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Study on the Evaluation Methodology of Landslide Susceptibility Based on Spatial-scale Analysis

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Abstract: Landslides are significant natural geological hazards. Landslide susceptibility evaluation involves the quantitative assessment and prediction of potential landslide locations and their probabilities. Research has explored susceptibility assessment methods based on spatial-scale analysis. This evaluation integrates two models—global and local scale—using a CNN model and a PSO-CNN coupled model. Key aspects include selecting evaluation factors and optimizing model parameters for landslide susceptibility at different scales. A major focus of current landslide research is utilizing prediction results to enhance prevention and control measures.

Keywords: Landslide susceptibility evaluation; Spatial-scale analysis; Lixian county; Geographical weighted regression; Particle swarm algorithm

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1. Introduction

Seismic landslides are phenomena in which seismic shaking causes a rock or soil mass to shear and slide a certain distance along a gently sloping surface [1]. Seismic landslides are the most common type of seismic geological hazards in large seismic events in mountainous areas within continents and are not only numerous and large in scale, but also extremely hazardous, often causing particularly serious damage to human activities [2]. Landslide risk assessment involves the quantitative evaluation and prediction of potential landslide locations, probabilities, and associated risks. The prediction results serve as a reliable foundation for landslide prevention and mitigation in mountainous regions, making it a longstanding focus of landslide research [3].

Landslide susceptibility evaluation methods are mainly divided into two categories, one is the simulation test method that uses geotechnical models combined with basic spatial geological information to predict the probability of landslides occurring in a specific area; the other is a statistical method to evaluate and predict the possibility of landslide occurrence in the study area by studying the relationship between landslide sample points and their geological environment through computer and mathematical statistics [4].

This paper explores a landslide susceptibility evaluation method based on spatial scale analysis. Drawing on theories and techniques from computer science, surveying and mapping, geology, and statistical analysis, a spatial scale model-based evaluation method is established. The study integrates two evaluation models—the CNN model and the PSO-CNN coupled model—and applies them to real-world cases for landslide susceptibility assessment. Additionally, the relationships among landslide susceptibility evaluation results, evaluation factors, and model parameters at different spatial scales are quantitatively analyzed. Evaluate model parameters at a spatial scale and quantitatively analyze their intrinsic relationships.

2. Research methodology

As a geological issue, landslide disasters exhibit spatial scale relevance. As natural phenomena occurring within specific temporal and spatial contexts, landslides inherently possess scale attributes. Additionally, as regional natural events, their main controlling factors, characterization features, and evolutionary processes are significantly influenced by scale [5]. Therefore, scale is an unavoidable issue in landslide susceptibility assessment. Addressing the limitations in theoretical methods and scale considerations in landslide susceptibility assessment, this study integrates theories and technical approaches from disciplines such as computer science, surveying and mapping, geology, and statistical analysis. Focusing on Li County in Sichuan Province as the study area and incorporating real-world cases, a methodological study on landslide susceptibility assessment is conducted based on multiscale analysis. A geographically weighted regression method is used for local segmentation and a coupled PSO-CNN model is established to complete the regional landslide susceptibility mapping. By comparing the results of different scales and different models, we explore the relationship between spatial scales and the results of landslide susceptibility evaluation, evaluation factors and parameters of the evaluation model, as well as the intrinsic reasons.

2.1. Establishment of a unified framework and process for multi-source data processing

In the challenging and important research field of landslide susceptibility evaluation, Geographic Information System (GIS) plays an important role as an indispensable hero behind the scenes. Among them, providing a unified data processing platform is an extremely key function. In the field of actual geographical research, the sources of spatial data are extremely complex, including the macro surface information captured by satellite remote sensing and the micro terrain dynamic data monitored by ground sensors [6]. GIS is like an efficient data integration master, which can methodically integrate these spatial data with different characteristics into standard projections and coordinate systems one by one. In this way, the original chaotic data has a unified spatial benchmark, which lays a solid foundation for the subsequent in-depth spatial analysis work, so that the analysis results are more scientific and accurate.

