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MAPPING THE LINK BETWEEN RIVERBANK EROSION AND RESEARCH ATTRIBUTES: A GLOBAL RESEARCH OVERVIEW

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Abstract: Riverbank erosion significantly impacts sediment dynamics and river formation, but research in this area is often fragmented, focusing on isolated aspects. This study seeks to establish global connections between erosion topics and research attributes to advance knowledge and provide a comprehensive framework for understanding riverbank erosion. Using CiteSpace software for scientometric analysis, this study examines 2,323 publications from the Web of Science database, covering the period from 2003 to 2022. The largest clusters highlight the most significant topics in riverbank erosion research: "Cohesive floodplain," "fluvial system," and "cloud computing." These clusters represent key areas of impact and innovation within the field. High-impact journals in the field include Geomorphology and Earth Surface Processes & Landforms. Author co-citation analysis highlights key figures, particularly Simon A and Walling DE, with Simon A having the highest centrality. Global collaboration networks emphasise significant contributions from the United States, China, India, and European countries. The average publication year of documents within a cluster provides an indicator of its recency and relevance. It can be concluded that the "cloud computing" theme is the most recent, indicating that this topic is currently attracting the most interest and represents a cutting-edge area of research in the field.

Keywords: Riverbank erosion, bibliometric analysis, CiteSpace, scientometric analysis, Web of Science.

Introduction

Riverbank erosion is a natural geomorphic process that occurs when the banks of a river or stream are worn away by water and other environmental forces. It is an important factor in sediment dynamic, meander development, excessive volumes of sediment transportation to downstream reach and riparian lands losses (Lawler *et al*., 1997). Riverbank erosion is the result of multiple interrelated processes, including subaerial processes, soil moisture changes, fluvial entrainment, and seepage erosion which can result in bank failure (Thorne, 1982; Watson & Basher, 2006; Ayob *et al*., 2019). Riverbank erosion through mass failure is a substantial kind of channel adjustment and a major source of sediment in disturbed rivers, frequently contributing 60 to 80% of the suspended sediment load (Simon & Rinaldi, 2006).

These erosion processes have caused numerous negative impacts on the environment, including loss of land and associated resources, threaten property and infrastructures, degrade water quality, as well as aquatic habitat (Wilson *et al*., 2007; Midgley *et al*., 2012). Riverbank erosion may also be a major river management issue since it may cause land loss, damage to structures near river channels, and changes in the connection between river level and the phreatic surface under the floodplain (Casagli *et al*., 1999). In extreme situations, riverbank erosion may have long-term effects on the human population by destroying lands and ecosystems and displacing vulnerable populations (Best, 2019). However, bank erosion is also important to the ecology of rivers, as erosion and deposition generate a diversity of habitats for flora and fauna, which contributes to ecological diversity (Environmental Agency, 1999).

Numerous studies have been conducted on riverbank erosion processes covering various aspects. This includes the effect of weathering and weakening (subaerial processes) on bank erodibility (Lawler, 1993; Couper & Maddock, 2001), evaluating the impact of bank hydrology on mass failure (Simon *et al*., 2000; Rinaldi *et al*., 2004), understanding the role of riparian vegetation (Simon & Collison, 2002; Pollen, 2007), bank failure related to seepage erosion and undercutting (Wilson *et al*., 2007; Cancienne *et al*., 2008), relation between bank stability and underground water movement and surface water (Thorne, 1982; Rinaldi & Casagli, 1999; Fox *et al*., 2007), development of specific on-site measuring techniques (Haigh, 1977; Pizzuto & Meckelnburg, 1989; Lawler, 1993; Abidin *et al*., 2017), and river restoration and stabilisation techniques (Holanda *et al*., 2008; Roni & Beechie, 2013; Bo *et al*., 2015; Sulaiman *et al*., 2021; Haron *et al*., 2022). Despite the extensive research conducted on riverbank erosion, the field remains fragmented with numerous studies focusing on isolated aspects such as sediment dynamics, meander formation, and erosion control. This fragmentation hampers the development of a comprehensive understanding and synthesis of the field, making it difficult to identify key research trends, influential studies, and emerging areas of interest. By conducting a bibliometric analysis, we can systematically map the intellectual structure of riverbank erosion research, identify influential publications and authors, and uncover the evolution of research themes over time. This analysis is crucial for guiding future research efforts, fostering interdisciplinary collaboration, and ensuring that research efforts are aligned with the most pressing challenges in the study of riverbank erosion.

Currently, bibliometric data, in conjunction with article metadata are widely employed as a tool to determine research performance and the comparative standing of published studies (Mejia *et al*., 2021; Szomszor *et al*., 2021). Scientometric analysis serves as a method for tracking emerging trends and research development in specific fields. Among the various tools used for scientometric studies, the CiteSpace software stands out as one of the most extensively utilised. In the context of riverbank erosion, a scientometric study holds the potential of shedding light on the current state of global publications and offers crucial insights into future research directions, aligning with the escalating trend in riverbank erosion-related publications. While scientometric studies have been applied to describe trends in publications across various topics in recent years, a dedicated scientometric analysis focused on riverbank erosion is notably absent. This scientometric study on riverbank erosion represents the inaugural and most up-to-date exploration, conducted by examining Web of Science databases and employing the CiteSpace application. This study seeks to identify the most impactful research topics, articles, researchers, journals, institutions, and countries contributing to the field of riverbank erosion. By uncovering these key contributors, the study aims to establish global connections between erosion topics and research attributes, thereby advancing knowledge and providing a comprehensive framework for understanding riverbank erosion.

Materials and Methods

Data Collection

Publications were extracted from the Web of Science (WoS) database using the keywords "Riverbank erosion." WoS offers several advantages including comprehensive coverage, quality and reliability, citation tracking, advanced search capabilities, analytical tools, historical data, and global scope. A comprehensive set of literature data spanning 20 years, from 2003 to 2022 was collected for the analysis. This period was chosen because it encompasses a substantial number of publications that emerged after 2000, reflecting the growing body of research on riverbank erosion. The two-decade range provides a robust dataset that captures significant developments and trends in the field, ensuring a thorough examination of the literature's evolution and impact over time. Since the data retrieval occurred in August 2023, that year was excluded from the analysis because it lacks a full 12 months of publication data. The data selected from the WoS core collection was refined, encompassing only entries from the Science Citation Index Expanded (SCI-EXPANDED) and Emerging Sources Citation Index (ESCI). The document type was further narrowed down to include only articles. Following these criteria, a total of 2323 publications were identified, each featuring the term "riverbank erosion" in its topic. These articles were subsequently exported as a plain text file, encompassing full records and cited references, serving as the input data for the analysis using the CiteSpace software. Additionally, various data points from WoS such as publication years, authors, countries, categories, and publishers were analysed using Microsoft Excel.

Visualisation and Analysis

This study uses CiteSpace software to conduct analysis on Riverbank erosion articles. CiteSpace is a popular and continuously evolving visual analytics program, created, and developed for analysing and visualising structural and temporal trends in scientific publications (Chen, 2004; 2006). CiteSpace is a Java-based information measuring software that is intended to elucidate the structure of knowledge growth and to identify emerging trends and temporary patterns in scientific literature.

