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Modeling of water erosion under future scenarios: a literature review

Modelagem de erosão hídrica sob cenários futuros: uma revisão da literatura

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Abstract: Water erosion ranks among the leading environmental problems, and its intensity is expected to grow over the coming decades, leaving landscapes increasingly degraded. Even so, the specialized literature on the subject remains scarce. This article therefore sets out to identify the trends, methods, and variables that shape studies on water erosion modeling under future scenarios. To that end, we searched the Scopus database and then combined bibliometric techniques with tools drawn from systematic review. The results point to a rise in publications from 2020 onward, likely spurred by the growing frequency of extreme climatic events and by advances in climate models. RUSLE (Revised Universal Soil Loss Equation) emerged as the dominant method, a pattern echoed in the recurrence of variables such as rainfall erosivity, soil erodibility, slope length, slope steepness, land use and land cover, and soil conservation practices. Notable gaps nonetheless surfaced, chiefly the absence of validation in several studies and the shortage of research in semi-arid regions. Taken together, the article brings the essential features of this field into focus, offering a coherent view of current trends and a foundation for future work.

Keywords: Water erosion; Future scenarios; Climate change.

Resumo: A erosão hídrica configura-se como um dos principais problemas ambientais, e estima-se que sua intensidade tende a aumentar nas próximas décadas, resultando em ambientes mais degradados. Apesar de sua relevância, a literatura especializada ainda é limitada. Nesse contexto, o presente artigo tem como objetivo identificar tendências, métodos e variáveis utilizados nos estudos sobre modelagem de erosão hídrica em cenários futuros. Para tanto, realizou-se uma busca na base de dados Scopus, seguida da aplicação de técnicas bibliométricas e de ferramentas da análise sistemática. Os resultados revelaram um aumento das publicações a partir de 2020, possivelmente impulsionado pela maior frequência de eventos climáticos extremos e pelos avanços nos modelos climáticos. Observou-se o predomínio do método RUSLE (Revised Universal Soil Loss Equation), refletido na recorrência de variáveis como erosividade da chuva, erodibilidade do solo, comprimento das encostas, declividade, uso e cobertura da terra e práticas de conservação do solo. Contudo, foram identificadas lacunas relevantes, especialmente associadas à falta de validação em alguns estudos e a escassez de pesquisas em regiões semiáridas. De modo geral, o artigo evidencia aspectos essenciais dessa área de pesquisa, oferecendo uma visão consistente das tendências atuais e servindo como base para investigações futuras.

Palavras-chave: Erosão hídrica; Cenários futuros; Mudanças climáticas.

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1. Introduction

Soil erosion is one of the greatest global threats and the leading driver of land degradation in humid tropical and subtropical regions. Each year it inflicts agricultural losses on the order of billions of dollars, degrading vast stretches of arable land and threatening food security worldwide (WANG *et al.*, 2020). Recent studies indicate that, over the past century, the global average erosion rate reached roughly 10.2 t ha^{-1} yr^{-1}, with projections of an increase of up to 14% by the end of the twenty-first century (BUSICO *et al.*, 2023).

Given the complexity of erosion processes, water erosion modeling has become an essential tool for understanding and predicting the phenomenon. It makes it possible to simulate how soil behaves under different climatic, land use, and management conditions, with direct application in conservation planning and public policy. Building models to estimate erosion poses considerable challenges, largely because soil and climate characteristics differ across the regions where the models are applied (MINELLA *et al.*, 2007).

Broadly speaking, erosion is a natural process defined by the removal of soil particles by agents such as water and wind (GANASRI; RAMESH, 2015). Human activity, however, and agricultural activities in particular, has sped this process up considerably, undermining essential ecosystem services such as crop production, carbon sequestration, water filtration, and the maintenance of vegetation cover (KIANI-HARCHEGANI *et al.*, 2019).

Climate change has also contributed to rising erosion rates through shifts in precipitation patterns. By 2050, erosion could cut global agricultural output by 10% and strip away some 75 billion tonnes of soil (FAO, 2022). In Brazil, water erosion is the most common form and the one that most compromises soil quality, owing to climatic conditions that include high-intensity rainfall together with poor land use and management, which intensify surface runoff and the loss of fertile topsoil. In response to these challenges, erosion research has gained prominence in recent years, given its clear consequences for agricultural productivity, water quality, hydrological systems, and environmental balance (SILVEIRA *et al.*, 2023).

Amore *et al.* (2004) note that soil-erosion problems are likely to worsen in the future across many parts of the world, driven by climate change and the resulting intensification of processes tied to the hydrological cycle. The literature devoted to analyzing future water-erosion scenarios is still relatively young and marked by uneven publication rates. Against this backdrop, scientific output plays a decisive role in the technical advancement and specialization of the topic. Hybrid review approaches allow for a deeper, more comprehensive analysis by pairing the bibliometric quantification of trends and patterns in scientific output with the careful synthesis and methodological rigor typical of systematic reviews (VASCONCELOS *et al.*, 2024).

From this standpoint, bibliometrics and systematic review complement one another: the former reveals collaboration networks, emerging themes, higher-impact journals, and key producing countries, while the latter enforces explicit criteria for searching, screening, and appraising study quality (CHEN, 2017). Their complementarity makes the conclusions more reliable, since it fosters an integrated reading of the state of the art that blends quantitative and qualitative perspectives and brings to light gaps and research opportunities that a single method, used alone, would leave obscured (JOHRI, 2024). The aim of this article is therefore to analyze the scientific literature on water erosion modeling under future scenarios and to identify the trends, methods, and variables associated with the field. To this end, eleven years (2013–2024) of scientific publications were examined, with a view to outlining the current panorama of the topic.

