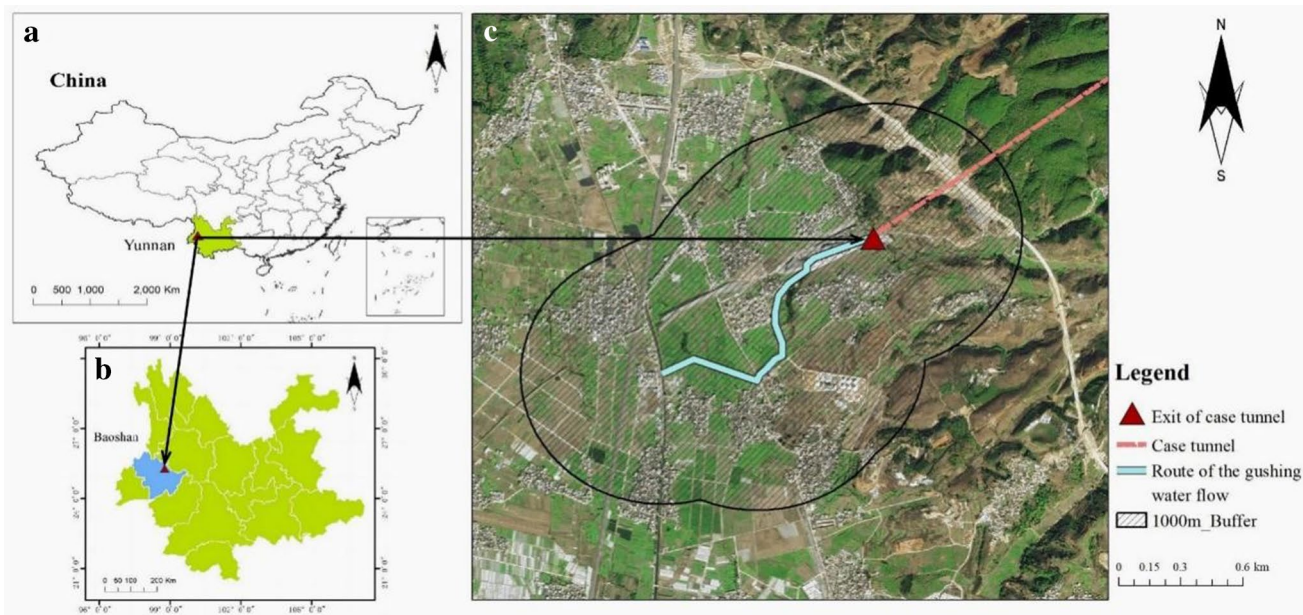
Fig. 2 Study area

surge of water occurred again when the construction reached YHK0+092; and the surge of water occurred again when the construction reached YHK0+083 in the meandering guide pit (Yan et al. 2009). Since then, along with the construction of the tunnel digging, water surge occurs constantly, and the construction has been blocked many times and has built seven pumping stations. The maximum recorded water surge rate on the back slope section of the tunnel after excavation was 802,546 m^3/day. The maximum recorded discharge in a single day was 220,000 m^3. The environmental pressure in the area around the tunnel was considered high.

During the actual construction, due to the geological condition of terrestrial heat and heat dissipation from electric heating equipment, the ambient temperature inside the cave ranged from 34 to 45°C. High-temperature water can have a large impact on vegetation growth (Du and Gao 2017). At the case study site, sensitive areas were concentrated around the tunnel exit, so this paper selected the tunnel exit for close examination. Some studies have shown that the radius of the impact area of water surge due to tunnel construction ranges within 520–643 m (Jin et al. 2016). Therefore, in this paper, we selected 500 m, 1000 m, and 1500 m buffer zone along the flow path.

Data

Data sources

This study used remote sensing images from the Landsat 5-TM and Landsat 8-OLI datasets acquired from the US Geological Survey (USGS) (http://earthexplorer.usgs.gov/) from 2005 to 2020 to calculate RSEI. Of the factors that influenced water flow, terrain-related data such as DEM, slope, and slope direction were obtained from USGS (https://www.nasa.gov/), and the data of type of land use were obtained from the Resource and Environmental Science and Data Center of the National Academy of Sciences of China (https://www.resdc.cn/). The data such as distance to water system, distance to administrative district, distance to tunnel exit, and distance to road were calculated using the Euclidean distance from ArcGIS.

Data processing

To reduce the influence of cloudiness on data, the remote sensing images were screened for those with less than 10% cloudiness. To avoid uncertainty caused by seasonal differences and ensure the similar growth states of vegetation and comparability of ecological observations, images in November and December were selected. The maximum difference did not exceed 1 month. Because the remote sensing images of 2007 had extremely high cloud coverage and did not meet the criteria of this paper, images from 2006 were used as substitutes. The selected remote sensing images are described in detail in Table 1.

Based on the actual construction process and the time of the first water influx (2009), we classify the period before 2009 as the pre-construction period, the period from 2009 to 2019 as the construction period because the tunnel is basically open after 2019, and the period after 2020 as the

Table 1 Description of remote sensing image data

Satellite	Year	Sensor	Satellite	Year	Sensor
Landsat 5	2005.11.13	TM	Landsat 8	2013.11.19	OLI
	2006.11.16			2015.12.27	
	2009.12.10			2017.12.16	
	2011.10.29			2019.12.22	
				2020.12.08	

post-construction period. Given the availability of images of the tunnel area, the years 2005 and 2006 were classified as the pre-construction period; 2009, 2011, 2013, 2015, 2017, and 2019 as the construction period; and 2020 as the post-construction period.

All datasets were subjected to a series of pre-processing steps (geometric correction, radiometric calibration, atmospheric correction, and image cropping). Due to the discrepancies among sources and spatial resolutions, the data were resampled based on the nearest neighbor method to conduct the influential factor study. The uniform resolution was 30 m and the uniform projection was WGS_1984_UTM_Zone_48N.

After water exits the tunnel, its flow direction will not only be affected by the elevation, slope, slope direction, and other natural factors of the area; human activities will also affect its direction, flow rate, and spread. Therefore, the actual flow situation of the case tunnel study area was established from previously published studies. In this paper, based on the natural elements and man-made elements, we selected eight influential factors. These factors are directly related or indirectly related to the water surge. The driving force indicator system constructed in this paper is shown in Table 2. Separately, each driving factor was discretized.

Referring to the practice of Cao et al. (2013), the influential factors were discretized. In this paper, the equal interval method was selected to discretize the distance to the water system, the distance to the administrative area, the distance to the highway, and the distance to the tunnel exit and then divide them into five sectors separately. The digital elevation model (DEM) with 30-m resolution was discretized using the equipartition method and divided into five sectors. The slopes of the study area were divided into three sectors according to the objective criteria wherein 0–5° was flat,

5–15° was gentle, and 15–25° was sloped. According to the objective standard, 23–67° was northeast, 68–112° was east, 113–157° was southeast, 158–202° was south, 203–247° was southwest, 248–292° was west, 293–337° was northwest, and 338–22° was north, so the direction aspect was divided into eight sectors making a full circle. Land use type was divided into 12 sectors according to the actual situation of the study area. The specific classification is shown in Table 3.

Models

RSEI

In recent years, remote sensing technology has been increasingly applied to ecological environment monitoring and evaluation by virtue of its advantages of real-time monitoring of the environment over a wide range, a long period of time, and in all weather conditions. However, most of the studies are based on a single indicator for monitoring and evaluation, while the ecosystem is a comprehensive expression of multiple elements and their functional structures in time and space scales. The remote sensing ecological index (RSEI) is based on remote sensing technology, and the indicators are easily accessible, avoiding artificial weight setting and visualizing the results.

RSEI can objectively and intuitively evaluate the regional ecological environment, which is essentially a comprehensive evaluation index obtained by integrating four important ecological indicators (greenness, wetness, dryness, and heat) representing the advantages and disadvantages of the ecological environment through the principal component analysis (PCA) method. Meanwhile, the long time series of remote sensing data provides us with the possibility to study the changes of ecological environment in various periods during the whole life cycle of tunnel construction.

