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Research Trends in Coastal Sediment Transport Using Numerical and Empirical Models

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Abstract

Coastal sediment transport remains a critical research area due to its importance in shoreline stability, erosion management, and sustainable coastal development. Despite extensive studies, challenges remain in integrating numerical and empirical models to represent the complex dynamics of sediment movement under varying hydrodynamic conditions. This study addresses the research gap through a bibliometric analysis of global scientific literature on coastal sediment transport using numerical and empirical approaches. Data were retrieved from the Scopus database using advanced search techniques, resulting in 1,089 publications. The dataset was processed using OpenRefine to standardize author names, keywords, and affiliations, ensuring data accuracy and consistency. Publication trends, prolific authors, leading journals, and contributing countries were analysed using the Scopus analyzer. In addition, VOSviewer was used to visualize co-authorship networks, keyword co-occurrence, and citation patterns, providing insights into the relationships within the research field. The results show a steady increase in publications over the last two decades, with the United States, China, and the United Kingdom identified as major contributors through high research productivity and strong collaboration networks. Frequently occurring keywords indicate a strong emphasis on sediment transport modelling, shoreline evolution, and climate change-related coastal dynamics. The visualisation also reveals clusters of international collaboration and thematic research streams, highlighting the interdisciplinary nature of the field. Overall, this bibliometric study provides a comprehensive overview of research trends, key contributors, and collaborative structures in coastal sediment transport. The findings highlight the important role of numerical and empirical modelling while suggesting future research directions to improve predictive capabilities and support sustainable coastal management practices.

1. Introduction

Numerical and empirical models are essential tools for understanding and predicting sediment transport in various environments. Numerical models, such as 3D flow simulations, are increasingly used to simulate flow, sediment transport, and morphological changes in rivers. These models often couple with empirical sediment transport models to simulate bedload transport. However, the application range of widely used empirical models is limited by hydraulic and sedimentological features, making it challenging to apply them to complex situations involving multiple morphological processes like local scouring, bed armoring, and aggradation of finer particles. To address this, combining multiple bedload transport formulas can widen the application range and improve simulation reliability, as demonstrated by laboratory experiments [1]. Additionally, numerical models can simulate sediment transport in different environments, such as rivers, estuaries, and shelf seas, by considering specific physical processes like the formation of bottom Ekman spirals, which affect sediment transport direction and rate [2].

Despite the advantages of numerical models, empirical models remain widely used due to their simpler implementation and lower computational requirements. However, these models often face limitations in predictive accuracy because of the complexity of sediment transport mechanisms. Data-driven approaches, such as artificial neural networks (ANNs) and model trees, have been employed to enhance the accuracy of traditional empirical models like the Engelund and Hansen model. These data-driven models have shown improved predictive accuracy when tested with large datasets, suggesting that they can provide better relationships than traditional models [3]. Moreover, integrated models that combine deterministic numerical models with data-driven approaches, such as ANNs, have been developed to predict suspended sediment distribution under non-uniform flow conditions. These integrated models have shown promising results in various tests, highlighting their potential for more accurate sediment transport predictions [4].

Although numerical and empirical approaches have demonstrated considerable potential, several limitations still affect their performance and applicability in sediment transport studies. For instance, traditional models often assume a weak interaction between fluid and sediment phases, which may not hold true in high sediment transport scenarios. In such cases, models may need to analyze high and low concentration subdomains separately, employing different constitutive equations. A two-phase description of the entire domain can provide more consistent results with experimental data [5]. Additionally, numerical models must account for various factors, such as climatic forces, which significantly impact sediment transport processes. For example, storm events can dominate sediment delivery to reservoirs, while winds can lead to bed erosion in shallow regions [6]. These factors highlight the importance of understanding the specific processes and systems being modeled to achieve accurate predictions.

Similarly, empirical models encounter challenges in representing the spatial and temporal variability of sediment transport processes, particularly in large and complex basin systems. For large basins, lumped empirical models often fail to consider this variability, leading to less accurate predictions. To address this, small-scale mechanistic models can be adapted for large basins, integrating dynamic water routing to capture sediment transport dynamics more accurately. Such models have shown promising results in large-scale applications, such as the Fraser River Basin, where they provided insights into sediment load dynamics and the importance of network connectivity [7]. Overall, both numerical and empirical models play crucial roles in sediment transport studies, and their integration, along with advancements in data-driven approaches, can lead to more accurate and reliable predictions.