2. Methodology

Traditional bibliometric techniques were combined with qualitative and quantitative descriptors, incorporating elements of systematic review protocols. This approach allowed for a targeted analysis of specific sections within the selected articles, with emphasis on extracting information about the simulation of water erosion under future scenarios. Working from this framework, we formulated questions of different kinds, in line with the study's objective (Table 1). The procedure comprised selecting the database, defining the search terms, and applying filters to refine the results, followed by exclusion criteria to remove studies that fell outside the scope of the research (Figure 1). The analyses were carried out on the final set of selected articles. Table 1 summarizes the relationship between the research questions, the analyses performed, and the texts used, while Figure 1 lays out the study's methodological stages.

Table 1 – Research questions.

Questions	Analyses	Texts used
What are the trends in scientific output on future simulations of water erosion?	Contribution by country (bibliometrix)	All articles
Which countries lead the publication of water erosion studies?	Keyword co-occurrence (VOSviewer)	All articles
Which are the most influential journals in the field?	Top 5 most relevant journals (bibliometrix)	All articles
Which are the most globally cited documents in this research area?	Top 5 most cited documents (bibliometrix)	All articles
Which climatic regions have most often been modeled in the studies analyzed?	Title/Abstract/Materials and methods	27 articles
Which simulation methods are most commonly used in water erosion research?	Abstract/Materials and methods	All articles
Which climate models are most widely used?	Materials and methods	All articles
Which environmental variables are most used, and which are most influential?	Materials and methods/Results and discussion	All articles
Are the applied models validated? If so, which validation metrics are used?	Materials and methods	All articles
Which water-erosion behavior patterns does the reviewed literature point to?	Results and discussion	All articles

Source: Authors (2025).

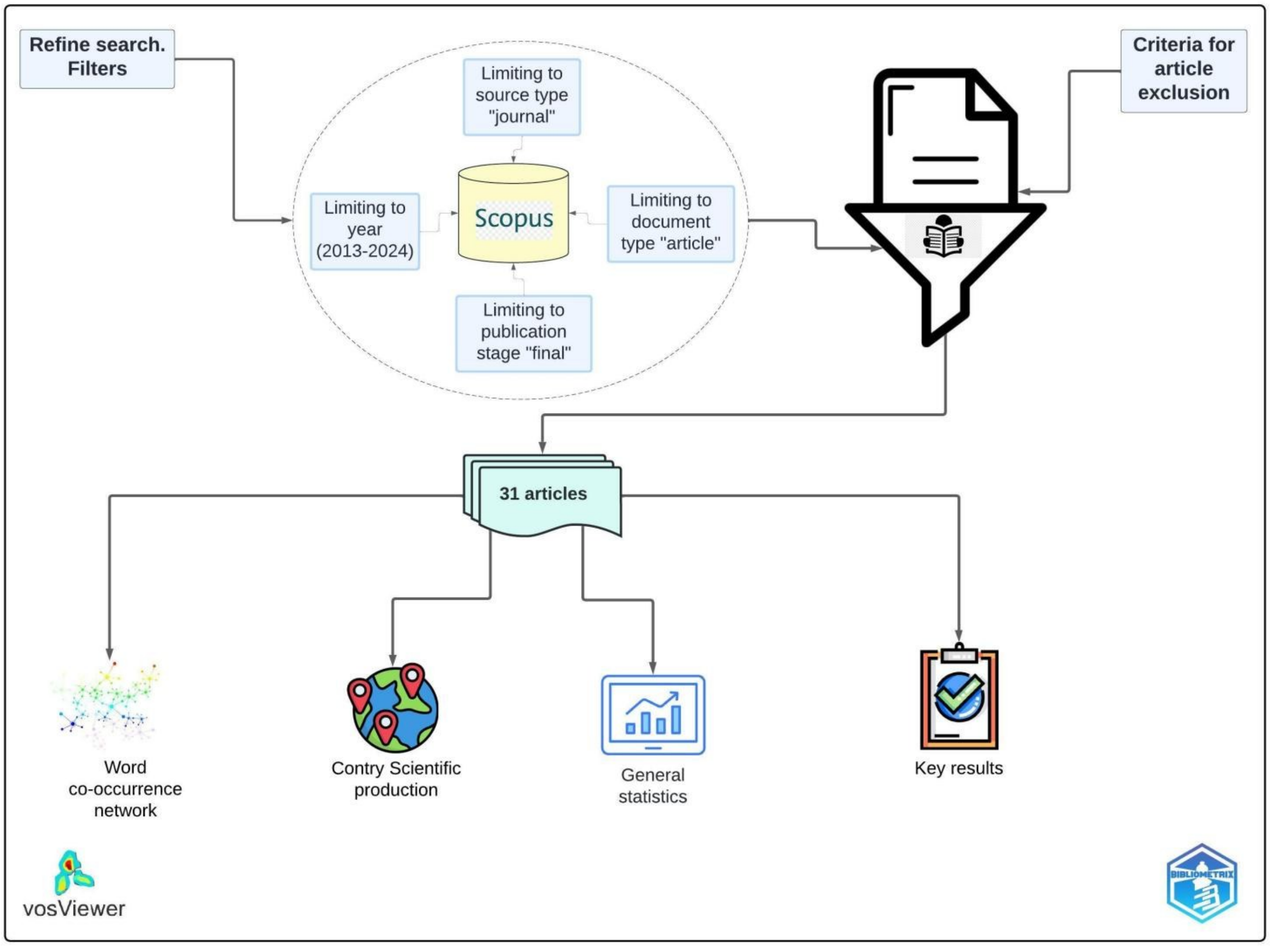

Figure 1 – Methodological scheme of the steps performed for the bibliometric analysis.
Source: Authors (2025).