Among them, the greenness index is commonly represented by the normalized difference vegetation index (NDVI). NDVI is the most widely used vegetation index. It is commonly used to monitor plant growth and eco-environments. It reflects the natural attributes of the area and the degree of greenery; wetness, WET, reflects changes in water content, which is directly affected by tunnel water surge; dryness, the normalized building index, reflects anthropogenic activity. Human activity is

Table 2 Driving force index system

Indicator type	Indicator name	Unit	Indicator type	Indicator name	Unit
Natural factor	DEM	m	Human activity factor	Distance to administrative district	km
	Slope	°		Distance to road	km
	Slope direction	°		Distance to tunnel exit	km
	Distance to water system	km		Type of land use	-

Table 3 Classification criteria of land use types

Primary classification	Primary land use classification type	Secondary classification	Secondary land use classification type
1	Cultivated land	11	Paddy field
		12	Dry land
2	Woodland	21	Forested land
		22	Shrub land
		23	Sparse forest land
		24	Other forest land
3	Grassland	31	High coverage grassland
		32	Medium coverage grassland
		33	Low coverage grassland
4	Urban and rural land, industrial and mining land, residential land	41	Urban
		42	Rural settlements
		43	Industrial and transportation construction land

high during tunnel construction. Construction requires clearing areas, resulting in large areas of bare soil. Furthermore, bare soil increases "dryness"; heat, LST, is the land surface temperature. Temperatures are variable due to the complex mountain terrain. Furthermore, tunnel water has high-temperature properties. The atmospheric correction method was used

Table 4 Equations and descriptions of WET, NDVI, LST, and NDBI

Index	Equation	Description
WET	$\rho_{WET-TM} = 0.0315\rho_{BLUE} + 0.20.21\rho_{GREEN} + 0.3012\rho_{RED} + 0.1594\rho_{NIR} - 0.806\rho_{SWIR1}$ $\rho_{WET-OLI} = 0.1511\rho_{BLUE} + 0.1973\rho_{GREEN} + 0.3283\rho_{RED} + 0.3407\rho_{NIR} + 0.7117\rho_{SWIR1} - 0.4559\rho_{SWIR2}$	$\rho_i (i = 1, ..., 5, 7)$ is the reflectance of each band of TM and OLI
NDVI	$\rho_{NDVI} = (\rho_{NIR} - \rho_{RED})/(\rho_{NIR} + \rho_{RED})$	ρ_{NIR} and ρ_{RED} indicate the reflectance in the near-infrared and red bands, respectively
LST	$\varepsilon_{surface} = 0.962\,5 + 0.061\,4P_v - 0.046\,1P_V^2$ $\varepsilon_{building} = 0.958\,9 + 0.086\,0P_v - 0.067\,1P_V^2$ $P_v = \begin{cases} 0, \text{NDVI} < 0.05 \\ \dfrac{\text{NDVI} - \text{NDVI}_s}{\text{NDVI}_V - \text{NDVI}_s}, \ 0.05 \le \text{NDVI} \le 0.7 \\ 1, \text{NDVI} > 0.7 \end{cases}$ $B(ts) = [L_{6/10} - T_\uparrow - \tau(1-\varepsilon)T_\downarrow]/\tau\varepsilon$ $\text{LST} = {}^{K_2}/_{\ln}[K_1/B(ts) + 1] - 273$ $L_{6/10} = gain \times DN + bias.$	L6/10 is the radiance value of TM band 6 and OLI/TIRS band 10 pixel at the sensor; DN is the pixel gray value, gain is the band gain value, and bias the bias value $\varepsilon_{surface}$ and $\varepsilon_{building}$ are the specific emissivity of natural surface and town area image elements, respectively, and the specific emissivity of water image element takes the value of 0.995, P_v is the degree of vegetation cover, NDVI_S is the NDVI value of non-vegetation-covered area and takes the empirical value of 0.05, and NDVI_V is the NDVI value of purely vegetated image element and takes the empirical value of 0.7: $B(ts)$ is the brightness value of the blackbody radiation, $T_\uparrow$, $T_\downarrow$, and τ are the atmospheric upward and downward radiant brightness and transmittance in the thermal infrared band, respectively. LST is the surface temperature, K_1 and K_2, respectively, are calibration parameters that take values of 607.76 and 1260.56 in the TM image and 774.89 and 1321.08 for OLI/TIRS band 10
NDBI	$\rho_{IBI} = \dfrac{2\rho_{SWIR1}/(\rho_{SWIR1} + \rho_{NIR}) - [\rho_{NIR}/(\rho_{NIR} + \rho_{RED}) + \rho_{GREEN}/(\rho_{GREEN} + \rho_{SWIR1})]}{2\rho_{SWIR1}/(\rho_{SWIR1} + \rho_{NIR}) + [\rho_{NIR}/(\rho_{NIR} + \rho_{RED}) + \rho_{GREEN}/(\rho_{GREEN} + \rho_{SWIR1})]}$ $\rho_{SI} = \dfrac{(\rho_{SWIR1} + \rho_{RED}) - (\rho_{NIR} + \rho_{BLUE})}{(\rho_{SWIR1} + \rho_{RED}) - (\rho_{NIR} + \rho_{BLUE})}$ $\rho_{NDBI} = \dfrac{\rho_{IBI} + \rho_{SI}}{2}$	

ρ_{BLUE}, ρ_{GREEN}, ρ_{RED}, ρ_{NIR}, ρ_{SWIR1}, and ρ_{SWIR2} represent the corresponding bands of Landsat-TM/OLI images

while calculating the LST (Hu and Xu 2019). The formulae for the four component ecological indices are shown in Table 4. The RSEI formula is shown in Eq. (1):

$$\text{RSEI} = f\{\text{WET}, \text{NDVI}, \text{LST}, \text{NDBI}\} \tag{1}$$

The spatial principal component analysis (PCA) transformation was used to couple the above four component indicators. The weights are objectively determined by determining their principal component contributions so that the multi-indicator information can be presented as a single indicator. However, the magnitudes of different indicators can vary, and before the principal component transformation, the magnitudes of each indicator need to be unified and the four indicators need to be normalized. To transform the values of each indicator so that they range between 0 and 1, Eq. (2) is used.

$$\text{RB}_1 = (b_1 - b_{\min})/b_{\max} - b_{\min} \tag{2}$$

where RB_1 is the normalized image element value and b_1, $b_{\min}$, and $b_{\max}$ denote the original, maximum, and minimum values of the image element, respectively.

Each ecological index was synthesized into a single image and then subjected to principal component analysis. The following principal components were constructed: RSEI_1 from PC_1; RSEI_2 from PC_1- and PC_2-weighted summation; RSEI_3 from PC_1-, PC_2-, and PC_3-weighted summation; and RSEI_4 from PC_1-, PC_2-, PC_3-, and PC_4-weighted summation, as shown in Eq. (3):

$$\text{RSEI}_i = \begin{cases} PC_i, \ i = 1 \\ \sum_{i=1}^{j} \beta_i, \ i = 1, 2, 3; \ j = 2, 3, 4 \end{cases} \tag{3}$$

where β_i is the contribution of the ith principal component and PC_i denotes the ith principal component, $i = 1, 2, 3, 4$.

Based on the analysis, the most representative principal component model PC_0 was screened out. Based on PC_0, a representation of RSEI_0 can be calculated using Eq. (4):

$$\begin{aligned} \text{PC}_0 &= [a\text{PC}_1 + b\text{PC}_2 + c\text{PC}_3 + d\text{PC}_4] \\ \text{RSEI}_0 &= 1 - \text{PC}_0 \end{aligned} \tag{4}$$

where PC_0 is the optimal principal component of the four indicators (WET, NDVI, LST, and NDBI); a, b, c, and d represent the contribution of PC_1, PC_2, PC_3, and PC_4 principal components, respectively; and RSEI_0 ranges from 0 to 1. The closer the value is to 1, the better the environmental quality.

Spatial analysis

Change vector analysis The change vector analysis (CVA) method can be used to detect spatial changes in the RSEI values (Chen and Chen 2016). The CVA calculates the change in the RSEI (ΔRSEI) from 1 year to another. The value in the "From-to" change analysis indicates the degree of change in the RSEI from 1 year to another, e.g., a "From-to" value of "23" indicates a change in the RSEI from level 2 (poor) in year 1 to level 3 (moderate) in year 2. The CVA values and the workflow of the "From-to" change analysis are visualized in Fig. 3.

Gradient analysis Gradient analysis methods were originally used to analyze landscape changes from urban to rural areas (Jayalakshmy et al. 2021). In one of the first ecology-related uses, White applied gradient analysis methods to vegetation analysis (White 1985). Subsequently, gradient analysis methods have been widely used in ecological studies. In this study, the more commonly used buffer gradient analysis method was selected. Here, the tunnel exit was taken as the radiation origin, and cross sections were used to divide the circular buffer zone into equal steps (Zhou et al. 2021). These methods help illustrate the distribution law of the research target using the circle layers. Using the exit of the case study tunnel as the center, 20 gradient bands were generated over the study area at intervals of 50 m; at the same time, 10 gradient bands were generated over the study area at intervals of 100 m (Fig. 4). The mean value of RSEI in each gradient zone was calculated, to analyze the gradient change law of the ecological environment over distance from the tunnel exit.

