International Journal of Environment, Agriculture and Biotechnology
Vol-11, Issue-3; May-Jun, 2026
Peer-Reviewed International Journal
Journal Home Page Available: https://ijeab.com/
Journal DOI: 10.22161/ijeab

Characteristics of Soil Erosion in Guangdong Province Based on the USLE and InVEST Models

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Received: 10 Apr 2026; Received in revised form: 04 May 2026; Accepted: 08 May 2026; Available online: 16 May 2026

***Abstract*— Taking Guangdong Province as the study area, this research integrates multi-source geospatial data—including DEM, precipitation, soil, and land cover—and couples the USLE and InVEST models. The study calculates five core factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), vegetation cover (C), and conservation practice (P), to reveal the spatial heterogeneity and formation mechanisms of both potential and actual soil erosion. The results indicate that rainfall erosivity exhibits a spatial pattern that is generally higher in the south and west, and lower in the north and east. High values of soil erodibility are concentrated in the core Pearl River Delta (PRD) region and the coastal areas of western Guangdong (Zhanjiang), while low values are distributed in the mountainous and hilly regions of northern and eastern Guangdong. Land use is dominated by forestland, whereas construction land is clustered within the PRD urban agglomeration. High-risk zones for potential soil erosion are primarily located in the Nanling Mountains of northern Guangdong and the hilly areas of western Guangdong, largely controlled by natural background conditions such as topography and soil properties. Although vegetation cover and conservation measures significantly mitigate regional soil erosion intensity, moderate to severe erosion risks persist in the Leizhou Peninsula and the low-hilly agricultural areas of northern Guangdong. This study clarifies the spatial distribution patterns of soil erosion, providing a scientific basis for precise soil and water loss prevention, ecological restoration, and territorial spatial planning.*

Keywords*— Guangdong Province, USLE model, InVEST model, Soil Erosion

I. INTRODUCTION

Soil erosion is a natural process in which the Earth's surface soil is detached, transported, and deposited under the action of wind and water. This process leads to the thinning of soil layers, the decline of soil fertility, and the reduction of water retention capacity, ultimately resulting in land degradation, climatic deterioration, ecological degradation, and an increase in natural disasters [1]. Currently, soil erosion has become one of the major environmental issues on a global scale [2], posing severe threats to regional ecological security and the sustainable development of agriculture. Scientifically assessing regional soil erosion and revealing its spatial heterogeneity are fundamental to implementing precise prevention and control of soil and water loss, as well as optimizing ecosystem services.

The Universal Soil Loss Equation (USLE) is a classic method for the quantitative assessment of soil erosion. In conducting regional soil erosion assessments and predictions, some researchers have developed their own slope soil erosion prediction models by using the USLE as a reference framework and integrating local actual conditions [3-10]. Although the USLE can efficiently estimate slope soil erosion, it has certain limitations, as it tends to overlook sediment retention capacity at the plot scale and watershed hydrological processes during calculations [11]. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model, jointly developed by Stanford University, the World Wide Fund for Nature (WWF), and other institutions, can integrate multi-source data such as topography, climate, soil, and land use. By accounting for both upslope sediment interception and the impact of watershed reservoirs, the InVEST model achieves precise quantification and spatial visualization of soil conservation services, thereby overcoming the shortcomings of the traditional USLE model [12-13].

Regarding the application of the InVEST model in soil conservation, foreign scholars have already conducted relevant studies. For instance, Marques et al. (2021) modeled sediment retention services and soil erosion changes in Portugal using a spatiotemporal analysis method [14], and Ureta et al. (2021) quantified the ecological benefits of landscapes through an analysis of the impacts of land cover change on ecosystem services in the United States [15]. Domestically, scholars have also successively applied the InVEST model to soil erosion research. For example, Zhou et al. (2010) simulated soil erosion in the mountainous areas of Beijing [2]; Wang et al. (2014) studied the soil conservation function of the ecosystem in Ningde, Fujian [16]; Chen et al. (2020) investigated the current status and function of soil conservation in the Qilian Mountain National Nature Reserve [17]; He et al. (2019) researched the characteristics of soil erosion in the Qihe River Basin of the Taihang Mountains [18]; and Wang et al.(2019) examined the soil erosion intensity in Yan'an City before and after the Grain for Green Program [19].

Located on the southern coast of China, Guangdong Province features a subtropical monsoon climate with abundant rainfall and concentrated rainstorms. The terrain is dominated by mountains and hills with complex geological conditions. Coupled with rapid urbanization and intensive land development, the risk of soil erosion in the region is prominent. Currently, existing studies on soil erosion in Guangdong mostly adopt a single model (either USLE or InVEST) or are limited to specific watersheds. At the provincial scale, there is a scarcity of research that systematically couples USLE (for calculating erosion potential) with InVEST (for ecosystem service assessment) to analyze the entire erosion-retention process. Meanwhile, relevant studies have largely focused on specific watersheds or local areas, and systematic analyses of erosion characteristics based on the coupling of USLE and InVEST models at the provincial scale remain relatively lacking. Therefore, this paper takes Guangdong Province as the study area and couples the USLE and InVEST models to quantitatively assess actual and potential soil erosion. It aims to clarify the spatial distribution patterns and driving factors of erosion, providing a scientific basis for soil and water loss prevention, ecological protection and restoration, and the optimization of territorial space.

II. DATA AND METHODS

2.1. Overview of the Study Area

Guangdong Province is located between 20°13′N–25°31′N and 109°39′E–117°19′E at the southernmost tip of mainland China. It borders Fujian Province to the east, Guangxi to the west, Hunan and Jiangxi provinces to the north, and faces the South China Sea to the south, with a total land area of approximately 179,800 km². The province administers 21 prefecture-level cities and features a prominent land-sea location, characterized by a vast sea area and a mainland coastline stretching 4,114.3 km (Fig. 1).

The overall terrain is high in the north and low in the south. The geomorphology is dominated by mountains and hills, which together account for nearly 60% of the province's area, while terraces and plains make up the remaining 40%. The northern Nanling Mountains and the eastern Lianhua Mountains have relatively high elevations, with Shikengkong (1,902 m) being the highest peak in the province. The central region features an alternating distribution of hills and basins, while the south and coastal areas are mainly composed of the Pearl River Delta, Chaoshan Plain, and Leizhou Terrace. Granite is the most widely distributed bedrock in the region, followed by sandstone and metamorphic rocks. Large areas of limestone are distributed in northwestern Guangdong. The complex lithology easily induces natural soil erosion.

