Research Progress of Ecological Environment Profit and Loss Analysis of Highway Road Area in Karst Landform

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Abstract: Karst is a kind of ecosystem with peculiar topography, special physical, chemical and biological structure and ecological function. With the continuous development of China's urbanization, the highway network has been continuously expanding and improving, the construction of highways in karst areas will inevitably damage the original local geomorphic structure and ecological environment, and the solution of the contradiction between highway construction and ecological protection has become a hot research topic nowadays. The article summarizes the research progress of ecological environment profit and loss analysis of highway road area in karst landform, introduces the characteristics of karst landform and the impact of highway construction on it, and then focuses on the research results of the selection and investigation of ecological evaluation indexes of highway construction in karst area, environmental impact assessment, and ecological environment profit and loss assessment methods. The current research progress and future development direction are summarized, aiming to provide theoretical support and practical guidance for the sustainable development of highway construction and environmental protection in karst region.

Keywords: Karst Landform; Road Construction; Ecological Profit and Loss; Environmental Impacts

1. Introduction

Karst landforms are shaped by processes of dissolution, collapse, and accumulation of rock masses due to the interaction between soluble rock components and water, including surface water, groundwater, and biological factors [1]. Due to their distinctive ecological structures, karst landforms are highly sensitive to external disturbances, exhibit reduced ecological resilience, and are characterized by poor stability [2]. These landforms feature complex geological conditions and fragile ecosystems, making them particularly susceptible to environmental pollution, geological damage, and limited natural recovery after disturbances. With the rapid urbanization in China, the national highway network has expanded significantly. Highways, as large-scale infrastructures with extensive stretches and substantial land use, have long-term and often irreversible impacts on surrounding ecosystems during both construction and operation phases [3]. Given the unique structure of karst landforms, highway construction in these areas poses heightened risks to the ecological environment [4].

Considering the necessity of societal convenience and economic development, highway construction is indispensable. Simultaneously, environmental protection, as a core component of sustainable development, remains a national priority. Therefore, during highway construction, it is crucial to achieve the goal of “harmonious coexistence between humans and nature” [5], while minimizing damage to the surrounding ecological environment, a task that presents significant challenges. This paper summarizes the characteristics of karst landforms, evaluates the ecological gains and losses associated with highway construction in karst areas, and reviews research on environmental impact assessment and ecological cost-benefit evaluation methods. It consolidates current research progress and outlines future directions, aiming to provide theoretical support and practical guidance for the construction design and environmental protection of highways in karst regions.

2. The Characteristic of Karst Landform

Karst landform, also known as limestone dissolution landform, represent a unique type of terrain characterized by soluble rocks in various forms, primarily carbonates rocks, present both on the surface and underground. These soluble rocks dissolve in water, forming landforms through processes of erosion and deposition [6]. The ecological environment in karst regions is fragile, with complex geological conditions, pronounced structural differentiation, and poor self-recovery capacity, making these areas more vulnerable to damage compared to other regions [7]. As such, they are typical examples of ecologically fragile zones. Additionally, according to research by Jiang et al., karst landforms contain diverse aquifer, offering abundant groundwater resources and vast underground spaces [8]. These landforms exhibit a diverse hydrogeological environment, closely connected to the atmosphere, hydrosphere, lithosphere, and biosphere. As an integral part of Earth's ecological system, karst landforms are rich in natural resources, making their protection highly important [1].

In addition to ecological fragility and complex structures, karst landforms are characterized by a high density of caves, loose soil structure, weak water retention, high permeability, and harsh conditions for the growth of flora and fauna. These factors make it difficult for karst landforms to recover once damaged [5]. Construction in such regions presents significant challenges. Prior to construction, rigorous evaluation and design are necessary, as construction can lead to irreversible damage to karst landforms, such as vegetation destruction, habitat loss, soil and water loss, cave collapses, and fragmentation of geographical structures [9].