Identification of influencing factors

Geo-Detector, a spatial analysis model, is commonly used to measure the relationships between geographic phenomena and their potential influencing factors (Ju et al. 2016; Lyu et al. 2019). In this paper, we used Geo-Detector to study the relationship between the dependent variable Y (RSEI) and the independent variable X (the main influencing factors associated with tunnel water surge). Geo-Detector includes factor and divergence detectors, risk detectors, and interaction detectors.

The factor detector uses q values to determine whether X influences Y and the magnitude of its explanatory intensity, calculated using Eq. (5):

$$q = 1 - S_{\text{SW}}/S_{\text{ST}} = 1 - \sum_{K=1}^{L} N_K \sigma_K^2 / N_\sigma^2. \tag{5}$$

where S_{SW} and S_{ST} are the sums of variance within the layer and the total regional variance, respectively, q is the explanatory power of the tunnel water surge-related influencing factor on RSEI, k is the category or stratification of the influencing factor, N is the number of sample units within the whole region, N_k is the number of sample units within the sub-domain; L is the number of sub-domains, and σ_k^2 and σ^2

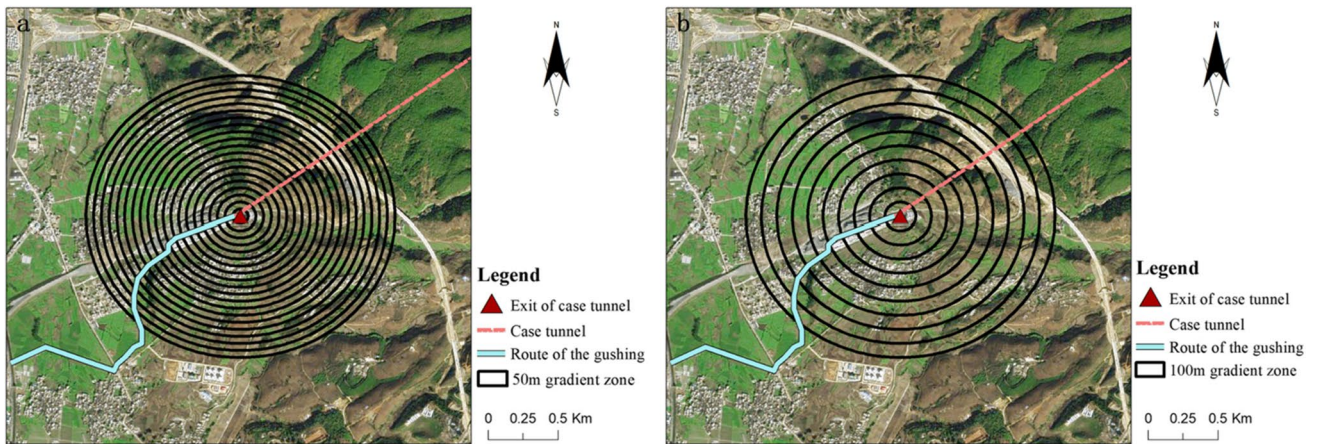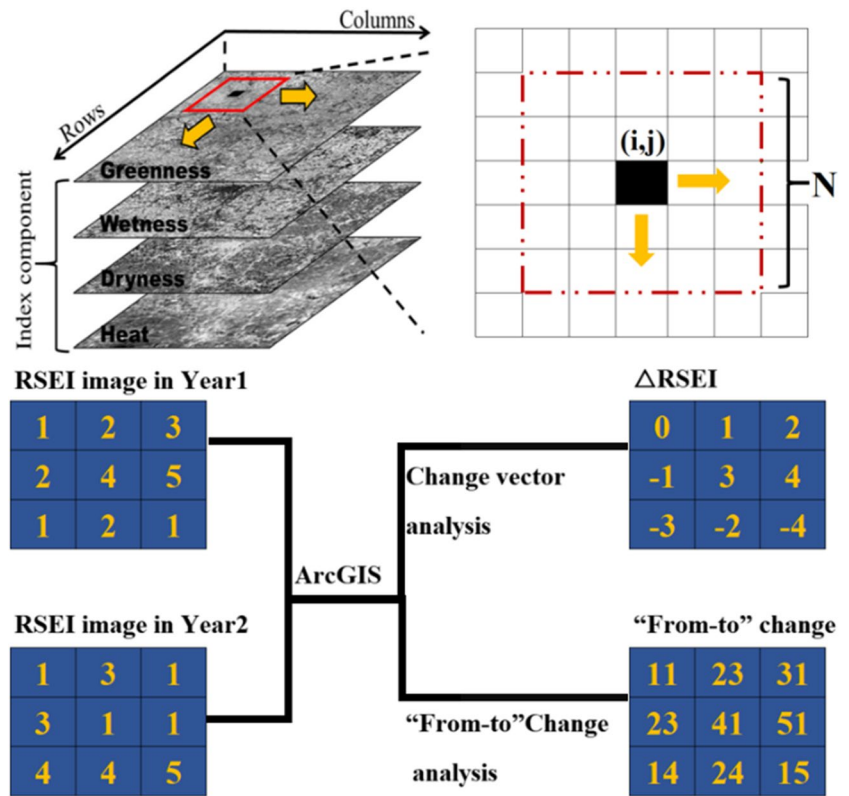**Fig. 3** CVA workflow and "From-to" change analysis

Fig. 4 Divisions of gradient zones

are the variances of RSEI values in layer k and in the whole region, respectively .

The risk detector evaluates the variability around the mean values of different influencing factors. The optimal range or characteristics of different factors contributing to the development of RSEI can be determined and tested with the t-statistic. The specific formula is (6):

$$t = N_{X1}(N_{X2} - 1)S_{SWX1} / N_{X2}(N_{X1} - 1)S_{SWX2} \qquad (6)$$

where N_{X1} and N_{X2} denote the sample sizes of influences X_1 and X_2, respectively, and S_{SWX1} and S_{SWX2} denote the sums of the within-layer variance of the strata formed by X_1 and X_2, respectively.

The interaction detector assesses whether there are any interactions among X_K or whether they are independent. That is, influencing factors X_1 and X_2 are evaluated together to determine whether their explanatory power for the variability in the dependent variable RSEI is enhanced or diminished when combined. The type of interaction between the

Table 5 Types of interactions between covariates

Reference for Judging	Interaction type
$q(X1 \cap X2) < \text{Min}(q(X1), q(X2))$	Nonlinear attenuation
$\text{Min}(q(X1), q(X2)) < q(X1 \cap X2)$ $< \text{Max}(q(X1), q(X2))$	Single-factor nonlinear weakening
$q(X1 \cap X2) > \text{Max}(q(X1), q(X2))$	Double-factor enhancement
$q(X1 \cap X2) = q(X1) + q(X2)$	Independent
$q(X1 \cap X2) > q(X1) + q(X2)$	Nonlinear enhancement

factors is determined by comparing the q-values. The specific types are shown in Table 5.

Results

RSEI analysis

After the principal component analysis, principal component 1 (PC_1) was identified as describing the ecological environmental quality of the area along the tunnel water flow path (Table 6). The results showed that the percentage contribution of PC_1 was greater than 70% in all cases. This indicated that PC_1 contained the most of the information available in the four ecological factors. However, to ensure that the selected RSEI comprehensively represented the ecological health information of the study area, this study, drawing on the previously established methods (Xu et al. 2019), multiplied each principal component with its contribution percentage and then summed them one by one to calculate the year-by-year optimal RSEI.

Analysis of the RSEI and the four ecological factors revealed that the greenness and moisture components had significant positive effects on RSEI. In contrast, the heat and dryness components had negative effects on RSEI. This was consistent with expectations based on general ecological trends.

Through a comparative analysis, we found that the ecological environment within 500–1000-m bands centered on the case study tunnel exit still experienced a large change. However, in the 1000–1500-m range, the ecological environment change was less obvious. Therefore, to best investigate the regional ecological environment changes along the case

study tunnel water flow path, we focused on the ecological environment changes within the 1000-m scale buffer zone for further analysis.

Temporal analysis of RSEI

Figure 5 shows the change in the RSEI of the case study tunnel within a 1000-m diameter buffer zone over time. The RSEI values during the study period fluctuated between 0.25 and 0.75. In general, the RSEI decreased, indicating that the ecological environment quality was gradually deteriorating.