A set of bibliographic records obtained from WoS database was visualised and analysed using version 6.2.R4 of CiteSpace (Figure 1). In this study, a 20-year analysis, spanning from January 2003 to December 2022 was structured with a one-year slice per segment. Within the nodes

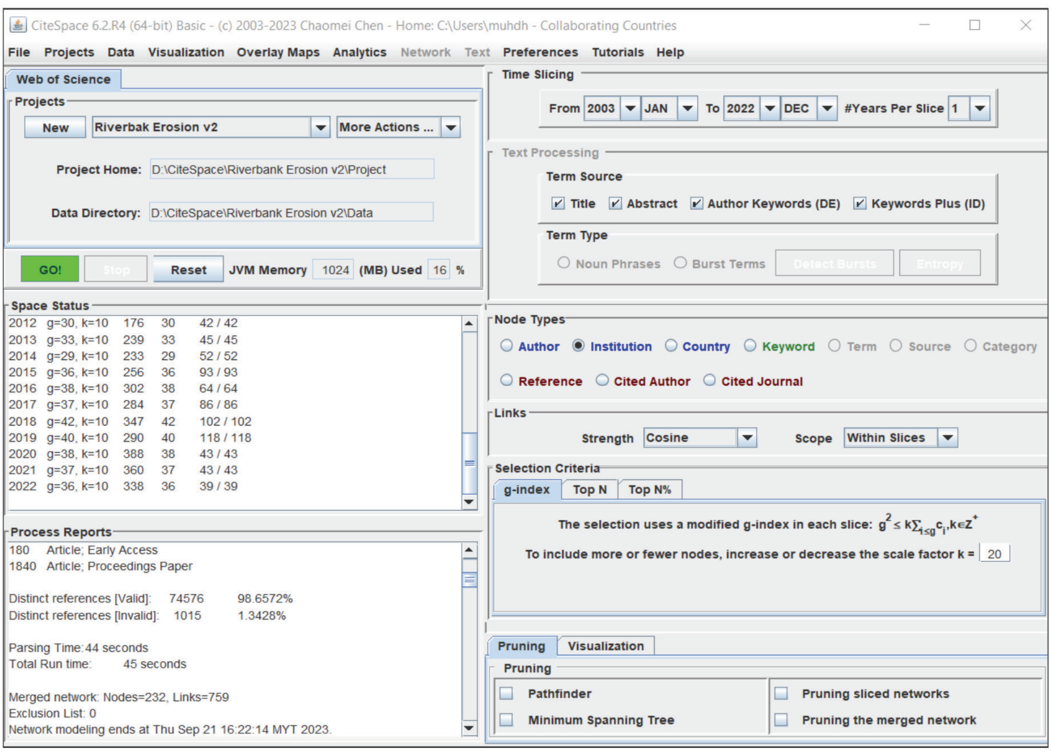

Figure 1: CiteSpace main user interface

type section, where nodes symbolise entities, CiteSpace facilitates various bibliographic studies derived from published articles. These include author and cited author analysis, country collaboration analysis, institution collaboration analysis, references analysis, keyword analysis, and cited journal analysis. All these node types were incorporated for a comprehensive analysis. While it is possible to form multiple types of nodes, our discussions focused on a singular type of node for each visualisation. Users have the flexibility to select criteria suitable for their analysis and determine whether to apply network pruning. The remaining settings were kept at their default configurations. Refer to Figure 2 for a workflow diagram illustrating the process of riverbank erosion analysis.

Results and Discussions

The Current Status of Riverbank Erosion Research

Figure 3 illustrates a comprehensive overview of riverbank erosion research, encompassing a total of 2,323 publications retrieved from the Web of Science database from 2003 to 2022. The visual representation highlights a discernible upward trend in the number of publications, escalating

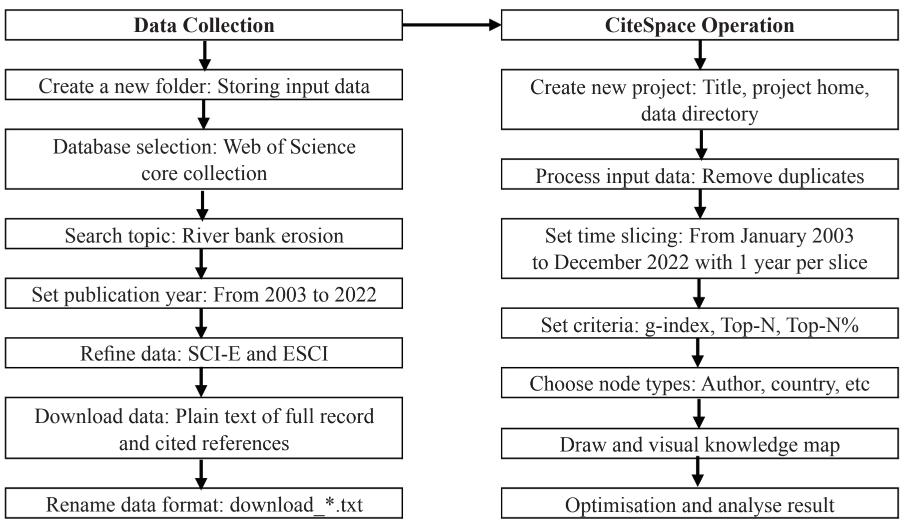

Figure 2: Workflow diagram of riverbank erosion research

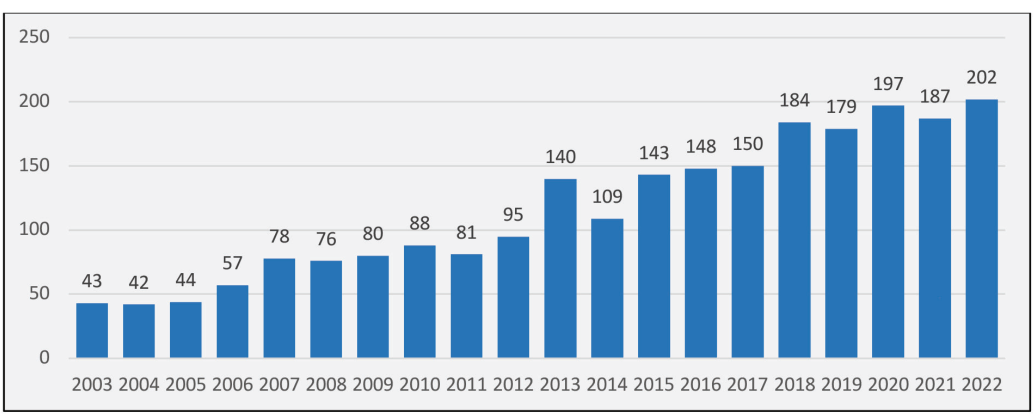

Figure 3: The number of publications per year

from 43 in 2003 to 202 in 2022. This progressive increase suggests a growing scholarly interest in the field of riverbank erosion. Examining the yearly distribution, the number of published articles exhibits a gradual growth trajectory from 2003 to 2013. However, a notable turning point occurred in 2013 when the figure sharply spikes to 140 articles. Subsequently, the number of publications remained consistently above 100 in the subsequent years, reaching a peak of 202 articles in 2022. This data indicates a significant surge in scholarly contributions to riverbank erosion research, particularly in the latter part of the analysed period.