2.1 Bibliographic database

Scopus was chosen as the database for its broad coverage and advanced analytical resources. The platform allows data to be exported in multiple formats according to predefined variables, providing comprehensive information for bibliometric and systematic analyses (VIANA *et al.*, 2017). It has also offered citation data since 1996, which supports detailed analyses of global research trends and scientific output across a range of fields (OLIVEIRA *et al.*, 2025).

Scopus currently indexes more than 53 million records from over 24,000 peer-reviewed scientific journals across a wide disciplinary spectrum. Its online interface offers advanced search features, including Boolean operators and field-specific filters, which favors an efficient, reproducible, and methodologically consistent retrieval of the literature (OLIVEIRA *et al.*, 2025).

The decision to rely on a single database was based on the need to ensure the consistency and homogeneity of the data collected, avoiding duplicates, indexing inconsistencies, and biases that arise when databases with differing criteria are merged. Using Scopus exclusively thus made it possible to build a robust and methodologically reliable dataset, well suited to represent the state of the art in water erosion modeling under future scenarios.

One acknowledged limitation is the exclusion of other databases, such as the Web of Science. Even so, this choice does not appear to undermine how representative the results are, given the breadth and standing of Scopus in international scientific production.

2.2 Search strategy

The search was refined to include publications available up to 2024, covering all relevant literature from the first indexed record in the database through that year. It thus spanned the period from 2013 to 2024, a total of eleven years, focusing on studies that dealt with the simulation of future scenarios in the context of water erosion.

The search strategies were built through testing and adjustment, combining keywords related to the topic and using Boolean operators (AND and OR) to refine and steer document retrieval. The asterisk (*) was used to allow for variations in keyword suffixes, thereby broadening the reach of the results.

Finally, the search equation was implemented as follows: TITLE-ABS-KEY(("Soil erosivity" OR "Soil erosion*" OR "Soil erosion vulnerability" OR "Soil erosion degradation" OR "Soil loss" OR "Soil erosion susceptibility" OR "Surface runoff effects" OR "Runoff effects") AND ("Prediction future scenarios" OR "Simulation Future*" OR "Future* Scenarios" OR "Scenario* Simulation* Future*" OR "Past and Future Scenarios")) AND PUBYEAR > 2000 AND PUBYEAR < 2025 AND PUBYEAR > 2000 AND PUBYEAR < 2025 AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (DOCTYPE,"ar")), enabling the search within the titles, abstracts, and keywords of the articles.

After this step, the articles were screened manually by reading titles and abstracts and applying the exclusion criteria. Studies were excluded if they (i) did not address water erosion modeling, (ii) focused exclusively on sediment yield, (iii) did not include future-scenario simulations, or (iv) were literature reviews.

2.3 Software used

All articles retained after the manual screening were subjected to keyword co-occurrence analysis, counting one occurrence per term. For this purpose, VOSviewer was used, a program that builds and visualizes bibliometric maps, which facilitates the identification of connections among articles, authors, and journals, as well as to map co-authorship relationships, institutional affiliations, and the co-occurrence of relevant terms. According to Van Eck and Waltman (2009), VOSviewer produces high-quality bibliometric maps, which eases interpretation and makes it one of the best options in its class.

We also used the bibliometrix package, which provides a set of tools for quantitative analysis in bibliometrics and scientometrics. The package was developed in R, an open-source environment offering statistical algorithms, access to high-quality numerical routines, and integrated resources for data visualization (ARIA; CUCCURULLO, 2017).

3. Results and discussion

3.1 Publication trends

The search of the Scopus database returned 77 articles in total. After the exclusion criteria were applied, 31 documents remained, making up the study's global corpus, with a mean and standard deviation of 2.58 ± 2.50 articles per year. The cumulative number of publications rose in recent years, reaching 25 articles between 2020 and 2024, or 80.6% of the total (Figure 2). Before 2020, scientific output was low and irregular, amounting to just six articles. Three productivity peaks stand out, in 2020, 2023, and 2024, with six publications each, together accounting for 58.0% of the total output. It is also worth noting that every document analyzed (100%) was published in English.

These results suggest that the field is relatively young, about a decade old, and still taking shape. Since 2020, scientific output has grown markedly, signaling the continued expansion and dynamism of the field, which may be linked to the intensification of extreme climatic events, such as more severe storms, prolonged droughts, and a heightened risk of wildfires (BUSICO *et al*., 2023). In addition, advances in the climate models developed under the Coupled Model Intercomparison Project (CMIP) have helped these studies expand by providing more consistent and more detailed projections (O'NEILL *et al.*, 2013; PEDERSEN *et al.*, 2021). Added to this are the growing availability of remote sensing data and the development of advanced computational techniques, which have widened the analytical possibilities in the field.