In summary, compared to other regions, karst landforms exhibit more complex and unique geological structures, water systems, plant and animal communities. These factors contribute to the increased ecological fragility of karst areas, rendering them more susceptible to the impacts of highway construction. Moreover, once the ecological environment in karst regions is disrupted by human activities, the recovery process is difficult.

3. Monitoring Ecological Environmental Indicators in Karst Road Areas

To conduct an ecological profit and loss analysis of road areas in karst landforms, the first step is to select the relevant ecological background indices. By monitoring changes in these indicators, it can be determined whether the ecosystem in the area has been disturbed. Ecological indicators for road areas represent the environmental background values, covering various factors and offering a comprehensive reflection of the overall environmental system. According to the research of He and Wei, the current selection of background indicators for ecological evaluation in karst road areas includes the degree of rocky desertification, karst water abundance, vegetation coverage, terrain slope, and land use type. These indicators effectively reflect the ecological state of karst regions [4,5].

3.1 The Degree of Rocky Desertification

Rocky desertification is a significant environmental issue in karst landforms, leading to reduced soil fertility, decreased vegetation coverage, and weakened water retention capacity, which ultimately results in soil and water loss [10]. Human construction activities within road area disrupt surface vegetation, exposing rock and soil, increasing the rate of rock exposure on mountains and surfaces, and thereby exacerbating soil erosion [11]. According to monitoring by Cao et al., rocky desertification in the Bijie karst region of Guizhou Province increased significantly between 2003 and 2006. The area covered by rocky and semi-Rocky Mountains expanded to 1,533 km^2, with its share of the total land area rising from 5.63% to 5.82% [12].

Long et al. analyzed MODIS data and digital elevation models, using a NDRI (normalized difference rock index) to assess the rate of rock exposure in the study area. They found that between 2000 and 2021, the total area of rocky desertification in the southwestern karst region fluctuated between 134,800 km^2 and 177,000 km^2, indicating a significant increase in rocky desertification [13]. Xi et al. using Sentinel-2A data to extract rocky desertification information in the karst region of Wenshan prefecture, discovered that moderately and severely desertified areas accounted for 63.25% of the study area. Their research also showed that rocky desertification occurs more frequently in limestone areas, steep slopes and high elevations areas [14].

This indicates that rocky desertification in most karst landform areas, and the incidence of rocky desertification is high and covers a large area. Rocky desertification leads to soil and water loss and land degradation in karst landforms, further reducing vegetation cover and ultimately resulting in a loss of biodiversity. As the region’s capacity for soil and water conservation weakens, the ecological environment is adversely affected, with significant implications for the local ecosystem and socioeconomic conditions.

3.2 The Water Yield Property of Karst Landform

The water yield property of karst regions refers to the quantity of groundwater and the distribution patterns of karst water within the karst system. Due to the high permeability of the rock in these areas, karst water bodies typically exhibit higher water yield capacity [4]. In carbonate rock areas of karst landforms, water-rich aquifers form. The unique underground structures formed by karst processes result in large volumes of groundwater, high flow velocities, and widespread distribution. These intricate structures also make the groundwater system highly susceptible to external disturbances [8]. The water yield property of karst systems reflects the spatial and temporal distribution of water resources, providing valuable insights for the protection and utilization of water resource. Liu et al. drilled 17 exploration wells in the Shunping karst region of Beijing. Based on the pumping results, they found that the maximum water output from these wells was 10,780 m^3/d, while the minimum was 4,464 m^3/d, demonstrating the area's strong water-rich characteristics and abundant groundwater resources [15]. Luo et al., through groundwater monitoring in the karst areas of the Chengdu-Guiyang Railway, discovered that the region's underground karst water resources are abundant. The area features both underground rivers with large volumes of flow and smaller streamflow moving through fractures. The highest recorded flow rate for the underground rivers was 1,500 L/s, and karst springs also exhibited flow rates of up to 1,500 L/s, with single wells yielding up to 2,400 m^3/d [16]. He et al. conducted a survey of karst water resources in Puding County, Guizhou, and found that water commonly emerges as springs in low-lying areas and on slopes. They investigated five springs, all located at elevations around 1,300 meters, with flow rates ranging from 0.0017 to 0.08 L/s. This indicates that the region's shallow karst water resources are abundant and could be reasonably developed for use [17].