The temporal changes in RSEI throughout the tunnel construction cycle are shown in Fig. 6. The RSEI exhibited a "spiked" distribution during the construction cycle. Compared with the pre-construction period (Fig. 6a), the RSEI during the construction period (Fig. 6b) and post-construction period (Fig. 6c) showed significant leftward shifts. These changes reflected the significant increases in the median and low value regions of the RSEI. Areas with good ecological environments before tunnel construction were significantly deteriorated after construction.
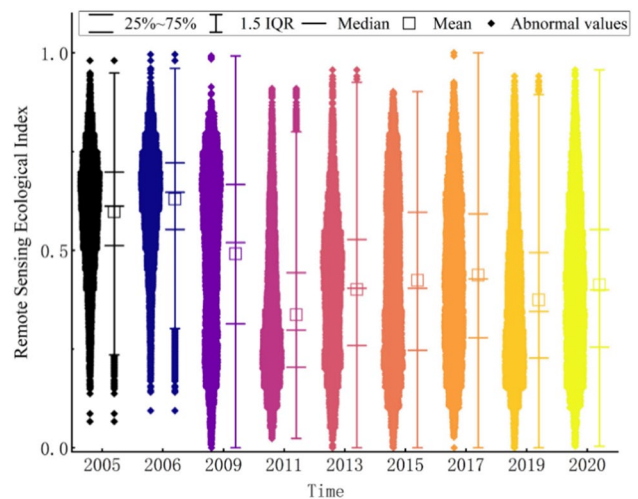

Fig. 5 RSEI temporal distribution

Table 6 Contribution of each principal component

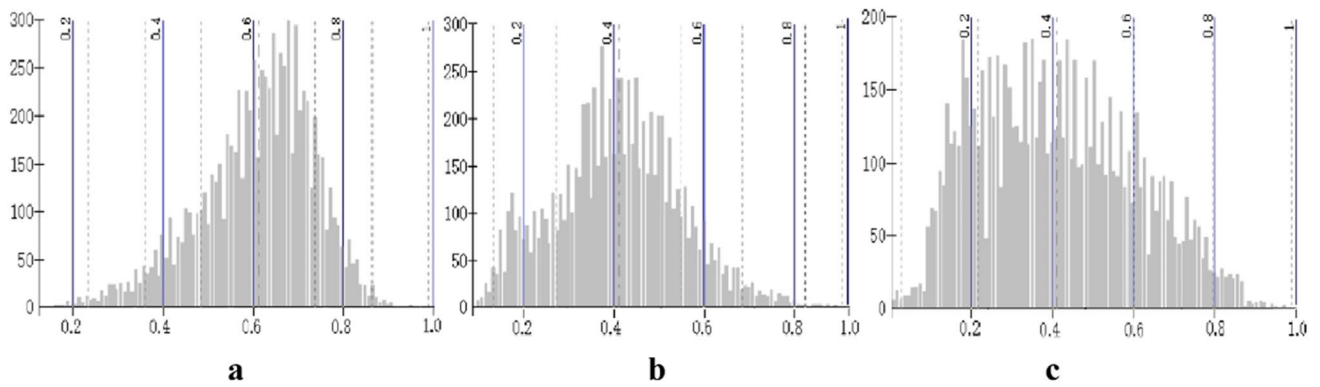| Principal component components (%)	2005	2006	2009	2011	2013	2015	2017	2019	2020
PC_1	73.03	76.87	77.29	77.67	74.32	70.20	77.39	72.22	74.28
PC_2	15.76	11.33	12.5	13.29	12.95	13.99	13.23	16.43	15.52
PC_3	8.97	9.41	5.98	6.18	9.08	9.16	8.47	9.12	8.91
PC_4	2.24	2.39	4.23	2.86	3.65	6.65	1.91	2.23	1.29

Fig. 6 Temporal change in RSEI throughout the construction cycle (**a** pre-construction period, **b** construction period, and **c** post-construction period)
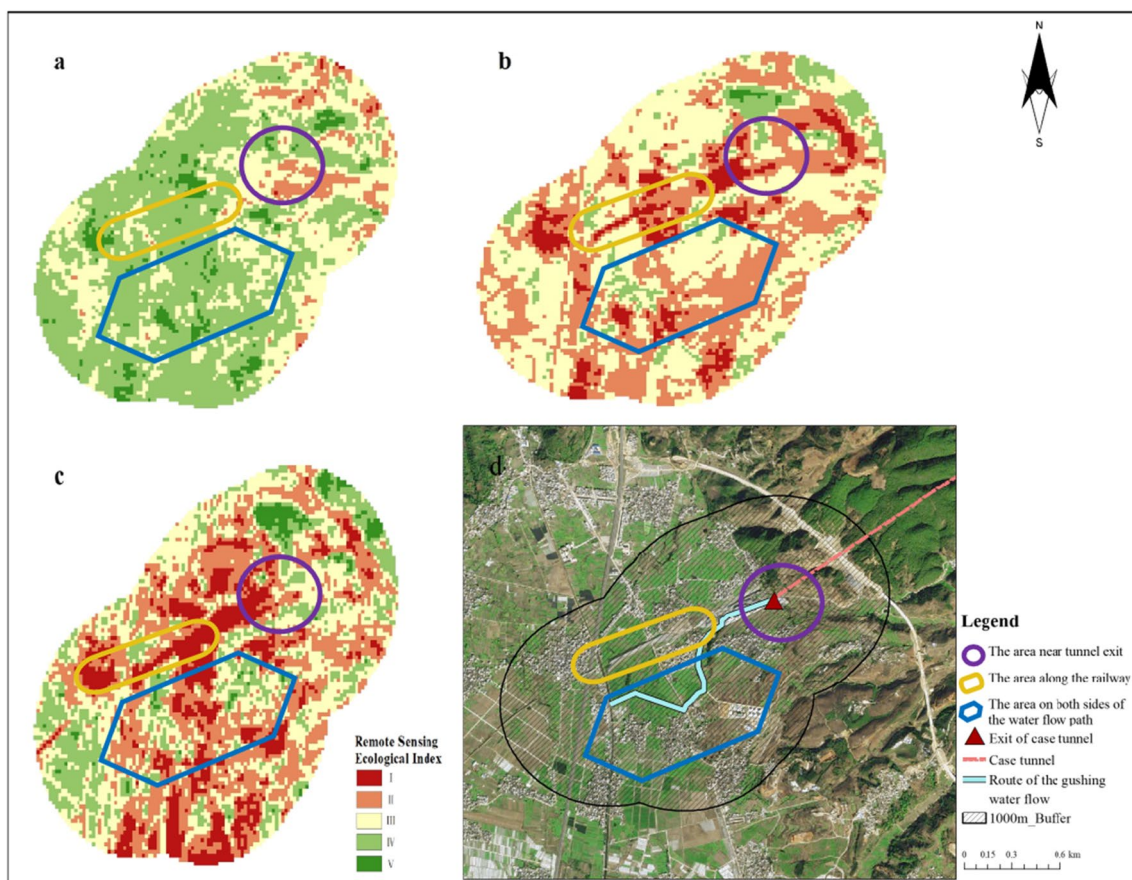

Fig. 7 Spatial distribution of RSEI during the construction cycle (**a** pre-construction period, **b** construction period, and **c** post-construction period)

Spatial analysis of RSEI

The RSEI was classified into five grades using the natural breaks method: bad (1), poor (2), moderate (3), good (4), and better (5). Fig. 7 shows the spatial distribution of RSEI during pre-construction period, construction period, and post-construction period. The environment of the study area was classified as "better" level in the pre-construction period. However, relative to the other areas, the condition quality of the area to the northeast of the tunnel exit was poor. During the construction period, disturbed by the construction and surge water, the ecological environment of

the area near the tunnel exit, along the railway line, and on both sides of the water flow path deteriorated significantly. Compared with the construction period, the ecological environment near the tunnel exit improved slightly in the post-construction period, but along the railroad line and the areas on either side of the surge water runoff path, the deterioration of the ecological environment continued.

Based on CVA, the RSEI grade changes were classified as significantly decreasing (−3, −4), slightly decreasing (−1, −2), no significant change (0), slightly increasing (1, 2), and significantly increasing (3, 4). Fig. 8 shows that, in general, the ecological environment was obviously deteriorated along the tunnel exit, railway line, and flow path due to disturbance from tunnel construction and surging water during the construction cycle. At the same time, the ecological environments of the area radiating outward from the center of the tunnel exit and along railway line and flow path were slightly deteriorated.

The ΔRSEI values were separated into five types, and the area coverage of each change type is shown in Fig. 9. The percentage coverage by the different ΔRSEI change levels in the study area during the tunnel construction cycle

were, from largest to smallest, as follows: slightly decreasing (49%) > basically stable (20%) > slightly increasing (16%) > significantly decreasing (14%) > significantly increasing (1%).