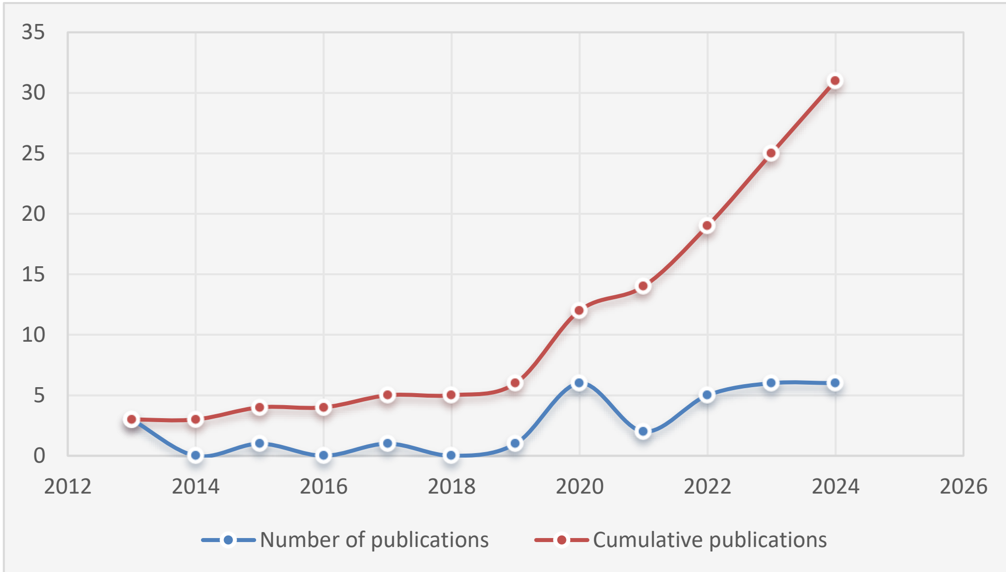

Figure 2 – Annual growth rate of publications.
Source: Authors (2025).

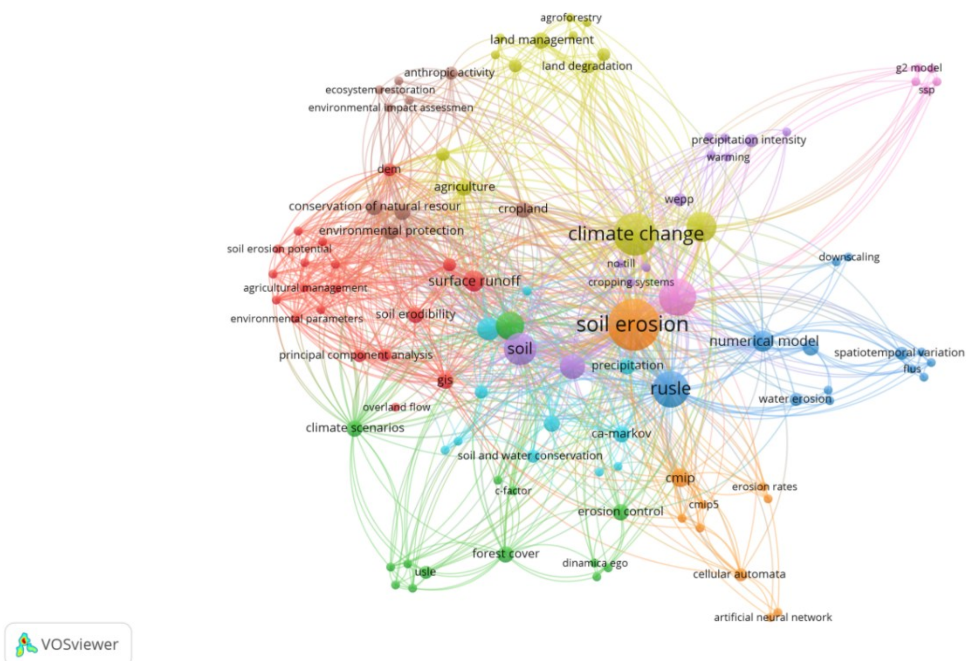

Figure 3 – Word co-occurrence network.
Source: Authors (2025).

As for the word co-occurrence network, nine clusters were identified (Table 2), totaling 107 terms (Figure 3). The most frequent terms were soil erosion (30 occurrences), climate change (21 occurrences), land use/land cover change (16 occurrences), revised universal soil loss equation (15 occurrences), soil (12 occurrences), future scenarios (10 occurrences), rainfall erosivity (9 occurrences), and climate modeling (7 occurrences).

Table 2 – Clusters identified in the keyword co-occurrence analysis.

Color	Cluster	Approach
	Cluster 1	Groups the core elements of water erosion modeling, with emphasis on soil erodibility and key hydrological processes such as surface runoff and overland flow.
	Cluster 2	Links terms tied to climate projections and extreme events, especially heavy rainfall, which raises rainfall erosivity and intensifies erosion processes.
	Cluster 3	Presents the main methods used in water erosion modeling and in the simulation of land use and land cover.
	Cluster 4	Addresses climate change and the relevance of sustainable practices for soil management. It also gathers methods frequently used in these studies.
	Cluster 5	Covers terms related to climatic variables, such as temperature and precipitation, that influence soil properties and increase its susceptibility to erosion.
	Cluster 6	Deals with spatial simulation models, such as CA-Markov, fuzzy logic, and the InVEST model, applied in land use and land cover and water erosion studies.
	Cluster 7	Highlights advanced modeling techniques, referring to computational methods such as artificial neural networks and cellular automata. It likewise stresses the importance of remote sensing products and the incorporation of CMIP climate data.
	Cluster 8	Encompasses themes related to the role of socio-environmental dimensions. It further stresses the importance of sustainable land management, environmental impact assessment, and actions to protect and restore ecosystems
	Cluster 9	Brings together statistical methods and algorithms applied to water erosion modeling, including Random Forest, regression, and Gaussian approaches.

Source: Authors (2025).