Climatically, the province belongs to the East Asian monsoon region, spanning the central subtropical, southern subtropical, and tropical zones from north to south. The annual average temperature ranges from 19 to 24℃, and the annual average precipitation reaches 1,771 mm. Rainfall is concentrated from April to September, with frequent rainstorms and typhoons. The high intensity and concentrated duration of rainfall provide sufficient hydrodynamic conditions for soil erosion. The dominant soil types include red soil, latosolic red soil, laterite, and paddy soil. These soils are generally heavy in texture, with poorly developed aggregate structure and relatively weak anti-erodibility and anti-scourability.

Land use is primarily composed of forestland, cultivated land, and construction land. Forestland is concentrated in the northern and eastern mountainous and hilly regions, while cultivated land is mostly distributed in coastal and river valley areas. The expansion of construction land is particularly significant in the Pearl River Delta and the central urban areas of various cities. Influenced by the combined effects of complex topography, a rainy climate, fragile soil texture, and high-intensity human activities, the risk of soil erosion in mountainous and hilly areas is prominent. Therefore, conducting research on soil erosion characteristics in this region holds significant practical implications.

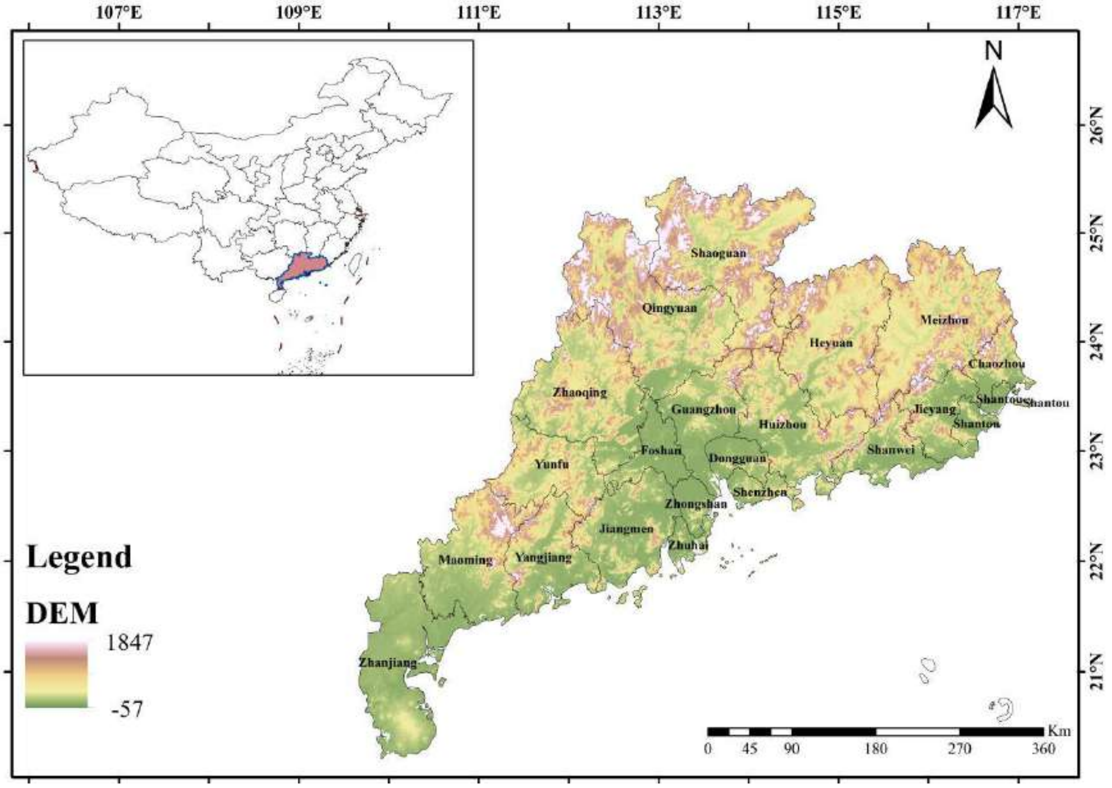

Fig. 1 Topographic overview of Guangdong Province

2.2. Data Sources

The operation of the InVEST model requires raster layers and parameter tables with consistent resolution and projected coordinate systems. In this study, all raster data were uniformly processed to a 90 m × 90 m resolution under the WGS_1984_EASE_Grid_Global projected coordinate system. The data required for the model and their sources are listed in Table 1. Specifically:

(1) The Rainfall Erosivity (R) layer was derived from the monthly precipitation data for the year 2020, which were downloaded from the Geographical Resources Sub-center of the National Earth System Science Data Center (National Science and Technology Infrastructure of China), and subsequently calculated using ArcGIS raster calculator.

(2) The Soil Erodibility (K) layer was calculated

using the Erosion-Productivity Impact Calculator (EPIC) model, based on the China soil dataset from the Harmonized World Soil Database (HWSD) downloaded from the National Tibetan Plateau Data Center.

(3) The Slope Length and Steepness factors (L, S) were derived from the 90 m SRTM DEM data downloaded from the Geospatial Data Cloud, and calculated using the topographic relief tools in ArcGIS.

(4) The watershed data for the study area were extracted from the 90 m SRTM DEM data (sourced from the Geospatial Data Cloud) using the hydrological analysis tools in ArcGIS.

(5) The land cover raster data were obtained from the annual 30 m resolution land cover dataset for China released by Professors Jie Yang and Xin Huang of Wuhan University, available on the Zenodo platform, and subsequently processed through reclassification in ArcGIS.

(6) The Biophysical Table consists of the land use code (lucode), the cover-management factor (usle_c), and the support practice factor (usle_p).

Table 1 Research data and their sources

Data Requirements	Data Sources	Purpose
Annual precipitation data	(https://gre.geodata.cn)	Generate R factor layer
Soil texture data	（https://data.tpdc.ac.cn/home）	Generate K factor layer
90m DEM data	（https://www.gscloud.cn/home#page1/1）	Generate K factor layer
Land cover raster data	（https://zenodo.org/records/18180184）	Generate land use layer

2.3. Research Methods

2.3.1. Technical Route

This study is based on data including 90m DEM, precipitation in 2020, HWSD, and land cover raster data of Guangdong Province. The main analysis steps (as shown in Fig. 2) are as follows:

(1) Preparation of parameters required for the InVEST model operation: The 90m DEM data were mosaicked and extracted by mask to obtain the topographic relief of the study area using the Focal Statistics tool in ArcGIS. Subsequently, the mosaicked 90m DEM data were processed using the Hydrological Analysis tools in ArcGIS to extract the watershed data of the study area.

(2) The monthly precipitation data for 2020 were extracted by mask. The annual precipitation was first calculated using the Raster Calculator in ArcGIS, and then the R factor was computed based on the R factor formula.

(3) The HWSD data were extracted by mask, and the K factor was calculated using the Raster Calculator in ArcGIS based on the EPIC model.

(4) The land cover raster data were reclassified according to the *Current Land Use Classification (GB/T 21010—2017)* standard to obtain the land use data meeting the model requirements.