1.1 Research Question

1. What are the prevailing research trends in coastal sediment transport studies over the years of publication?
2. Which subject areas are predominantly associated with coastal sediment transport research, and what proportion does each area represent?
3. Which publications have attained the highest citation impact within the field of coastal sediment transport research?
4. Which countries rank among the top ten in terms of publication output related to coastal sediment transport studies?
5. What are the most frequently occurring keywords associated with coastal sediment transport research using numerical and empirical models?
6. How is international collaboration reflected through co-authorship networks among countries in coastal sediment transport research?

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2. Methodology

Bibliometrics entails the collection, organization, and examination of bibliographic data from scientific literature [8], [9], [10]. In addition to basic statistical information—such as publishing journals, publication years, and prominent authors [11] it also employs advanced methods like document co-citation analysis. A rigorous literature review requires an iterative process involving careful keyword selection, systematic searches, and detailed analysis to build a comprehensive bibliography and ensure reliable outcomes [12]. Accordingly, this study concentrated on high-impact publications, as they offer valuable insights into the theoretical foundations shaping the research field.

To guarantee data accuracy, SCOPUS was chosen as the main database for data retrieval [13], [14], [15]. Furthermore, to uphold quality standards, only peer-reviewed journal articles were included, while books and lecture notes were excluded [16]. Publications indexed in Elsevier's Scopus, recognized for its extensive coverage, were collected from 1969 to September 2025 for further analysis.

After data collection, OpenRefine was employed for data cleaning and preprocessing. This step was essential to identify and correct inconsistencies such as duplicate records, incomplete metadata, inconsistent author names, journal titles, and variations in keywords. OpenRefine's clustering and transformation functions allowed standardization of terms and ensured uniformity across datasets. By refining the data before analysis, the study minimized potential errors and biases, thereby strengthening the reliability of the bibliometric results.

2.1 Data Search Strategy

The bibliometric data for this study were retrieved from the Scopus database using a well-defined search string to ensure relevance and precision. The query applied was TITLE-ABS-KEY (sediment AND transport AND coastal AND (equation OR formula) AND (numerical OR model)) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")), which was designed to capture publications that explicitly discuss sediment transport in coastal settings, with emphasis on both numerical and empirical approaches through equations and models. By restricting the results to the English language and final-stage publications, the dataset emphasizes peer-reviewed, completed works suitable for bibliometric analysis, excluding drafts, incomplete records, or non-English contributions that may limit comparability. The search strategy aligns with standard bibliometric practices, ensuring that the retrieved literature represents a coherent body of knowledge within the specified research domain.

Following the application of this search strategy, a total of 1,089 documents were identified as of the access date in September 2025. This dataset forms the foundation for subsequent bibliometric analyses, including the evaluation of publication trends, influential journals, highly cited works, and collaboration networks among researchers and institutions. The chosen search parameters provide a balanced dataset that is neither too narrow—risking omission of relevant studies—nor too broad, which could introduce irrelevant material. Thus, the retrieved data offer a comprehensive and representative overview of the state of research on coastal sediment transport equations and modeling approaches, enabling deeper insight into knowledge development, research hotspots, and emerging themes within this field.

Table 1 presents the search string applied in the Scopus database. The query includes a combination of keywords sediment, transport, coastal, equation or formula, and numerical or model, targeted in the title, abstract, and keyword fields to ensure that only directly relevant studies were captured. Filters were also applied to restrict the results to English-language documents and publications marked as final. The access date of September 2025 is recorded to ensure transparency and reproducibility of the search process.

Table 2 outlines the inclusion and exclusion criteria used in the data collection process. Only English-language documents were included, while non-English publications were excluded to maintain consistency in interpretation and analysis. Similarly, only publications at the final stage were included, excluding those still in press or under review to ensure that the dataset represented completed and peer-reviewed research outputs. These criteria were applied to strengthen the reliability and validity of the bibliometric dataset, providing a solid basis for the subsequent analysis of research trends and patterns in coastal sediment transport studies.