Table 1 shows the top 10 categories in the field, revealing the multidisciplinary nature of riverbank erosion research. The preeminent category, 'Geosciences Multidisciplinary' stands out with 1,025 publications, constituting 44.124% of the total publications. Following closely is the 'Water Resources' category, boasting 722 publications and representing 31.08% of the overall publications. Other prominent categories include 'Environmental Sciences' with 705 publications, 'Geography Physical' with 564 publications, 'Engineering Civil' with 168 publications, 'Engineering Environmental' with 128 publications, 'Soil Science' with 125 publications, 'Ecology' with 111 publications, 'Geology' with 70 publications, and the final category, 'Limnology' with 67 publications. This diverse distribution underscores the interdisciplinary nature of riverbank erosion research, encompassing a spectrum of scientific disciplines and highlighting its broad relevance across various fields.

Table 2 provides an overview of the top 10 research areas in riverbank erosion research, with some areas aligning with specific research subject categories. Leading the list is 'Geology' with 1,025 publications, followed by 'Environmental Sciences Ecology' with 762 publications, 'Water Resources' with 722 publications, 'Physical Geography' with 564 publications, and 'Engineering' with 349 publications. Notably, the top five research areas also correspond to the subject categories. Additionally, the 6^{th} to 10^{th} most popular subsequent research areas exhibited fewer publications, each amounting to less than 10% of the total publications. This distribution underscores the prominence of the top five research areas in riverbank erosion studies, highlighting their substantial contribution to the existing body of knowledge in this field.

Table 3 outlines the top 20 most frequently referenced articles in riverbank erosion research, encompassing publications from the years 2003 to 2022. This table offers a snapshot of influential research articles in the domain of riverbank erosion, showcasing the diversity of topics and sources contributing to the field.

Table 1: Top 10 subject category of Web of Science (2003-2022)

Web of Science Categories	Number of publications	% share in publication
Geosciences Multidisciplinary	1025	44.124
Water Resources	722	31.08
Environmental Sciences	705	30.349
Geography Physical	564	24.279
Engineering Civil	168	7.232
Engineering Environmental	128	5.51
Soil Science	125	5.381
Ecology	111	4.778
Geology	70	3.013
Limnology	67	2.884

Table 2: Top 10 of research area (2003-2022)

Research Areas	Number of Publications	% Share in Publication
Geology	1094	47.094
Environmental Sciences Ecology	762	32.802
Water Resources	722	31.08
Physical Geography	564	24.279
Engineering	349	15.024
Agriculture	160	6.888
Marine Freshwater Biology	118	5.08
Science Technology Other Topics	79	3.401
Meteorology Atmospheric Sciences	64	2.755
Oceanography	60	2.583

Table 3: Top 20 most used articles of WoS in riverbank erosion research (2003-2022)

Authors, Year	Article Title	Number	Source
Gurnell, 2014	Plants As River System Engineers	446	Earth Surface Processes and Landforms
Borrelli *et al*., 2020	Land Use and Climate Change Impacts on Global Soil Erosion by Water (2015-2070)	409	Proceedings of the National Academy of Sciences of The United States of America
Dosskey *et al*., 2010	The Role of Riparian Vegetation in Protecting and Improving Chemical Water Quality in Streams1	329	Journal of the American Water Resources Association
Tal, 2007	Dynamic Single-Thread Channels Maintained by The Interaction of Flow and Vegetation	316	Geology
Meade & Moody, 2010	Causes For the Decline of Suspended-Sediment Discharge in The Mississippi River System, 1940-2007	299	Hydrological Processes
De Vente *et al*., 2007	The Sediment Delivery Problem Revisited	288	Progress In Physical Geography-Earth and Environment
Tal & Paola, 2010	Effects of Vegetation on Channel Morphodynamics: Results and Insights from Laboratory Experiments	237	Earth Surface Processes and Landforms
Chu *et al*., 2006	Changing Pattern of Accretion/Erosion of The Modem Yellow River (Huanghe) Subaerial Delta, China: Based on Remote Sensing Images	237	Marine Geology
Braudrick *et al*., 2009	Experimental Evidence for The Conditions Necessary to Sustain Meandering in Coarse-Bedded Rivers	236	Proceedings of the National Academy of Sciences of The United States of America

Knox, 2006	Floodplain Sedimentation in The Upper Mississippi Valley: Natural Versus Human Accelerated	234	Geomorphology
Piegay *et al*., 2005	A Review of Techniques Available for Delimiting the Erodible River Corridor: A Sustainable Approach to Managing Bank Erosion	227	River Research and Applications
Milan *et al*., 2007	Application Of A 3D Laser Scanner in The Assessment of Erosion and Deposition Volumes and Channel Change in A Proglacial River	226	Earth Surface Processes and Landforms
Simon & Rinaldi, 2006	Disturbance, Stream Incision, And Channel Evolution: The Roles of Excess Transport Capacity and Boundary Materials in Controlling Channel Response	223	Geomorphology
Lawler *et al*., 2006	Turbidity Dynamics During Spring Storm Events in An Urban Headwater River System: The Upper Tame, West Midlands, UK	219	Science of the Total Environment
Guo *et al*., 2007	Mobilisation Pathways of Organic Carbon from Permafrost to Arctic Rivers in A Changing Climate	216	Geophysical Research Letters
Collins *et al*., 2010	Apportioning Catchment Scale Sediment Sources Using a Modified Composite Fingerprinting Technique Incorporating Property Weightings and Prior Information	214	Geoderma
Hughes *et al*., 2006	Accuracy Assessment of Georectified Aerial Photographs: Implications for Measuring Lateral Channel Movement in A GIS	212	Geomorphology
Sweeney & Newbold, 2014	Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, And Organisms: A Literature Review	211	Journal of the American Water Resources Association
Paris *et al*., 2009	Tsunamis As Geomorphic Crises: Lessons from The December 26, 2004, Tsunami in Lhok Nga, West Banda Aceh (Sumatra, Indonesia)	207	Geomorphology
Parker *et al*., 2011	A New Framework for Modeling the Migration of Meandering Rivers	201	Earth Surface Processes and Landforms

'Earth Surface Processes' and 'Landforms', along with 'Geomorphology' are the journals with the highest number of most-cited articles, each having published four influential articles.

Table 4 displays the top 20 most productive publishers in riverbank erosion research. Elsevier leads the list, contributing nearly one-third of the total publications with 719 articles. Next is Wiley with 388 articles, followed by Springer Nature with 280 articles, and the American Geophysical Union with 128 publications, among others.

Table 4: Top 20 publisher in riverbank erosion research (2003-2022)

Publishers	Number of Publications	% Share in Publication
Elsevier	719	30.951
Wiley	388	16.703
Springer Nature	280	12.053
Amer Geophysical Union	128	5.51
Mdpi	99	4.262
Taylor & Francis	82	3.53
Asce-Amer Soc Civil Engineers	63	2.712
Irtces	40	1.722
Science Press	35	1.507
Copernicus Gesellschaft Mbh	32	1.378
Geological Soc Amer, Inc	31	1.334
Coastal Education & Research Foundation	19	0.818
Indian Acad Sciences	17	0.732
Iwa Publishing	16	0.689
Gebruder Borntraeger	12	0.517
Sage	12	0.517
Amer Soc Agricultural & Biological Engineers	11	0.474
Sepm-Soc Sedimentary Geology	11	0.474
Soil Water Conservation Soc	11	0.474
Frontiers Media Sa	10	0.43