(5) The values for the C and P factors were assigned based on existing literature.

(6) The above parameters were input into the InVEST model to obtain the actual and potential soil erosion moduli.

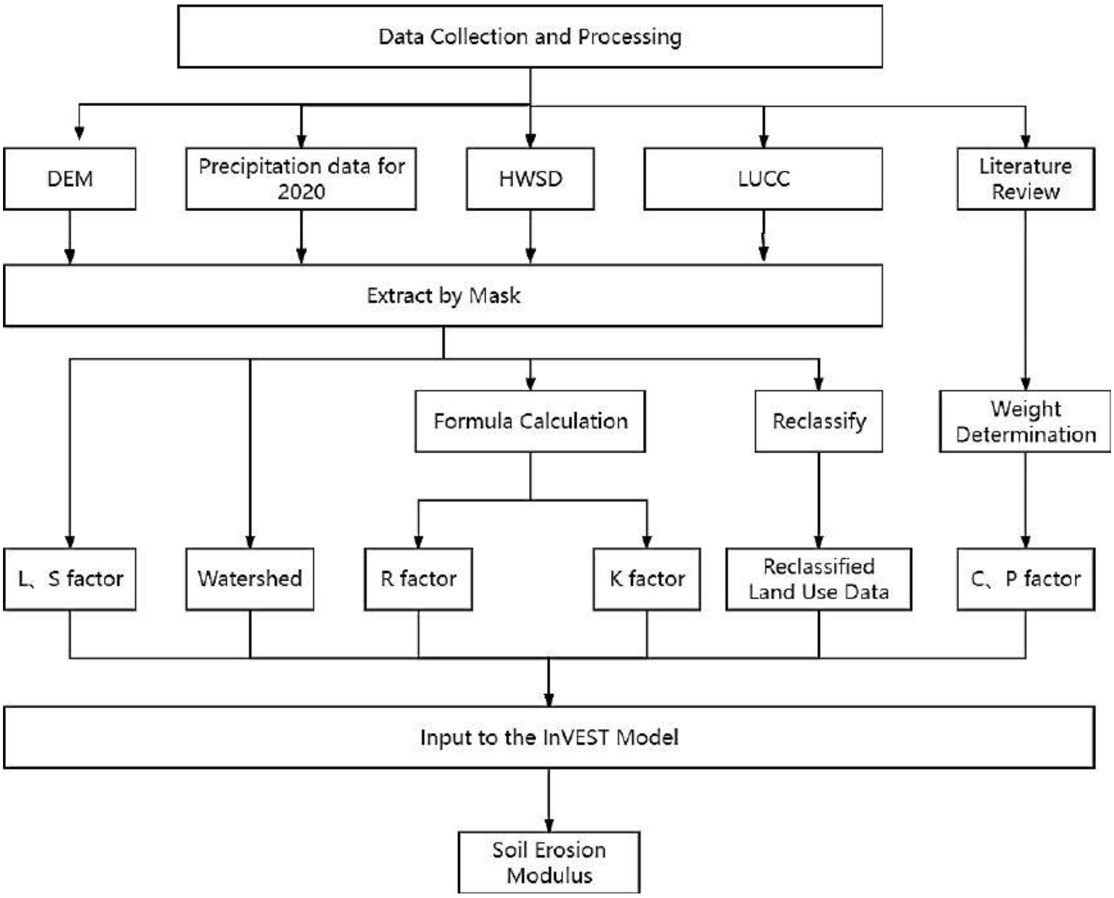

Fig. 2 Flowchart of the technical route

2.3.2 USLE and InVEST Models

The InVEST model is a comprehensive assessment tool for ecosystem services and tradeoffs. Supported by the Natural Capital Project, it was successfully developed in 2007 through the collaboration of Stanford University, the World Wildlife Fund (WWF), and The Nature Conservancy (TNC). Currently, it has been widely applied both domestically and internationally. The model not only achieves quantitative assessment of ecosystem service functions but also realizes their spatial expression with the support of 3S technology. The assessment results are presented in the form of maps, which can reflect the spatial heterogeneity of ecosystem service functions, enabling decision-makers to better grasp the actual situation and make further plans and countermeasures [20].

According to module service types, InVEST can be divided into three groups: supporting services, ultimate services, and enhancement tools (Table 2) [21]. Among them, supporting services serve as the foundation for other types of ecosystem services, from which humans cannot directly benefit. Ultimate services are divided into two parts: biophysical provision and services, from which humans can directly benefit [22].

Table 2 InVEST Model Framework

Supporting Services	Ultimate Services		Enhancement Tools
	Provision: Services	Undifferentiated Provision and Services	
Habitat Quality	Forest Carbon Edge Effect	Timber Production and Management	Scenario Generator: Proximity Based
Habitat Risk Assessment	Coastal Blue Carbon	Wave Energy Production	Coastal Vulnerability

Crop Pollination	Carbon Storage and Sequestration	Visitation: Recreation and Tourism	DelineateIt
Water Quality	Water Yield	Coastal Protection	Scenario Generator
	Nutrient Delivery Ratio	Wind Energy Production	Script and API
	Viewshed: Scenic Quality	Marine Fisheries Production	Route DEM
	Sediment Delivery Ratio（SDR）	Marine Aquacultur	GLOBIO
	Nutrient Delivery Ratio	Crop Production	

This study employs the Sediment Delivery Ratio (SDR) module within the soil conservation component. This module represents various integrated measures capable of preventing soil erosion, conserving soil resources, and maintaining or enhancing land productivity. The soil conservation service function refers to the ability of surface cover, such as vegetation, to reduce soil erosion on a given plot while simultaneously intercepting sediment originating from upstream areas [23].

The Universal Soil Loss Equation (USLE) is currently the most widely used method for calculating soil conservation. Its principle involves calculating the potential soil erosion (RKLS) and the actual soil erosion (USLE) for each raster cell, respectively. The soil conservation for each cell is then obtained by subtracting the actual erosion from the potential erosion. The relevant formulas are as follows (1) and (2):

$RKLS=R\times K\times LS$ ………………（1）

$ULSE=R\times K\times LS\times C\times P$ ……（2）

where R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the topographic factor, C is the cover-management factor, and P is the support practice factor.

However, in the actual soil erosion process, not all actual soil erosion reaches the watershed outlet. There exists a Sediment Delivery Ratio (SDR) in this process, because downstream plots cause deposition of the sediment load coming from upstream plots. The amount deposited during the entire flow process towards the watershed outlet is defined as the sediment deposition amount [24].