Table 1 *Search string*

Scopus	TITLE-ABS-KEY (sediment AND transport AND coastal AND (equation OR formula) AND (numerical OR model)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBSTAGE , "final")) Access Date: September 2025

Table 2 *Selection criterion is searching*

Criterion	Inclusion	Exclusion
Language	English	Non-English
Publication Stage	Final	In Press

2.2 Data Analysis

VOSviewer is a widely used bibliometric software developed by Nees Jan van Eck and Ludo Waltman at Leiden University, Netherlands [17], [18]. Designed for visualizing and analyzing scientific literature, it specializes in generating intuitive network visualizations, clustering related items, and creating density maps. The software enables the exploration of co-authorship, co-citation, and keyword co-occurrence networks, offering researchers a comprehensive view of research landscapes. Its interactive interface, combined with ongoing updates, ensures effective handling of large datasets. Moreover, VOSviewer's ability to calculate bibliometric indicators, provide customizable visualizations, and support multiple data sources makes it a powerful tool for scholars investigating complex research domains.

For this study, datasets containing publication year, title, author names, journal, citations, and keywords were extracted from the Scopus database in PlainText format, covering the period from 1969 to September 2025. These datasets were analyzed using VOSviewer version 1.6.20. The analysis employed the full-counting method, where each occurrence and co-occurrence link was counted equally across all publications. This method was selected to ensure that all bibliometric relationships contributed proportionally to the network structure without additional weighting. To improve the clarity and relevance of the visualization maps, several thresholds were applied during the analysis. For keyword co-occurrence analysis, a minimum threshold of five occurrences per keyword was used, reducing the total number of keywords from 3,879 to 656 significant terms. Similarly, for country co-authorship analysis, a minimum threshold of five documents per country was applied, filtering the dataset from 83 countries to 35 active contributors. In addition, the minimum cluster size was set to one to retain smaller but meaningful thematic and collaborative groupings within the network visualization.

By applying VOS clustering and mapping techniques, the software enabled the construction of visual maps to reveal patterns and relationships. Unlike the traditional Multidimensional Scaling (MDS) method, VOSviewer positions items in a low-dimensional space in which the distance between any two items reflects their degree of relatedness [19]. While sharing similarities with MDS [20], which commonly employs similarity measures such as cosine or Jaccard indices, VOSviewer adopts a more suitable approach by normalizing co-occurrence frequencies through the association strength (ASij), calculated as [21] shown in Equation 1:

$$AS_{ij} = \frac{C_{ij}}{w_i w_j} \tag{1}$$

which is "proportional to the ratio between on the one hand the observed number of cooccurrences of i and j and on the other hand the expected number of co-occurrences of i and j under the assumption that co-occurrences of i and j are statistically independent" [21].

3. Results and Discussion

RQ 1. What are the prevailing research trends in coastal sediment transport studies over the years of publication?

The publication trend from 1969 to 2025 demonstrates a gradual but significant increase in research output in coastal sediment transport studies, reflecting the continuous development and growing importance of the field over time (Figure 1). During the early years (1969–1990), publication output remained relatively low, with fewer than 10 publications annually in most years, indicating limited research activity and restricted accessibility to advanced modelling techniques. A notable shift began in the mid-1990s, particularly with the increase recorded in 1997 (31 publications), although publication growth remained inconsistent during this period. From 2000 onwards, research output became more stable and sustained, with annual publications consistently exceeding 20. Significant increases were observed in 2007 (47 publications), 2010 (49 publications), and 2014 (52 publications), likely driven by advancements in numerical modelling, computational technologies, and growing global interest in coastal management and sediment dynamics

Between 2015 and 2025, publication patterns indicate that coastal sediment transport research entered a mature phase of scientific development. Although yearly outputs fluctuated, publication counts consistently remained above 26, demonstrating sustained academic interest in the field. Higher publication outputs in 2020 (41 publications) and 2024 (49 publications) may reflect increasing research attention toward climate change impacts, shoreline evolution, and improved sediment transport modelling approaches. The slight decline

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observed in 2025 (31 publications) is likely associated with incomplete indexing of recent publications or normal annual variation. Overall, the long-term upward trend confirms that coastal sediment transport research has evolved from a relatively specialized topic into an established and continuously expanding area of scientific investigation.

