RESEARCH ARTICLE

Ecological safety early warning and emergency management system of tourist attractions based on spatiotemporal evolution analysis

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The rapid expansion of global tourism has transformed tourist attractions into key drivers for local economic diversification and cultural preservation. However, this growth has also placed unprecedented pressures on the natural environment, leading to widespread concerns regarding ecological security. This study focused on advancing the research on ecological security early warning and emergency management systems in tourist attractions. It constructed a scientifically grounded, operational, and representative ecological safety evaluation index system, optimized the early warning model using advanced spatiotemporal analysis technology, and designed a set of efficient emergency management systems. Additionally, the study explored how to strengthen the intelligent management and service of ecological security using cutting-edge technologies such as the Internet of Things and artificial intelligence within the context of smart tourism. Empirical studies on typical scenic spots such as Huangshan were conducted to verify the practical application effect of theoretical models and management strategies, providing a scientific basis for wider application. The results showed an average environmental quality score of 78 out of 100 indicating generally good conditions, an average species richness index of 70 and an evenness index of 0.6 for biodiversity suggesting relatively rich and evenly distributed biodiversity, moderate levels of environmental pollution based on monitoring indicators, a tourist carrying capacity assessment showing that the actual daily visitor volume was generally within safe limits with some areas close to saturation, and a 15% improvement in visitor satisfaction, a 20% decrease in congestion index, and a 10% increase in ecological recovery rate following the implementation of incident response service measures. Through these efforts, this study provided a set of solutions combining theory and practice for the ecological security management of tourist attractions, contributing new knowledge and technical support to promote sustainable tourism development. The results of this study would help tourist attractions to respond quickly, manage effectively, and recover gradually when facing ecological crises, moving towards more sustainable future development. This study also emphasized the importance of emergency management system design in ensuring the effective operation of tourism scenic spot ecological security evaluation systems and constructed a solid ecological security defense line through a scientific response process, efficient resource allocation, and a forward-looking recovery strategy.

Keywords: spatiotemporal evolution analysis; tourist attractions; ecological security warning; emergency management.

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Introduction

The continuous expansion of global tourism has transformed tourist attractions into vital drivers for local economic diversification and cultural preservation. However, this growth has also imposed significant pressures on the natural environment, leading to growing societal concerns. The influx of tourists often results in excessive resource consumption, biodiversity loss, and degradation of ecosystem functions. Additionally, waste generation, noise pollution, and water shortages associated with tourism infrastructure construction and operations are increasingly prevalent, posing serious threats to ecosystem stability and ecological security. Ecological security is crucial for maintaining the balance of nature and is fundamental to ensuring the long-term welfare and sustainable development of human societies [1]. Considering these challenges, the development of ecological security warning and emergency management systems for tourist attractions has emerged as a significant research focus in both academia and practice. These systems leverage advanced technologies such as geographic information systems (GIS), remote sensing (RS), global positioning systems (GPS), and big data analytics. By enabling high-precision spatial positioning, multi-dimensional data acquisition, and intelligent analysis, they can monitor and analyze subtle changes in the ecological environment of tourist attractions in real-time, which allows for the identification of potential ecological vulnerable areas and risk sources, providing timely and accurate early warning information to management departments and assisting decision-makers in initiating effective incident response services and targeted protective and restorative measures [2].

Ecological security, the core issue of ecology and environmental science research, constitutes the solid foundation of environmental protection and sustainable development theory. It is rich in connotation, covering many dimensions such as deep concern for biodiversity protection, sustainable maintenance of ecosystem services, effective regulation of environmental pollution, rational and sustainable utilization of natural resources, *etc*., which are woven together into a network to maintain the health and stability of the earth's life system. The concept of ecological security was first articulated in 2019 by Li *et al*. [3], who elaborated on the indispensability of the stability of ecosystem structure and function to ensure the well-being and quality of life of human society and stressed that, only when the internal structure of the ecosystem was stable and the function was smooth, it could provide the necessary ecological support for the sustainable development of human society. In this framework, the concept of ecosystem services reveals the priceless treasures of nature-the basic services that directly benefit human survival and the cultural values that indirectly nourish the human spirit. These services range from basic material supplies such as clean water and abundant food to complex regulatory functions such as climate regulation, air purification, and water quality to cultural services that nourish the human mind such as recreation and spiritual comfort provided by natural landscapes to seemingly invisible but vital support services such as soil fertility maintenance and ecological cycle promotion. These services are not only precious treasures given by nature to mankind, but also indispensable cornerstones for the development of human society [4]. The tourism impact refers to the life cycle theory of tourism destination, which takes time as the axis and vividly describes the dynamic impact process of tourism development on destination environment, socio-economic structure, and cultural characteristics [5]. This theory not only shows the stages of tourism from initial exploration, rapid development, maturity and stability to possible decline, but also sharply points out the challenges that must be faced in tourism management as how to avoid or mitigate damage to fragile natural environment and cultural heritage while promoting economic development and cultural exchange and seek a delicate balance between development and protection.