The InVEST model calculates regional soil conservation based on an improvement of the Universal Soil Loss Equation. Specifically, the InVEST model fully accounts for sediment deposition, thereby enabling a more accurate estimation of regional soil conservation services. The relevant formulas are as follows (3), (4), and (5):

$SM_i=RKLS_i-USLE_i+SR_i$ ………（3）

$SR_i=SE_{i-1}\times(1-SDR_i)$ …………（4）

$SE_i=USLE_i+SE_{i-1}\times SDR_i$ ………（5）

where SM is the soil conservation amount, SR is the sediment deposition amount, SE is the sediment transport amount, and i－1 represents the upstream pixel of pixel i.

2.4 Model Parameter Construction

2.4.1 Rainfall Erosivity Factor (R)

Rainfall erosivity is the primary foundational factor of the USLE model. It is a dynamic indicator used to evaluate rainfall-induced soil detachment and transport, reflecting the potential impact of rainfall conditions on soil erosion [18]. In this study, following the Guidelines for Calculating Soil Loss in Production and Construction Projects (SL773-2018), the rainfall erosivity factor R was assigned the value of Rd after obtaining the average precipitation data for 2020. The annual average precipitation erosivity factor was calculated using Formula (6):

$R_d=0.067\,P_d^{\,1.627}$ ………（6）

In Formula (6): Rd is the annual precipitation erosivity factor, with units of MJ·mm/(hm²·h); Pd is the annual average precipitation, with units of mm.

2.4.2 Soil Erodibility Factor (K)

Soil erodibility is a crucial indicator for evaluating the sensitivity of soil to erosion and is also a vital parameter for soil erosion prediction [25]. The most commonly used methods for determining the K value include the median particle size method, direct measurement, and the EPIC model. Most of these methods require numerous soil property parameters, such as soil texture, structure, organic matter, and permeability. However, acquiring data on soil structure and permeability is often challenging. Therefore, this study adopts the K value calculation method from the Erosion-Productivity Impact Calculator (EPIC) model proposed by Williams et al. [26-27] as a surrogate model. This method is primarily related to the contents of sand, silt, clay, and organic matter. Focusing more on soil properties, this model can scientifically reflect soil erodibility. Thus, it was calculated using soil particle composition and organic carbon content data. The result was multiplied by 0.1317 to convert it to international units. The calculation method is shown in Formula (7):

$$K=\{0.2+0.3\exp[-0.0256\,SAN(1-SIL/100)]\}\,[SIL/(CLA+SIL)]^{0.2}\,\{1-0.25C/[C+\exp(3.72-2.95C)]\}\,\{1-0.7SN_1/[SN_1+\exp(-5.51+22.9SN_1)]\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

In Formula (7): K is the soil erodibility [$t\cdot hm^2\cdot/(MJ\cdot mm\cdot hm^2)$]; SAN is the sand content (%); SIL is the silt content (%); CLA is the clay content (%); $SN_1=1-SAN/100$; C is the organic carbon content (%) [28].

2.4.3 Slope Length and Steepness Factors (L, S)

The L and S factors are among the most critical parameters in the USLE equation. They reflect the relationship between slope gradient and the land surface, and their essence lies in the distance a raindrop or sediment travels until its energy is exhausted. Slope height characterizes ground flatness; generally, slope length refers to the specific projection length of the water flow trajectory on the slope surface onto the horizontal plane. The steeper the slope, the more severe the soil erosion; conversely, the longer the slope, the more the runoff formation tends to decrease. The InVEST model automatically completes the calculation of the L and S factors based on user-inputted slope thresholds and generates the corresponding L and S layers [18]. It is worth noting that the model automatically selects different formulas for calculations in low-slope and high-slope areas [12].

2.4.4 Land Cover Raster Data

Land cover raster data can reflect the different land use types within the study area. Since different land use types have varying erosion intensities and soil and water conservation measures, they must be analyzed and understood. In this study, we downloaded the annual land cover raster data of China with a 30-meter resolution, released by Professors Yang Jie and Huang Xin from Wuhan University, via the Zenodo platform. According to the *Current Land Use Classification (GB/T 21010—2017)* standard, the remote sensing image data were reclassified into six land use types: cultivated land, forest land, grassland, water bodies, unused land, and construction land.

2.4.5 Cover-Management Factor (C)

The cover-management factor C is defined as the ratio of soil erosion under a specific vegetation cover and management condition to the soil erosion on a continuously fallow, clean-tilled plot. It reflects the impact of vegetation or crops and management practices on soil loss, with values ranging between 0 and 1 [29].

2.4.6 Support Practice Factor (P)

In the InVEST or USLE model, the P factor is typically not determined by a formula but is assigned empirically based on land use types and soil and water conservation engineering. The support practice factor P refers to the ratio of soil loss after adopting conservation measures to the soil loss when planting along the slope (up and down the slope). Its value ranges from 0 to 1; an extreme value of 0 represents an area with no erosion, while an extreme value of 1 indicates an area where no conservation measures have been taken [13]. According to previous studies [30], after years of soil and water loss control in the local area, soil erosion in some regions has been effectively controlled.

III. RESULTS AND ANALYSIS

3.1. Spatial Distribution of the R Factor

The rainfall erosivity factor is the core driver of soil erosion. The data results (Fig. 3) show that the rainfall erosivity (R factor) in Guangdong Province generally exhibits a spatial pattern of "higher in the south and lower in the north, and higher in the west and lower in the east." The northern Guangdong mountainous areas (Shaoguan, Qingyuan, Meizhou) and the eastern coastal regions (Chaozhou, Shantou, Jieyang, Shanwei) are low-value zones, with the R factor dropping to as low as 6428.13 $MJ\cdot mm/(hm^2\cdot h)$. In contrast, the southern part of Jiangmen

City and the southeastern part of Yangjiang City are high-value zones, with the R factor peaking at 16793.8 MJ·mm/(hm²·h). Although the eastern Guangdong region is coastal, it contains many mountainous areas. Influenced by the leeward slope effect or the seasonal distribution of precipitation, the rainfall erosivity index in this area is relatively low. In the core area of the Pearl River Delta (such as Guangzhou and Foshan), high urbanization and the urban heat island effect have altered the local microclimate. Additionally, station interpolation is affected by impervious surfaces, resulting in relatively low R factor values in this region compared to the rest of the province.