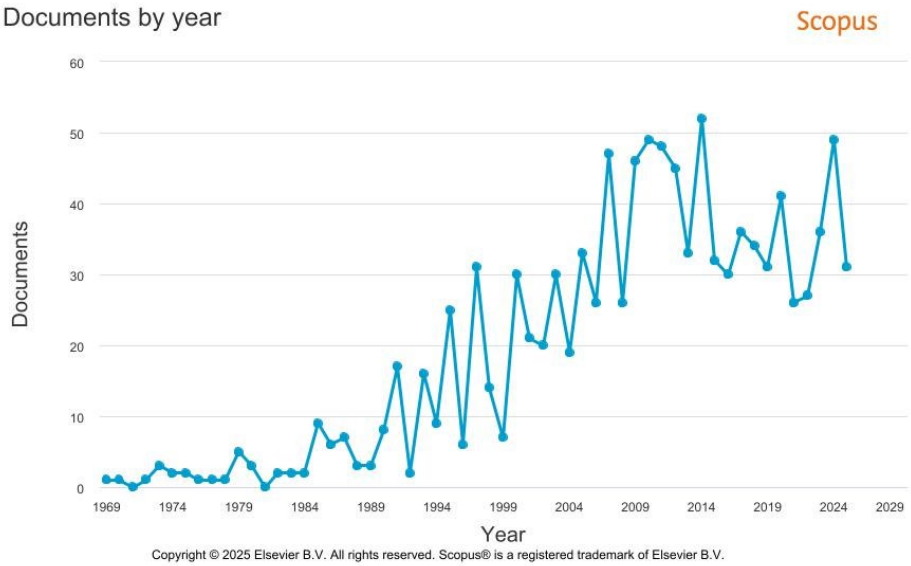

Fig. 1 *Trend of research in coastal sediment transport studies by years*

RQ 2. Which subject areas are predominantly associated with coastal sediment transport research, and what proportion does each area represent?

The distribution of publications across subject areas highlights the dominant role of Engineering, Environmental Science, and Earth and Planetary Sciences in coastal sediment transport research, collectively accounting for nearly 80% of the total publications (Figure 2). Engineering leads with 594 publications (31.1%), reflecting its important role in developing numerical models, analytical tools, and practical coastal management solutions. Environmental Science (24.2%) and Earth and Planetary Sciences (23.8%) follow closely, demonstrating the strong relationship between sediment transport processes, environmental sustainability, and natural coastal dynamics. The dominance of these subject areas indicates that coastal sediment transport research is strongly driven by concerns related to climate change, coastal erosion, shoreline evolution, and resource management.

