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REVIEW

An overview of water erosion modeling in China: a bibliometric and statistical analysis

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KEYWORDS

Physically based model, empirical model, sediment yield, soil erosion modeling, bibliometric analysis, water erosion

HIGHLIGHTS

- Water erosion models mainly applied in central China at large scales.
- After 2006, the focus shifted from erosion characteristics to influencing factors and spatio-temporal analysis.
- The study areas are primarily concentrated in southeastern and central China.
- Limitations included lack of field validation, restricted model applicability, weak physical models, and paucity of research on erosion mechanisms.
- Physical models have limited accuracy and application range.

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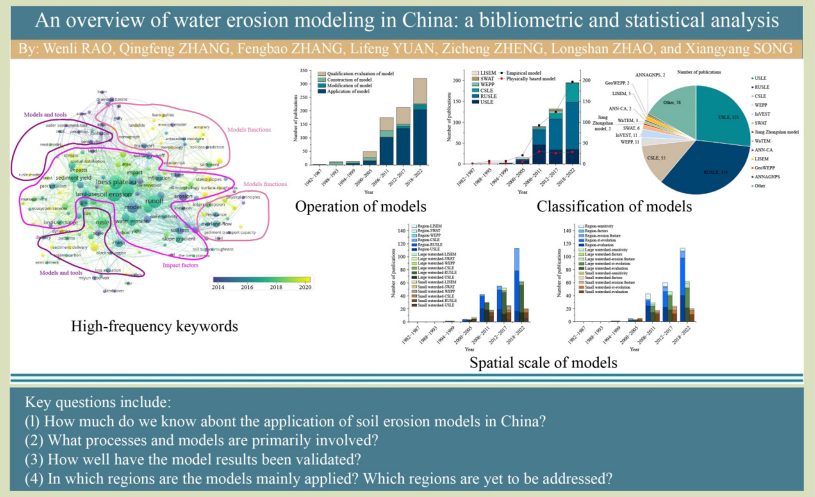
GRAPHICAL ABSTRACT



An overview of water erosion modeling in China: a bibliometric and statistical analysis

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Key questions include:
(l) How much do we know abont the application of soil erosion models in China?
(2) What processes and models are primarily involved?
(3) How well have the model results been validated?
(4) In which regions are the models mainly applied? Which regions are yet to be addressed?

ABSTRACT

Soil erosion models are effective tools for assessing soil erosion indicators and simulating erosion processes. China has some of the most severe soil erosion in the world. To better apply soil erosion models to address soil erosion issues, it is necessary to understand the development process and current status of soil erosion modeling research in China. In this study, a combination of bibliometric analysis and statistical methods was used to review and organize Chinese soil erosion models (1982–2022) from various perspectives, including keywords, model operations, model classification, model spatiotemporal scales, and model geographical applications. This findings of this analysis indicate that the study of soil erosion models in China mainly focuses on large scales (regional and large river basins) using empirical models including USLE, RUSLE, and CSLE. The research areas are primarily concentrated in southeastern and central China. The research content has gradually shifted from studying soil erosion characteristics to analyzing influencing factors, spatiotemporal evolution of erosion, and erosion process and morphology stages. However, there are several issues in current Chinese soil erosion modeling research. These include a lack of validation of model application results with field measurements, limited application areas for the models, and relatively weak research on erosion process mechanisms. On this basis, it is recommended that future research should increase the observation of soil erosion processes and establish methods for data or mathematical formula conversion based on different geographical environments. Also, there is a need to strengthen research on erosion process mechanisms. The findings of this study should provide a valuable resource for researchers to future understand the development process and current issues of Chinese soil erosion models, providing insights for future research directions.

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1 Introduction

Severe water and soil erosion can lead to soil degradation and the destruction of land resources[1–3]. Currently, the methods for monitoring and evaluating water erosion mainly include remote sensing (RS) and geographic information systems (GIS) qualitative assessment, isotope tracing, rare earth element tracing techniques, and soil erosion model simulations[4–6]. Of these methods, soil erosion models are the most effective tools for quantitatively assessing soil erosion rates and intensities and simulating erosion processes[7,8]. The mathematical models are established based on an understanding of soil erosion mechanisms and processes, incorporating physical factors such as climate, soil characteristics, vegetation types, and topography[9]. Soil erosion models provide a means to comprehend soil erosion and its spatial distribution, serving as a basis for land use planning, soil and water conservation, and engineering design.

Since the 1940s, scientists have proposed various mathematical models, including empirical models, conceptual models, and process-based models, for predicting soil erosion processes at different spatial and temporal scales[10]. In China, the development of soil erosion models has gone through three stages. The first stage involved localized observations and quantitative expression of soil erosion. From 1923 to 1925, runoff plots were established, providing a data source for quantitative studies on soil erosion[5]. Subsequently, research focused on establishing relationships between soil erosion and driving factors such as rainfall, slope length, and slope gradient[11]. The second stage involved the development of empirical models based on observational data and the localization of foreign empirical models. Liu[12] first proposed an equation for calculating annual surface erosion based on data from soil and water conservation experimental stations. Many researchers then established empirical models for soil erosion in China[13–15]. Liu et al.[16] led a research team in China to establish the China soil loss equation (CSLE), which marked the maturity of empirical soil erosion models. The widely used foreign models, such as the universal soil loss equation (USLE) and revised universal soil loss equation (RUSLE), were developed based on the natural environment of the USA. Due to differences in geographical conditions between China and the USA, many studies modified the factors based on the natural environment of China[17–19]. The third stage involved the development of process-based models. Given that empirical models are limited in their application to specific regions and cannot explain sediment transport mechanisms[20], research in the late twentieth century began to use limited parameters to establish process-based models to reveal the mechanisms and processes of water and sediment movement[21]. During this period, research on process-based models primarily focused on the mechanisms of rainfall-runoff erosion on hill slopes and their interaction with rainfall[22]. In the early 21st century, the focus shifted to simulating erosion runoff processes caused by rainfall and sediment transport through process-based models[23,24]. The main influencing factors include event-based rainfall, land use, and the impact of vegetation on water erosion[25–27]. Over last decade, research has mainly focused on the spatial variation and spatiotemporal evolution of water, soil particles, and nutrient elements[28,29].

Despite significant progress in model development and parameterization, there still exist gaps in the effectiveness, quality and reliability of modeling application results. Due to the nonlinear relationship and thresholds between driving factors and erosion processes, as well as the challenges in scaling up model results from local to larger scales, uncertainties in model outputs persist. One of the challenges in improving soil erosion models is understanding the information on their usage in China. Key questions include: how much do we know about the application of soil erosion models in China; what processes and models are primarily involved; in which regions are the models mainly applied; which regions are yet to be addressed; and how well have the model results been validated.