GIS as an advanced technology of spatial data management and analysis plays an important role in the field of ecological security assessment. It can not only integrate a large amount of multi-source spatial information such as topography, land use types, biodiversity distribution maps, *etc*., but also through its powerful spatial analysis functions such as buffer analysis, network analysis, and superposition analysis, GIS can accurately identify and quantify potential ecological risks, laying the foundation for formulating scientific ecological protection measures [6]. A typical example is the use of GIS technology to draw ecological security pattern maps, which effectively guide tourism development activities and ensure the healthy development of tourism without destroying natural ecology [7]. Remote sensing (RS) technology with its unique advantages of wide coverage, rapid response, and non-invasiveness has become a powerful tool for monitoring global and local ecological environment dynamic changes. With satellite and aerial images in different bands, RS can regularly monitor land cover and calculate vegetation index (NDVI) to reflect vegetation growth status and ecosystem health. Combined with time series analysis, RS technology can deeply reveal the evolution law of ecosystem with time and space and provide early warning signals and trend prediction for ecological security [8]. In recent years, the rise of big data analytics has revolutionized ecological security assessment. By integrating and analyzing new data sources such as social media, mobile communication records, online reviews, *etc*., big data can not only monitor visitor traffic in real time, accurately predict travel demand trends, but also provide decision-makers with data-driven management strategies. The parameters are determined by optimization algorithm, thus providing scientific prediction of tourist volume for tourism management and helping to realize reasonable allocation of resources and reasonable control of ecological pressure [9]. Despite these advancements, there remain several research gaps and practical challenges that need to be addressed, which include a need for a comprehensive and adaptable ecological safety evaluation index system that accurately reflects the ecological status of tourist attractions. Moreover, improvements in spatiotemporal analysis techniques are required to enhance the accuracy and timeliness of early warnings. Additionally, there is a requirement for the design and validation of an efficient emergency management system that ensures seamless integration between early warning and response measures [10].

Building upon existing knowledge, this study focused on the advances of the research on ecological security early warning and emergency management systems for tourist attractions using spatiotemporal analysis to optimize the early warning model using advanced spatial and temporal data analysis techniques, and system design and validation to develop and test an integrated early warning and emergency management system [11, 12]. This study would provide a robust framework for the management of tourist attractions, enhance the understanding of ecological impacts, and offer practical solutions for mitigating negative effects, thereby supporting the transition towards more sustainable and resilient tourism practices. Furthermore, the findings would be instrumental in guiding policy development and fostering collaboration among stakeholders to achieve a green, lower-carbon, and more circular development model for the tourism industry.

Materials and methods

Construction of ecological security evaluation index system for tourist attractions

Biodiversity indicators usually include species richness index such as Shannon-Wiener diversity index and species uniformity index that are used to reflect the diversity and distribution equilibrium of biological species in the ecosystem [13, 14]. This indicator can be comprehensively evaluated by measuring the concentration of chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS) in water, and sulfur dioxide (SO_2), nitrogen oxides

(NOx), particulate matter (PM2.5, PM10) in air. The degree of contamination can be further determined by the Pollution Load Index (PLI) as below.

$$PLI = \left(\prod_{i=1}^{n} \frac{C_i}{C_{i,ref}} \right)^{\frac{1}{n}} \quad (1)$$

where C_i was the measured concentration of the i^{th} pollutant. $C_{i,ref}$ was the reference or background value for that pollutant. n was the number of pollutant species [15]. Fragmentation is often measured by landscape indices such as patch number (NP), mean patch area (MPS), and shape index. The landscape shape index was shown in the formula below [16].