This demonstrates that karst regions have highly developed and extensive groundwater systems. The complexity of these underground water networks also contributes to the intricate nature of the karst landform's underground structure, making its ecological fragility more pronounced and its resilience to external disturbances weaker. Additionally, interconnected groundwater systems can lead to widespread dissemination of pollutants in groundwater bodies and difficult groundwater pollution management.

3.3 Vegetation Coverage

Vegetation coverage in karst regions is a key indicator for assessing local ecological quality. Vegetation coverage influences water retention and plays a vital role in conserving biodiversity and maintaining ecological balance [4]. Human activities, such as highway construction, can significantly disturb vegetation. For instance, in densely vegetated karst areas, approximately 12% to 27% of the vegetation may be destroyed during construction [18].

vegetation coverage refers to the ratio of the vertical projection area of plant communities or individual plants to the total study area [10]. He et al. used the Reclassify function in ArcGIS's Spatial Analyst module to analyze vegetation coverage through the Normalized Difference Vegetation Index (NDVI). They found that areas with high and very high vegetation coverage accounted for 74.34% of the study area [4]. Qin et al. analyzed satellite images from 2004, 2010, and 2014 using NDVI and a pixel dichotomy model, showing that vegetation coverage in the region had improved to cover 1,922.96 km², or 97.34% of the total area [19].

Huang et al. employed Theil-Sen slope estimation and the Mann-Kendall significance test to analyze NDVI data from 2000 to 2018 for the southwestern karst region. Their results showed that vegetation coverage began to increase rapidly from 2009, and by 2018, 88.54% of the region had higher coverage compared to 2000 levels [20].

These findings indicate that karst landforms generally have high vegetation coverage, and recent restoration efforts in China's karst regions have been effective. Road construction will occupy a large area, which will inevitably cause environmental hazards such as destruction of vegetation, soil and water loss, and reduction of biodiversity in karst landforms with high vegetation cover.

3.4 Terrain Slope

The slope of the terrain is usually greater in karst areas, this is due to the particular geological formation and surface morphology of the area. Different terrain slopes significantly impact construction operations, especially in geological surveys and route selection for highway projects [4]. For example, Qin et al. conducted a survey of 27 karst counties in Guangxi, finding that in 11 counties, areas with slopes greater than 25° accounted for over 25% of the total area. As slope increases, surface runoff speeds up, soil stability decreases, and soil and water loss intensifies [21]. He et al. measured the terrain slope in the southwestern karst region using elevation points as base data, calculating slope indicators through ArcGIS9.3's Arc Toolbox. They classified the terrain slope's impact on highway construction into five levels, with slopes ≤3° having no impact and those >20° having an extremely severe impact, discovering that flat areas accounted for only about 25.21% of the region [4]. Yang et al. studying Longli County's karst region, categorized slopes into five levels, finding that areas with slopes between 6° and 25° comprised 90.97% of the region, indicating it is a mountainous area with high slopes [22].

This highlights that most karst regions have greater terrain slopes, with relatively few flat areas. The steep slopes in karst landforms make mountain and soil structures highly unstable. They are particularly susceptible to damage during highway construction activities, such as earth excavation and filling.