International Cooperation Collaboration Network Analysis

There is a significant imbalance in the geographical distribution of published articles on riverbank erosion. Country collaboration network from CiteSpace mapping consisted of 95 nodes, 530 links, and overall density is 0.1187. Figure 4 illustrates the country collaboration network. Each node represents a different country. The node's size corresponds to the quantity of documents produced by the organisation. In other words, an organisation that distributes more documents will have a larger node. The outermost purple circle of each node signifies the centrality of the respective countries. Thicker purple circles demonstrate higher centrality. Research indicates that nodes with high values of betweenness centrality often have the potential to span boundaries, which could lead to groundbreaking discoveries (Chen, 2017). The top 20 countries contributing to riverbank erosion research are listed in Table 5. Based on the size of the node, a large number of publications originated in the United States (US) with 708. A distant second is China (288), followed by India (198), England (183), France (165), and Canada (158). The rest of the countries, together, published less than 150 articles. In the context of centrality strength, the United States continues to lead with a score of 0.49, while France comes in second with a score of 0.34 and third by Germany with 0.16 score. Big Asian countries like China, India, and Japan only have 0.05 centrality. Besides, there

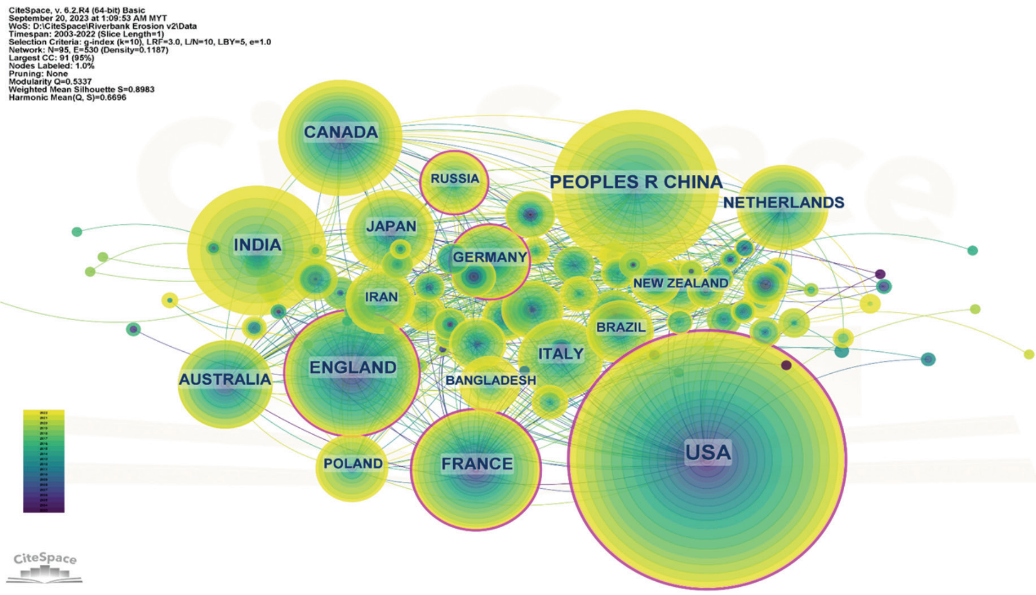

Figure 4: Visualisation of county collaboration network

are only a few Asian countries involved in this research, this suggests that Asia continues to be under-represented in this field. High centrality countries like the Unites States have a significant role as intermediaries in the domain of riverbank erosion research and underscores their crucial contribution in building relationships with other countries.

There are 232 nodes, 759 linked lines, and 0.0283 network density in the institution collaboration mapping from CiteSpace (Figure 5). The linked lines symbolise the collaborative

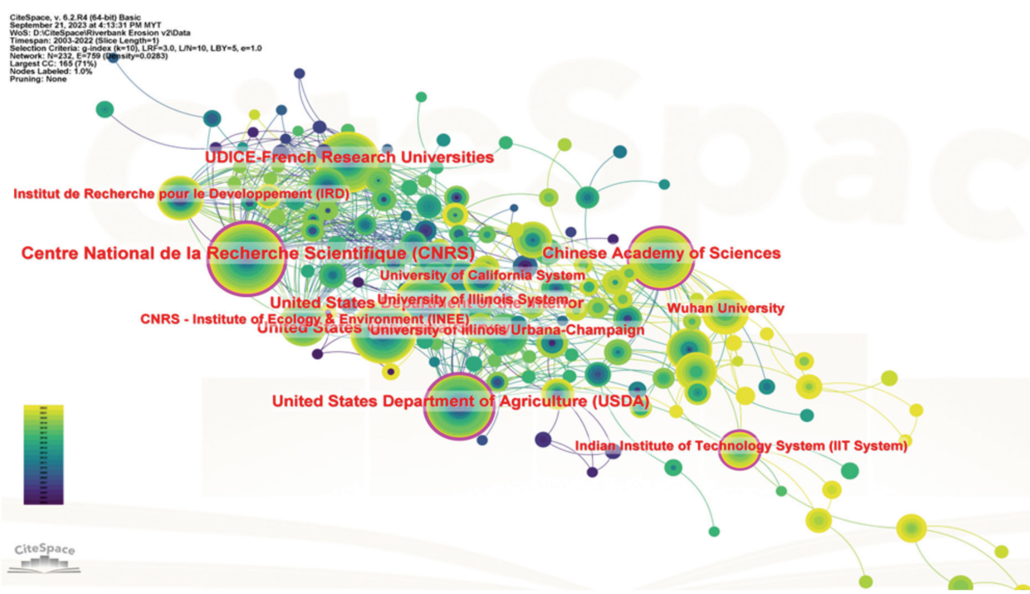

Figure 5: Visualisation of institution collaboration network

relationships between the organisations. The greater the number of links, the stronger and closer the cooperation between the organisations. The colour of the nodes corresponds to the year they were published. A yellow link signifies connections that had been established in recent years, while darker colours, like dark purple and blue, show the collaboration between both organisations developed in early years. It is evident that the relationships between various institutions are intricate. Table 6 listed 20 institutions with Centre National de la Recherche Scientifique (CNRS) ranked first in terms of publications count (115) and centrality (0.27), second position is the United States Department of the Interior publishing with 88 articles and third is the Chinese Academy of Sciences with 83 articles. In addition, of the 20 institutions, nine are located in the United States, five in France, and three in China. By looking at the data from Tables 5 and 6, it clearly shows that research on riverbank erosion is dominated by US institutions.

Reference Co-citation Network and Cluster Analysis

Reference co-citation analysis is a method that can pinpoint essential or foundational texts in riverbank erosion research. The complete mapping of the reference co-citation network is depicted in Figure 6. This network comprises 299 nodes and 983 links with a total network map density of 0.0221. The citation rings in this context symbolise the citation timeline of each

Table 5: Top 20 countries based on frequency in riverbank erosion research

Institution	Year	Frequency	Centrality
USA	2003	708	0.46
Peoples r China	2004	288	0.05
India	2003	198	0.05
England	2003	183	0.15
France	2003	165	0.34
Canada	2003	158	0.08
Australia	2003	110	0.06
Netherlands	2003	107	0.09
Italy	2003	101	0.04
Japan	2004	83	0.05
Germany	2003	71	0.16
Poland	2003	60	0.04
Iran	2007	54	0
Brazil	2003	52	0.02
New Zealand	2003	46	0
Bangladesh	2003	45	0.01
Russia	2003	44	0.12
Spain	2005	42	0.04
Switzerland	2004	36	0.06
Belgium	2005	31	0.03