Moreover, with the aid of digital scanning, image recognition, and other advanced digital technologies, traditional paper maps containing rich geological information—such as topographic maps that accurately depict terrain relief, geological maps that reveal subsurface structures, and water system maps that illustrate water flow patterns—can be seamlessly integrated into the GIS platform. On this platform, the data contained in these paper maps are no longer isolated but are interrelated and complementary with other types of data, achieving a deep integration of data.

However, the multi-source data obtained by the above conventional methods are difficult to work together directly in landslide susceptibility assessment because of the differences in collection technology, storage specifications, and other relevant standards, just like individuals from different countries and speaking different languages. At this time, it is urgent to build a scientific and reasonable standard data processing framework. This framework is like an excellent translator, which can effectively eliminate the differences in data format, coordinate system, spatiotemporal resolution, projection, and other aspects so that all data can be accurately applied to landslide susceptibility evaluation in a uniform standardized format and provide strong data support for the prevention and management of geological disasters.

2.2. Scaling methodology in landslide susceptibility assessment identified

To quantify the effect of different scales on the results of landslide susceptibility evaluation, the best scale for landslide susceptibility evaluation is searched. When local scale segmentation is carried out, the influence of evaluation factors should be taken into account and ensure that the segmentation results are directly related to the susceptibility in some way.

Through the screening of experimental results of various methods and ideas, a Geographical Weighted Regression (GWR) model with spatial regression idea, which can link the evaluation factors and the susceptibility evaluation results, is selected as the scale segmentation model. The predecessor of Geographical Weighted Regression (GWR) is Spatially Varying- Coefficient Regression Model (SVCR), which can combine data with spatial location information with regression idea and the obtained regression parameters also have spatial location information, which can be used in geospatial analysis. The spatial heterogeneity of different location attributes can be quantified by using this model in geospatial analysis.

The geographically weighted regression method is used for local segmentation to study the relationship between the evaluation results, evaluation factors, and evaluation model parameters for different local areas. Comparison with the global scale proves that the local segmentation in this way has better evaluation accuracy.

2.3. Landslide evaluation factors were identified

In the evaluation system of landslide susceptibility, landslide evaluation factor data is the core and key to establish landslide sample data set [7]. The accuracy of the data is directly related to the reliability of the evaluation results, and whether the extraction method is scientific and reasonable also has a profound impact on the accuracy and depth of the evaluation. Both of them are key elements that cannot be ignored and need to be emphasized in the evaluation process of landslide susceptibility. In this paper, a total of 14 landslide evaluation factors, including landslide background factors and landslide inducing factors, were carefully screened and accurately extracted by drawing on the wisdom of predecessors and closely combining the fruitful results obtained by previous researchers in the study area with highly similar geological environmental conditions. To deeply analyze the spatial distribution law of landslide disasters, the frequency ratio method is further used to deeply integrate it with landslide data and a special study on the spatial distribution of landslide disasters for each evaluation factor is carried out, to provide more solid data support and theoretical basis for landslide susceptibility evaluation. The landslide evaluation factors include the following:

(1) Topographic and geomorphological factors: elevation, slope, slope direction, plane curvature, profile curvature, slope morphology, surface roughness, surface relief

(2) Geological factors: stratigraphic lithology, distance from faults

(3) Hydrological factor: distance from water system

(4) Triggers: NDVI (Normalised Difference Vegetation Index), distance from roads, distance from settlements

2.4. Application of coupled different landslide susceptibility assessment models is realised

Convolutional Neural Network (CNN) is an optimization algorithm based on the TDNN model. It is mainly used for intelligent recognition of speech and pictures. Particle Swarm Optimization (PSO) is an optimization algorithm improved from Complex Adaptive System (CAS), which is essentially an optimization process [8]. The optimization principle of PSO can be understood as follows: in a multi-dimensional space, multiple moving points, known as "particles", navigate the space following specific motion rules. After function calculations, these particles seek the Fitness Value within the space. Their movement is not only governed by the initial algorithm's rules but also influenced by their ability to "perceive" their position and relative relationship to the Fitness Value throughout the motion process. By coupling the two algorithms and utilizing PSO to optimize the selection of activation functions, the number of nodes in convolutional and pooling layers, and the number of convolutional kernels, the CNN algorithm can maximize its computational efficiency in vulnerability evaluation. This approach enhances both the accuracy and speed of the evaluation process.