3.5 Land Use

Land use reflects the degree of human interference with the natural environment in karst regions, directly impacting the ecological and structural stability of these areas. Changes in land use types are crucial considerations in construction planning and design [23]. Li et al. took the karst basin in Guizhou Province as the research object, using ArcGIS to analyze the dynamic changes in land use of three watersheds from 2000 to 2020, and employed the InVEST model to evaluate different land use types in the watersheds. It was found that over the past 20 years, cultivated land has shown a declining trend, with the largest reduction observed in grassland. From 2000 to 2010, the comprehensive land use dynamic degree was 0.38%, with the rate of land use change gradually accelerating afterward [24]. According to the investigation of Yang et al. , Longli County covers an area of 1,520.0769 km², with forest land accounting for the largest portion at 62.85%, followed by cultivated land at 20.76%, looking at the big picture, indicating a high level of vegetation cover and well-maintained vegetation. [22]. Additionally, Yin et al. used ArcGIS, Fragstats 4.2, and land use change models and landform index analysis to study land use changes in the Guangxi karst region from 2009 to 2020. They found that over the 11-year period, cultivated land decreased by 24,200 hectares, forest land increased by 32.61 hectares, and construction land expanded by 11,400 hectares. This suggests a continuous decline in cultivated land, accelerated growth of forested areas, and a significant expansion of construction land [25].

This indicates that after highway construction in karst landforms, the area of cultivated land, forest land, and grassland tends to decrease. These three land types provide critical ecosystem services, and their reduction directly leads to a decline in vegetation coverage and biodiversity. This results in the degradation of the entire ecosystem of the karst landform, making it difficult to recover.

In summary, the selection of ecological indicators for karst landforms is diverse, but the key indicators include the degree of rocky desertification, terrain slope, vegetation coverage, land use changes, and karst water resources. If these few ecological indicators are damaged, it will affect the ecological environment of the entire karst landform. Therefore, monitoring the ecological environment of karst road areas should incorporate these indicators. Investigating karst water resources helps assess local water availability and the distribution of water systems, while terrain slope analysis aids in route selection and construction design for highways. The investigation of changes in vegetation coverage includes changes in land use types such as forest land, grassland, and cultivated land. These assessments, combined with changes in land use types, offer theoretical support for ecological profit and loss analysis evaluation methods, allowing for a more intuitive analysis of the effects of highway construction on the local environment and socio-economic conditions from both ecological and economic perspectives.

4. Environmental Impact Assessment of Roads in Karst Landforms

The environmental impact assessment of roads in karst landforms is a comprehensive process to assess the impact of road construction on the ecological environment of karst areas by collecting information on the ecological environment of karst areas, so as to provide a scientific basis for road planning and design. The assessment typically focuses on key ecological indicators such as the degree of rocky desertification, the water yield property of karst landform, vegetation coverage, terrain slope, and land use. When conducting an environmental impact assessment in karst landforms, it is crucial to use a combination of GIS, remote sensing technologies, and mathematical models to ensure accuracy and scientific rigor [5]. Additionally, it is essential to adhere to relevant laws, regulations, and standards to guarantee that the evaluation results are compliant and reliable.

Zhou et al. conducted an environmental impact assessment of a proposed highway project in the Yongzhou region of southwestern Hunan, focusing on vegetation cover characteristics, soil properties, and hill distribution. They evaluated the environmental impacts of highway construction by analyzing various ecological indicators. For instance, certain areas of the project had a significant presence of calciphilous and drought-tolerant plants, and the vegetation succession was at a critical stage. If the construction did not avoid these areas, it could destabilize the ongoing vegetation succession. Additionally, the surface substrate in the area was primarily composed of carbonate, with thin and poorly structured soil. Without an appropriate construction plan, this could lead to the destruction of rock layers as well as soil and water loss. By carefully considering the rationality of the highway route layout and the ecological sensitivity of the surrounding environment, they selected the optimal construction route to minimize damage to the ecosystem [2].

He et al. used the Hedu Highway as a case study, proposed five key ecological baseline indicators for evaluating the ecological status of karst road regions: vegetation coverage, karst water abundance, rocky desertification, terrain slope, and land use types. Supported by RS-GIS technology, they monitored these background indicators and assigned different weights to each, creating a mathematical model to assess the ecological index of karst regions. The ecological index was divided into five levels, with each level reflecting the background ecological value, allowing them to predict the environmental impact of highway construction. This method provides theoretical guidance for the construction, operation, and environmental protection of roads in karst regions [4].