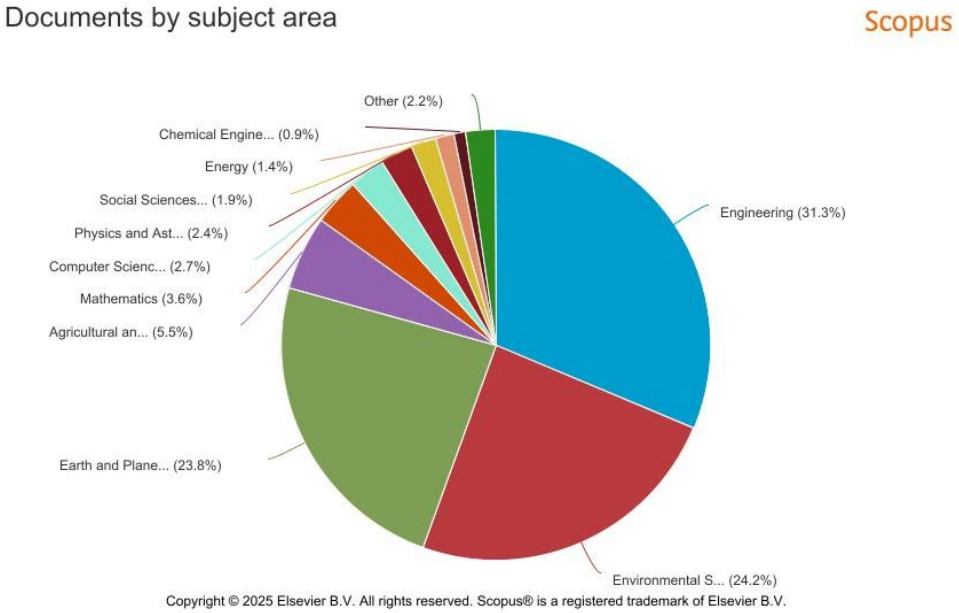

Fig. 2 *The popular subject area and percentages*

The remaining subject areas contribute smaller but still significant proportions, demonstrating the interdisciplinary nature of the field. Agricultural and Biological Sciences (5.5%) and Mathematics (3.6%) reflect the integration of ecological considerations and quantitative modelling approaches in sediment transport studies. Meanwhile, Computer Science (2.7%) and Physics and Astronomy (2.4%) indicate the growing application of computational methods and physical process analysis in improving research accuracy and simulation capabilities. Social Sciences (1.9%) contribute perspectives related to policy development, human impacts, and community resilience. Energy (1.4%) and Chemical Engineering (0.9%) represent more specialized research contributions, while the "Others" category (2.2%) includes emerging or less represented disciplines. In general, the distribution of subject areas demonstrates that coastal sediment transport research is inherently interdisciplinary, with engineering and environmental sciences forming the primary research foundation while additional disciplines enhance the broader applicability of research outcomes.

RQ 3. Which publications have attained the highest citation impact within the field of coastal sediment transport research?

Table 3 presents the publications with the highest citation impact in coastal sediment transport research, including the authors, publication years, journals, and total citation counts. The findings show that the article by Warner et al. published in Computers and Geosciences recorded the highest citation count with 704 citations, indicating its major influence on the development of numerical modelling approaches for waves, currents, and sediment transport processes. The second highest cited publication is the study by van Rijn in the Journal of Hydraulic Engineering with 599 citations, which introduced a unified perspective on sediment transport driven by currents and waves.

Other influential studies include the works of Ribberink and Fenton published in Coastal Engineering and Computers and Geosciences, with 312 and 269 citations, respectively. The continued high citation counts of these earlier studies demonstrate their lasting contribution to the theoretical and methodological foundations of sediment transport research.

Overall, the results indicate that studies related to computational modelling, hydraulic processes, and sediment transport simulation dominate the highly cited literature. This trend suggests that numerical and hydraulic modelling approaches continue to play a central role in advancing coastal sediment transport research and supporting practical coastal engineering applications.

Table 3 *Most cited author*

Authors	Title	Year	Source Title	Cited by
J.C., Warner, John C.; C.R., Sherwood, Christopher R.; R.P., Signell, Richard P.; C.K., Harris, Courtney K.; H.G., Arango, Hernan G.[22]	Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model	2008	Computers and Geosciences	704
L.C., van Rijn, Leo Cornelius [23]	Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport	2007	Journal of Hydraulic Engineering	599
J.S., Ribberink, Jan S.[24]	Bed-load transport for steady flows and unsteady oscillatory flows	1998	Coastal Engineering	312
J.D., Fenton, John D. [25]	The numerical solution of steady water wave problems	1988	Computers and Geosciences	269
M., Voss, Maren; J.W., Dippner, Joachim W.; J.P., Montoya, Joseph P. [26]	Nitrogen isotope patterns in the oxygen-deficient waters of the Eastern Tropical North Pacific Ocean	2001	Deep-Sea Research Part I: Oceanographic Research Papers	237
F.C.K., Ting, Francis C.K.; J.T., Kirby, James T. [27]	Dynamics of surf-zone turbulence in a strong plunging breaker	1995	Coastal Engineering	227

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Authors	Title	Year	Source Title	Cited by
H.J., de Vriend, Huib J.; J.A., Zyserman, Julio A.; J., Nicholson, John; D.J., Roelvink, Dano J.A.; P.H., Péchon, Philippe H.; H.N., Southgate, Howard Neil [28]	Medium-term 2DH coastal area modelling	1993	Coastal Engineering	220
D., Liang, Dongfang; L., Cheng, Liang; F., Li, Fangjun[29]	Numerical modeling of flow and scour below a pipeline in currents. Part II. Scour simulation	2005	Coastal Engineering	210
A.D., Ashton, Andrew D.; A.B., Murray, A. Brad [30]	High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature	2006	Journal of Geophysical Research: Earth Surface	201
M.J.F., Stive, Marcel J.F.; H.J., de Vriend, Huib J.[31]	Modelling shoreface profile evolution	1995	Marine Geology	197

RQ 4. Which countries rank among the top ten in terms of publication output related to coastal sediment transport studies?