$$SHAPE = \frac{Perimeter^2}{Area} \quad (2)$$

The evaluation of tourist carrying capacity (TCC) usually involves many aspects such as environmental capacity, facility capacity, social and cultural capacity, which can be determined as follows.

$$TCC = min\{ECC, FCC, SCC\} \quad (3)$$

where ECC was the environmental capacity. FCC was the facility capacity. SCC was the social and cultural capacity. The minimum value principle ensured the implementation of sustainable tourism. The specific indicator system was designed and shown in Figure 1. Species richness index and species evenness index were included to measure the richness and even distribution of biodiversity. The water and air quality indicators covered chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM2.5, PM10), which were used to monitor the status of the water bodies and air quality. The pollution load index comprehensively reflected the degree of environmental pollution. The landscape fragmentation index included landscape index and shape index (SHAPE) to assess the degree of landscape fragmentation. Visitor carrying capacity index was divided into environmental carrying capacity (ECC), facility carrying capacity (FCC), and social and cultural carrying capacity (SCC) to assess the carrying capacity of the scenic area in terms of environment, facilities, and social and cultural aspects. Together, these indicators constituted a framework for the comprehensive evaluation of the selected tourist attractions, providing a scientific basis for the management and protection of the scenic area.

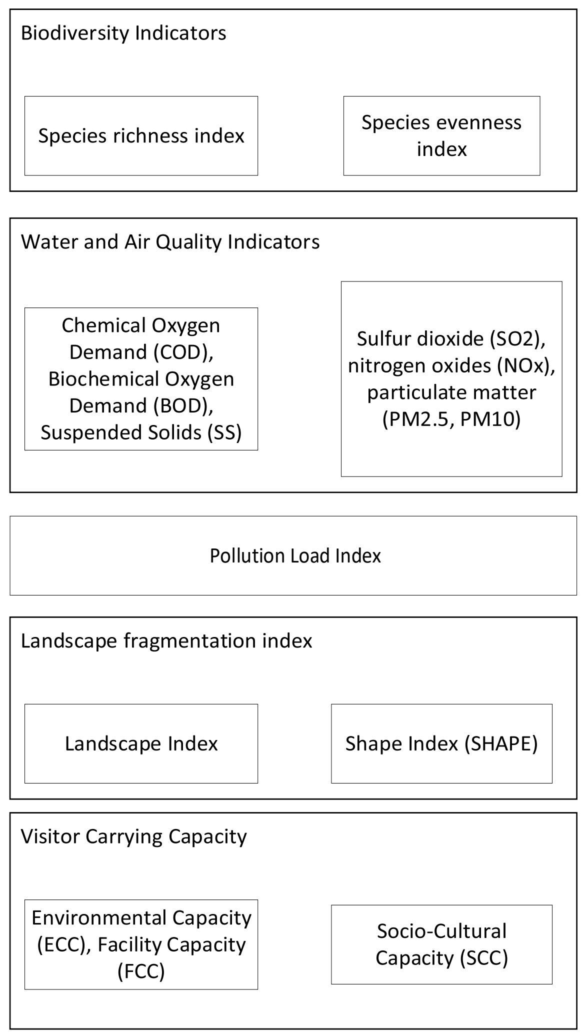

Figure 1. Design of index system.

To ensure the scientificity and accuracy of eco-safety evaluation of tourist attractions, it is very important to assign reasonable weight to each evaluation index. Analytical hierarchy process (AHP) was adopted to complete this task. The method systematically determined index weights through four progressive steps including a hierarchical structure constructed with target layer, criterion layer, index layer, and the logical relations among different levels were clarified. The judgment matrix was constructed by expert scoring mechanism to quantify the relative importance of each index between criterion layer and index layer followed by a consistency test to calculate the ratio of the largest eigenvalue to consistency of the judgment matrix to ensure the reliability of the analysis. A consistency ratio (CR) value below 0.1 was required. The weights of each index were then calculated based on the normalized eigenvectors, which realized the scientific weighting of the evaluation index system and enhanced the accuracy and practical guidance significance of the evaluation results [17, 18]. Based on the judgment matrix, its eigenvalue (λ_{max}) and CR were calculated, and then the weight of the index was obtained by normalizing the eigenvector. The CR calculation was shown below.

$$CR = \frac{\lambda_{max} n - 1n}{RI} \tag{4}$$

where *n* was the order of the judgment matrix. *RI* was the random consistency index. There were fixed *RI* values for different order judgment matrices, and RI was about 0.10 for order 4 matrix. If CR was 0.1, the matrix passed the consistency test. The weight of each index was obtained through the normalized eigenvector that was obtained by solving the eigenvalue problem. The final weights needed to be normalized with each element divided by their sum, ensuring that the sum of the weights equaled to 1. [19, 20].