Cao et al. selected five environmental indicators: vegetation resources, soil and water loss, land use, terrain slope, and water environment. They applied a fuzzy comprehensive evaluation method to determine the weight of each indicator, conducting a comprehensive analysis based on these weights. By establishing a mathematical model for environmental evaluation, they assessed the ecological environment road areas in the southwestern karst region of the Yunnan-Guizhou Plateau. Based on the analysis of the weights and proportions of ecological indicators, different scores are assigned to various ecological conditions. The road area ecological environment is classified, and the ecological status of different areas is divided into five levels. This classification is used to evaluate the baseline ecological conditions and the environmental impact after highway construction. It provides guidance for highway construction and local ecological restoration [26].

In summary, the environmental impact assessment of karst road areas first involves identifying the ecological indicators that need to be investigated. Then, with the help of GIS, remote sensing technology, and satellite imagery, data on changes in these indicators are collected. Finally, a mathematical model is established to evaluate and analyze the environmental changes. Many case studies show that by assigning different weights to the ecological indicators and categorizing the ecological conditions, the impact of road construction on the surrounding environment can be evaluated in a clear and scientific manner.

5. Evaluation Method of Road Area Ecological Profit and Loss

The ecological profit and loss assessment of road areas involves analyzing the positive and negative impacts of road construction and subsequent operation on the environment, society, and economy, as well as the ecological compensation value required for restoring ecosystems [27]. This assessment includes examining the potential effects on the ecological environment, the economic costs and benefits of the project, and the positive contributions to social services [28]. The karst landform road area is also part of the road area, can adopt ecological profit and loss assessment methods used in other regions as references.

For instance, Yang et al. applied both material quantity and value assessments to evaluate the ecological cost-benefit of a highway in Hunan during its construction and operation. The assessment of the aquatic ecosystem included evaluating fishing productivity, hydrological and climate regulation, as well as educational, research, and recreational functions. For the terrestrial ecosystem, the evaluation focused on product provision, environmental regulation, biodiversity, and cultural functions. By analyzing more than ten indicators from 1993 to 2009, it was found that the CO_2 absorption capacity of the aquatic ecosystem increased by 26% and continued to improve annually, while the CO_2 absorption capacity of the terrestrial ecosystem decreased by 44%, heavily impacted by road construction [29].

Li et al. divided the ecological profit and loss of highway construction into two parts: ecological function cost-benefit and socio-economic cost-benefit. The evaluation primarily focused on three aspects: geotechnical processes, landform impact, and operational influence. The geotechnical process involves the excavation, disposal, and filling of soil and rocks, altering land use types and the geological structure within the road construction area. Highway construction creates artificial corridors in the natural environment, leading to landform fragmentation, vegetation damage, and destruction of animal habitats. During the operational phase, the main influences come from road maintenance and traffic, which incur maintenance costs while also causing noise and pollution from vehicle emissions.

So, Li et al. proposed calculating the ecological function cost-benefit of highway construction based on changes in land use types, temperature increases, solid, gaseous and noise pollution, and the degree of landform fragmentation. They used conceptual formulas to calculate the impact, such as the formula for pollution impact on ecosystem services: Epollution= EhP+ EaP+ EpP. Where EhP, EaP, and EpP represent the impact of pollutants on residents, animals, and plants, respectively [28].

Shao et al. conducted a study on the Xiangtan-Hengyang highway, employing environmental economics methods such as the market value method, shadow engineering method, and alternative market value method to estimate the economic and ecological losses caused by changes in land use and vegetation damage during highway construction. These losses were expressed in monetary terms. They calculated the economic loss from the reduction of forest vegetation, including the loss of timber production, carbon sequestration and oxygen release, flood control, and water resource utilization, as well as soil conservation benefits. For example, the economic loss caused by the occupation of forest land was calculated using the formula: $V=G\times T\times P$, where: V represents the total economic loss (in yuan), G is the volume of trees lost (in cubic meters), T is the tree yield rate (%), P is the price of timber (in yuan per cubic meter). Based on their calculations, the economic loss due to the highway's occupation of forest land and farmland amounted to

161.02 million yuan [30].