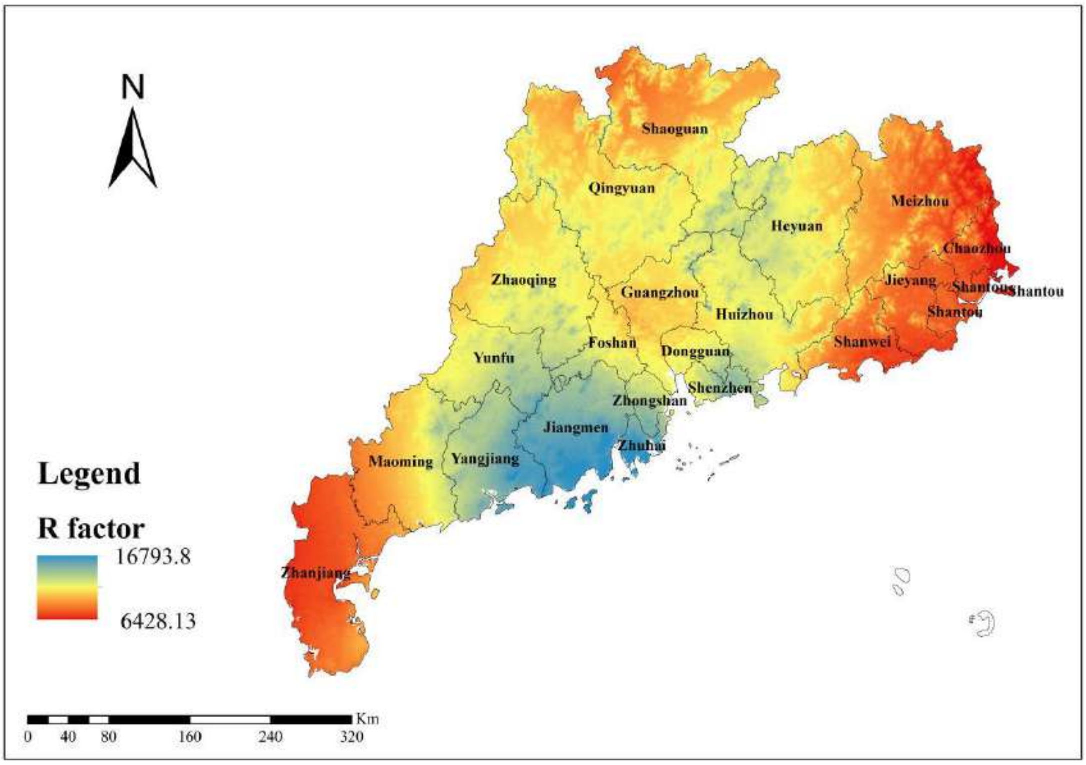

Fig. 3 Spatial distribution of the R factor

3.2. Spatial Distribution of the K Factor

Soil erodibility reflects the sensitivity of soil to erosion. Data analysis results indicate significant spatial differences in the soil erodibility factor (K factor) across Guangdong Province (Fig. 4). High-value zones are concentrated in the core area of the Pearl River Delta and the coastal zones of Zhanjiang in western Guangdong. These areas are dominated by latosolic red soil and laterite, characterized by heavy soil texture and loose structure, resulting in weak resistance to erosion. Low-value zones are mainly distributed in the mountainous and hilly regions of northern and eastern Guangdong, where red soil and yellow soil prevail. These soils have relatively high organic matter content and well-developed aggregate structure, leading to lower erodibility. Overall, the intrinsic soil conditions in the Pearl River Delta and coastal plain areas are more susceptible to erosion, making them key regions for soil conservation efforts.