The keyword co-occurrence network shows that understanding water erosion calls for an integrated approach, one able to connect physical-hydrological processes, climate projections, changes in land use and land cover, and socio-environmental dimensions, underscoring how multidisciplinary the topic is. Methodologically, traditional modeling approaches based on empirical equations coexist with more recent ones grounded in machine learning. Studies such as that of Guo *et al.* (2024), which pairs the RUSLE model with machine learning algorithms to identify spatial patterns of susceptibility to water erosion, illustrate this trend. The picture suggests a methodological shift in the field, marked by the gradual integration of conventional methods and data-driven approaches. Such advances carry real implications for environmental planning and management, since bringing together climate modeling, land use change, and the analysis of erosion processes is essential to inform sustainable management strategies.

3.2 Countries leading the publications

The global collaboration and distribution of publications revealed 48 connections among different regions of the world, as shown in Figure 4. The varying thickness of the lines represents the strength of these connections, offering useful insight into collaborative efforts in the field and the exchange of knowledge among nations. The strongest collaborations appear between Ireland and Belgium, Spain and Germany, and the United States and Hungary.

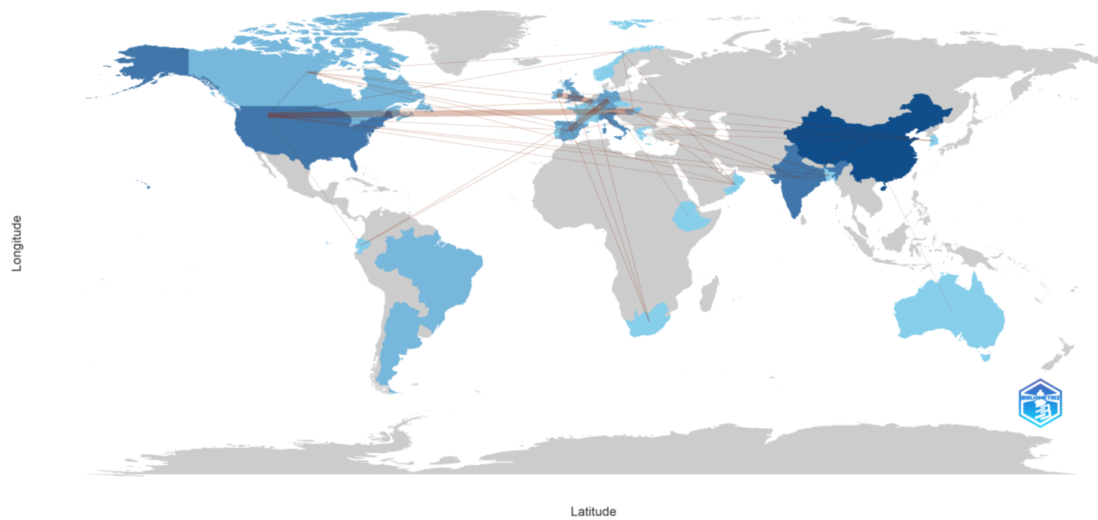

Figure 4 – Publication collaboration between countries.
Source: Authors (2025).

Table 3 – Contribution of scientific output by country.

Color	*Countries*	*Number of publications*
	China	35
	India	21
	Italy	19
	United States	19
	Brazil	12
	Spain	9
	United Kingdom	7
	Ireland	6
	Argentina	5
	Belgium	4
	Germany	4
	Canada	3
	Malta	3
	Oman	3
	Czech Republic	2
	Hungary	2
	South Korea	2
	Switzerland	2
	Australia	1
	Bangladesh	1
	Ecuador	1
	Ethiopia	1
	France	1
	Greece	1
	Norway	1
	Portugal	1
	South Africa	1

Source: Authors (2025).

These interactions are essential for exchanging ideas and resources among researchers, extending the reach and relevance of research on water erosion under future scenarios. In terms of output by country, China was the largest contributor, with 35 publications, followed by India (21), Italy (19), the United States (19), and Brazil (12) (Table 3). This pattern may be tied to growing investment in research and development, particularly in countries such as China, where environmental issues like water erosion carry considerable socioeconomic weight. In Brazil's case, although the number of publications is lower, the topic remains important nationally, since water erosion is one of the country's main environmental problems, linked to loss of soil fertility, siltation of rivers, and a reduced capacity of the land to support vegetation (MONDAL *et al.*, 2017).

By contrast, when scientific impact is measured by citation count, Switzerland ranked first, with 1,009 citations, followed by India (224), Belgium (160), the United Kingdom (140), China (125), and Ecuador (124). These figures highlight the gap between volume of output and scientific impact, giving a broad view of each country's role in both generating and disseminating knowledge through international collaboration.

3.3 Most influential journals

The journal analysis showed that 22 distinct journals contributed to output in this field. Among them, Catena stood out as the leading source, with six articles (19.4% of the total), which speaks to its relevance in research on future water-erosion scenarios. Next came Land and Land Degradation & Development, with three publications each. Other journals, such as Agricultural Water Management and Climate, contributed just one article each, pointing to a more occasional presence in the topic (Figure 5).