Table 6: Top 20 Institutions based on frequency in riverbank erosion research

Institution	Country	Frequency	Centrality
Centre National de la Recherche Scientifique (CNRS)	France	115	0.27
United States Department of the Interior	US	88	0.08
Chinese Academy of Sciences	China	83	0.18
United States Geological Survey	US	81	0.07
United States Department of Agriculture (USDA)	US	79	0.23
UDICE-French Research Universities	France	79	0.04
University of Illinois System	US	42	0.05
University of Illinois Urbana-Champaign	US	42	0.05
Indian Institute of Technology System (IIT System)	India	39	0.13
University of California System	US	37	0.08
CNRS - Institute of Ecology & Environment (INEE)	France	35	0.05
Institut de Recherche pour le Developpement (IRD)	France	34	0
Wuhan University	China	34	0.03
Delft University of Technology	Netherlands	33	0.03
University of Chinese Academy of Sciences	China	30	0.01
CNRS - National Institute for Earth Sciences & Astronomy (INSU)	France	28	0.03
University of Minnesota System	US	28	0.02
Utrecht University	Netherlands	27	0.03
University of Minnesota Twin Cities	US	25	0.01
Colorado State University	US	24	0.04

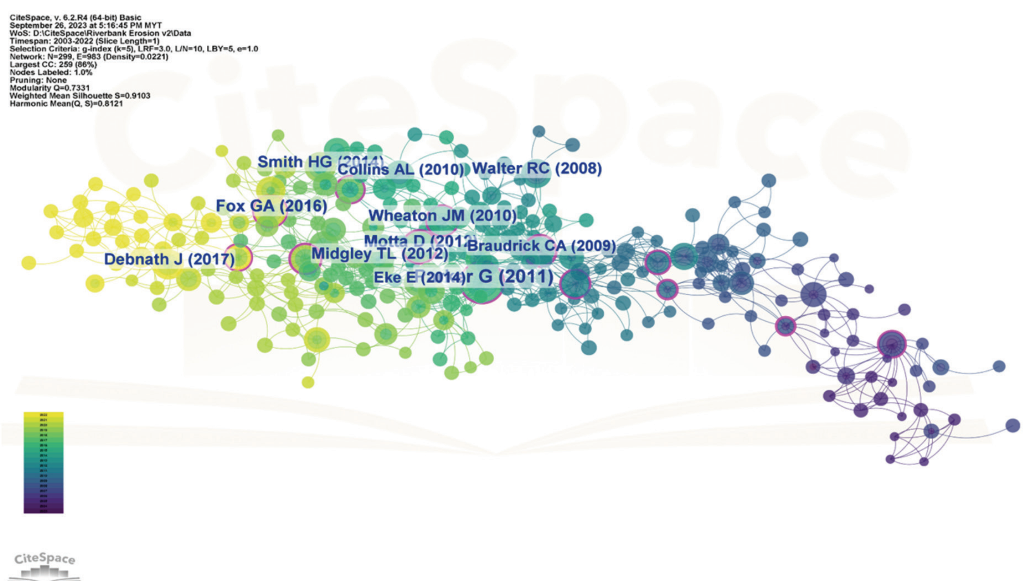

Figure 6: Visualisation of reference co-citation network

paper. The colour of these citation tree-rings is indicative of the time they were cited from darker purple (early years) to brighter yellow (recent years) and their thickness is directly related to the count of citations during that timeframe. By employing multivariate statistical analysis techniques like cluster analysis, the complex co-citation network relationship among numerous analysis objects is reduced to a few groups and visually displayed. The outcomes post-literature clustering is shown as a timeline visualisation diagram in Figure 7. The entire network is broken down into 8 major groups and these principal groups are marked by index terms from their individual citers, denoted with a '#' on the right side of Figure 7. It is worth noting that the co-citation network relationships are mapped utilising title terms and a log-likelihood ratio (LLR.) weighting algorithm for the labelling of clusters. LLR. is a method used to compute and establish each kind of label, thereby representing the fundamental concept of each cluster using specialised words (Fang *et al*., 2018).

The results of the top 8 clusters were tabulated in Table 7. The largest cluster (#0) 'cohesive floodplain' contains 37 members' reference, followed by cluster '#1 fluvial system' which has 36 members' reference, '#2 cloud computing' has 36 members' reference, '#3 agricultural watershed' has 31 members' reference, '#4 seepage erosion' has 29 members' reference, '#5 floodplain soil heterogeneity' has 28 members' reference, '#6 watershed scale' has 23 members' reference, '#7 dynamic meandering' has 20 members' reference, and the last cluster is '#8 clay-sand network structure' with 12 members' reference. The average silhouette is commonly utilised to evaluate the clusters. In general, a silhouette value greater than 0.5 signifies that the cluster is reasonable. If it surpasses 0.7, the cluster is deemed to be extremely efficient and convincing. The silhouette scores of the top 10 clusters presented in Table 7 are all above 0.7, suggesting that these clusters are productive and persuasive. The average publication year of the document can serve as an indicator to infer if the cluster is recent or old. Cluster #2 is the most recent, revealing that 'cloud computing' is a topic of much interest in the current field of research. This analysis offers significant understanding into the historical progression of research on this subject and can serve as a tool for forecasting upcoming research trajectories and developments.

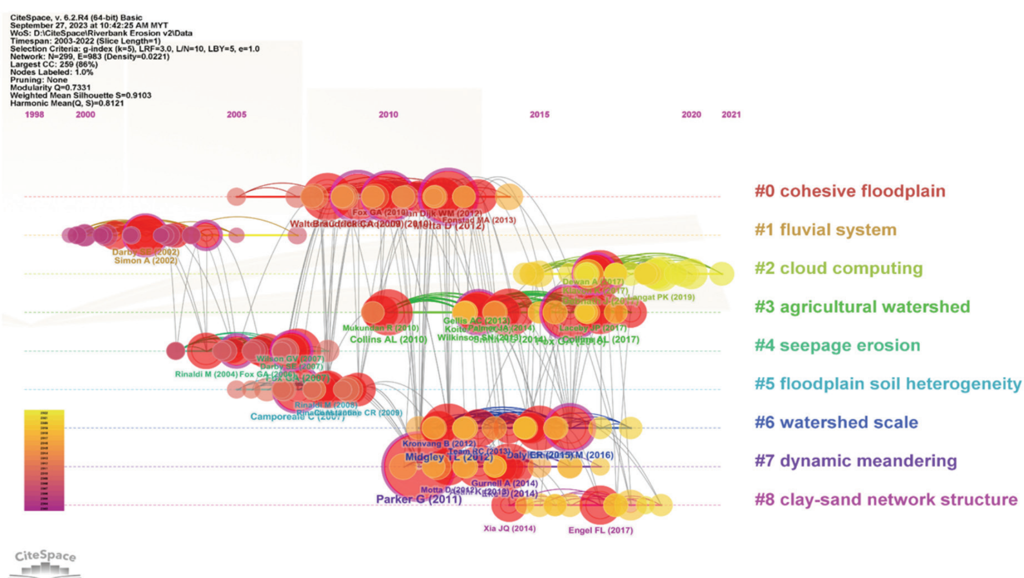

Figure 7: Timeline visualisation of references in the field of riverbank erosion

Table 7: Reference cluster analysis

Cluster ID	Size	Silhouette	Label (LLR)	Average Year
0	37	0.788	cohesive floodplain (101.54, 1.0E-4)	2010
1	36	0.927	fluvial system (103.49, 1.0E-4)	2002
2	36	0.95	cloud computing (99.25, 1.0E-4)	2017
3	31	0.914	agricultural watershed (133.47, 1.0E-4)	2014
4	29	0.952	seepage erosion (127.27, 1.0E-4)	2005
5	28	0.932	floodplain soil heterogeneity (101.98, 1.0E-4)	2007
6	23	0.915	watershed scale (134.65, 1.0E-4)	2014
7	20	0.959	dynamic meandering (101.5, 1.0E-4)	2013
8	12	0.818	clay-sand network structure (82.58, 1.0E-4)	2016