From the pre-construction to construction periods, 69% of the area saw negative ΔRSEI values, which was much more than the area where RSEI increased (11%). Between these two periods, the most abundant type of RSEI change was "slightly decreasing" (49%). From the construction period to post-construction period, the RSEI change type covering the most area was "basically stable" (53%); the percentage area where RSEI increased (25%) was slightly larger than the area where RSEI decreased (22%). Comparing the construction period to post-construction period, there was a significant decrease in the area where ΔRSEI was "slightly decreasing," a significant increase in the area that was "basically stable," and a small increase in the area that was "slightly increasing."

The different types of change in ΔRSEI are shown in Table 7. In the whole tunnel construction cycle, the areas where the RSEI significantly increased are mainly changed from poor (2) to better (5); areas with slight increases
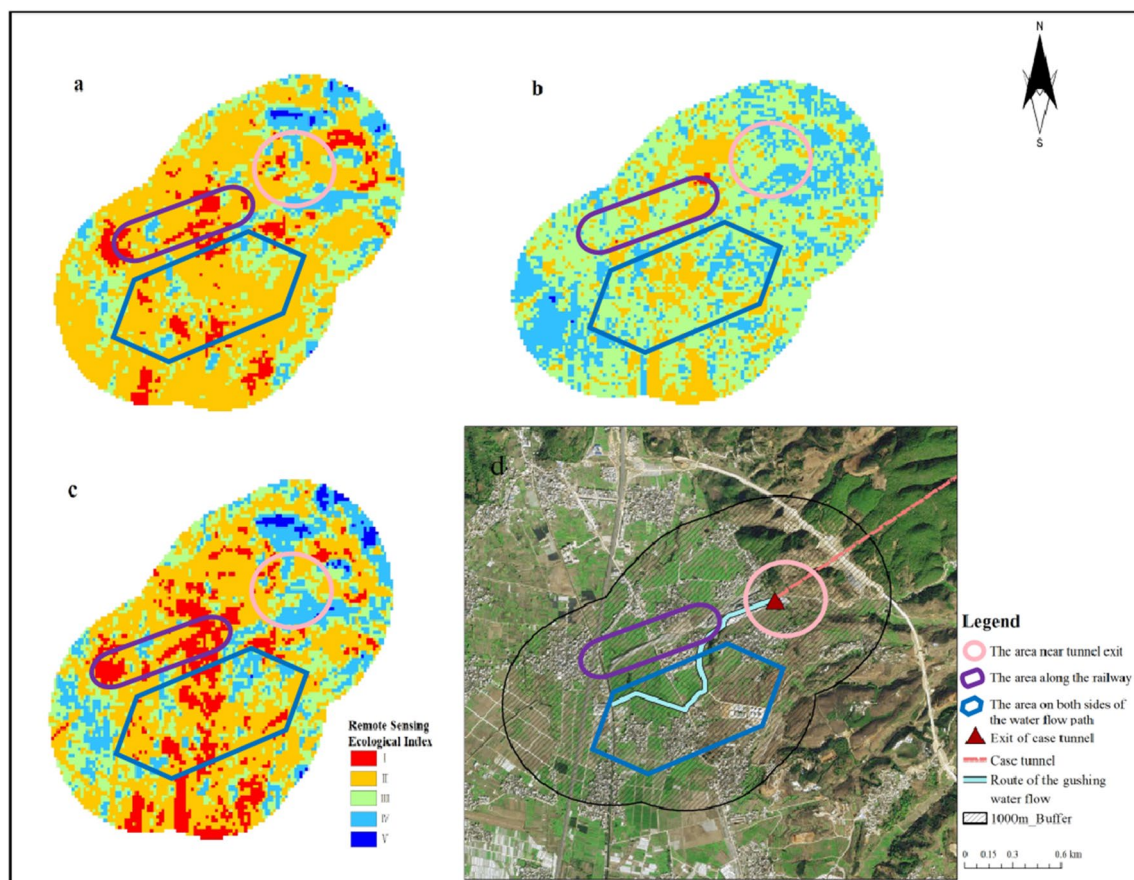

Fig. 8 Spatial distribution of ΔRSEI throughout the construction cycle (**a** pre-construction period, **b** construction period, and **c** post-construction period)
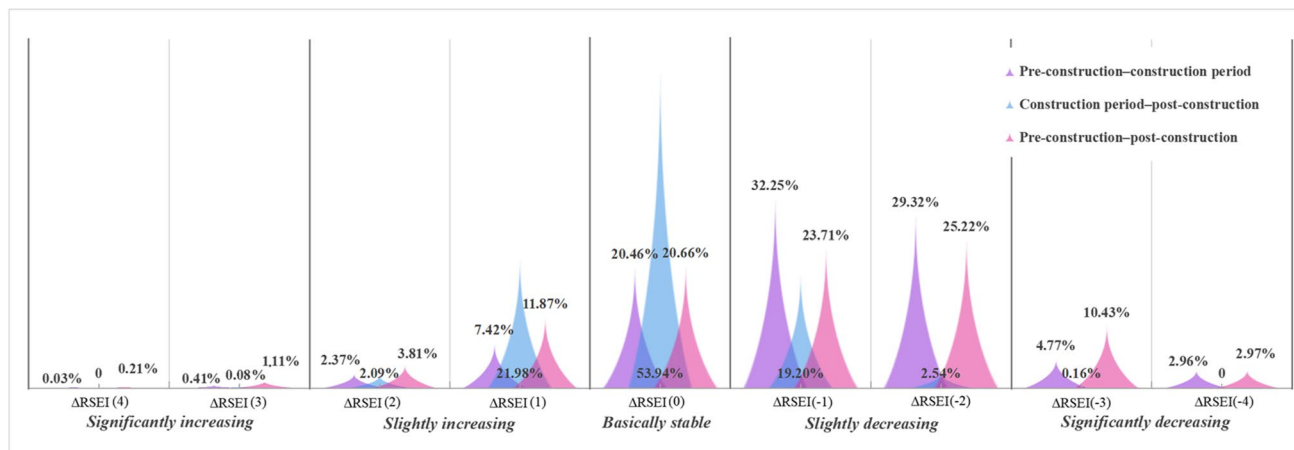
Fig. 9 Area coverage by different ΔRSEI change types

Table 7 Specific types of ΔRSEI changes

Class of ΔRSEI	Class type of ΔRSEI	Area (m^2)					
		Pre-construction–construction period	Ratio	Construction period–post-construction	Ratio	Pre-construction–post-construction	Ratio
4	15	1800	0%	-	-	15,628	0%
3	14	11,700	0%	1527	0%	5195	0%
	25	19,799	0%	4120	0%	77,447	1%
2	13	899	0%	10,466	0%	5914	0%
	24	172,800	2%	128,891	2%	211,039	3%
	35	4500	0%	17,266	0%	69,472	1%
1	12	-	-	129,230	2%	2761	0%
	23	222,299	3%	640,057	9%	215,955	3%
	34	334,799	4%	748,907	10%	656,002	9%
	45	-	-	131,494	2%	16,479	0%
0	11	-	-	466,155	6%	-	-
	22	44,100	1%	1,609,210	21%	100,079	1%
	33	1,404,000	19%	1,589,404	21%	1,092,146	15%
	44	86,399	1%	358,314	5%	358,526	5%
	55	-	-	26,657	0%	-	-
−1	21	9900	0%	520,024	7%	22,096	0%
	32	710,999	9%	832,499	11%	769,991	10%
	43	1,698,300	23%	86,820	1%	979,175	13%
	54	1800	0%	2084	0%	8337	0%
−2	31	86,400	1%	170,236	2%	239,371	3%
	42	2,076,300	28%	20,401	0%	1,619,337	22%
	53	38,700	1%	-	-	34,257	0%
−3	41	284,399	4%	12,436	0%	683,526	9%
	52	73,799	1%	-	-	99,877	1%
−4	51	222,299	3%	-	-	223,378	3%

mainly changed from moderate (3) to good (4); areas with slight decreases mainly changed from good (4) to poor (2) and good (4) to moderate (3); and areas with significant decreases mainly changed from good (4) to bad (1). This showed that areas with better condition ecological environments were more vulnerable to construction and water

surge. The areas where RSEI remained basically stable from pre-construction to the construction period were mainly in moderate (3) condition; and from the construction period to the post-construction period, unchanged areas were mainly in moderate (3) and poor (2) conditions. This showed that the poor condition areas changed less after construction was finished.

Gradient analysis of RSEI

The mean RSEI gradient analyses of the ecological environment of the study area with 50-m and 100-m intervals are shown in Fig. 10. There were clear differences between the mean RSEI distribution maps for the 50-m and 100-m gradient intervals.