In the field of landslide susceptibility evaluation, to achieve more accurate and efficient risk assessment, this study focuses on integrating intelligent algorithms with deep learning models and conducts in-depth research on the development of a PSO-CNN coupled model. We apply the PSO algorithm to the CNN model to optimize its parameters. In the landslide evaluation scenario, the attributes of each slope unit in the study area serve as the training sample dataset, encompassing detailed information on slope gradient, slope direction, rock and soil types, hydrological conditions, and other relevant factors. The PSO algorithm functions like an intelligent explorer, continuously iterating through the complex parameter space to identify the CNN model parameters that best fit the sample data. This approach not only significantly enhances the accuracy of model training and improves the precision of landslide susceptibility assessment but also increases training efficiency, saving considerable time and computing resources. Additionally, it provides strong support for the prediction and prevention of landslide disasters.

2.5. Explored the relationship between different scales and landslide susceptibility assessment models and parameter selection

To capture the differences in landslide susceptibility evaluation results at different scales, relying solely on the susceptibility zoning map is insufficient and further quantitative analysis is necessary. Therefore, this paper quantifies the differences in the evaluation results of the PSO-CNN model at global and local scales using class-specific accuracy analysis, overall prediction accuracy analysis, and receiver operating characteristic (ROC) curve analysis. Additionally, it examines the reasons for these differences, the relationship between scale and model parameters, and other influencing factors. The differences, the relationship between scale and model parameters, and other influencing factors were analyzed.

Through the analysis of the relationship between scale and landslide evaluation factors, as well as the importance of these factors in different local areas at local scales, the following conclusions were drawn:

(1) The category-specific accuracy of landslide susceptibility zoning at the local scale is higher than at the global scale across all susceptibility zones, making the local-scale assessment more precise.

(2) The overall prediction accuracy analysis indicates that the results at the local scale outperform those at the global scale, both in individual local areas and when combined.

By analyzing the relationship between spatial scale and the parameters of the landslide susceptibility assessment model, the following conclusions were drawn:

(1) The parameters of the landslide susceptibility evaluation model at the same scale have a significant impact on both the evaluation results and their accuracy.

(2) The optimal model parameters obtained by PSO vary between global and local scales, and even among different local scales. The fundamental reason for this difference is the variation in sample data across different local areas. As the PSO algorithm searches for the optimal parameters that best fit the characteristics of each dataset, the resulting optimal solutions differ accordingly.

3. Conclusion

Based on the ArcGIS platform, data from multiple sources were collected and organized, the characteristics and attributes of various data were analyzed, and 14 landslide evaluation factors were extracted by combining the relevant data in Li County. A PSO-CNN coupling model is constructed and the optimal solution of CNN model parameters is searched by PSO algorithm to improve the accuracy and efficiency of model training. Applying the multi-scale analysis method throughout the landslide susceptibility evaluation process involves dividing the evaluation scale into global and local levels, conducting an in-depth comparison of the evaluation results at both scales, and analyzing the underlying reasons for these differences.

Geographically weighted regression is proposed to address the issue of local segmentation within the study area. This segmentation ensures that landslide evaluation factors within each local area have a similar influence on landslides while minimizing the mutual influence of evaluation factors between different local areas, thereby refining the evaluation process. Various methods were used to quantify the differences between landslide susceptibility evaluation results at global and local scales, including category-specific accuracy analysis, overall prediction accuracy analysis, and ROC curve analysis. The three indices at the global scale were 61.31%, 84.44%, and 0.832, respectively, while at the local scale, they were 72.07%, 88.27%, and 0.914. The results indicate that the local-scale evaluation outperforms the global-scale evaluation, demonstrating the effectiveness of local segmentation in improving evaluation accuracy.

The influence of landslide susceptibility evaluation factors on landslides at both the global and local scales were analyzed, as well as the optimal model parameters for landslide susceptibility evaluation at different scales. The results indicate that the importance of evaluation factors at the global scale is approximately the average of their importance across all local areas. Compared to the global scale, the local scale has a smaller sample size with more consistent characteristics. As a result, optimizing evaluation model parameters through sample-based training yields improved results.

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Disclosure statement

The authors declare no conflict of interest.

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