The publication output by country indicates that coastal sediment transport research is largely dominated by developed nations with well-established scientific and research systems, led by the United States with 230 publications (21.1%) (Figure 3). The United Kingdom (13.1%) and China (11.8%) rank as the second and third highest contributors, reflecting their strong research productivity and active participation in international scientific collaboration. The Netherlands (7.6%) and Japan (7.2%) also demonstrate substantial contributions despite their relatively smaller populations, indicating strong specialization in coastal engineering, hydrodynamics, and environmental research. Collectively, these top five countries account for more than 60% of the total publications, suggesting that research output in coastal sediment transport studies is concentrated among countries with advanced research capabilities and extensive academic networks.

The remaining countries in the top ten include Italy (5.3%), Australia (5.2%), France (4.9%), Spain (3.5%), and Greece (3.4%). Although their publication shares are comparatively lower, these countries contribute significantly to the diversity of regional studies, methodological advancements, and international collaboration within the field. The inclusion of countries such as Greece and Spain highlights the important role of regional coastal research expertise in expanding the global understanding of sediment transport processes. Overall, the distribution demonstrates that coastal sediment transport research is strongly influenced by scientifically advanced nations while also benefiting from broader international participation and cross-border research collaboration.

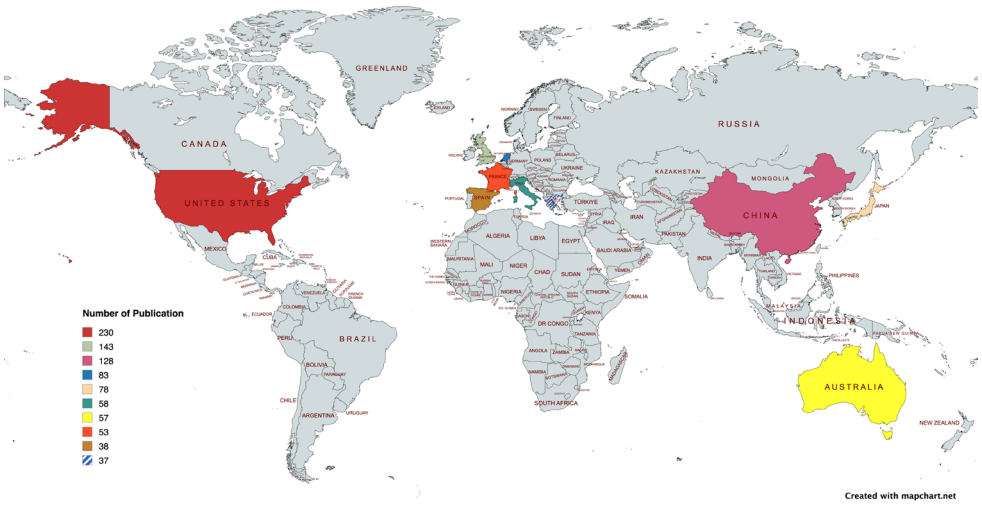

Fig. 3 *Distribution of research publications by country/territory, highlighting the top 10 contributing nations*

RQ 5. What are the most frequently occurring keywords associated with coastal sediment transport research using numerical and empirical models?

The co-occurrence analysis of author keywords using VOSviewer was conducted to identify the most frequently occurring keywords and their relationships within coastal sediment transport research (Figure 4). This bibliometric approach reveals the intellectual structure of the field by examining how often keywords appear together within the same publications. The analysis shows that keywords such as *sediment transport*, *numerical model*, and *coastal engineering* appear most frequently and demonstrate strong interconnections with other related terms. This indicates that these topics represent the central research themes within the field, particularly in studies involving numerical and empirical modelling approaches.