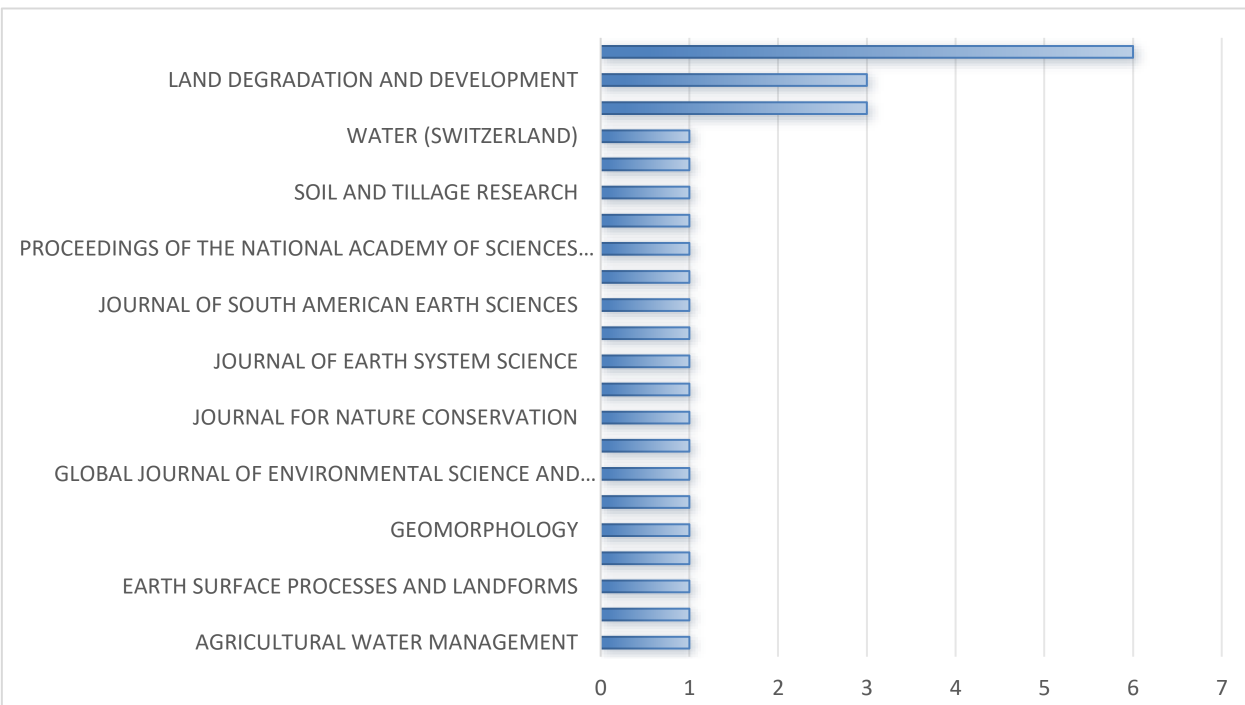

Figure 5 – Most influential journals.
Source: Authors (2025).

These results show that, although the subject is interdisciplinary, scientific output remains concentrated in a small number of specialized journals, which act as the main channels for disseminating knowledge. This concentration reflects, in part, the role of well-established journals with a clearly defined thematic scope and a specific readership, which encourages the submission of studies aligned with the field. The predominance of these journals suggests, however, that the visibility and impact of research depend on the choice of journals recognized in the field.

3.4 Most globally cited documents

Among the most cited documents, the study by Borrelli *et al.* (2020), published in the Proceedings of the National Academy of Sciences, stands out sharply, amassing 1,009 citations and establishing itself as the leading global reference in the field. At a second level of influence are the works of López-Vicente *et al.* (2013), with 170 citations, and Mullan (2013), with 110 citations, both published in Catena, alongside the article by Ochoa-Cueva *et al*. (2015), which records 133 citations and appeared in Land Degradation & Development. The study by Chuenchum *et al*. (2020), for its part, shows moderate impact, with 95 citations, and appeared in International Soil and Water Conservation Research (Figure 6).

Overall, citations are heavily concentrated in a small number of studies, with the striking dominance of Borrelli *et al.* (2020), which points to a highly skewed distribution of scientific impact in the field. This pattern indicates that a fraction of the academic literature exerts substantial influence on how knowledge takes shape, hinting at possible biases and prevailing tendencies in which certain studies cement their centrality and steer the direction of research and the methodological choices adopted. The temporal clustering of the most cited works in particular years, such as 2013 and 2020, also points to key moments of scientific advance, tied both to the early investigations and to the recent surge of interest in the topic.

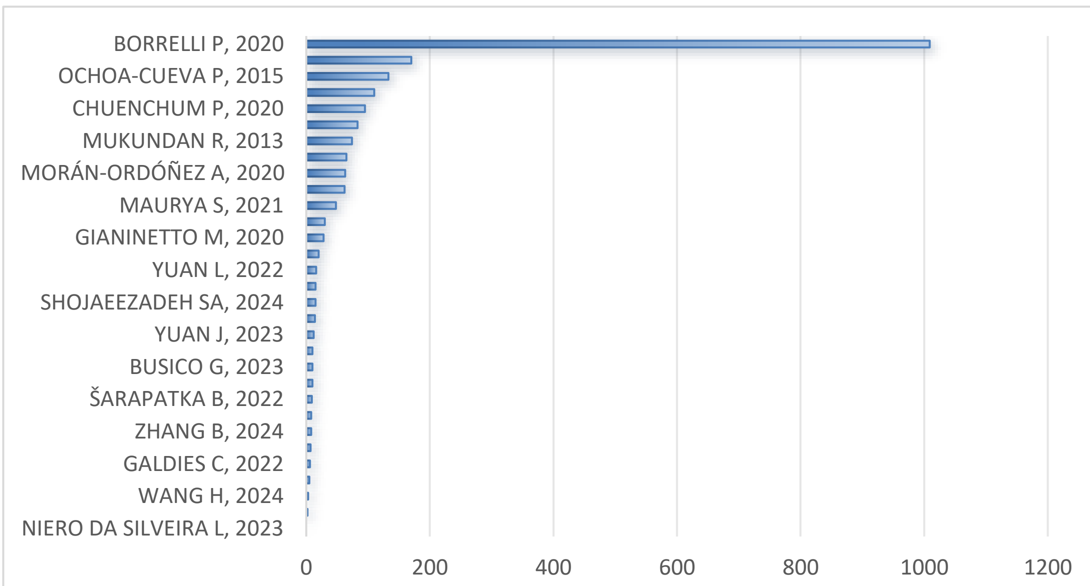

Figure 6 – Most globally cited documents.
Source: Authors (2025).