Table 8 represents the top 20 most cited references from 2003 to 2022. The references included in this article are the most frequently cited among the 2,323 documents that were reviewed, not necessarily the most cited in Web of Science or Google Scholar. These references contain foundational knowledge and indicate the direction of ongoing research in the field as reflected in the literature. The highest cited reference was by Parker *et al*. (2011), entitled "A new framework for modelling the migration of meandering rivers" with 36 citations. The article presented a new model, in which distinct relationships are established for the depositing bank and the migrating of the eroding bank. The model accommodates both (a) migration where erosion expands the channel, leading to deposition on the opposite bank, and (b) migration where deposition constricts the channel, causing erosion on the opposite bank. The next publication by Fox *et al*. (2016) discusses the issue of sediment and phosphorus (P) pollution in surface waters, focusing on the role of streambanks as a source of these pollutants. It highlights the lack of data on sediment and P loading from streambanks at a watershed scale. The paper reviews current knowledge on streambank erosion and failure mechanisms, P concentrations in streambanks, and the contribution of streambanks to P loading. It also identifies areas for future research. From the top 20 references, five publications were in cluster '#3 agricultural watershed' and four publications represent the relationship of 'cohesive floodplain' in riverbank erosion.

Table 8: Top 20 references based on frequency in riverbank erosion research

Reference	Title	Freq.	Journal	Cluster
Parker *et al*. (2011)	A new framework for modelling the migration of meandering rivers	36	Earth Surface processes landforms	7
Fox *et al*. (2016)	Streambanks: A net source of sediment and phosphorus to streams and rivers	23	Journal of environmental management	3
Motta *et al*. (2012)	A simplified 2D model for meander migration with physically based bank evolution	23	Geomorphology	0
Midgley *et al*. (2012)	Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral retreat on composite streambanks	21	Geomorphology	6

Debnath *et al*. (2017)	Channel migration and its impact on land use/land cover using RS and GIS: A study on Khowai River of Tripura, North-East India	20	The Egyptian Journal of Remote Sensing Space Science	2
Smith and Blake (2014)	Sediment fingerprinting in agricultural catchments: a critical re-examination of source discrimination and data corrections	19	Geomorphology	3
Wheaton *et al*. (2010)	Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets	19	Earth Surface processes landforms	0
Walter and Merritts (2008)	Natural streams and the legacy of water-powered mills	19	Science	0
Braudrick *et al*. (2009)	Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers	18	Proceedings of the National Academy of Sciences	0
Eke *et al*. (2014)	Numerical modelling of erosional and depositional bank processes in migrating river bends with self-formed width: Morphodynamics of bar push and bank pull	18	Journal of Geophysical Research: Earth Surface	7
Collins *et al*. (2010)	Apportioning catchment scale sediment sources using a modified composite fingerprinting technique incorporating property weightings and prior information	18	Geoderma	3
Konsoer *et al*. (2016)	Spatial variability in bank resistance to erosion on a large meandering, mixed bedrock-alluvial river	17	Geomorphology	6
Camporeale *et al*. (2007)	Hierarchy of models for meandering rivers and related morphodynamic processes	17	Reviews of Geophysics	5
Daly *et al*. (2015)	Modelling streambank erosion and failure along protected and unprotected composite streambanks	17	Advances in Water Resources	6
Collins *et al*. (2017)	Sediment source fingerprinting as an aid to catchment management: a review of the current state of knowledge and a methodological decision-tree for end-users	17	Journal of environmental management	3
Fox *et al*. (2007)	Measuring streambank erosion due to ground water seepage: correlation to bank pore water pressure, precipitation and stream stage	16	Earth Surface processes landforms	4
Wilkinson *et al*. (2013)	Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia	15	Agriculture, Ecosystems Environment	3
Asahi *et al*. (2013)	Numerical simulation of river meandering with self-evolving banks	15	Journal of Geophysical Research: Earth Surface	7
Simon and Collison (2002)	Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability	14	Earth Surface processes landforms	1
Darby *et al*. (2002)	Numerical simulation of bank erosion and channel migration in meandering rivers	14	Water Resources Research	1

Author Co-citation Network Analysis

The study of author co-citations allows us to identify key figures in the field of riverbank erosion research, offering a guide for talent acquisition in related institutions. The network depicted in Figure 8 comprises 274 nodes and 947 links with a total density of 0.0253. It is important to note that only the primary author was considered in this study. The most cited author Simon A is represented by the largest node with a citation frequency of 416. This node, marked by a purple outer ring has a centrality of 0.12, signifying Simon A's significant role in this field. Table 9 shows the top 20 most cited authors with citation frequencies exceeding 131. The node for Walling DE has the highest centrality at 0.12 alongside Simon A, making it a key node. High centrality is indicative of the potential for transformative scientific contributions.

Journal Co-citation Network Analysis

Riverbank erosion research literature spans a variety of journals. Gaining insight into the core journals' distribution in this field can serve as a reliable foundation for literature collection. A total of 293 nodes and 1,179 links makes up the network of journals. The overall density is 0.0276 and the nodes represent the journals (Figure 9). From Table 10 we can perceive that the top journals in this field are Geomorphology, Earth Surface Processes Landforms, Water Resources Research, Journal of Hydrology, Hydrological Process, CATENA, Bulletin of the Geological Society of America, Journal of Hydraulic Engineering, River Research and Application, and Journal of Geophysical Research: Earth Surface. Among all these journals, Geomorphology has the highest cited frequency with 1,600 co-citations and the highest centrality with 0.09. Other journals with high co-citation frequency above 1,000 are Earth Surface Processes Landforms and Water Resources Research. In terms of impact factor, Journal of Hydrology has the highest factor of 6.69. All of these journals have a significant value to riverbank erosion researchers.

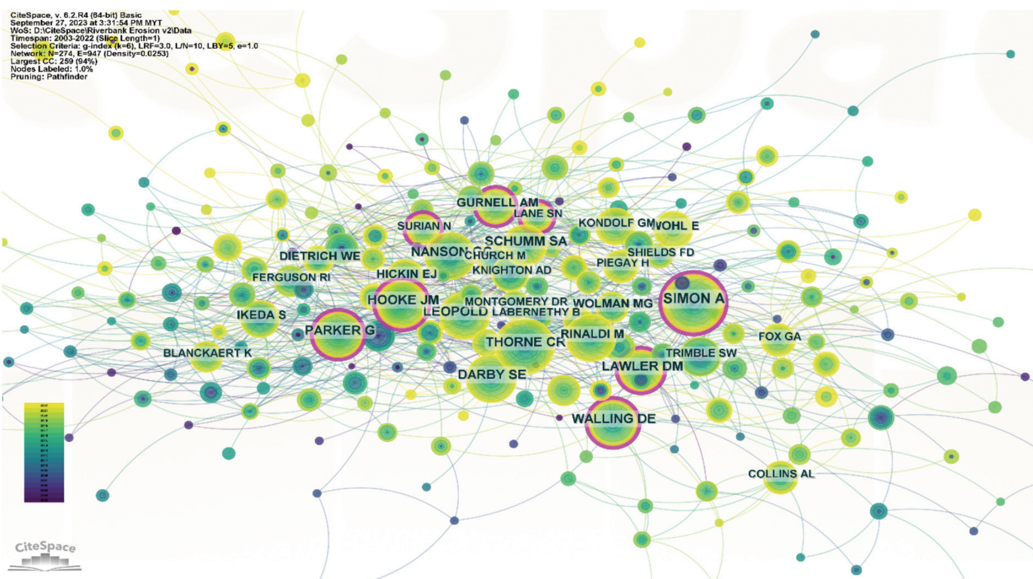

Figure 8: Visualisation of author co-citation network

Table 9: Top 20 most cited author based on frequency in riverbank erosion research