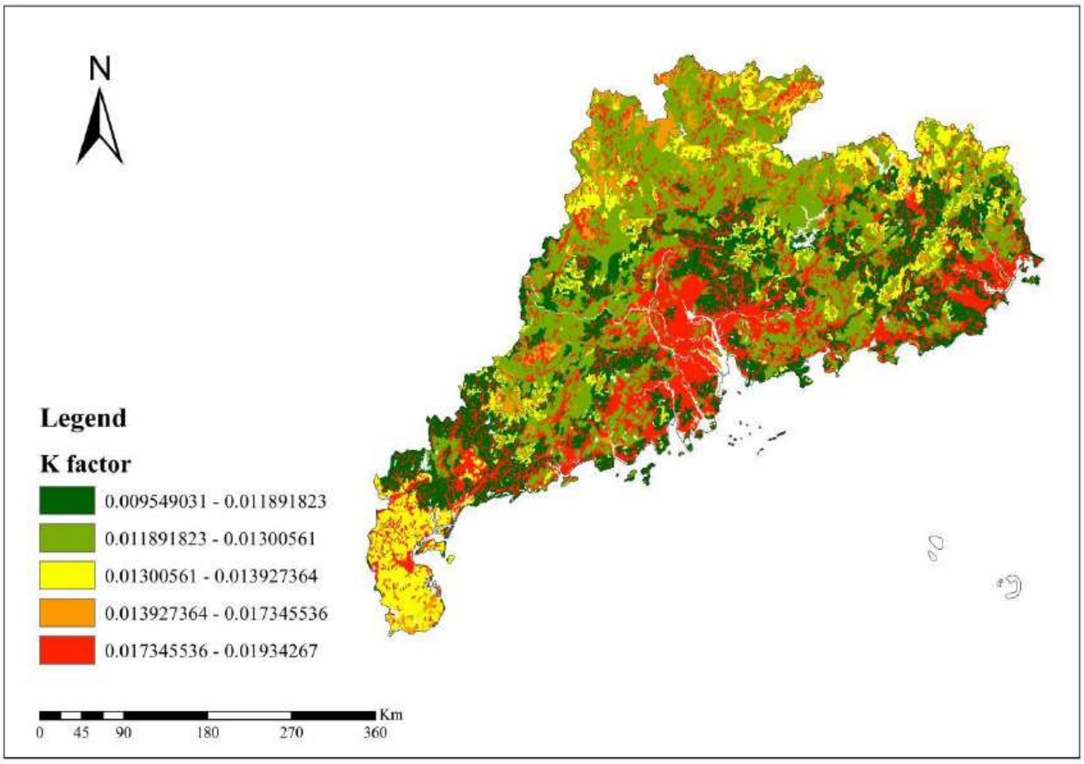

Fig. 4 Spatial distribution of the K factor

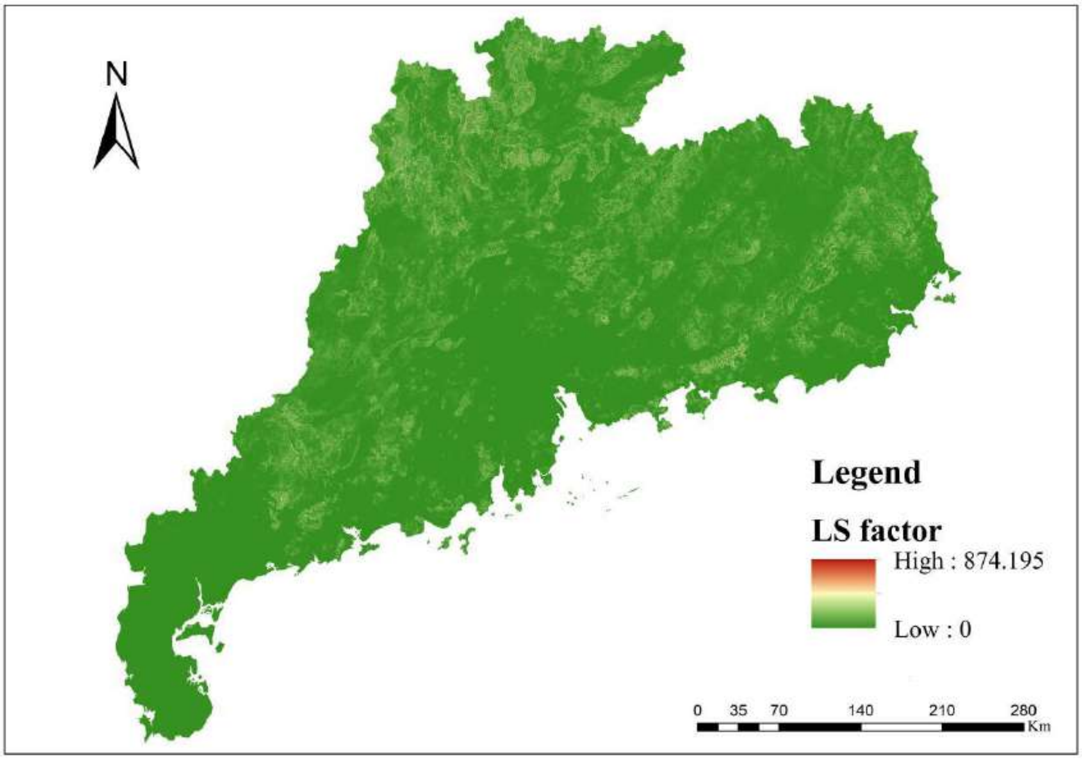

Fig. 5 Spatial distribution of the L and S factors

3.3. Spatial Distribution of the L and S Factors

The spatial distribution maps of the slope length (L) and steepness (S) factors, extracted based on a 90 m × 90 m resolution DEM, reveal that the topographic relief in

Guangdong Province exhibits a distinct gradient feature of "higher in the north and lower in the south, and higher in the west and lower in the east" (Fig. 5). This pattern aligns closely with the distribution of geomorphological units in the province.

The high-value zones of the L and S factors are mainly concentrated in the Nanling Mountains of northern Guangdong (Shaoguan, northern Qingyuan), the Yunwu Mountain system of western Guangdong (Yunfu, northern Maoming), and the Lianhua Mountains of eastern Guangdong (Meizhou, eastern Heyuan). These areas are characterized by high elevation, intense terrain dissection, and extended slope lengths, constituting the peak zones for the L and S factors. In the absence of vegetation cover and human intervention, these regions serve as the strongest natural driving sources of potential soil erosion. The low-value zones of the LS factors are widely distributed across the Pearl River Delta alluvial plain (Guangzhou, Foshan, Dongguan, southern Huizhou) and coastal zones (Zhanjiang, southern Maoming, and the Chaoshan Plain in Shantou). These areas feature flat terrain, minimal slopes, and short slope lengths. The slow velocity of water flow convergence results in a weak topographic driving force for soil erosion.

3.4. Spatial Distribution of Land Use

Land use directly influences surface cover and the intensity of human activities. The land use pattern in Guangdong Province is dominated by forest land (Fig. 6), which accounts for over 60% of the total area. It is mainly concentrated in the mountainous and hilly regions of northern and eastern Guangdong, playing a significant positive role in soil conservation. Cultivated land is primarily distributed in Zhanjiang (western Guangdong), the periphery of the Pearl River Delta, and the plains of eastern Guangdong, serving as the main area of disturbance from agricultural activities. Construction land is concentrated in the urban agglomerations of the Pearl River Delta (such as Guangzhou, Shenzhen, and Dongguan) and the central urban areas of various prefecture-level cities, exhibiting a distribution pattern that radiates from the center outward. High-intensity development in these areas tends to destroy surface vegetation and exacerbate local erosion risks. Water bodies, grassland, and unused land account for a relatively low proportion, being sporadically distributed along rivers, coastal zones, and the edges of mountainous areas.

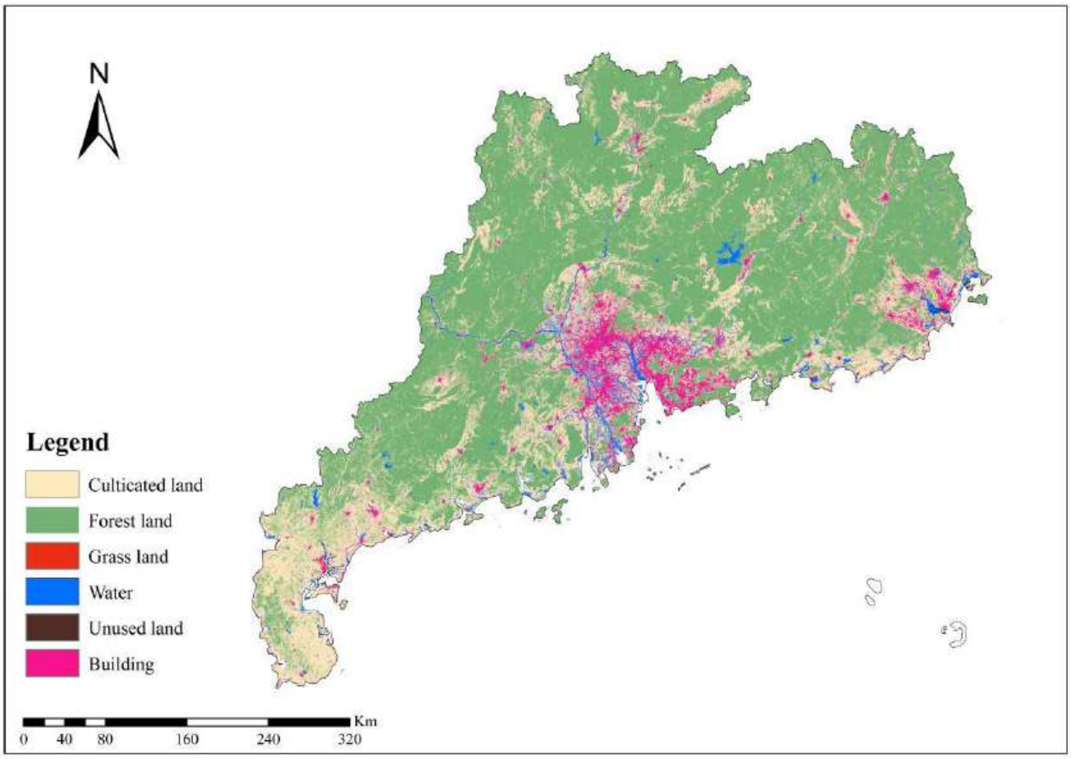

Fig. 6 Spatial distribution of land use types

3.5. Assignment of C and P Factors

The values of the C factor were referenced from the studies of Ma Guofu and Pan Meihui et al. [31-32]. The value was assigned as 0.05 for cultivated land, 0.03 for forest land, 0.04 for grassland, 0 for water bodies and construction land, and 1 for unused land, as shown in Table 3.