Model construction

A rich historical data repository covering a wide range of in-depth ecological information including but not limited to spatial distribution maps of ecological elements provided by GIS, environmental changes monitored by remote sensing technology (RS), tourist dynamic trajectories tracked by global positioning systems (GPS), and tourist behavior patterns extracted from big data analysis was employed. The integration of these multivariate data laid a solid foundation to construct a fine spatiotemporal dynamic model. A range of advanced spatiotemporal series analysis tools such as time series analysis (ARIMA model) that was good at capturing and predicting trends over time was applied. Spatial autocorrelation analysis (Moran's I index) was used as below.

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i\overline{x})(x_j\overline{x})}{s^2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{5}$$

where w_{ij} was the spatial weight. x_i and x_j were the ecological index value of each position, respectively. $\overline{x}$ was the average value. s^2 was the variance. When the *I* value approached 1, it revealed a strong spatial positive correlation, which was very important for understanding the spatial diffusion trend of landscape fragmentation with time. Space-Time Cube was a visualization tool that helped to visualize how ecological security evolved in three space-time dimensions [21, 22]. This series of analysis, combined with other spatiotemporal sequence analysis methods, constituted a powerful toolbox to describe, predict, and understand the spatiotemporal dynamics of the ecological security state of scenic spots, providing scientific basis for formulating targeted protection strategies and incident response service [23].

Early warning threshold setting

Based on the results of ecological security assessment, the warning threshold was set by comprehensively considering the evaluation scores of biodiversity, environmental pollution, landscape fragmentation, tourist carrying capacity, and other indicators, and using principal component analysis (PCA) to reduce dimensions to determine different levels of ecological security status. Threshold values could be set based on the percentile of the principal component score, For example, PC1 score below 10% was a red alert, 10%-30% was an orange alert, 30%-70% was a yellow alert, 70%-100% was a blue alert, and above 100% was a green safe state [24].

Early warning mechanism design

The design of pre-warning mechanism included the issue of warning signal, the classification of warning level, and the suggestion of response strategy. Once the model predicted that an area was about to reach or had reached the early warning threshold, the system automatically triggered the corresponding early warning signal and released it through various channels such as SMS, APP push, official website, *etc*. to ensure the rapid transmission of information. The warning signal issuance included designing color coding system (red, orange, yellow, blue, green) to match the corresponding emergency level to visually convey the warning level. The early warning levels were classified by percentile to ensure timeliness and accuracy of response. Spatiotemporal evolution analysis and construction of ecological security early warning model were key steps to realize sustainable management of tourist attractions. Through scientific data analysis and early warning mechanism design, ecological risks could be effectively prevented and mitigated, and harmonious coexistence between tourism and natural environment could be promoted [25].

Emergency management system design

Emergency management system design was an essential part to ensure the effective operation of ecological security assessment system in tourist attractions. It focused on the rapidity of early warning response, efficient allocation of resources, and scientific planning of post-disaster recovery to ensure the long-term stability of ecosystem and sustainable development of tourism activities. The process of incident response service design covered key links such as early warning trigger, information confirmation, decision-making, execution and disposal, effect evaluation and feedback improvement, forming closed-loop management. Plan-Do-Check-Act (PDCA) cycle model could be adopted to ensure continuous optimization of the process [26]. Early warning trigger was the first step in the ecological security early warning and emergency management system of tourist attractions. According to the output of ecological security early warning model, once it reached the predetermined threshold, the system would trigger early warning automatically. This was followed by an information validation phase, where affected areas were rapidly located through GIS and RS, and field data were collected to verify the accuracy of the warning information. Subsequently, the decision-making phase called emergency meetings to make rapid decision response strategies based on Team Hierarchical Decision Process (AHPPT) models. In the implementation and disposal stage, according to the decision-making results, measures such as personnel evacuation and resource allocation should be implemented to ensure rapid and orderly actions. The effect evaluation and feedback were then carried out. Impact-probability-performance (CIPP) evaluation model was used to evaluate the effect of incident response service, and the response process was adjusted and optimized according to the evaluation results to improve the efficiency and effect of future emergency management. Flexibility and efficiency in resource allocation were core elements in building an emergency management system to ensure that the most critical resource requirements could be accurately located quickly according to the specific nature and urgency of the emergency. Linear programming (LP) models were introduced as powerful mathematical tools aimed at optimizing resource allocation with the core goal of optimizing resource use to maximize overall benefits. The specific system design framework for an ecological safety early warning response process was shown in Figure 2 [27]. Specifically, the model was expressed as follows.