Bibliometrics is a quantitative technique for evaluating information whose main focus is the measurement of science. This technique can offer a meaningful understanding of the potential of any given area of research, the current state of the literature, research foci and future directions[30]. Barretto et al.[31] approached the formation of accelerated soil erosion research in Brazil from a bibliometric perspective, emphasizing the use of the USLE predictive model. Zhuang et al.[32] analyzed publications related to soil erosion in the Web of Science (WoS) database from 1932 to 2013, revealing scientific outputs, primary disciplinary categories, geographical distribution and research foci in soil erosion studies, offering potential guidance for future research. Delcourt et al.[33] used bibliometric analysis tools to explore the evolution and strategic directions of land-use temporal dynamics research, concluding that land-use temporal dynamics serve as a crucial indicator for assessing soil vulnerability. He et al.[34] conducted a comprehensive analysis of research topics in the Yellow River Basin using bibliometrics, highlighting “Loess Plateau” as the most frequently searched keyword term in the past decade and a sharp increase in the popularity of “climate change” over the past 5 years. Finally, da Silva Luz et al.[30] undertook a bibliometric analysis of simulated rainfall research in Brazil to assess the temporal evolution of publications, primary themes and technological developments in equipment used.

This study provides a comprehensive review of the development and application of soil erosion models in China. It analyzes the current status of soil erosion models, including the predominant types of applied models and their publication proportions, the main regions and spatial scales of model application, and the resolved and unresolved issues in modeling. The objective of this research is to reveal the research and application of soil erosion models in China from a quantitative perspective, using a combination of bibliometrics and statistical analysis. This approach entails examining research foci, model operations, model or problem classifications, spatial scales, geographic regions, and other quantitative aspects. Also, by integrating data related to river networks, climate, agricultural zoning, administrative divisions, and erosion areas, the study presents the distribution of various model-related issues across the entire country. The findings of this research provide valuable information from multiple perspectives to support future studies on soil erosion modeling.

2 Materials and methods

2.1 Data collection and database

The purpose of this study is to provide a comprehensive review of soil erosion models in China, specifically focusing on water erosion models. Therefore, the research data should include studies on soil erosion models conducted in the Chinese region or studies on foreign soil erosion models applied in the Chinese region. Based on this requirement, the SQL query statements in Table 1 were used to retrieve 13,989 papers from the China National Knowledge Infrastructure (CNKI) database and 16,647 papers from the WoS core collection database. Although the SQL statements limited the search to papers from China, the retrieved literature is not precise enough and presents several issues: (1) it includes papers authored by Chinese researchers that focus on regions outside of China, which does not meet the data requirements; (2) some papers cover other types of soil erosion models, such as wind erosion; and (3) some papers have keywords related to soil erosion but are not directly relevant to soil erosion models or model

Table 1 Parameters setting for different bibliographic databases

Data source	Source type	SQL
WoS	SCI	(TS = ‘SOIL EROSION MODEL’ OR TS = ‘SOIL EROSION’ OR TS = ‘SOIL LOSS’ OR TS = ‘SOIL LOSS MODEL’ OR TS = ‘SOIL WATER EROSION’) AND (AD = ‘CHINA’ OR CU = ‘CHINA’)
CNKI	EI, Chinese Core Journal Criterion of PKU, CSSCI, CSCD	SU = ‘SOIL EROSION MODEL’ + ‘SOIL EROSION’ + ‘SOIL LOSS’ + ‘SOIL LOSS MODEL’ + ‘SOIL WATER EROSION’

Note: Analysis type is keywords co-occurrence. Node type is keywords. EI, Engineering Index; CSSCI, Chinese Social Sciences Citation Index; CSCD, Chinese Science Citation Database.

parameters. Therefore, further direct screening of these papers was conducted to obtain highly relevant papers related to water erosion model research. The direct screening process involved researchers filtering the papers obtained from the SQL query based on the screening criteria. The direct screening followed two principles: (1) the study must focus on the Chinese region as the research area; and (2) the research must be relevant to soil water erosion models. Following direct screening, a total of 786 papers that met the requirements were selected, including 112 papers from WoS covering the period from 1982 to 2022 and 674 papers from CNKI.

One of the most demanding tasks was to further extract information from the selected 786 papers. The information indicators to be extracted are provided in Table 2. These information indicators can address the following questions: (1) the capability and parameters of the models; (2) the internal algorithms and controls of the models; (3) the applicable scales and data accuracy of the models; (4) the purposes, background conditions (including land-use types, soil types and topography), and quantities of model construction or application; and (5) the strengths, weaknesses, and future improvement directions of the models.

Other data are shown in Table 3.

2.2 Bibliometric networks

To gain a comprehensive understanding of soil erosion modeling research in China from multiple perspectives, both bibliometric analysis and statistical methods were used. Bibliometric analysis is a quantitative statistical approach used to study academic research by analyzing metrics such as the quantity, quality and citation relationships of scientific literature[41,42]. This method provided an objective means to uncover research trends, influence and development directions in the academic field[43]. However, it did not focus on specific details of the research content, such as the terrain, scale and distribution of the study areas, research methods, research findings, and limitations. Therefore, statistical analysis was used an additional way to analyze this type of information and address the limitations of bibliometric analysis. By combining these two methods, a comprehensive understanding of the current state, research gaps and future directions of soil erosion modeling research in China could be achieved.

Commonly used literature analysis software tools include MATLAB, Gephi, VOSviewer, CiteSpace, and Histcite[44]. Of these, CiteSpace and VOSviewer, both developed in Java, have dual features of “graph” and “spectra” and have been applied to identifying the frontiers and key issues in research. The visualization software can handle multiple database formats, dynamically adjust maps, optimize clustering algorithms and offer various customization options. CiteSpace can extract information based on LLR, LSI and MI algorithms, and it provides multiple styles that can be adjusted according to user preferences. However, this software is complex, requiring a significant amount of time to master, and most of its features

Table 2 The key recorded information

Category	Content
Basic information of model	Inputs and outputs, model capability, model shortcomings, and strengths and future development ideas
Detail of model	Space and time domain, scale, data accuracy, and model accountability
Application of model	Research subject, operation of models, application scenarios and erosion stage, study area and scale, land use, soil type, geography, method(s) used for performance evaluation, sensitivity analysis, and results or conclusions
Algorithm and governing	Description, algorithm, and model sample

Table 3 Other data sources and descriptions obtained to cover the whole of China

Year	Data	Format	Source
1978	Climate division	Shapefile	Resource and Environment Science and Data Center[35]
1979	Agricultural division	Shapefile	Resource and Environment Science and Data Center[36]
2003 and 2021	Water erosion area by province, autonomous region or city	PDF	National Soil and Water Conservation Monitoring Bulletin released by the Ministry of Water Resources[37,38]
2014	River network	Shapefile	Resource and Environment Science and Data Center[39]
2015	Administrative division	Shapefile	Resource and Environment Science and Data Center[40]

must be purchased. In contrast, VOSviewer is user-friendly and offers fixed styles for network visualization, overlay visualization, density visualization, and other useful features. VOSviewer software (version 1.6.18) was used to conduct bibliometric analysis based on the keywords in the literature.

2.3 Statistical methods

The two main statistical methods, summation and proportions, were primarily used to analyze the distribution of literature information. Based on manually extracted literature information, statistical data analysis was conducted from various perspectives, including model operations, model classification, temporal and spatial scales, geographical distribution of model applications, and whether the models were process models. These perspectives were used to analyze the statistical data as listed in Table 4.