Author	Frequency	Centrality
Simon A	416	0.12
Thorne CR	339	0.06
Leopold LB	297	0.11
Hooke JM	287	0.07
Darby SE	277	0.08
Schumm SA	270	0.07
Nanson GC	267	0.09
Walling DE	267	0.12
Lawler DM	260	0.09
Parker G	248	0.08
Rinaldi M	230	0.03
Gurnell AM	201	0.07
Ikeda S	167	0.03
Wolman MG	158	0.04
Hickin EJ	156	0.07
Dietrich WE	152	0.07
Wohl E	149	0.02
Kondolf GM	147	0.02
Trimble SW	143	0.06
Ferguson RI	131	0.04

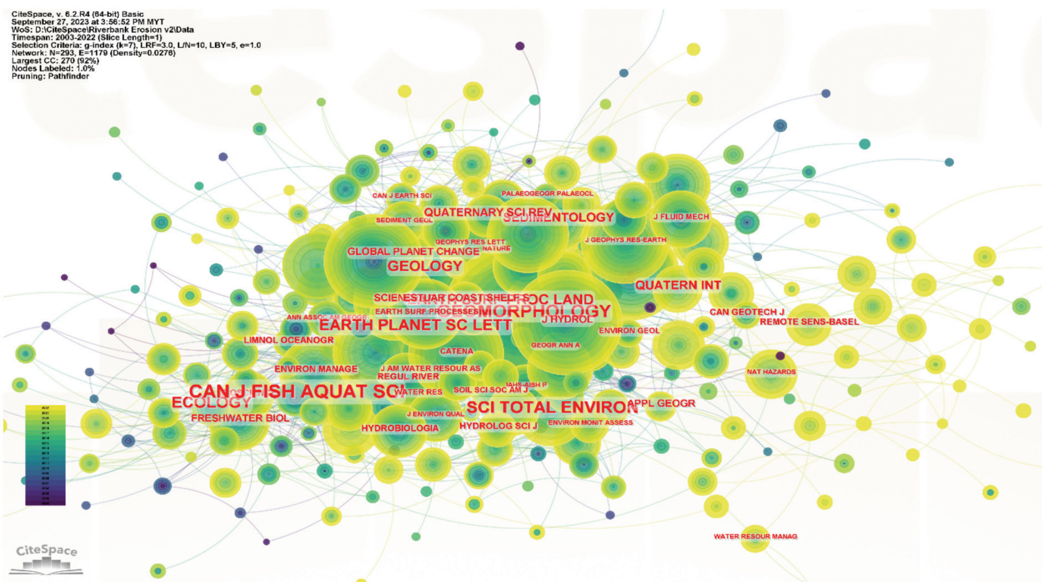

Figure 9: Visualisation of journal co-citation network

Table 10: Top 10 most cited journal based on frequency in riverbank erosion research

Journal	Freq.	Centrality	Impact score	Year
Geomorphology	1600	0.09	4.29	2003
Earth Surface Processes Landforms	1366	0.07	3.55	2003
Water Resources Research	1206	0.02	5.16	2003
Journal of Hydrology	933	0.05	6.69	2003
Hydrological Process	891	0.02	3.17	2003
CATENA	727	0.04	6.61	2003
Bulletin Of the Geological Society of America	702	0.02	5.21	2003
Journal of Hydraulic Engineering	674	0.02	2.07	2003
River Research and Application	565	0.03	2.5	2006
Journal Of Geophysical Research: Earth Surface	545	0.04	3.98	2008

Co-occurring Keywords Analysis

Keywords, which are essentially words and phrases that encapsulate the core concepts of articles can serve as a tool to monitor the evolution of research fields and domains (Lee & Su, 2010). The main themes were identified through a clustering analysis of co-occurring keywords, which was performed using CiteSpace. From CiteSpace, 285 keywords and 1,224 links were retrieved between 2003 and 2022. The large array of research on riverbank erosion was shown in Figure 10 with a complex linkage between keywords. An analysis of high-frequency keywords identified eight categories that represent the current research trends and emerging areas in the study of riverbank erosion (Table 11): #0 "Bank erosion," #1 "River restoration." #2 "seepage erosion," #3 "land use," #4 "sediment fingerprinting," #5 "remote

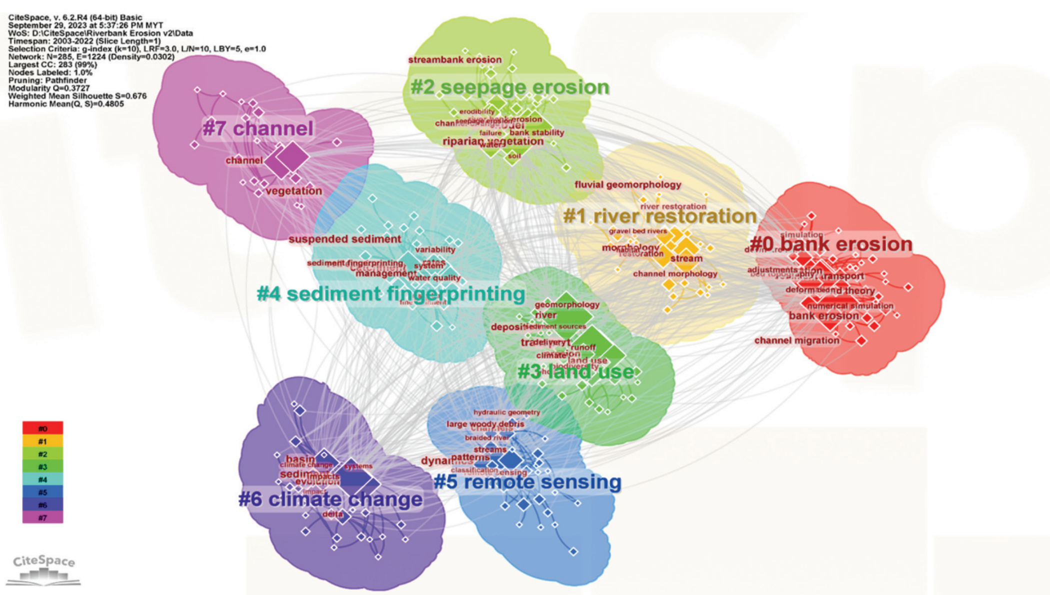

Figure 10: Keyword clustering analysis

Table 11: Most frequent keyword label describing the cluster label for riverbank erosion research (2003-2022)