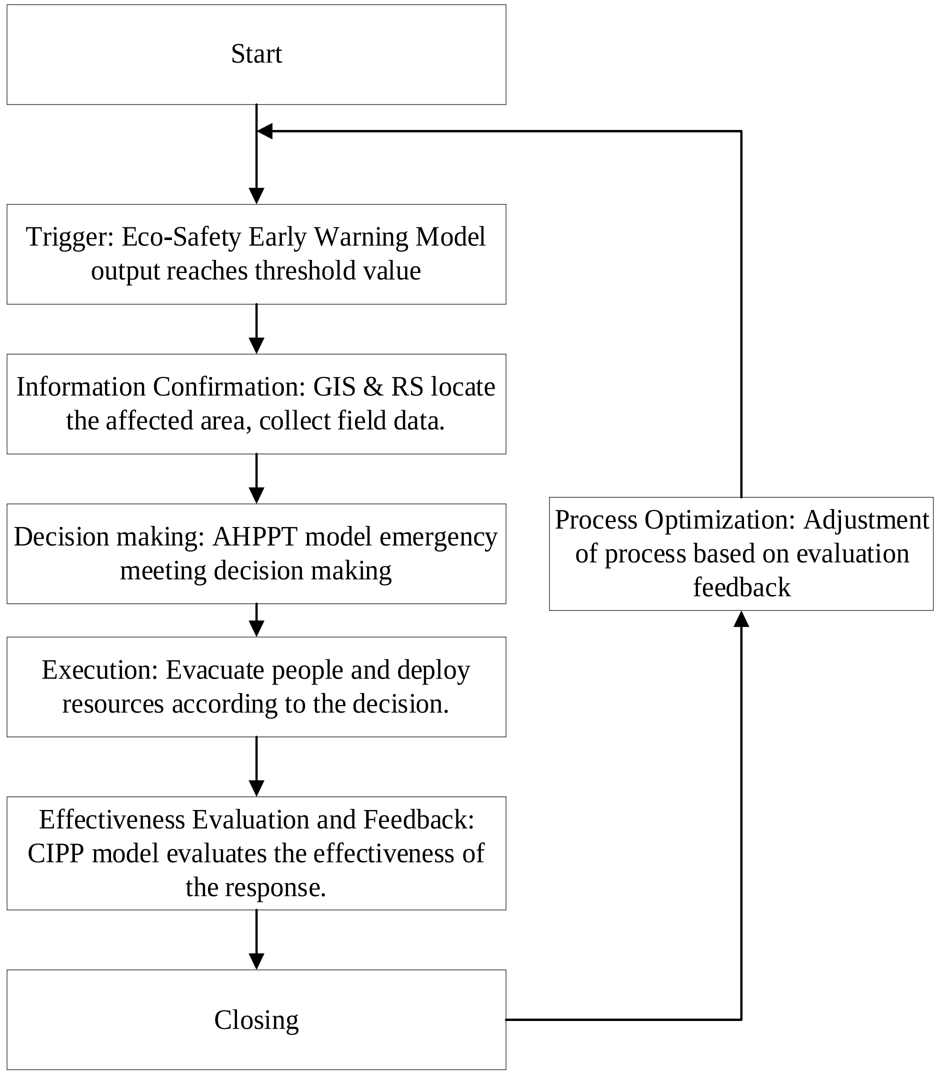

Figure 2. Emergency Management System Design.

$$Maximize\ Z = \sum_{j=1}^{m} c_j x_j \tag{6}$$

This objective function Z represented the maximization of the overall benefit of resource allocation, where it represented the unit benefit of allocation to resource *j* and emphasized the utilization value of each resource. In practice, resource allocation was constrained by various realistic conditions. The model ensured the feasibility of the solution through the following conditions as shown below [28].