3.5 Modeled climatic region

Of the 31 articles identified, 27 were analyzed with respect to climatic regions, since the rest addressed areas at a global scale. Among the studies considered, research concentrated most heavily in subtropical regions (25.9%), followed by temperate (22.2%), tropical (18.5%), and Mediterranean (14.8%) climates. Semi-arid regions, by contrast, received far less attention, accounting for just 11.1% of the literature analyzed.

This gap matters, because such regions are highly vulnerable to erosion, a vulnerability compounded by rainfall concentrated into short periods and by environmental degradation (QUEIROZ *et al.*, 2020). The predominance of studies in other climatic regions may limit how applicable existing models are in semi-arid contexts, since such approaches do not always adequately capture the specific conditions of these environments.

3.6 Most widely used simulation methods

The literature shows a predominance of the RUSLE method (Revised Universal Soil Loss Equation), found in 58% of the documents analyzed. In more recent studies, this method is combined with more advanced approaches, such as machine learning techniques (9.6%). The USLE (Universal Soil Loss Equation) and WEPP (Water Erosion Prediction Project) methods each account for 12.9% of the studies, making them the second most used approaches. The SWAT (Soil and Water Assessment Tool) model appeared in 6.4% of the output. Less common, with a single study each, were the D-RUSLE (Dynamic Revised Universal Soil Loss Equation), RMMF (Revised Morgan–Morgan–Finney Model), and SWAT-WB (Soil and Water Assessment Tool – Water Balance) methods, the last considered an adaptation of SWAT-2005, along with the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) and EPM (Erosion Potential Method) approaches.

RUSLE is an empirical, quantitative model that estimates soil loss from the interaction of factors such as rainfall erosivity (R), soil erodibility (K), the topographic factor (LS), land use and management (C), and conservation practices (P) (WISCHMEIER; SMITH, 1978). It is an update of the USLE equation, developed to ease computational application and improve the accuracy of erosion estimates. In the Brazilian context, the model fits climatic and environmental conditions well and is widely used in large-scale studies supported by Geographic Information Systems (PANAGOS *et al.*, 2015).

Despite its wide use, in semi-arid regions the model has limitations, particularly in estimating the R factor (rainfall erosivity), because rainfall data are scarce and climatic variability is high. The WEPP model, by contrast, is a dynamic model grounded in the physical principles of the erosion process (LANE *et al.*, 1992). Its ability to incorporate variables such as soil condition, vegetation cover, and antecedent moisture lends greater robustness to the simulations. Studies conducted in Brazil show its potential for use in different settings, including semi-arid regions, where the model performed well in predicting erosion (PISCOYA *et al.*, 2020). Even so, the input data must be properly adjusted to reflect the specific conditions of each study area.

The SWAT model, in turn, is notable for its ability to simulate at the watershed scale, allowing an integrated analysis of hydro-sedimentological processes (BLAINSKI *et al.*, 2017). SWAT works with daily time-step data and is used to simulate the water and nutrient cycle at the basin scale and to assess environmental efficiency. Its use in Brazil is widespread (LIMA *et al.*, 2020), and it is particularly useful for assessing the impacts of management and land use practices. Its performance can vary with the scale of analysis, however, yielding better results in meso-basins than in micro-basins, where the gap between simulated and observed data tends to widen (NETO *et al.*, 2014). In addition, coupling machine learning techniques with RUSLE points to an emerging trend in the literature, one that helps select relevant variables and contributes to more accurate estimates, especially in complex environments such as the semi-arid zone.

3.7 Most widely used climate models

About 54.8% of the studies draw on data from the Coupled Model Intercomparison Project (CMIP), spanning its different phases (CMIP3, CMIP5, and CMIP6). CMIP serves as the scientific basis for the Intergovernmental Panel on Climate Change (IPCC), providing a broad set of numerical experiments that make it possible to simulate changes in precipitation under past, present, and future scenarios (O'NEILL *et al.*, 2013). It is also common for CMIP-based studies to use multiple models in their simulations as a way to reduce individual biases and strengthen the projections (GUPTA; SINGH; JAIN, 2020).

A further 9.6% of the studies use Regional Climate Models (RCMs), such as the model from the Royal Netherlands Meteorological Institute (KNMI) and the Coordinated Regional Climate Downscaling Experiment (CORDEX), which allow for greater spatial detail in the projections. Roughly 35.6% of the studies, on the other hand, do not specify the climate model used, rely on previously estimated erosivity values, or base their projections solely on land use and land cover change.

As for climate scenarios, about 64.5% of the studies use the Shared Socioeconomic Pathways (SSPs) or the Representative Concentration Pathways (RCPs). The SSPs update the RCPs by folding socioeconomic assumptions into the modeling of greenhouse gas emissions (RIAHI *et al.*, 2016). Complementing the RCPs, the SSPs take into account variables such as population growth, economic dynamics, urbanization patterns, and technological progress, offering an integrated set for long-term climate projections. The most widely used scenarios include SSP1-2.6/RCP2.6, an optimistic future with steadily falling emissions across the century; SSP2-4.5/RCP4.5, an intermediate scenario with a higher emissions peak but a slower decline; and SSP5-8.5/RCP8.5, the most pessimistic scenario, which assumes rapid economic growth heavily dependent on fossil fuels (O'NEILL *et al.*, 2013).