ID	Cluster label (LLR)	Freq	Silhouette	Mean Year	Keyword label
#0	Bank erosion	47	0.775	2011	bank erosion, flow, sediment transport, migration, channel migration, bank, simulation, numerical, simulation, downstream, bend theory
#1	River restoration	37	0.46	2010	morphology, stream, restoration, river restoration, fluvial geomorphology, channel morphology, flood, gravel bed rivers, habitat, lateral, migration
#2	seepage erosion	37	0.691	2012	riparian vegetation, model, stability, streambank erosion, water, riverbank erosion, channel change, soil, bank stability, erodibility
#3	land use	36	0.701	2011	erosion, river, transport, land use, runoff, deposition, phosphorus, climate, sediment sources, sediment budget
#4	sediment fingerprinting	36	0.766	2010	suspended sediment, soil erosion, catchment, management, rates, variability, water quality, discharge, system, fine sediment
#5	remote sensing	35	0.689	2009	dynamics, patterns, streams, remote sensing, channels, gis, classification, braided river, large woody debris, hydraulic geometry
#6	climate change	33	0.682	2010	sediment, evolution, basin, impact, impacts, climate change, delta, systems, dams, sediments
#7	channel	22	0.584	2013	channel, vegetation, yellow river, valley, loess plateau, diversity, magnitude, fallout radionuclides, channel changes, forests

sensing," #6 "climate change," #7 "channel." Highly effective cluster labels with silhouettes greater than 0.7 were found in cluster #0 "bank erosion," #3 "land use," and #4 "sediment fingerprinting."

The term 'keywords with citation bursts' refers to keywords that receive a high frequency of citations within a specific timeframe. Figure 11 illustrates the top 20 keywords that have experienced the most significant citation bursts. The green line symbolises the entire duration, while the red line indicates the timeframe in which a burst in citations for a particular keyword was detected. The keywords "bend theory," "large woody debris," "bed topography," and "riparian vegetation" had early citation bursts. Among them, "bend theory" had the strongest citation burst. The latest burst was observed in articles featuring the keywords "climate change," "remote sensing," "morphodynamics," "riverbank erosion," "land use," and "failure," which peaked between 2019 and 2022. "Climate change" has the highest strength burst although it only began to peak in 2019. A swift rise in keyword searches can indicate emerging trends in a particular field and predict potential future growth trajectories.

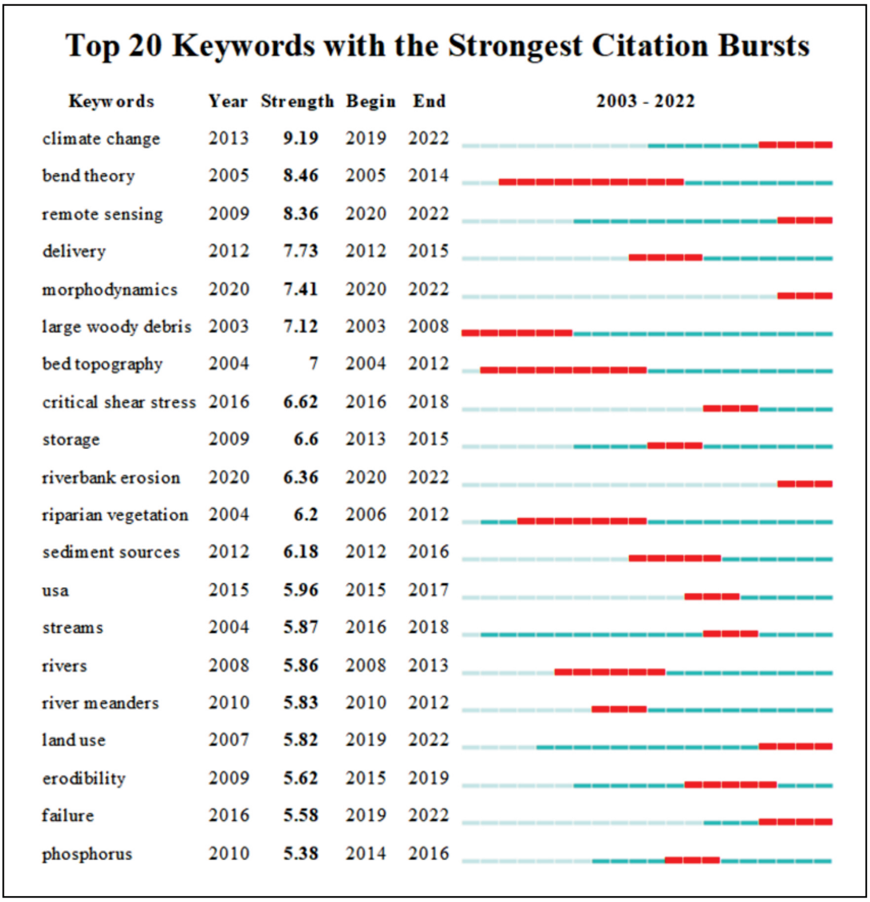

Figure 11: Top 20 keywords based on burst strength in riverbank erosion research

Conclusions

In conclusion, this study provides a comprehensive analysis of riverbank erosion research using scientometric methods and data obtained from the Web of Science database. The key findings and implications can be summarised as follows:

(1) Increasing Scholarly Attention: The study reveals a gradual increase in scholarly attention to riverbank erosion research over the past two decades with the number of publications rising from 43 in 2003 to 202 in 2022. This indicates a growing interest and recognition of the importance of studying riverbank erosion.

(2) Multidisciplinary Nature: Riverbank erosion research has evolved into a multidisciplinary field with categories such as Geosciences Multidisciplinary, Water Resources, and Environmental Sciences dominating the literature. This multidisciplinary approach reflects the complexity of the processes involved in riverbank erosion.

(3) Global Research Landscape: The study highlights the dominance of the United States institutions in riverbank erosion research, both in terms of the number of publications and centrality strength in international collaboration. However, the

under-representation of Asian countries suggests a geographical imbalance in research contributions.

(4) Key Research Areas and Journals: The paper identifies key research areas such as ‘cohesive floodplain’ and ‘fluvial system,’ through cluster analysis of reference co-citation networks. Additionally, it recognises top journals like Geomorphology, Earth Surface Processes Landforms, and Water Resources Research as central to riverbank erosion literature.

(5) Authorship Analysis: Simon A and Walling DE emerge as key figures in riverbank erosion research with high citation frequencies and centrality. The author co-citation network provides insights into influential contributors and potential collaborators in the field.

(6) Keyword Trends: Co-occurring keyword analysis reveals current research trends, including ‘bank erosion,’ ‘river restoration,’ ‘seepage erosion,’ ‘land use,’ and ‘climate change’. The identification of keywords with citation bursts such as ‘climate change,’ indicates emerging areas of interest and potential future research trajectories.

(7) Implications for Future Research: The study not only provides a snapshot of the current state of riverbank erosion research but also offers valuable insights into future research directions. The theme of ‘cloud computing’ is a topic gaining much interest in the current field of research. It refers to the use of cloud-based technologies to enhance data management, analysis, and real-time monitoring related to riverbank erosion. Data management and analysis allows researchers to store large volumes of geospatial and environmental data such as satellite imagery, topographic maps, and erosion measurements on remote servers. This facilitates easy access, sharing, and management of extensive datasets from multiple sources. Cloud computing supports real-time data collection and analysis through integration with remote sensors and monitoring systems. This enables continuous tracking of erosion processes and immediate updates to models and predictions.

In summary, this study contributes to the understanding of the global landscape of riverbank erosion research, emphasising its multidisciplinary nature and the need for international collaboration. The findings can inform future research agendas, facilitate collaboration among researchers and institutions, and contribute to the sustainable management of riverbank ecosystems.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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