Table 3 C factor assignment table

lucode	USLE_C
1（Cultivated land）	0.05
2（Forest land）	0.04
3（Grass land）	0.03
4（Water）	0
5（Unused land）	1
6（Building）	0

The values of the P factor were referenced from the study of Li Ting et al. [13]. The P value for cultivated land was assigned as 0.35. Except for water bodies and construction land, which were assigned a value of 0 as no erosion occurs, the remaining land use types were assigned a value of 1, as no soil and water conservation measures were adopted. The specific assignments are shown in Table 4.

Table 4 P factor assignment table

lucode	USLE_P
1（Cultivated land）	0.35
2（Forest land）	1
3（Grass land）	1
4（Water）	0
5（Unused land）	1
6（Building）	0

3.6. Soil Erosion Characteristics

The distribution of potential soil erosion (RKLS) in Guangdong Province exhibits distinct spatial differentiation between mountainous areas and plains (Fig. 7). Data analysis results show that areas with intense and extremely intense erosion are concentrated in the Nanling Mountains of northern Guangdong (such as Shaoguan and Qingyuan) and the hilly regions of western Guangdong (such as Yunfu and Maoming). These areas are characterized by drastic topographic relief. Influenced by natural topography (L and S factors) and soil properties (K factor), they constitute the natural high-risk background for soil erosion across the province.

In contrast, the Pearl River Delta region (surrounding Guangzhou and Shenzhen) and coastal plains (such as Zhanjiang and Chaoshan) are predominantly shown in dark green and light green, indicating slight and mild erosion. This indicates that under ideal conditions excluding the interference of vegetation and human activities, the flat terrain greatly weakens the erosive power of surface runoff, keeping the potential erosion risk in plain areas at an extremely low level.

With the introduction of vegetation cover (C factor) and soil and water conservation measures (P factor), the spatial pattern of actual soil erosion (USLE) undergoes significant changes, and the overall erosion intensity is substantially mitigated compared to potential erosion (Fig. 8). The most prominent feature is that the color of the mountainous areas in northern Guangdong (Shaoguan and Qingyuan) has noticeably faded from the orange-yellow in the RKLS map to predominantly light green, indicating a decline in erosion intensity from intense to mild or moderate levels. This shift intuitively reflects the remarkable effectiveness of large-scale afforestation projects in this region, where forest land effectively intercepts storm runoff and reduces the actual erosion modulus.

However, in western Guangdong and some low mountainous and hilly gentle slope areas of northern Guangdong, the actual erosion map still retains a considerable number of yellow and partially light orange patches, indicating the presence of moderate erosion and some intense erosion. These areas are often associated with a lack or simplification of vegetation cover caused by agricultural reclamation (such as dryland farming and orchards). This suggests that human agricultural activities have, to a certain extent, offset the improvement of natural geographical conditions, leading to relatively obvious risks of soil and water loss in local areas.