To improve the relevance of the analysis, the full counting method was applied, where each keyword occurrence was counted equally across all publications. A minimum threshold of five occurrences reduced the total number of keywords from 3,879 to 656, allowing the analysis to focus on the most significant and widely used terms. Based on the co-occurrence relationships, four thematic clusters were identified. These clusters represent major research areas related to sediment transport modelling, hydrodynamic processes, coastal morphology, and environmental assessment, highlighting the diversity and interdisciplinary nature of coastal sediment transport studies.

The findings demonstrate that numerical modelling, sediment dynamics, and coastal engineering remain dominant themes in the literature, reflecting the growing importance of predictive modelling and environmental analysis in coastal research. The keyword relationships also indicate strong integration between engineering applications, physical coastal processes, and environmental management. In general, the co-occurrence analysis provides valuable insight into current research priorities, thematic developments, and emerging directions within coastal sediment transport research using numerical and empirical approaches.

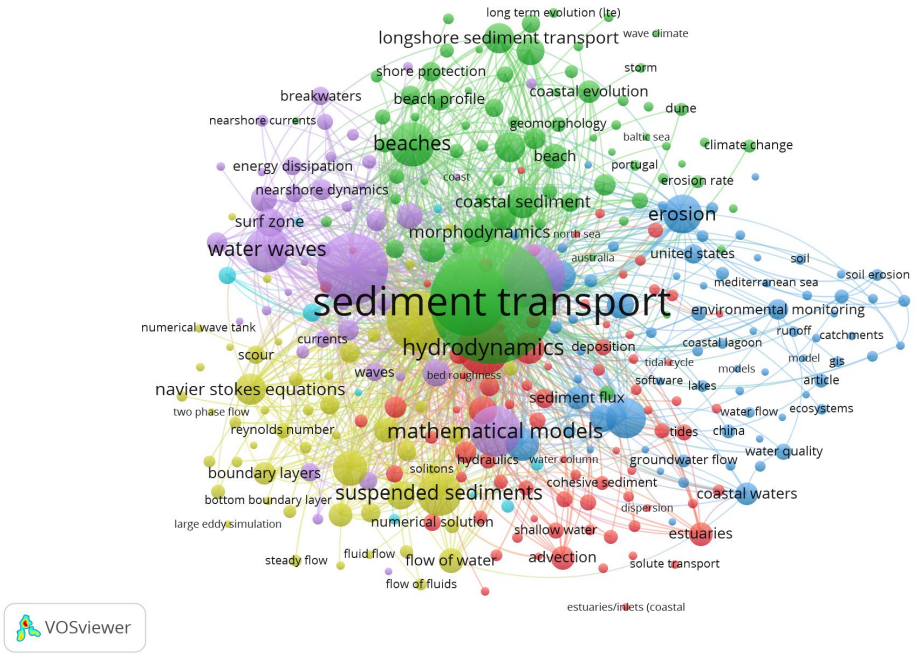

Fig. 4 *Network visualization map of keywords' co-occurrence*

RQ 6. How is international collaboration reflected through co-authorship networks among countries in coastal sediment transport research?

Figure 5 presents the co-authorship network among countries involved in coastal sediment transport research based on bibliometric analysis using VOSviewer. In the visualization, node size represents publication output, while line thickness indicates the strength of collaboration between countries. The United States, United Kingdom, and China emerge as the main collaboration hubs, demonstrating both high research productivity and strong international research connections. The co-authorship network illustrates the global structure of scientific collaboration, where a small number of leading countries maintain extensive partnerships with multiple nations.

The analysis was conducted using the full counting method with a minimum threshold of five publications per country, reducing the dataset from 83 countries to 35 active contributors. Based on the collaboration patterns, seven clusters were identified, representing groups of countries with strong co-authorship relationships. These clusters reflect regional and international collaboration networks, including European partnerships, Asia-Pacific

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cooperation, and trans-Atlantic research linkages. The clustering structure demonstrates that coastal sediment transport research is supported by extensive cross-border collaboration and shared scientific expertise.

The findings further indicate that, although major contributors such as the United States and the United Kingdom dominate the collaboration network, emerging countries including Malaysia, Iran, and Vietnam are increasingly participating in international research activities. This suggests a gradual expansion of global research participation within the field. Overall, the co-authorship analysis highlights the importance of international collaboration in strengthening knowledge exchange, improving research quality, and advancing coastal sediment transport studies through shared expertise and multidisciplinary cooperation.