From an operational perspective, model research in the field of soil erosion can be classified into four categories: application, modification, development and qualitative evaluation. Model application mainly refers to the application of empirical or physical models in soil erosion studies in China. For example, Kong et al.[45] applied the RUSLE to calculate soil erosion in the Yanhe River Basin. Model modification involves adapting empirical or physical models to suit research in China. For example, Tian et al.[46] modified the P-factor of the RUSLE to assess soil erosion in Hubei Province, China. Model development pertains to the construction of empirical or physical models specifically tailored for soil erosion research in China. Qualitative evaluation involves conducting related studies on soil erosion in China using other techniques, including GIS and RS, observational experiments and GeoCA (geo-cellular automata). This includes assessments of erosion rates, influencing factors, soil erosion characteristics and other factors.

According to the manually extracted information, soil erosion models in China can be broadly classified into two categories: empirical models and physically-based models. Empirical models are mathematical relationships derived from statistical analysis of a large amount of observed meteorological, hydrological and sediment data[47]. Based on observed data on soil erosion and sediment yield, empirical models express the erosion or sediment yield as a multivariate regression relationship with influencing factors[48]. Physically-based models, in contrast, use fundamental physical principles to simulate the process of soil erosion, aiming to elucidate the underlying principles and erosion processes associated with the model[49]. Generally, the models are described by one or more mathematical equations and numerically solved using physically meaningful parameters based on actual hydrological and sediment physical processes, either on hill slopes or in river channels.

According to the different study areas, the spatial scales of soil erosion model applications can be classified into four categories: small-scale, farmland scale, watershed scale, and region scale[50]. The temporal scales of soil erosion can be divided into seven types: event-based rainfall, daily scale, monthly scale, seasonal scale, annual scale, continuous scale, and long-term scale[50]. However, in the context of model application research in China, there has been limited emphasis on the temporal scale. Therefore, the statistical data regarding the temporal scale is incomplete, and this study did not analyze the data related to temporal scales.

According to the manually extracted information, the geographical distribution of model applications has generated four analytical perspectives.

3 Results

3.1 High-frequency keywords

Figures 1 and 2 depict the research foci and their temporal

Table 4 Data analysis perspectives

Category	Content
Operation of model	Application, modification, construction and qualitative evaluation.
Classification of model	Empirical and physically-based models
Spatial scale of model	Spatial scale: plot, field, watershed and region
Geography of model application	(1) The distribution of the publications number in different provinces or cities, (2) the distribution of the publications number in the three spatial scales (region, large watershed, and small watershed), (3) the distribution of the publications number of models (USLE, RUSLE, and CSLE), and (4) the distribution of the publications number at five research points (the evaluation, the spatial-temporal evolution, features of soil erosion, impact factors, and the sensitivity assessment of soil erosion)

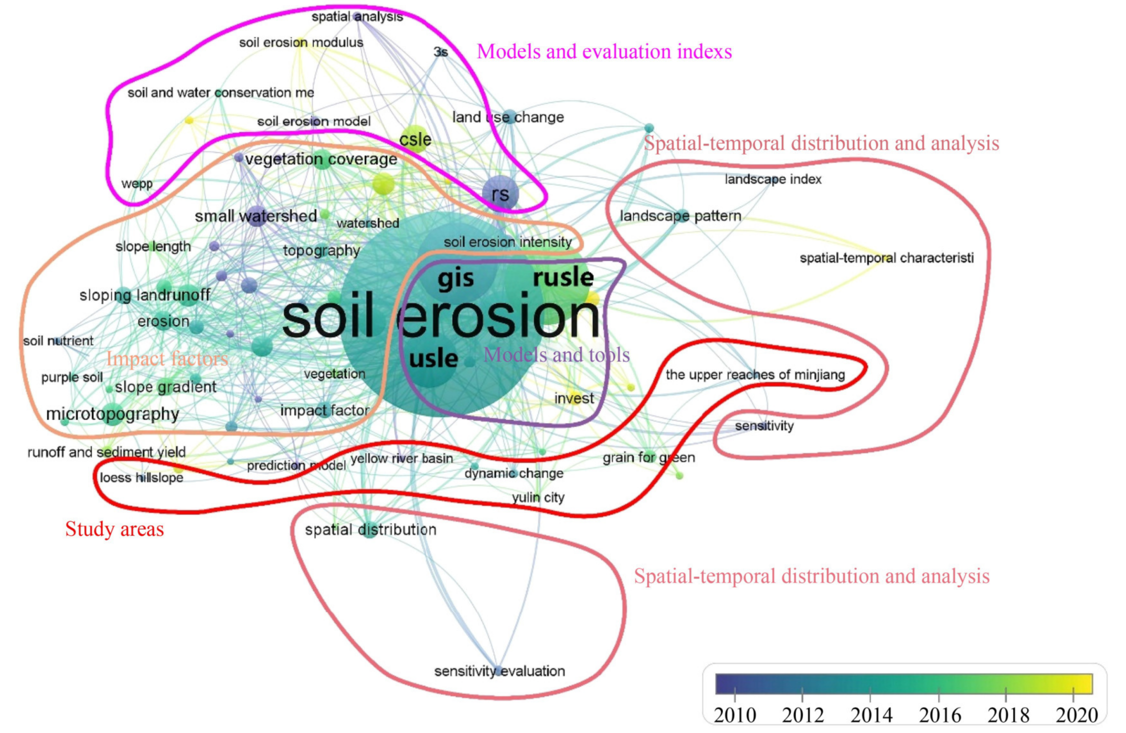

Fig. 1 Network map of keywords from 674 papers in CNKI. The blue words are Chinese translations in English.

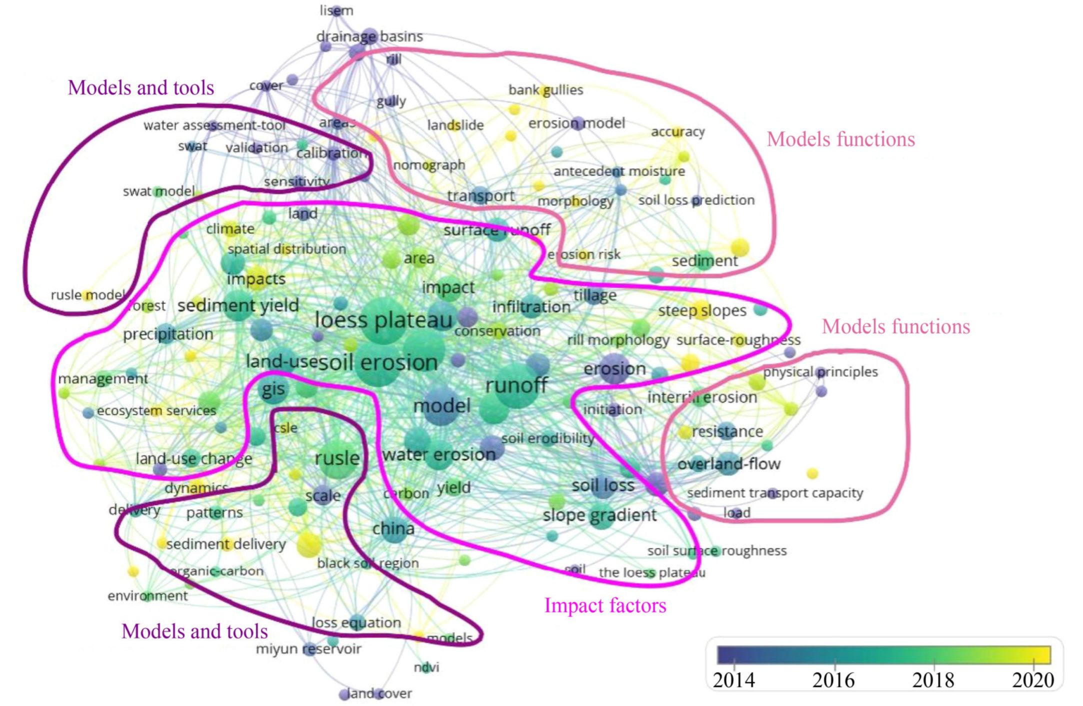

Fig. 2 Network map of keywords from 112 papers in WoS.