3.8 Most widely used environmental variables

With regard to environmental variables, 74.1% of the articles use, in the modeling process, the classic factors that make up the USLE equation and, by extension, the RUSLE method: rainfall erosivity, soil erodibility, slope length, slope steepness, land use and land cover, and soil conservation practices. The remaining 25.8% of the studies use variables defined according to the modeling method adopted. Among these are:

- Climatic variables: precipitation, minimum and maximum temperature, solar radiation, relative humidity, wind speed, and, in some cases, CO_2 concentration.
- Soil variables: physical properties such as texture, organic matter or organic carbon content, profile depth, and porosity.
- Topographic variables: derived from digital elevation models, such as altitude, slope, slope length and shape, contributing area, and various topographic indices.
- Land use and land cover variables: crop types, vegetation cover, deforestation, and agricultural expansion.
- Hydrological variables: surface runoff volume, peak flow, sediment yield, and rainfall kinetic energy.

As for the variables that most influence water erosion, 80.8% of the studies identify at least one dominant factor in the erosion dynamics. Of these, 38.8% single out rainfall erosivity as the main trigger of erosion. A further 22.5% report that erosion is driven mainly by the interaction between rainfall erosivity and land use and land cover. Another 13% attribute the rise in erosion to land use and land cover together with the management practices adopted in the regions studied. A smaller share, 6.5% of the articles, hold that slope length and steepness carry the greatest weight in intensifying water erosion.

Studies in semi-arid regions, such as those by Yuan *et al.* (2023) and Zhang *et al.* (2024), indicate that the rise in water erosion is chiefly associated with more erosive rainfall and with changes in land use and land cover. The authors also note that pastureland and steeper slopes are more susceptible to erosion. Behera *et al.* (2020), on the other hand, link the future increase in water erosion to shifts in precipitation patterns interacting with topographic and soil variables. Taken together, these results reveal the complexity of water erosion and show that, although some factors weigh more heavily on erosion processes, the environmental particularities of each region bear directly on its intensity and spatial distribution.

3.9 Model validation

The analysis of model validation showed that only 54.8% of the articles use some metric to validate the performance of their estimates. Validation is carried out mainly by comparing estimated soil losses with observational data from field measurements or historical series. Several studies also employ statistical metrics to quantify the models' predictive performance, chief among them the coefficient of determination (R^2), the Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and the root-mean-square error (RMSE). Where reliable soil-loss data are unavailable for validation, it is common to assess the accuracy of the modeling's core components—erosivity, erodibility, topography, and land use and land cover—through correlations and agreement measures, so as to ensure the reliability of the variables used. Yet 45.2% of the articles make no reference to validation procedures, which undermines the reliability and practical applicability of their results. The data reveal that, for all the progress in water erosion modeling, validation remains one of the main methodological limitations found in the literature reviewed.

3.10 Erosion pattern

As for the erosion pattern, 58.0% of the articles indicate that, under certain climate-change scenarios, erosion tends to rise substantially, largely as a result of increasing rainfall erosivity. Another 29.0% of the studies show contrasting regional behavior, with both decreases and increases in erosion depending on the period considered, the area analyzed, and the management practices adopted. A further 13.0% point to a downward trend, associated mainly with the conversion of agricultural areas into forest and with a rising aridity index.

According to Borrelli *et al.* (2020), the growing frequency of extreme events tends to increase soil losses substantially at the global scale, even in regions where mean annual precipitation shows no marked rise. Beyond climatic factors, agricultural expansion, deforestation, and the occupation of steep areas were frequently linked to worsening erosion, whereas scenarios with greater vegetation cover showed a partial reduction in soil losses. In this context, Ochoa-Cueva *et al.* (2015) stress that vegetation plays a key role in protecting the soil, reducing surface runoff and buffering the combined effects of precipitation and slope.

Another relevant point concerns the high spatial variability of erosion processes. Despite the overall tendency toward intensification, some studies found localized reductions tied to a drop in total precipitation and to more frequent droughts

(GALDIES *et al*., 2021). These results show that erosion's response to climate change is not uniform, varying with environmental conditions and land use in each region. Even so, the findings reinforce the need for integrated strategies of soil conservation and sustainable land management, especially in the most vulnerable areas. However, as highlighted by Borrelli *et al.* (2020), although conservation practices can partly reduce soil losses in less extreme scenarios, their effectiveness tends to be limited against the projected rise in rainfall erosivity under more severe climate scenarios, underscoring the need for more robust global policies of climate mitigation and adaptation.

4. Final remarks

This review shows that studies on future water-erosion scenarios form an emerging field, still marked by a low volume of publications, a global collaboration network in the making, and output concentrated in a few journals and in a small number of highly visible international articles. Countries such as China, India, Italy, the United States, and Brazil lead scientific production on the topic. The hybrid analysis, for its part, made it possible to broaden understanding of the subject and to identify relevant gaps, chief among them the scarcity of studies in semi-arid regions and the limited validation of the models used.

Methodologically, the RUSLE method was strongly predominant, together with the recurrent use of climate projections derived from CMIP. More complex models, such as WEPP and SWAT, were also identified, as was the coupling of machine learning techniques with RUSLE, which help select relevant variables and improve water erosion estimates.

Overall, the results point to a tendency toward more intense water erosion in the coming decades, tied to rising rainfall erosivity under extreme climate scenarios. That said, the erosion dynamics also proved strongly shaped by land use and land cover and by management practices. This study thus offers a broad synthesis of the topic, helping to strengthen the scientific base and to develop more effective strategies for mitigation and sustainable management in the face of the challenges posed by climate change.

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