$$Subjectto: \sum_{j=1}^{m} a_{ij} x_j \le b_i, i = 1, 2, ..., n \tag{7}$$

The consumption of resource *j* under the i[th] constraint condition was described, and the upper limit of the i[th] constraint was set, which meant that the resource allocation could not exceed the given total resource amount or bearing capacity. Such constraints ensured the reality and rationality of resource allocation from multiple dimensions such as resource supply limitation and operation restriction [29]. In addition, all allocated resource quantities must remain non-negative, guaranteed by the following condition, which meant that the use of any resource could not be negative, reflecting the logical rationality of resource allocation.

$$x_j \geq 0,\ j = 1, 2, \ldots, m \tag{8}$$

By solving the above linear programming model, how to allocate each resource optimally under certain constraints to maximize the overall benefit Z were scientifically determined. The application of this model provided emergency management departments with a rigorous set of decision support tools to ensure that resources could be deployed quickly, rationally, and efficiently in emergency situations to effectively meet various ecological security challenges [30]. Ecological restoration and long-term management planning were important links after emergency, aiming at restoring damaged ecology and improving the resilience of the system. Long-term safety management planning included establishing ecological safety supervision mechanism, adopting risk assessment cycle model with risk level (R), occurrence probability (P), severity (S), and exposure value (V), conducting regular assessment, guiding resource allocation and policy formulation, and ensuring continuous supervision and improvement of ecological safety.

Case study

Huangshan Mountain Scenic and Historic Spot (Anhui, China) was selected as a case study site with a total area of about 1,690 km^2 and was rich in biodiversity and a popular tourist destination for domestic and international tourists. The vegetation types and habitat distribution (http://www.ngii.org.cn/) were analyzed and processed by GIS to better understand and manage the natural environment of the scenic area. RS data was acquired from satellite images (https://earth.esa.int/web/sentinel/home) over the past five years and was used to monitor environmental changes such as vegetation cover, land use, and water quality. GPS data that was collected through a partnership with the local tourism authority in the city of Xiamen, Fujian, China recorded the travel paths of visitors between 2018 and 2022 to analyze visitor movement patterns and preferences. Big data came from online reviews and social media analysis through public platforms such as TripAdvisor (https://www.tripadvisor.com/) and Twitter (https://twitter.com/), through which visitors' behavior patterns and satisfaction could be understood to provide a basis for scenic area management. A total of 50,000 records including 35,000 (70%) records for training and 15,000 (30%) records for validation (testing) were used in this study, which ensured that the model could be effectively trained and then validated to assess its performance and reliability in predicting ecological vulnerabilities and managing emergency situations in tourist attractions.

Results and discussion

Comprehensive evaluation of indicators

Four main indexes of Huangshan Mountain Scenic and Historic Spot comprehensive evaluation index system included biodiversity, environmental pollution, landscape fragmentation, and tourist carrying capacity (Table 1). Each indicator had a weight indicating its importance in the overall evaluation, which was determined based on expert opinion and data analysis. Scores were based on actual survey and monitoring data and ranged from 0 to 100 with higher scores indicating better conditions. An evaluation of each indicator was given based on the score and was graded as "good", "moderate", "slightly polluted", and "near saturation" to help the understanding of overall situation of the area and guide the corresponding management measures. The simulation of tourist volume warning used ARIMA model to predict the tourist volume of each month in the next year according to historical data (Table 2). Seasonal factors were considered as visitor numbers increase significantly during certain seasons.

Biodiversity and environmental protection

The biodiversity survey data of the studied area included three species including plants, birds,

Table 1. Comprehensive evaluation index system of Huangshan scenic spot.

Indicators	Biological diversity	Environmental pollution	Scene fragmentation	Tourist carrying capacity
Weight	0.3	0.25	0.2	0.25
Score	80	65	75	85
Evaluation	Moderate	Moderate	Slightly polluted	Near saturation

Table 2. Prediction of visitor volume in Huangshan scenic spot (ARIMA model).

Month	Predicted visitors (10,000)	Warning state
1 month	15	normal
4 months	85	yellow warning
7 months	102	orange warning
10 months	116	blue warning

Table 3. Survey data of biodiversity in Huangshan scenic spot.