variations in the field of soil erosion modeling in China over the past decade. The most prominent keywords, in descending order, include “RUSLE”, “GIS”, “Loess Plateau”, “runoff”, “USLE”, “land use”, “spatial distribution and variation”, “surface runoff and sediment yield”, “impact”, “model”, “micro-topography”, “watershed”, and “steep slope”. Before 2012, research primarily focused on evaluating soil erosion modality and intensity using the USLE model and GIS technology. The research was mainly conducted for the Loess Plateau, and the predominant forms of erosion were rill and gully erosion. From 2012 to 2018, the emphasis shifted to studying the influencing factors of soil erosion, with research areas primarily concentrated in the Loess Plateau and the black soil region in North-east China. After 2018, RUSLE and CSLE models were widely used for soil erosion assessment. Researchers also started investigating soil erosion processes and erosion forms, while analyzing the spatiotemporal distribution characteristics and variations of soil erosion.

3.2 Operation of models

Figure 3 shows the statistical analysis of number of publications in different stages of soil erosion model-related research in China, categorized by model operations. For 40 years, the highest number of publications (*n* = 461) focused on model application studies. This was followed by qualitative evaluation of soil erosion (*n* = 231), model development (*n* = 62), and model modification (*n* = 32). Before 2000, the primary focus of research was on model development (*n* = 17), followed by model application (*n* = 6). Most of these studies involved the construction of empirical models (*n* = 12), and model application mainly concentrated on the assessment and spatial distribution of soil erosion (*n* = 5).

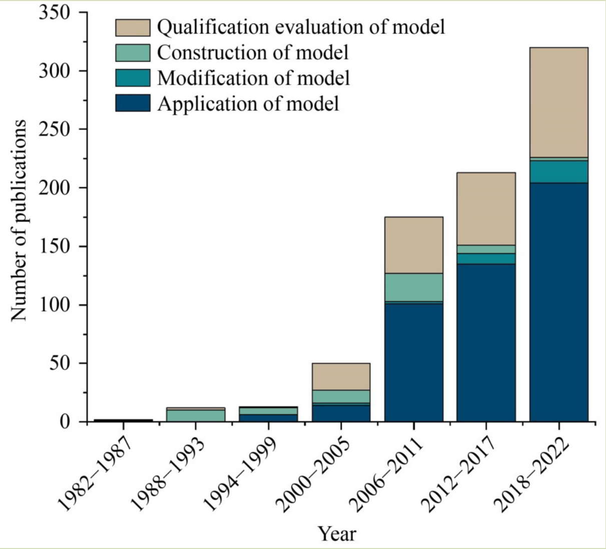

Fig. 3 Number of publications on the operation of soil erosion models from 1982 to 2022.

3.3 Classification of models

Figure 4 shows the proportion of publications for various soil

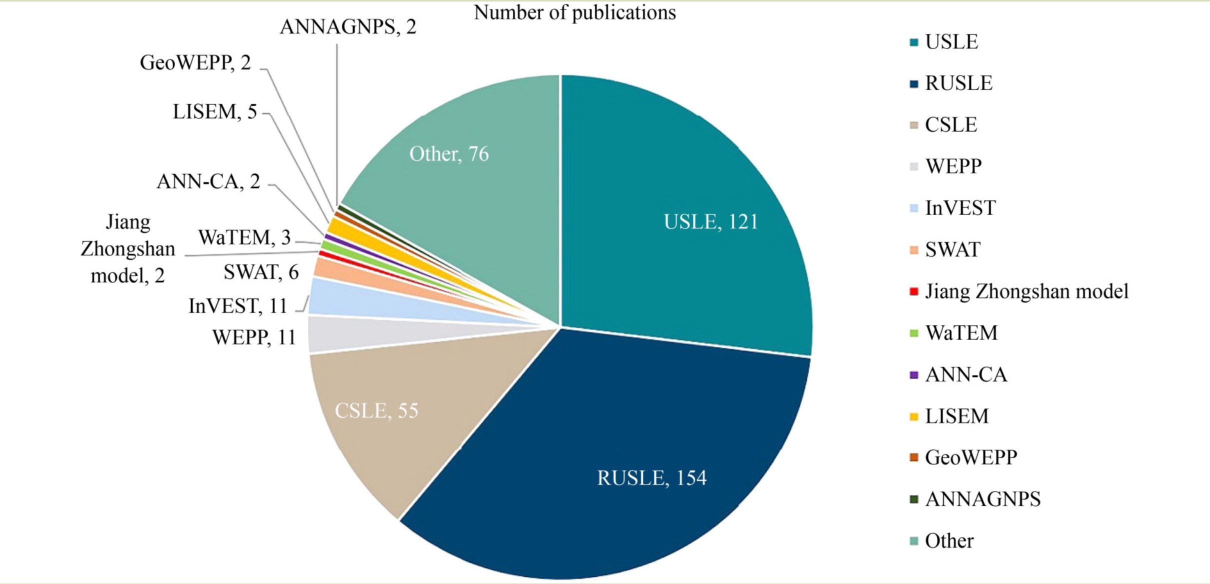

Fig. 4 Details of the classification of soil erosion models.

erosion models. Overall, the highest number of applications was observed for the RUSLE (n = 154), followed by USLE (n = 121) and CSLE (n = 55). These three empirical models accounted for nearly three-quarters of the total applications. Physically-based models had a smaller proportion of applications, with the main ones being the Water Erosion Prediction Project (WEPP), integrated valuation of ecosystem services and tradeoffs (InVEST), Soil and Water Assessment Tool (SWAT) and LISEM model. Other studies primarily focused on qualitative research related to soil erosion models.

Figure 5 shows the number of publications on soil erosion model research based on two categories: empirical models and physically-based process models, across different periods. Before 2005, there was moderate growth in the application of empirical models, while the number of physically-based process models was minimal. During this period, the primary focus was on the application of USLE, followed by RUSLE and LISEM. From 2006 to 2011, there was a sharp increase in the application of empirical models (n = 93), nearly four times that of 2005 (n = 21). The USLE and RUSLE accounted for the majority of applications. Similarly, the application of physically-based process models increased significantly compared to other periods, with an increase of 25 models. After 2012, the number of application of empirical models continued to rise to 197, while the number of application of physically-based process models remained relatively stable (n = 29). During this time, RUSLE became the predominant applied model, and there was a gradual increase in the application of CSLE. However, compared to empirical models, the number of physically-based process models was relatively lower, with their application mainly concentrated between 2000 and 2017.