The mean RSEI was lowest in the center, near the tunnel exit, in pre-construction period; the mean RSEI of the outer area was significantly higher than the center. Compared with pre-construction period, the maximum change in RSEI was observed in the interval range from 250 to 550 m from the tunnel exit during the construction period. The pattern is common in environment disturbances caused by tunnel construction and water surge. Compared with construction period, the changes in RSEI were largest in the ranges of 300–450 m and 750–850 m from the tunnel exit in the post-construction period. This indicated that the negative impact on the environment was gradually extended outward by tunnel construction and water surge. In general, these patterns

showed that the mean RSEI of the area closest to the tunnel exit was lowest and gradually increased with distance from the tunnel exit.

Factors influencing RSEI

In this study, we selected the environmental factors most closely related to the impacts of tunnel water outflow and the water flow path through the ecological environment for further impact factor analysis. The risk detection results of the impact factors during the construction cycle are shown in Fig. 11. The intensity of the impact factors on RSEI in the study area ranged from 0.11 to 0.2 in the pre-construction period. The top three factors in terms of explanatory intensity were DEM (0.2), distance to administrative district (0.18), and distance to water system (0.14). The intensity of the impact factors during the tunnel construction period ranged from 0.01 to 0.03, which was significantly lower than the previous period. The top three explanatory factors were slope (0.03), land use type (0.03), and DEM (0.03). The intensity of the impact factors ranged from 0.05 to 0.10 in post-construction period, which was a small increase compared to the previous period. The top three explanatory factors were distance to highway (0.10), distance to administrative district (0.09), and land use type (0.08).

The interaction detection analysis of the different factors on RSEI is shown in Fig. 12. Interactions between any two influencing factors during the three construction
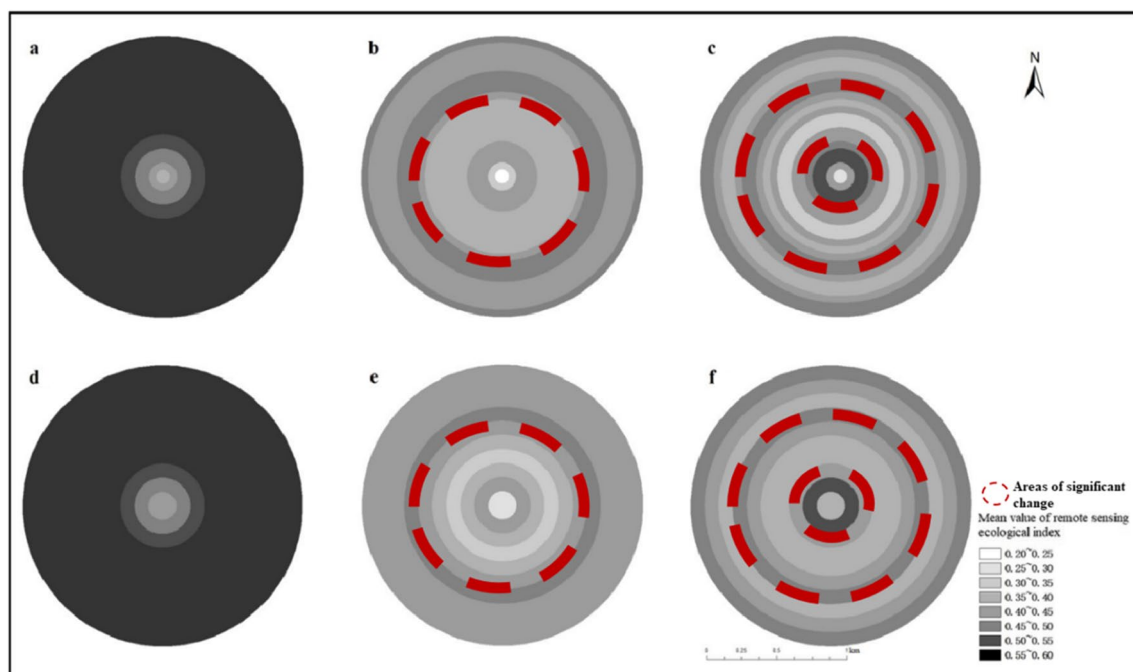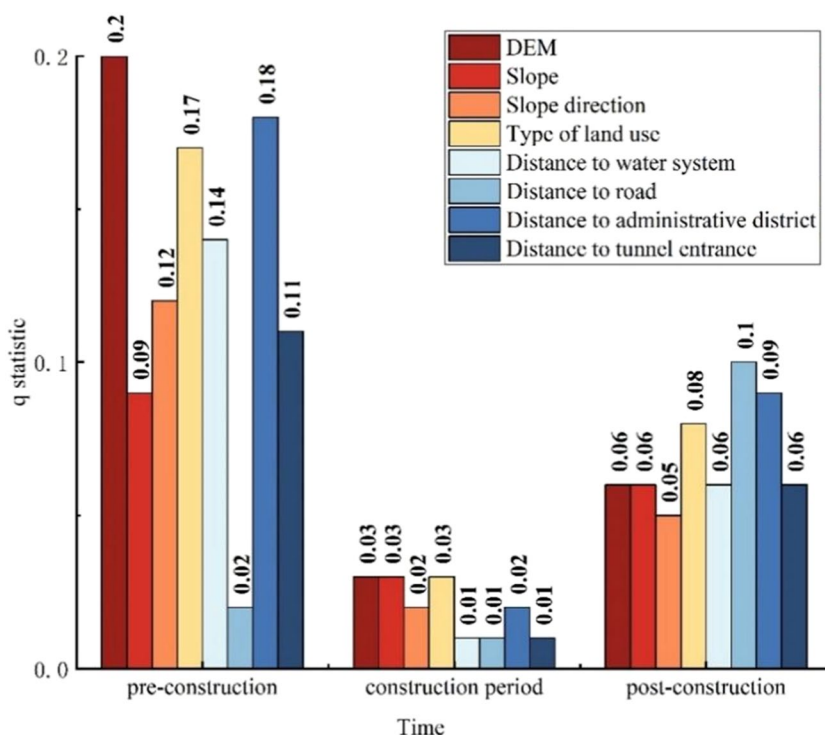

Fig. 10 Circle gradients of mean RSEI centered on the tunnel exit at 50-m and 100-m intervals during the pre-construction period (**a**, **d**), construction period (**b**, **e**), and post-construction period (**c**, **f**)

Fig. 11 Risk factor detection
analysis

periods were categorized as a double-factor enhancement or nonlinear enhancement. The interaction between DEM and slope direction was the strongest of all the interactions, reaching 0.29. During the construction period, the explanatory intensities of all the interactions between influencing factors on the RSEI were weakened, although the interaction between DEM and slope direction was still the strongest of the interactions, reaching 0.12. The overall interactive forces between different factors increased slightly in the post-construction period; furthermore, among the interactions with land use, the interaction between land use and distance to road was the strongest, reaching 0.18; the same was true for distance to road and when looking at interactions with DEM.

Discussion

Spatial and temporal analysis of RSEI

According to the results presented here, the RSEI of the study area exhibited an overall decreasing trend throughout construction cycle. However, there were significant increases in areas with low initial RSEI values. Despite this, the overall ecological environment of the study area had a significant trend of deterioration. These observations further showed that tunnel construction and tunnel water surge can disturb and damage the surrounding ecological environment to varying degrees (Li et al. 2012; Qiu et al. 2020; Li et al. 2021).

In terms of spatial distribution, the areas where the RSEI decreased were mainly concentrated in the vicinity of the tunnel exit, the railroad line, and both sides of the area along the water runoff path; this was because, as the connection point inside and outside the tunnel, the area around the tunnel exit will not only experience concentrated construction activity but also bear the full pressure of the large quantities of discharged water as it flows out of the tunnel (Hu et al. 2019; Liu et al. 2019). In the post-construction period, the ecological environment near the tunnel exit and the areas on both sides of the flow path close to the tunnel exit slightly improved; this was because the ecological environment possesses a self-recovery ability that becomes apparent after construction is complete. However, the recovery rate was slow and it did not eliminate the signs of ecological disturbance completely caused by the tunnel construction and water gushing during the study period. Difficulty in recovery of ecological environments that have been damaged by tunnel surge water has been previously observed (Stammel et al. 2016; Zhou et al. 2010). At the same time, the ecological deterioration along the flow path area far from the tunnel exit became worse after construction was completed. This indicated that the tunnel water surge will not only impact the surrounding ecological environment during the construction period but will continuously impact the surrounding ecological environment during the post-construction period and into the tunnel operation stage. This was consistent with the studies by Wang et al. (2020a) and Li et al. (2012).