Species	Species number	Homogeneous richness index	Homogeneity index
plant	12,000	9.5	0.6
birds	150	8.3	0.5
insects	350	9.1	0.4

and insects (Table 3). The number of species indicated the number of each type of species found in the area. The average species richness index and average species evenness index were applied to measure biodiversity. The higher the richness index was, the richer the species diversity was, while the higher the evenness index was, the more uniform the species distribution was. These results helped the understanding of the biodiversity status of the area and provided a basis for biodiversity protection and ecotourism. A summary of environmental pollution monitoring data in Huangshan scenic spot including entrance, central area, and exit was shown in Table 4. Monitoring indicators included chemical oxygen demand (COD), biochemical oxygen demand (BOD), PM2.5, sulphur dioxide (SO_2), and nitrogen oxides (NOx), which were important indicators for measuring water and air quality. State evaluation was based on monitoring data given and was divided into "light", "medium", and "poor" three grades to understand the environmental pollution situation of Huangshan

Table 4. Environmental pollution monitoring results of Huangshan scenic spot.

Monitoring points	COD (mg/L)	BOD (mg/L)	PM2.5 (μg/m³)	SO_2 (μg/m³)	NOx (μg/m³)	State evaluation
Entrance	3.2	4.5	25	20	0.05	0.04
Central area	2.8	3.0	30	25	0.08	0.06
Exit	2.0	2.5	28	30	0.1	0.07

Table 5. Evaluation of tourist carrying capacity of Huangshan scenic spot.

Region	Environmental capacity (person/day)	Capacity of facilities (person/day)	Social capacity (person/day)	Actual daily visitors (person/day)	State of bearing capacity
Yingkesong	5,000	4,500	4,800	4,200	Safe
Guangmingding	3,500	3,000	3,200	3,800	Close to saturation
Xihai Grand Canyon	2,000	2,200	2,400	2,500	Good

scenic spot and provided a basis for environmental management.

Visitor management and carrying capacity

The evaluation of tourist carrying capacity of Huangshan scenic spot included three regions that were Yingke Pine, Guangmingding, and Xihai Grand Canyon. Environmental capacity, facility capacity, and social capacity were three dimensions to measure tourist carrying capacity, which represented the restrictions of environment, facilities, and cultural and social factors on tourist volume, respectively. The actual daily visitor volume was used as the actual monitored visitor volume. The carrying capacity status was determined based on the comparison of actual visitor volume to the capacities and was defined as "safe", "close to saturation", and "good" (Table 5). The results helped the understanding of the tourist carrying status of Huangshan scenic spot and provided a basis for tourist management and tourism planning.

Emergency response services and feedback

The feedback on the implementation effect of Incident Response Service measures in Huangshan Scenic Spot included additional security and cleaning, traffic control, peak-shifting propaganda, and ecological restoration. Effectiveness indicators included the measurement of visitor satisfaction, congestion index, and ecological recovery rate (Table 6).

Conclusion

This study deepened the research of ecological security early warning and emergency management systems for tourist attractions based on spatiotemporal evolution analysis and the existing research. By constructing a more precise and adaptable ecological safety

Table 6. Feedback on implementation effect of incident response service measures in Huangshan scenic spot.

Measures	Success effectiveness indicators	Evaluation	Improvement suggestions
Additional security and cleaning	Tourist satisfaction	Good	Increase environmental education programs
Traffic control	congestion index	General	Real-time adjustment of control strategy
Off-peak propaganda	Changes in peak visitor volume	Good	Multi-channel promotion
Ecological restoration	Ecological restoration rate	Good	Regular monitoring and assessment

evaluation index system, optimizing the early warning model using advanced spatiotemporal analysis technology, and designing a set of efficient emergency management systems, a set of solutions combining theory and practice were proposed for the ecological safety management of tourist attractions. This study also explored the strengthening of the intelligent management and service of ecological security by using cutting-edge technologies such as the Internet of Things and artificial intelligence under the background of intelligent tourism, which provided a scientific basis for the popularization to more scenic spots. In addition, the empirical study on typical scenic spots verified the practical application effect of theoretical models and management strategies. The results of this study would help tourist attractions respond quickly, manage effectively, and recover gradually when facing ecological crises, moving towards more sustainable future development. In addition, this study emphasized the importance of emergency management system design in ensuring the effective operation of tourism scenic spot ecological security evaluation systems and constructed a solid ecological security defense line through a scientific response process, efficient resource allocation, and a forward-looking recovery strategy.

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