3.4 Spatial scale of models

Figure 6 shows the number of publications on six frequently applied soil erosion models (USLE, RUSLE, CSLE, WEPP, SWAT, and LISEM) at three spatial scales: region, large watershed and small watershed scales. The topography of the study area generally encompasses various landforms found in China, including mountains, hills, basins and plains. Before 2000, USLE had the highest number of research publications at the regional and large watershed scales. From 2000 to 2005, there was a moderate increase in the number of application of USLE. Concurrently, the application of RUSLE at the regional scale began to rise. The majority of model application studies were concentrated after 2006. These results show that the number of publications on models applied at the regional scale was significantly higher than at other scales, followed by the large watershed scale. The number of applications of USLE and RUSLE at the regional and large watershed scales experienced moderate growth. However, the number of models applied at the small watershed scale slightly increased from 2012 to 2017 (n = 26) and then declined to previous levels during 2018–2022 (n = 20). After 2006, the primary models used across different scales were the USLE, RUSLE and CSLE. Of these, the number of applications of RUSLE and CSLE gradually increased at the regional and large watershed scales. Additionally, the growth rate of the CSLE models applied at the regional scale was faster

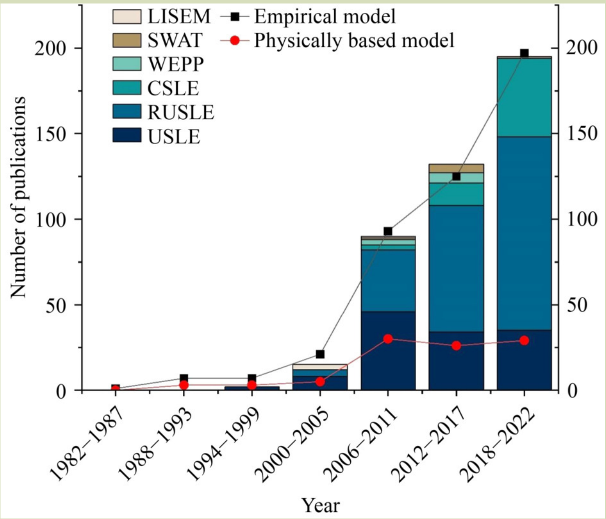

Fig. 5 Number of publications by classification of soil erosion models from 1982 to 2022.

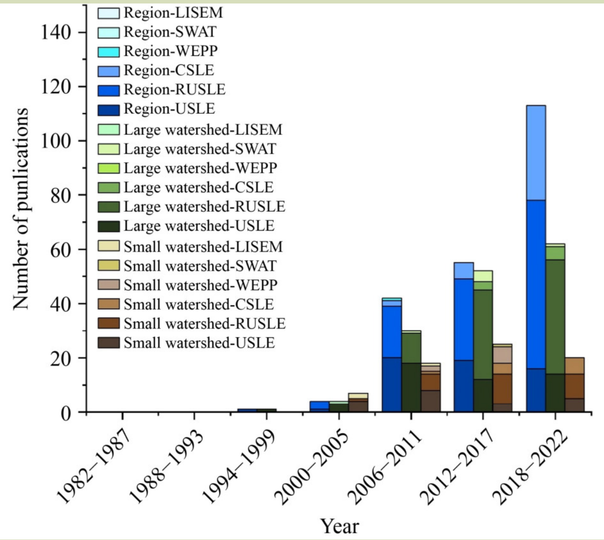

Fig. 6 Number of publications on a spatial scale of models in group from 1982 to 2022.

than at other scales. The number of applications of USLE remained relatively stable across all three scales.

Figure 7 shows the statistics of papers on five prominent research topics (assessment, spatiotemporal evolution, soil erosion characteristics, influencing factors and sensitivity assessment) based on the application of soil erosion models at the regional, large watershed, and small watershed scales. From Fig. 7, it is evident that after 2006, soil erosion assessment and spatiotemporal evolution became the main research topics, with a significant increase in research on the spatiotemporal evolution of soil erosion. The number of publications on sensitivity assessment of soil erosion was generally low, mainly concentrated at the regional and large watershed scales. Soil erosion characteristics were studied across the three scales. However, research on the influencing factors of soil erosion was relatively less, mostly concentrated at the small watershed scale from 2012 to 2017.

3.5 Geography of model application

Table 5 displays the statistical data of literature publications on soil erosion model research across different provinces in China: the application of three commonly used empirical models (USLE, RUSLE, and CSLE), research at different spatial scales, and the main research foci. Shaanxi Province has the highest number of publications (*n* = 120), significantly surpassing other provinces. The next in line are Yunnan (*n* = 40), Sichuan (*n* = 36), Guizhou (*n* = 31), and Hubei (*n* = 28). The number of publications for Heilongjiang (*n* = 23), Gansu (*n* = 21), Shandong (*n* = 19), and Inner Mongolia (*n* = 19) are relatively close. The number of publications for other provinces gradually decreases with fewer research points. In terms of overall distribution, the research is primarily concentrated in the south-eastern and central regions of China.

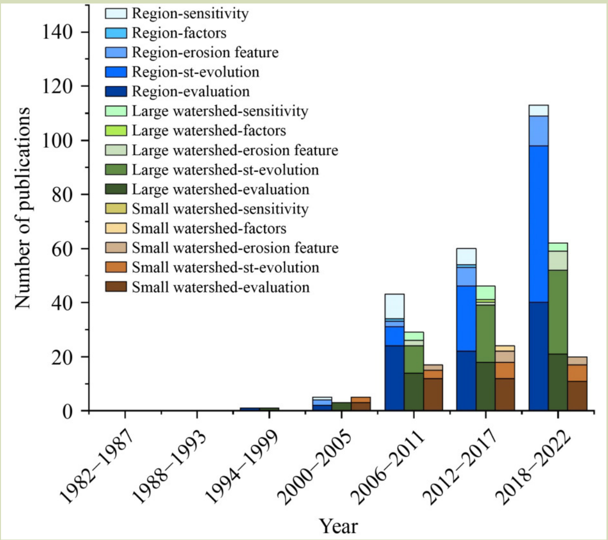

Fig. 7 Number of publications on research points in groups from 1982 to 2022. st, spatial-temporal.

At the regional scale, the research is primarily concentrated in the eastern and central parts of China, including provinces like Hubei, Henan, Jiangsu, Jiangxi, and Liaoning. For the watershed scale, the research is mainly focused on the southern part of China, including regions such as Guizhou, Yunnan, Guangxi, Guangdong, and Hainan. Regarding the small watershed scale, the research is primarily concentrated in several provinces, including Shaanxi, Gansu, Jilin, and Heilongjiang.

The application of USLE is mainly distributed in Yunnan (*n* = 14), Shaanxi (*n* = 10), Sichuan (*n* = 9), Hubei (*n* = 8), and Gansu (*n* = 6). For RUSLE, its application is primarily concentrated in Shaanxi (*n* = 28), Guizhou (*n* = 17), Yunnan (*n* = 13), Sichuan (*n* = 13), and Hubei (*n* = 11). The application of CSLE is mainly found in Shaanxi (*n* = 10), Xinjiang (*n* = 5), Shandong (*n* = 4), Heilongjiang (*n* = 4), and Hubei (*n* = 2). In terms of the overall distribution, the research on model applications is primarily dominated by the RUSLE, followed by USLE. The application of CSLE is still in its initial stages on a national scale.