Fig. 12 Interaction detection analysis (**a** pre-construction period, **b** construction period, and **c** post-construction period)
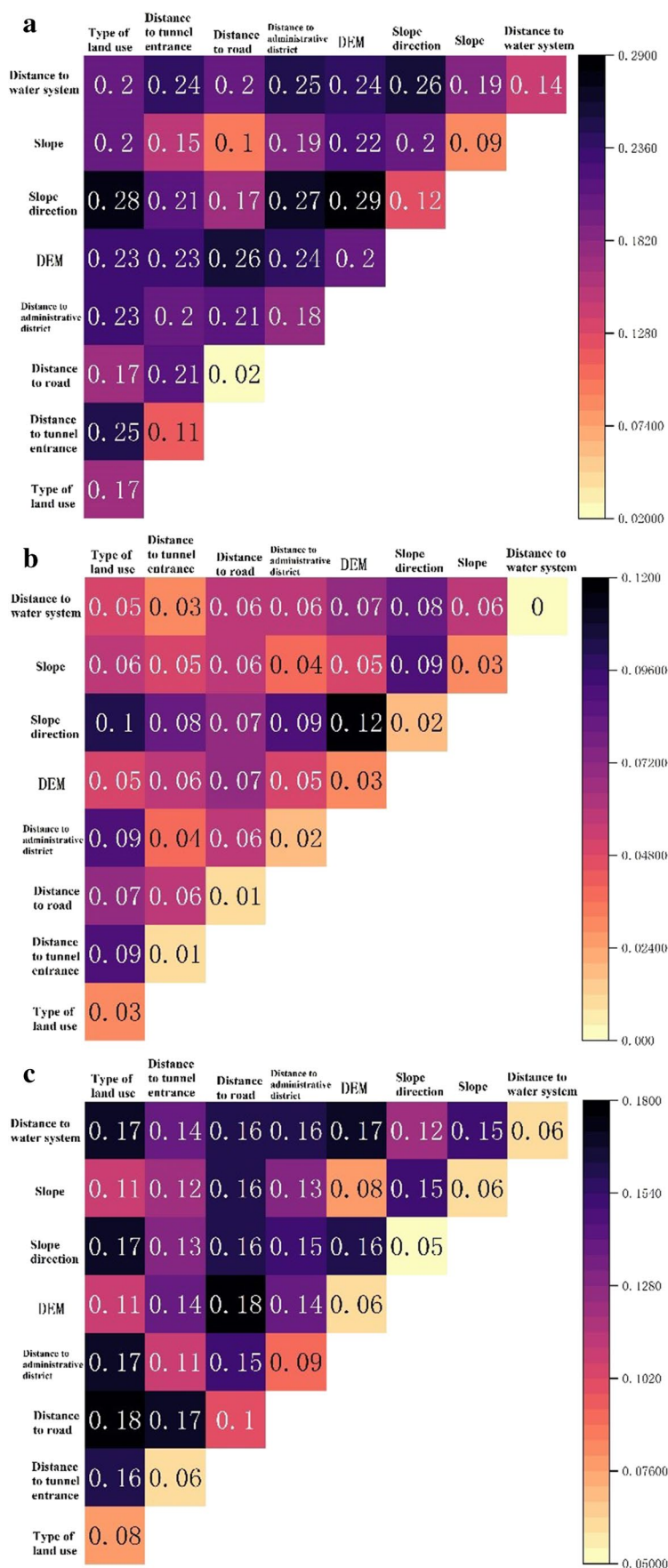
From the observed changes in RSEI during the construction cycle, from pre-construction to construction, the types of RSEI change in the study area were greatly influenced by tunnel construction and water surge; but from tunnel construction to post-construction, the predominant RSEI change category was "basically stable." Most areas that were basically stable are in the poor RSEI class. This further showed that the damage by tunnel water gushing to the surrounding ecological environment will be sustained for a long period of time because the restoration speed of the damaged ecological environment is very slow.

RSEI gradient analysis

RSEI gradient analysis showed that, generally, the average RSEI was lower near the tunnel exit center, gradually increasing along the interval outward. This was because the area around the tunnel exit experienced the most disturbance from construction and water surge. With distance from the tunnel exit, these forces had a lower impact. This pattern was in accordance with the law of distance attenuation (Elango et al. 2012; Zhao et al. 2015). While railway construction promotes urban development, it can negatively impact landscape richness, biodiversity, and environmental quality, as was shown by previous research (Daniela and Marco 2017). Human disturbances to landscapes can cause huge changes in the spatial structures of landscape patterns (Mamat et al. 2014).

During the tunnel construction period, the RSEI in the gradient from 250 to 550 m from the tunnel exit changed greatly. Though comparison with the real-time image, we found the main reason was that there were dense concentrations of construction sites on both sides of the railroad line in this area. At the same time, the vegetation cover on both sides of the flow path was low due to the impact of surging tunnel water. In the post-construction period, the RSEI in the ranges of 300–450 m and 750–850 m from the tunnel exit exhibited the larger changes, which was the result of the gradual outward extension of the influence of tunnel construction and water surge on the ecological environment.

Analysis of RSEI influencing factors

In the pre-construction period, the ecological environment of the study area was not disturbed by surging tunnel water. It was mainly influenced by natural elements such as elevation, distance to the water system, and urban developmental elements represented by the distance to the administrative district. This was consistent with the study by Xu (2015). The study area is in a hilly area with a large topographic relief. The area near the tunnel exit is at a high elevation and the water runoff traverses downhill. DEM became the main factor influencing the ecological

environment in the pre-construction period. Hadi et al. (2014) also observed that elevation will impact climate and precipitation. Thus, elevation will not only directly impact the ecology of the study area; it will have an indirect effect on the ecosystem by influencing climatic factors (Zheng and Ren 2013). The proximity to water sources and administrative districts were two factors that affected the ecological environment of the area through their influence on the growth of vegetation and the density and distribution of urban building sites. Most of the changes in RSEI corresponding to different interactions between impact factor combinations were more significant during the pre-construction period. The DEM and slope orientation were important influencing factors for the ecological environment of the study area. This confirmed that the ecological environment of the study area was more strongly influenced by natural elements in the pre-construction period.

During the tunnel construction period, the explanatory power of all the influencing factors decreased. This indicated that the impact by natural elements on the ecological environment was weakened. The combined effects of tunnel water surge and construction on the ecological environment of the study area were strong. Simultaneously, the influence of land use on the RSEI of the study area was gradually strengthened. This was due to the strong effect of the distribution of construction sites, including those involved in laying of railroad lines and the treatment of water surge during construction of the tunnel (Mamat et al. 2014; Chen et al. 2021b). The corresponding RSEI changes due to only a small number of impact factors made them all highly significant. DEM and slope orientation still had the most influential interaction effect, reaching 0.12. Side by side, it shows the gradual strengthening of the influence of elevation and slope orientation on how water surge and other construction factors influence the ecological environment. This showed that the gradual deterioration of the ecological environment in the study area was the result of multiple construction factors acting together.

In the post-construction period, the influence of two elements, distance to the road and distance to the administrative district, on the ecological environment was gradually strengthened. However, the explanatory intensities of the above-mentioned impact factors on the RSEI were still relatively low. This meant that the effects of water surge and construction factors on the ecological environment continued to be important but were gradually weakening. Among them, the distance to the road and the distance to the administrative district, which were representative of human activity, had significant effects on the RSEI. The environmental disturbances caused by the construction factors gradually weakened after tunnel construction was completed. This was more related to the gradual increase in the influence of urban development factors related to

highway construction on the ecological environment. The distance to the road, the distance to the water system, and land use type were important driving factors for the ecological environment, which also showed a gradual enhancement in the importance of natural elements, urban development, and other human factors on the ecological environment in the post-construction period and the gradual weakening of the influence of surging tunnel water on the ecological environment.

At the same time, with the completion of the tunnel and put into use, Baoshan City, the history of the inaccessibility of the train ended. Since its operation, Baoshan Railway Station has transported a total of more than 500,000 passengers, and Baoshan North Station has transported more than 300,000 tons of goods, which has substantially accelerated the development of tourism and logistics economy along the railroad. The year-end resident population of the whole region in 2021 was 904,000, which increased by 0.1 million people compared with the end of the previous year. After the tunnel is completed and used, the transportation conditions will be improved obviously, and the resident population will increase significantly, reflecting that the importance of urban development and other man-made factors to the ecological environment is gradually increasing, and the impact of tunnel water influx on the ecological environment is gradually weakening.

The results of this paper illustrated that, in addition to the tunnel water factors, human factors were also important influences on the ecological environment along the path of the mountain railroad tunnel water flow. The anthropogenic impacts were divided into positive effects (such as returning farmland to forest and protecting natural forests) and negative effects (such as urban traffic related construction, urbanization, and deforestation). Among them, land use also had a great impact on the ecological environment. Its effect was mainly manifested due to the degradation of grassland and forest land and the gradual increase in man-made surface area. This was caused by the construction equipment for handling wastewater and sludge and the construction of auxiliary facilities to meet the living needs of construction workers during the construction of railroad tunnels, which had a large impact on the ecological environment. Severe anthropogenic disturbances can put great pressure on ecosystem health and can lead to a decline in ecological quality (Jin et al. 2016; Du and Gao 2017). This is because, unlike densely populated urban centers, there is a clear high to low directionality in the land of the mountain railroad tunnel construction area. Human activities focused on cultivated land and grassland were the dominant factors driving land use change in the area (Daniela and Marco 2017). This is an unavoidable necessity during the tunnel construction. Therefore, it is extremely important that environmental protection

measures promote ecological restoration of the construction area in the post-construction period.