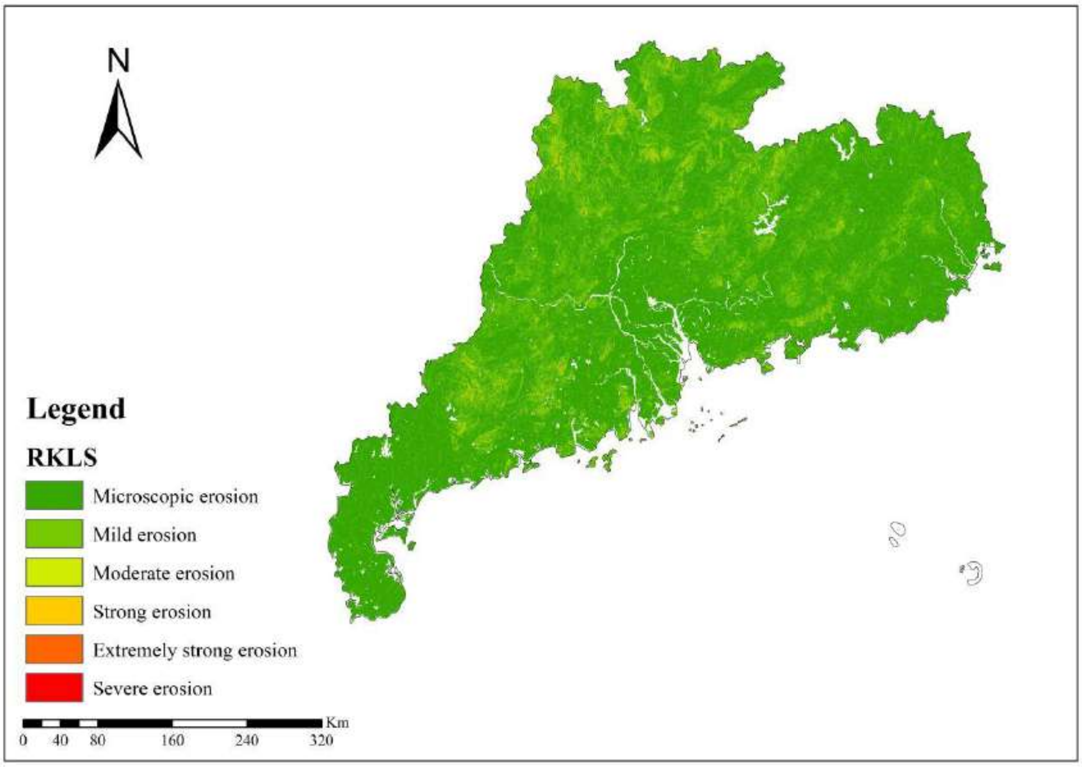

Fig. 7 Spatial distribution of potential soil erosion

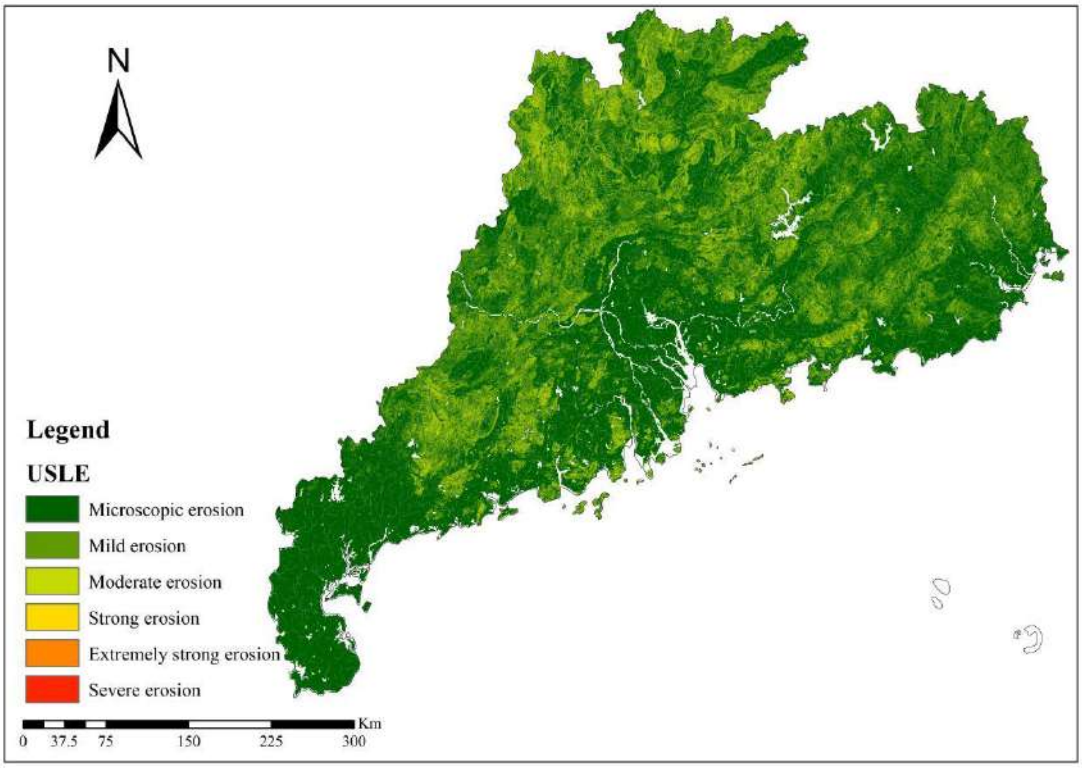

Fig. 8 Spatial distribution of actual soil erosion

IV. CONCLUSIONS AND PROSPECTS

4.1. Conclusions

Based on the USLE and InVEST models, combined with multi-source geospatial data from Guangdong Province, this study calculated the rainfall erosivity factor (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), vegetation cover factor (C), and support practice factor (P). Consequently, the spatial distribution map of soil erosion in the study area was generated to analyze the regional soil erosion characteristics.

Rainfall Erosivity (R factor): Exhibits a spatial pattern of "higher in the south and lower in the north, and higher in the west and lower in the east." High-value zones are concentrated in the southern parts of Jiangmen and the southeastern parts of Yangjiang. Low-value zones are distributed in the mountainous areas of northern Guangdong (Shaoguan, Qingyuan, Meizhou) and the eastern coastal regions (Chaozhou, Shantou, etc.). The rainfall erosivity in eastern Guangdong is relatively low due to the leeward slope effect, while the R factor in the Pearl River Delta remains at a low level due to localized microclimate changes caused by urbanization and interpolation deviations.

Soil Erodibility (K factor): High-value zones are concentrated in the core area of the Pearl River Delta and the coastal areas of Zhanjiang (dominated by latosolic red soil and laterite, characterized by heavy texture and weak erosion resistance). Low-value zones are distributed in the mountainous and hilly regions of northern and eastern Guangdong (dominated by red soil and yellow soil, with high organic matter content and good aggregate structure). This indicates that the intrinsic soil conditions in plain and coastal areas are more susceptible to erosion.

Land Use: The province is dominated by forest land (accounting for over 60%, concentrated in northern and eastern Guangdong). Cultivated land is mainly distributed in Zhanjiang, the Pearl River Delta, and the plains of eastern Guangdong, while construction land is concentrated in the urban agglomerations of the Pearl River Delta.

Potential Erosion (RKLS): Dominated by natural factors (topography LS, soil K, and rainfall R), high-value zones (intense/extremely intense erosion) are concentrated in the Nanling Mountains of northern Guangdong (Shaoguan, Qingyuan) and the hilly regions of western Guangdong (Yunfu, Maoming), constituting the natural high-risk background for the entire province. In contrast, potential erosion in the Pearl River Delta and coastal plains is predominantly slight/mild due to the flat terrain.

Actual Erosion (USLE): Significantly modulated by anthropogenic factors (vegetation C and measures P). In the mountainous areas of northern Guangdong, large-scale afforestation projects have reduced the erosion intensity from a potentially high level to mild/moderate. However, in the gentle slope areas of western Guangdong and the low mountains and hills of northern Guangdong, moderate/intense erosion patches persist due to the lack of vegetation cover caused by agricultural reclamation (dryland farming, orchards). This reflects the mutual offsetting effect between human agricultural activities and natural erosion resistance.

In summary, natural factors (R, K, LS) determine the potential high-risk areas for soil erosion, while anthropogenic factors (land use, vegetation cover, and soil and water conservation measures) are the key modulating variables for actual erosion intensity. Ecological engineering can effectively reduce erosion levels in natural high-risk areas such as northern Guangdong, whereas unreasonable agricultural activities exacerbate erosion risks in regions like western and northern Guangdong.

4.2. Limitations and Prospects

This study still has certain limitations, and future research can be deepened in the following directions:

(1) Data Precision and Parameter Optimization

The current study employs data with a 90 m resolution, which has limited accuracy in depicting small-scale erosion (such as on sloping farmland and construction sites). Furthermore, the C and P factors were assigned based on empirical values without calibration using local measured data from Guangdong Province. Future research can utilize long-term positioning monitoring and high-resolution satellite remote sensing (such as Sentinel-2) to retrieve dynamic C factors, thereby improving the localization level of the parameters.

(2) Quantitative Disentanglement of Driving Factors

This study primarily focuses on the qualitative description of the spatial correlation of factors. Future studies could introduce methods such as the Geodetector and Structural Equation Modeling (SEM) to quantify the contribution rates of factors like R, K, LS, C, and P to soil erosion. This would help reveal the coupling mechanisms between soil erosion and climate change (e.g., frequency of extreme rainfall) as well as the intensity of human activities (e.g., GDP, population density).

(3) Spatiotemporal Dynamics and Scenario Simulation

The existing analysis is based solely on data from the year 2020. Future research could incorporate long-term time-series data (e.g., 2000–2020) to analyze the spatiotemporal evolution trends of erosion. Meanwhile, scenarios involving different land use changes (such as urban expansion and cultivated land protection) and climate changes (such as RCP scenarios) can be established to simulate future erosion risks. This would provide more precise decision-making support for soil and water conservation planning and the construction of the Nanling ecological barrier in Guangdong Province.

ACKNOWLEDGEMENTS

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National Natural Science Foundation of China (22276041), the Guangdong Basic and Applied Basic Research Foundation (2023A1515030008), the Projects of Talents Recruitment of GDUPT (2022rcyj2002).

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