Research on soil erosion assessment and spatial distribution is primarily concentrated in Shaanxi (*n* = 14), Sichuan (*n* = 13), Hubei (*n* = 12), Yunnan (*n* = 11), and Heilongjiang (*n* = 10) Provinces. Studies on the spatiotemporal evolution of soil erosion are mainly focused on provinces such as Shaanxi, Sichuan, Hubei, Yunnan, and Guizhou. Research on soil erosion characteristics is primarily concentrated in the north-eastern region of China, including regions like Jilin, Heilongjiang, and Beijing. Sensitivity assessment studies are concentrated in the southern part of China, such as Yunnan, Sichuan, and Guangxi. Research on soil erosion influencing factors is mainly concentrated in Shaanxi Province (*n* = 53), while other provinces have relatively fewer studies in this area.

4 Discussion

This study used a data set of 786 papers to analyze the trends and development directions of soil erosion modeling research in China. First, a bibliometric analysis was conducted to reveal the publication patterns and spatial distribution of research on

Table 5 Statistics for the number of research papers by regions in China

Region	TA	Spatial scale of model			Empirical model			Research points				
		RN	LWN	SWN	USLE	RUSLE	CSLE	AN	STN	CN	EN	SN
Shaanxi	120	27	26	67	10	28	10	14	32	20	53	1
Yunnan	40	14	15	11	14	13	1	11	18	2	3	6
Sichuan	36	14	13	9	9	13	1	13	8	10	0	5
Guizhou	31	11	12	8	1	17	1	9	11	9	2	0
Hubei	28	16	6	6	8	11	2	12	9	3	4	0
Heilongjiang	23	10	5	8	4	7	4	10	5	6	1	1
Gansu	21	7	5	9	6	7	0	7	8	3	2	1
Inner Mongolia	19	8	5	6	4	4	0	4	6	4	4	1
Shandong	19	9	7	3	2	4	4	7	4	3	4	1
Jiangxi	17	11	3	3	6	4	0	4	8	2	1	2
Beijing	15	3	8	4	3	4	0	5	5	5	0	0
Guangxi	14	4	7	3	5	5	1	8	2	1	1	2
Qinghai	14	10	4	0	3	8	0	4	8	1	1	0
Shanxi	14	3	7	4	1	7	1	8	7	1	1	0
Liaoning	13	8	3	2	1	8	1	6	3	2	2	0
Chongqing	13	7	3	3	5	2	0	6	5	1	0	1
Fujian	12	3	7	2	2	5	1	4	3	0	3	2
Anhui	11	6	3	2	5	5	1	8	2	0	0	1
Guangdong	11	4	6	1	3	4	2	8	1	1	0	1
Hebei	11	6	1	4	1	5	2	4	4	1	1	1
Xizang	10	5	5	0	0	5	1	3	4	2	0	1
Henan	9	5	4	0	2	4	1	5	2	1	1	0
Jiangsu	8	4	1	3	3	3	1	3	3	2	0	0
Ningxia	8	4	2	2	0	1	0	2	2	1	2	1
Xinjiang	8	4	2	2	2	0	5	4	2	0	1	1
Jilin	7	1	2	4	1	1	0	1	1	4	1	0
Zhejiang	7	1	4	2	2	5	0	2	3	0	0	2
Hunan	4	3	1	0	1	0	2	1	3	0	0	0
Hainan	3	1	2	0	3	0	0	1	1	0	1	0
Tianjin	1	1	0	0	0	0	1	1	0	0	0	0

Note: TA, total number of papers; RN, the total number of papers with the region as the study area; LWN, the total number of papers with the large watershed as the study area; SWN, the total number of papers with the small watershed as the study area; AN, total number of papers on soil erosion evaluation; STN, total number of papers on spatiotemporal evolution of soil erosion; CN, total number of papers on the characteristics of soil erosion; EN, total number of papers on the effect factors of soil erosion; SN, total number of papers on the sensitivity assessment of soil erosion.

soil erosion models in China. Subsequently, using basic statistical methods, the study examined detailed information from 786 selected papers, focusing on aspects such as model operations, model categorization, spatial scales of models and the geographical distribution of model applications. In conjunction with this analysis, the study also examined discussions on the intrinsic characteristics of soil erosion models, such as their capabilities, strengths and limitations. The primary objectives of these discussions were to address the following objectives: (1) understand the development status of model construction, (2) identify the main regions where models are predominantly applied, (3) explore the research priorities and future directions of model applications, and (4) highlight unresolved issues in model research.

4.1 Model construction

Soil erosion models are typically constructed based on specific environmental conditions. Due to significant differences in climate, topography and soil between China and other countries, foreign models cannot be directly applied in China. Therefore, researchers have developed models tailored to the soil erosion conditions in China, taking into consideration the Chinese climate, topography, soil and other factors. The research on model construction has primarily focused on the past few decades (Fig. 3), with the main functions of the models being the assessment of soil erosion rates and sediment yield (Fig. 7). Initially, these empirical models considered limited driving factors such as rainfall, topography and soil properties[14,15]. As research progressed, empirical models gradually incorporated additional factors such as vegetation cover and soil conservation measures[51,52]. Also, most empirical models have shown high accuracy and application to small watersheds without distinguishing between hill slopes and channels. Although watersheds are the smallest geomorphic units in China, the terrain within a watershed is highly complex. Therefore, empirical models began to separately assess erosion on hill slopes and channels to improve the accuracy of results. Some studies have analyzed the proportion of erosion on hill slopes and channels to understand the main sources of sediment[1,53]. Subsequently, research started to evaluate channel erosion based on channel morphology, such as gullies, shallow channels and deep channels[54].

Physically-based models have also undergone a period of development, particularly between 2006 and 2015, during which models experienced rapid advancement, and most of the physically-based process models were constructed during this period (Fig. 3). The majority of these models provide simulations and calculations for runoff generation, confluence, erosion and sediment yield, and a few models also include hydrological modules[55,56] to simulate hydrological processes. The differences among these models lie in their application scenarios (such as topography, erosion patterns and available observational data), control algorithms and input-output parameters. Initially, physically-based models used the kinematic wave equation to simulate water flow. However, the kinematic wave theory was not effective for channel routing in large watersheds[57]. Therefore, subsequent models used mass conservation-based equations for both water flow continuity and sediment continuity to describe the routing process[16,58,59]. Runoff calculations typically applied the SCS curve method[60], while Fu et al.[58] used both the modified GAML (Green-Ampt Mein-Larson) equation proposed by Chu[61] and the SCS curve method to compute runoff with and without rainfall data observations. Manning's formula was used to calculate flow velocity[62,63]. The main runoff generation patterns include saturated runoff generation and infiltration excess runoff during rainfall events. Since most runoff in China is generated by infiltration excess, studies often employ the Horton equation to assess infiltration capacity[63–65]. To calculate sediment transport, Yuan et al.[66] applied equations derived from Yalin[67] and Foster et al.[68]. Jin et al.[63] used equations proposed by Govers[69] and Zhang[70] to calculate sediment transport on hill slopes and channels, respectively. To consider erosion in gullies and channels, Gong et al.[71] used the segmented Muskingum method, incorporating sediment transport time and sediment concentration coefficients in the channels to calculate sediment output rates.