Zhao et al. selected five regions to study the changes in land use types caused by highway construction and calculated the resulting changes in ecosystem service value. They employed the “Ecosystem Service Function Value Calculation Method” and the “China Terrestrial Ecosystem Unit Area Service Function Value Table” to build and calculate a mathematical model, with the final results expressed in monetary terms. For example, the ecosystem service value for air regulation provided by farmland was 12.39 yuan per hectare per year, while the recreational value of forest land was 297.36 yuan per hectare per year. Based on changes in land use types, they used a currency-based value assessment method to calculate the changes in ecosystem service values. In the end, four regions saw a decline in ecosystem service value, while one region experienced an increase from 8,600 yuan per kilometer to 50,200 yuan per kilometer [31].

Liu et al. examined the value loss caused by highway construction to the ecological environment and the compensation value required for environmental restoration using a highway project in Hunan as a case study. They proposed the formula: Ecological Environmental Value (f) = Use Value (u v) + Compensation Value (cv), and assigned use and compensation values to different land types. The calculation showed that the use value of the highway construction was approximately 32.7 billion yuan, while the ecological value loss was about 10.3 billion yuan, indicating that the use value was greater than the compensation value [32].

Li et al. used the CBAM method to quantify the compensation for environmental damage caused by urban roads in Beijing. They developed a formula for calculating ecological loss compensation based on various environmental indices, such as exhaust pollution, land occupation, garbage production, pavement oil pollution, and traffic noise. For example, the compensation value for ecological loss due to pavement oil pollution was calculated using the formula $V_4 = c \times x \times p + k \times f$, where c is the number of sanitation workers, p is their wage, x is the increase in workdays caused by oil pollution, k is the amount of water needed for cleaning, and f is the water cost. The final calculation estimated the ecological loss value caused by roads in 2009 to be 9.191 billion yuan [33].

In conclusion, it is found that there are various road ecological profit and loss assessment methods, and the road ecological profit and loss assessment methods in the rest of the region are mature and have complete practical experience, which can provide a theoretical basis and guidance for the road ecological profit and loss assessment methods in the karst region. The primary approach for assessing the ecological gains and losses of roadside environments involves using advanced scientific methods from environmental economics. These methods assign different weights and economic values to the environmental impacts caused by highway construction, ultimately expressing them in monetary terms. This approach comprehensively demonstrates the social, ecological, and economic impacts of highway construction on the construction area. It serves to evaluate highway construction projects and guide the preliminary design and subsequent ecological protection efforts.

6. Conclusion and Outlook

In conclusion, the analysis of the ecological costs and benefits of road areas in karst landforms is a complex and important task. By summarising the literature, it was found that road construction does cause some ecological damage to karst areas. Evaluating the degree of ecological loss involves setting and assessing ecological indicators specific to karst landforms, understanding the impact of road construction on the environment, and assessing how changes in the ecosystem affect the value of ecosystem services. This process begins with selecting and investigating ecological indicators for the road environment in karst areas. After analyzing the data from these indicators, the extent of pollution and damage to the karst road ecology can be determined. Ultimately, certain ecological indicators, such as CO_2 absorption and emissions, changes in land use, or the economic losses caused by pollutants, are used to quantify the environmental impact of road construction in monetary terms, reflecting the ecological, social, and economic costs and benefits.

This paper can provide a strong scientific basis for road construction and ecological environmental protection in karst landform areas. Looking ahead, it is hoped that we can learn from the experience of evaluating the ecological profit and loss of road areas in other regions, and set up a more comprehensive and scientific method for evaluating the ecological indicators and ecological profit and loss of karst landform, and according to the existing research to establish national or regional road ecological profit and loss evaluation standards, put forward and formulate the relevant standard requirements for the karst landform road ecological environment profit and loss analysis, improve the accuracy and degree of standardisation of the analysis of the impact of road ecological profit and loss, for the construction of highways to provide more authoritative and more guiding significance of the theoretical data as a reference, and through continuous efforts and innovations, to realise the harmonious coexistence of karst landform road construction and ecological environmental protection.

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