Limitations and future work

Although this study obtained valuable results from a temporal-spatial analysis of the factors influencing eco-environmental quality in the area of the flow path from a typical mountain railway tunnel throughout the tunnel construction process, there were several limitations. (1) Natural factors are numerous, but only representative factors related to water flow were selected in this study. (2) The accuracy of the images was not sufficient. To meet the research requirements for the whole construction cycle, this study selected Landsat remote sensing images that covered a longtime span. In the future research, we plan to build a more comprehensive monitoring system of influential factors based on Gao Fen satellite images to improve the reliability and accuracy of research into factors influencing ecological environments in areas along water flow paths of mountain railway tunnels.

Conclusions and suggestions

Conclusion

In this paper, using observations throughout the railroad tunnel construction cycle (pre-construction, construction period, and post-construction period) based on remote sensing ecological index model, an objective quantitative analysis of the regional ecological environment along the surge water flow path from a mountain railroad tunnel at both spatial and temporal scales was conducted to assess the importance of influencing factors. The following conclusions were made.

(1) RSEI can effectively assess the impact of tunnel surge water on the regional ecological environment during the whole life cycle. It can provide ideas for studying other aspects of long time series of ecological environment.

(2) The RSEI during the study period was mostly in the range of 0.25–0.75. In terms of spatial distribution, the deterioration of the ecological environment in the areas along the tunnel exit, railway line, and flow path were the most obvious. The RSEI changes were categorized by change direction and degree, and the change types covered different proportions of the study area in the following order: slightly decreasing > basically stable > slightly increasing > significantly decreasing > significantly increasing.

(3) The maximum change in RSEI was observed in the gradient increments between 250 and 550 m from the

tunnel exit during the construction period. In the post-construction period, the RSEI changes in the ranges of 300–450 m and 750–850 m from the tunnel exit were largest.

(4) Analysis of the factors influencing RSEI revealed that in the pre-construction period, changes in the ecological environment were mainly determined by natural factors; during the construction period, the combined effects of tunnel surge water and other construction factors had an elevated impact on the ecological environment; in the post-construction period, factors related to urban development, such as the distance to the highway and distance to the administrative area, gradually increased in importance. It also shows that the impacts of the tunnel surge water on the surrounding environment will not only occur during the construction period but will also continue after the tunnel has been constructed.

Suggestions

This paper has shown that the water surge from the case study tunnel not only impacted the environment during the construction period but also after construction of the tunnel was complete. In order to ensure the normal construction of railroad tunnels can proceed while also protecting the ecological environments of tunnel site areas, the following policies and recommendations should be implemented and followed.

(1) Before the construction of a railroad tunnel, construction plans should be designed with environmental protection in mind. Based on the findings of this paper, planting measures within the area 200–550 m from the tunnel exit may effectively prevent large decreases in

RSEI. Greening materials of mostly grasses and shrubs can be used in mountainous areas, focusing on greening both sides of roadbeds and on both sides of the tunnel water flow path.

(2) During the construction of railroad tunnels, environmental protection measures should be guided by the principles of "protection and prevention." A detailed investigation and analysis of the hydrogeology of the tunnel area should be carried out in advance. For areas with high pressure groundwater or large amount of recharge water source in front of tunnel excavation, water plugging using drilling should be carried out in advance for the surrounding rocks to reduce the sudden attack of pressurized water; after tunnel excavation, grouting water plugging work should be done. Furthermore, supervision and management should be enhanced during the construction period to ensure "green" construction.

(3) Finally, this paper showed that, after the construction of the case study railroad tunnel, the ecological environment of some areas along the surge path still exhibited deteriorating trends. Therefore, after the completion of the mountain railroad tunnel, high-resolution spatial data should be used as the basis to continue to monitor the ecological environment along the tunnel surge water flow path in order to record the environmental changes accurately and clearly. Monitoring time should extend past the end of the tunnel construction period and last for at least annual hydrological cycle. These actions will enable the comprehensive analysis of the extent of the impact of the tunnel projects on the environment and potentially reduce the continued harm from tunnel water flows on the local ecological environment.

Appendix

Fig. 13 Remote sensing images of the pre-construction period of the tunnel (**a** 2005, **b** 2006)
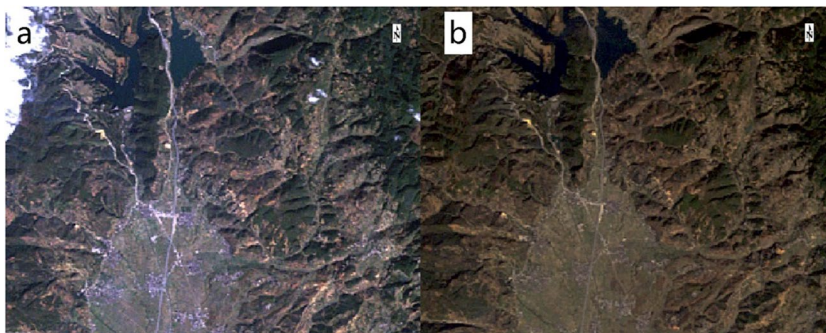
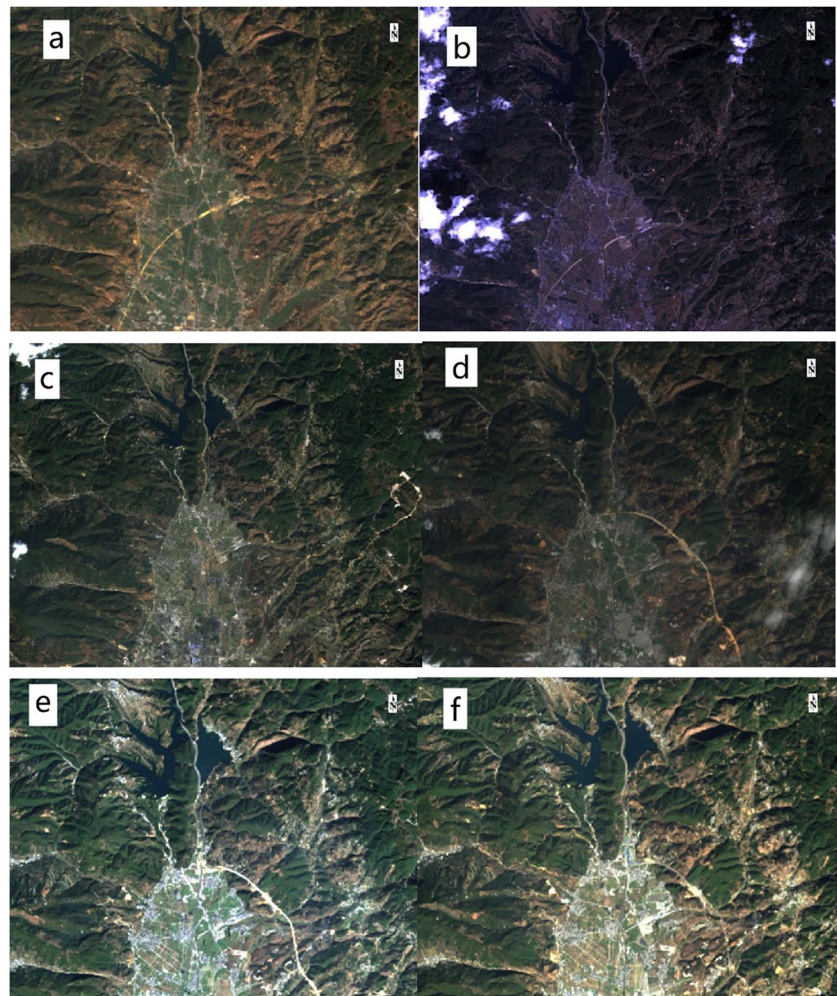**Fig. 14** Remote sensing images of the construction period of the tunnel (**a** 2009, **b** 2011, **c** 2013, **d** 2015, **e** 2017, **f** 2019)

Fig. 15 Remote sensing images of the post-construction period of the tunnel (2020)

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent to participate All authors agree to participate in this work.

Consent for publication All the authors listed have approved the manuscript that is enclosed.

Competing interests The authors declare no competing interests.

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