4.2 Regions where models were mainly applied

According to the results (Fig. 3), the overall publication numbers for the application of soil erosion models is highest in each period (except for 1988–1993). Of these, empirical models account for nearly three-quarters of the model application proportion (Fig. 4). Therefore, by combining the number of applications of empirical models with the distribution data of soil erosion areas in China (2003 and 2021) (Tables 5 and 6), regions that require enhanced model application and erosion control research can be identified. According to the National Soil and Water Conservation Monitoring Report released by the Ministry of Water Resources of China in 2003, the regions with the largest soil erosion areas were Sichuan (150×10^3 km^2), Inner Mongolia (150×10^3 km^2), Yunnan (143×10^3 km^2), Gansu (119×10^3 km^2), Shaanxi (118×10^3 km^2), Xinjiang (115×10^3 km^2), and Shanxi (93×10^3 km^2). The regions with relatively high ratios of soil erosion areas to their respective provincial areas are Chongqing (63.2%), Shanxi (59.3%), Shaanxi (57.4%), Guizhou (41.5%), Yunnan (36.2%), Hubei (32.8%), and Liaoning (32.6%). In 2021, the regions with the largest soil erosion areas are Sichuan (105×10^3 km^2), Yunnan (99×10^3 km^2), Xinjiang (82×10^3 km^2), Inner Mongolia (80×10^3 km^2), Heilongjiang (65×10^3 km^2), Gansu (63×10^3 km^2), and Shaanxi (62×10^3 km^2). The provinces with relatively high ratios of soil erosion areas to their respective provincial areas are Shanxi (37.0%), Chongqing City (30.1%), Shaanxi (30.0%), Guizhou (26.3%), Yunnan (25.2%), Liaoning (23.4%) and Sichuan (21.3%).

These results indicate that the regions with larger soil erosion areas are primarily distributed across the Loess Plateau, Sichuan Basin, Yungui Plateau, middle and lower reaches of the Yangtze River plain, and the Northeast Plain, located

Table 6 Erosion area by regions in 2003 and 2021

Region	Erosion area in 2003 (× 10^3 km^2)	Erosion area in proportion to province area in 2003 (%)	Erosion area in 2021 (× 10^3 km^2)	Erosion area in proportion to province area in 2021 (%)
Sichuan	150	30.6	105	21.3
Inner Mongolia	150	12.6	80.3	6.7
Yunnan	143	36.2	99.3	25.2
Gansu	119	26.1	63.4	13.8
Shaanxi	118	57.4	61.7	30.0
Xinjiang	115	7.0	82.0	5.0
Shanxi	92.9	59.3	58.0	37.0
Heilongjiang	86.5	19.7	65.2	14.8
Guizhou	73.2	41.5	46.4	26.3
Xizang	62.7	5.3	58.1	4.9
Hubei	60.8	32.8	31.1	16.7
Hebei	54.7	29.2	35.9	19.2
Qinghai	53.1	7.6	36.7	5.3
Chongqing	52.0	63.2	24.8	30.1
Liaoning	48.2	32.6	34.7	23.4
Henan	40.4	24.2	19.4	11.6
Hunan	40.4	19.1	29.5	13.9
Jiangxi	35.1	21.0	23.3	14.0
Shandong	32.4	20.5	22.5	14.2
Ningxia	20.9	31.5	10.6	15.9
Jilin	19.3	10.2	28.8	15.1
Anhui	18.8	13.4	11.9	8.5
Zhejiang	18.3	17.7	7.31	7.1
Fujian	14.8	12.1	9.05	7.4
Guangdong	11.0	6.2	17.4	9.7
Guangxi	10.4	4.4	38.0	16.0
Beijing	4.38	26.7	2.00	12.2
Jiangsu	4.11	4.0	2.20	2.2
Tianjin	0.463	3.9	0.190	1.6
Hainan	0.205	0.6	1.68	4.9

around the Yellow River, Lancang River, Yangtze River, and Heilongjiang River, respectively. Also, these regions are mainly situated in the temperate sub humid and tropical humid zones. Due to environmental factors such as climate, these regions are prone to water erosion. The region with the highest number of model applications is Shaanxi Province (Table 5), which is located in a semiarid climate wheat-growing area. However, other wheat-growing areas such as Heilongjiang and Shanxi, and Chongqing have larger soil erosion areas but significantly fewer model applications compared to Shaanxi. In contrast, the erosion areas in rice-growing regions are relatively small, resulting in a moderate number of model applications in those areas. Despite the increased focus on model applications in these regions with larger soil erosion areas, their erosion issues remain serious. The Chinese government should continue to strengthen erosion research and control measures in these regions, particularly in Heilongjiang and Shanxi Provinces, and Chongqing City. Overall, the erosion areas in regions have decreased between 2003 and 2021, reflecting the effectiveness of conservation efforts. However, there has been moderate growth in erosion areas in Guangxi, Guangdong, and Jilin, with comparatively fewer model applications. Therefore, the governments of these three regions should address the erosion issues in their respective regions.

4.3 Research points that models mainly focused on

According to the results (Figs. 1, 2, 6, and 7, and Table 5), the modeling studies primarily focus on assessing erosion using USLE, RUSLE, and CSLE. These models are predominantly applied for evaluating erosion at large scales, such as regional and watershed levels, and conducting spatiotemporal evolution analyses. A limited number of studies use the models for sensitivity assessment and analysis of influencing factors. Erosion assessment mainly employs empirical models, GIS, and RS to estimate erosion indicators such as modulus, area and intensity, followed by the analysis of influencing factors. Soil erosion influencing factors involve land use, rainfall, slope, vegetation cover, and human activities (such as grazing, cultivation, construction, and deforestation). Additionally, due to the application of remote sensing technology, data acquisition for land use, slope and vegetation cover is relatively straightforward, resulting in a higher proportion of publications in these studies. Similarly, there is also a considerable amount of research on rainfall factors. Future studies can strengthen research on other influencing factors, such as soil conservation measures, cultivation practices, and crops.

The spatiotemporal evolution of soil erosion can be categorized into three main aspects: (1) temporal variation and distribution of erosion, including erosion area, intensity and quantity; (2) detection and spatiotemporal changes of influencing factors; and (3) impact of erosion on landscape patterns and ecological environment. Over recent decades, research on the influencing factors of erosion has primarily focused on rainfall, land use, vegetation cover, micro-topography and human activities (Figs. 1 and 2). Of these factors, land use and vegetation have received the most attention. In recent years, research has predominantly used the geographic detector method for quantitative attribution analysis of factors, principal component analysis for qualitative analysis of factors, semivariogram analysis to explore the correlation between factors and erosion, soil erosion intensity index to assess the impact of land use on erosion, and statistical analysis methods to analyze linear regression data and fit the relationship between factors and erosion according to the quality standards of natural scientific research.