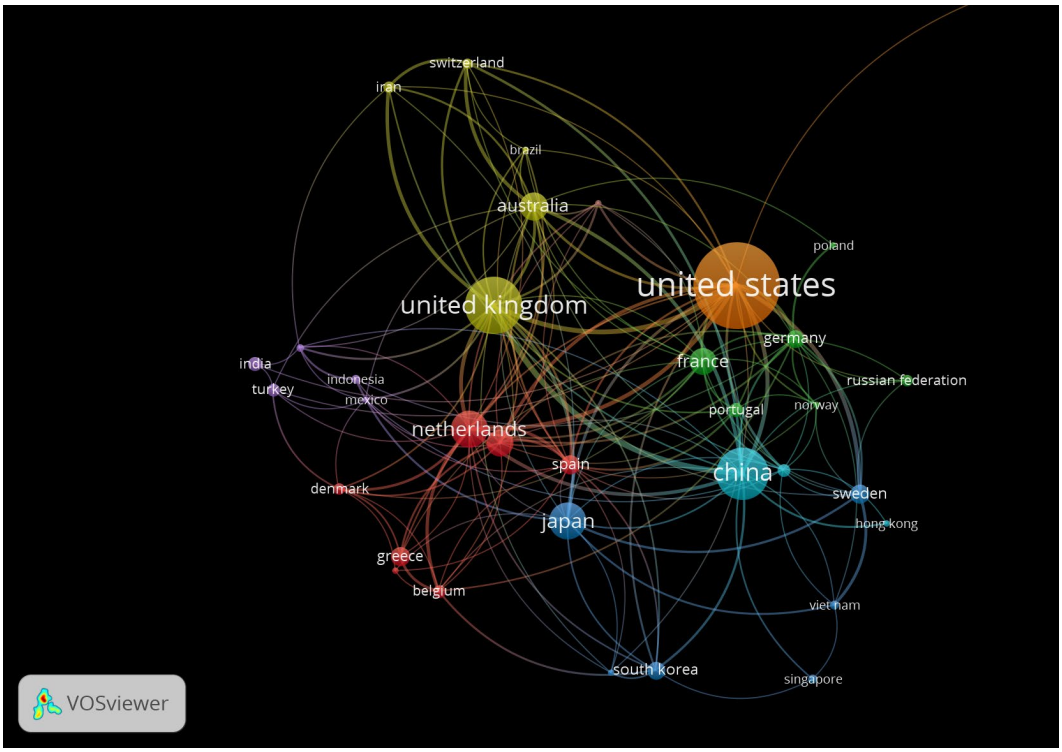

Fig. 5 *Co-authorship by countries' collaboration*

4. Conclusion

This bibliometric review offers a comprehensive understanding of global research trends in coastal sediment transport, emphasizing the complementary roles of numerical and empirical modeling approaches. The analysis reveals a steady increase in scholarly output over the past two decades, driven by growing awareness of coastal erosion, sediment dynamics, and the need for sustainable management strategies. Engineering, Environmental Science, and Earth and Planetary Sciences dominate the field, reflecting its multidisciplinary foundation and the integration of theoretical, experimental, and computational advancements. The most cited works and leading contributors highlight the central influence of developed nations and well-established research institutions, supported by strong international collaborations that enhance the scientific depth and global relevance of the field.

Overall, the study demonstrates that research on coastal sediment transport continues to evolve toward greater interdisciplinarity and methodological integration. Future directions should focus on bridging numerical and empirical approaches with data-driven and machine learning techniques to improve predictive accuracy and applicability under diverse coastal conditions. Strengthening global collaboration, particularly involving emerging research communities, will be crucial to advancing comprehensive, adaptive, and sustainable coastal management solutions.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: Nor Baizura Hamid and Mardiha Mokhtar;* ***data collection and analysis****: Nor Baizura Hamid;* ***interpretation of results****: Nor Baizura Hamid and Mohd Effendi Daud;* ***draft manuscript preparation****: Nor Baizura Hamid;* ***review and editing****: Mardiha Mokhtar and Mohd Effendi Daud;* ***supervision****: Mardiha Mokhtar. All authors reviewed the results and approved the final version of the manuscript.*

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