4.4 Problems unaddressed by models

Empirical models are simple and user-friendly, providing reasonably accurate estimations of erosion quantities within specific regions. When combined with GIS technology, empirical models enable spatial distribution analysis of erosion areas, quantities and intensities. However, soil erosion is a dynamic process that undergoes spatiotemporal changes. Empirical models can capture the influence of erosion factors, without describing the movement of soil and water particles. Also, the practicality of empirical models is limited by the observed region and scale. For example, Zhang et al.[72] developed an empirical model considering surface runoff coefficients for soil erosion calculations on red soil slopes, which was straightforward to use. However, the model requires validation in other regions. Similarly, the cellular automaton-based model[73] relies on a small number of input parameters but also needs validation and application in other regions. Regarding model application (Figs. 3, 5, and 7), many studies employ models such as USLE, RUSLE and CSLE to assess erosion quantities and areas within a region or analyze the distribution of erosion. However, these studies often lack verification of the model application results with actual observational data. Additionally, these models have certain environmental requirements and usage conditions in the study area, such as the definition of standard sample plots and the spatial scale of the application (Table 5). Accurate results can be obtained if the study meets the conditions for model application. If the conditions are not met, environmental parameters need to be transformed into standardized ones. However, most studies directly apply empirical models for erosion assessment, overlooking the transformation process. Also, these empirical models involve multiple factors, and their formulas are specific to particular regions. Before calculations, it is necessary to test the correlation between the formula and the region to minimize errors. If there are significant errors, formula adjustments are required. However, most studies directly apply formulas from others without validation. We recommend that future research strengthen the study of parameter transformation methods from the study area to the standard sample plots of the model. Additionally, to enhance the accuracy of model results, it is important to validate the research findings using observational data or other materials. From an engineering perspective, future research can focus on erosion assessment at smaller scales or the development of corresponding prediction models. Also, future studies can pay more attention to the impact assessment of factors such as human activities and soil conservation measures on soil erosion, including factor monitoring, data acquisition, and quantification.

Models based on physical processes have high extrapolation capabilities and can be effectively applied to regional transfer and the expansion of design conditions. These models use physical parameters that describe hydrological and sediment transport processes, enabling the simulation of spatiotemporal variations in soil erosion and sediment yield. Soil erosion is affected by a set of factors that exhibit strong temporal and spatial distribution characteristics, such as rainfall and temperature. Climate change gives rise to changes in rainfall intensity, frequency and its spatial distribution, which then impact the production of runoff and soil erosion intensity. Standard empirical models struggle to account for these new rainfall features and usually homogenize rainfall data that have spatially distributed features. Rising temperatures affect soil physical, chemical and biological processes, altering soil erodibility. Describing this influence through simple empirical relationships is challenging. Model parameters based on physical processes have clear physical meanings, which are advantageous for analyzing the impact of climate change on these parameters. They also provide a better description of the mechanisms through which climate change affects the soil erosion process. By coupling soil-vegetation-hydrological processes, it is possible to more comprehensively predict erosion responses under different climate change scenarios. However, physical process-based soil erosion models also have some limitations, especially when using the steady-state sediment continuity equation. The assumption of the steady-state sediment continuity equation is based on the sediment balance under steady-state conditions. This equation, grounded in the principle of mass conservation, assumes that the input and output of sediment remain balanced in time and space. It overlooks the spatial heterogeneity of the surface slope and assumes that sediment transport processes are uniform across the entire study area. Also, this equation cannot describe the non-steady behavior of sediment transport processes, such as instantaneous sediment scour and transport caused by heavy rainfall. Additionally, this equation fails to capture the temporal changes in soil characteristics (such as soil particle size distribution and organic matter content), despite these properties significantly influencing the erosion process. Also, physical process-based models also present other issues. Due to the detailed description of erosion processes, these models have complex parameter structures, increasing computational complexity and limiting their application range. Additionally, the lack of observational data poses challenges for parameter sensitivity analysis and optimization in developing high-precision models. For example, some models lack the necessary parameters during the construction process, leading to significant deviations between simulated results and actual conditions, thereby limiting simulation accuracy. Similarly, certain models have limited precision and require further improvements in the accuracy of model data and the refinement of simulation processes. Also, some models exhibit errors in simulating water-sediment processes, especially in cases of high sediment concentration during peak flows. Likewise, there are discrepancies between simulated results and actual conditions. For example, certain models fail to effectively reflect shallow gully erosion and do not incorporate other erosion patterns. Overall, models based on physical processes are still in the early stages of development in terms of construction. In terms of model application, both domestic and foreign models have relatively limited application in China, primarily due to differences in model backgrounds. Different regions have distinct geomorphic environments, erosion patterns, and characteristics. In addition to enhancing in-depth descriptions of erosion processes, it is important to improve the accuracy and validation of models based on physical processes. Specifically, research should focus on increasing parameter sensitivity analysis and calibration studies. Future studies can integrate erosion process models of different scales with model conversion methods to enhance research on erosion processes at various scales. This approach can provide a comprehensive understanding of erosion mechanisms from both macroscopic and microscopic perspectives. Additionally, it is recommended to combine models based on physical processes with various erosion patterns specific to China to enhance model applicability.

5 Conclusions

This study using bibliometric and statistical methods analyzed 786 Chinese papers related to soil erosion models from five perspectives: keywords, model operations, model classification, spatial scales of models and geographic distribution of model applications. The results of the study indicate that research on soil erosion models in China primarily focuses on large scales (region and large watersheds) and employs empirical models such as USLE, RUSLE and CSLE. The research has covered the following aspects: (1) assessment of erosion rates, areas and intensities; (2) analysis of the impacts of influencing factors on erosion, particularly rainfall, land use and vegetation cover; (3) spatiotemporal evolution and distribution analysis of erosion, including rates, areas and intensities; and (4) detailed studies on erosion processes and morphology. After 2006, research on soil erosion models in China underwent rapid development, with a focus on the south-eastern and central regions of the country. The research gradually transitioned from studying soil erosion characteristics to analyzing influencing factors and spatiotemporal evolution of erosion. Currently, for the north-eastern region this is still in the stage of studying soil erosion characteristics, with relatively less research conducted. In terms of the intensity of soil erosion research, Shanxi and Liaoning Provinces have fewer studies, although the degree of erosion is relatively high. It is recommended t soil erosion research should be strengthened in Heilongjiang, Liaoning and Shanxi Provinces, taking into account the local geographical characteristics and experimental conditions, and gradually align the research with the foci in erosion studies. However, there are several apparent shortcomings in current soil erosion model research in China: (1) the lack of validation using field data undermines the reliability and accuracy of the model results; (2) the application of models is limited to specific regions, making it difficult to generalize the models; (3) research on models based on physical processes is relatively weak and overly complex, with some input parameters difficult to measure, leading to challenges in application; and (4) there is a relative lack of research on the mechanisms of erosion processes. It is recommended that future research improve the study of erosion process mechanisms, increases observations of soil erosion processes, and establishes data or mathematical formula conversion methods according to different geographical environments. The findings of this study should provide a valuable resource for researchers to better understand the development process and current issues of Chinese soil erosion models, providing insights for future research directions.

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Compliance with ethics guidelines

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