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Links between Flash Floods and Hydrogeomorphic Approach: A Bibliometric Analysis

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Abstract

Understanding the hazards associated with water requires the use of a hydrogeomorphic approach, which considers both hydrologic and geomorphic aspects. In recent decades, research on flash floods has increasingly adopted this approach. However, the overall number of studies and their trends have not been thoroughly documented. Our study aims to analyze the evolution of scientific publications examining flash floods from a hydrogeomorphic perspective on a global scale to understand the trends and research gaps based on a bibliometric analysis. A comprehensive search for relevant publications was conducted in the Web of Science and Scopus databases, covering the period from 1973 to 2024. The resulting data were processed using R software, whereas the spatial distribution network of the publications was analyzed using VOSviewer software. Our analysis identified 212 articles focusing on flash floods as a hydrogeomorphic process. The number of publications has increased since 2012, peaking in 2023 with 21 new articles. Twenty-eight percent of the publications originated from the United States, Spain, and Italy, whereas the most extensive global collaboration network involved researchers from France, the United States, and Canada. A total of 87% of the publications on temperate zones, whereas 13% addressed intertropical environments, where hydrogeomorphic hazards can be particularly devastating. Our study underscores the importance of future research on flash floods hazards in intertropical zones, highlighting the need to incorporate hydrogeomorphic characteristics and processes into studies of flash floods and related phenomena such as floods, debris flows, landslides, and erosion.

Key words: emerging trends, hazards, hydrogeomorphology, network analysis.

Resumen

La comprensión de los peligros asociados al agua requiere utilizar un enfoque hidrogeomórfico, el cual considera tanto aspectos hidrológicos como geomórficos. En las últimas décadas, la investigación sobre inundaciones repentinas ha adoptado cada vez más este enfoque. Sin embargo, el número total de estudios y sus tendencias no se han documentado exhaustivamente. Nuestro estudio busca analizar la evolución de las publicaciones científicas que examinan las inundaciones repentinas desde una perspectiva hidrogeomórfica a escala global para comprender las tendencias y los huecos de las investigaciones mediante un análisis bibliométrico. Se realizó una búsqueda exhaustiva de publicaciones relevantes en las bases de datos Web of Science y Scopus, cubriendo el período de 1973 a 2024. Los datos resultantes se procesaron utilizando el software R, mientras que la red de distribución espacial de las publicaciones se analizó utilizando el software VOSviewer. El número de publicaciones ha aumentado desde 2012, alcanzando su punto máximo en 2023 con 21 nuevos artículos. El 28% de las publicaciones provinieron de Estados Unidos, España e Italia, mientras que la red de colaboración global más extensa involucró a investigadores de Francia, Estados Unidos y Canadá. El 87% de las publicaciones se centraron en zonas templadas mientras que el 13% abordó entornos intertropicales, donde los riesgos pueden ser particularmente devastadores. Nuestro estudio subraya la importancia de futuras investigaciones sobre los peligros de inundaciones repentinas en zonas intertropicales, destacando la necesidad de incorporar características y procesos hidrogeomórficos como flujo de escombros, inundaciones, deslizamientos de tierra y erosión.

Palabras clave: tendencias emergentes, peligros, hidrogeomorfología, análisis de redes.

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1. Introduction

Flash floods are primarily caused by sudden water overflows, influenced by initial soil moisture, and typically develop within one to six hours after heavy rainfall (Ballesteros-Cánovas *et al.*, 2017; Archer and Fowler, 2018; Tichavský *et al.*, 2020). They commonly occur in steep terrains with high drainage density and are influenced by factors such as climatic conditions, basin shape, and surface permeability (Crozier, 2005). During flash flood events, debris flows, and hyper-concentrated flows may also occur, amplifying their impacts. It has been suggested that themes related to complex geophysical processes may influence the dynamics of drainage systems, where catastrophic events occur (Marchi *et al.*, 2010; Ballesteros-Cánovas *et al.*, 2015b; Šilhán *et al.*, 2018; Estrany *et al.*, 2020). Between 1990 and 2015, flash floods resulted in 56,483 human deaths and economic losses of approximately $65 billion (UNDRR, 2019).

In the United States, most research has focused on arid and semi-arid regions, where storms frequently impact intermittent rivers (Bucherie *et al.*, 2022; Cabré *et al.*, 2023). In Europe, studies in temperate zones have highlighted flash floods triggered by extreme hydroclimatic conditions and inadequate management of hydrographic basins (Boudou *et al.*, 2016). In intertropical and subtropical regions, intense rainfall associated with hurricanes is a major cause of flash floods, often leading to severe economic losses and loss of life (Ruidas *et al.*, 2022; Quesada-Roman, 2023 De La Peña *et al.*, 2024). For example, in 2021, extreme weather events in Recife Brazil, caused landslides and flash floods, resulting in approximately 290 deaths (Marengo *et al.*, 2023).

Understanding flash floods and their relationship with hydrogeomorphic processes requires an integrated approach encompassing meteorology, hydrology, and geomorphology, analyzed through a spatiotemporal lens (Schumm, 1979; Borga *et al.*, 2007; Penna *et al.*, 2013; Vannier *et al.*, 2016). Hydrogeomorphic analysis examines water as both a hydrological and geomorphological trigger across various scales. This pioneering approach explores the intricate relations between geological structures and hydrological processes (Scheidegger, 1973). Studies by Tichavský and Šilhán (2016), Ballesteros-Cánovas *et al.* (2017), and Tichavský (2019), emphasize the importance of analyzing flash floods alongside other hydrogeomorphic processes. For instance, researchers in the Czech Republic, Saudi Arabia, and India have investigated the interaction between floods and debris flows, whereas studies in Canada and Italy have focused on the relationship between floods and landslides (Gomi *et al.*, 2004; Guzzetti *et al.*, 2005). These efforts have been supported by several international institutions, contributing to the development of new methodologies and approaches. Therefore, bibliometric analysis plays a crucial role in identifying trends and relevance in research by examining foundational studies, recent publications, and citation metrics (Lopes and de Carvalho, 2018). Such analyses have provided valuable insights into the evolution of geomorphological approaches and hydrology research trends (Doyle and Julian, 2005; Qin *et al.*, 2021; Visser *et al.*, 2021). Similarly, research on flash floods, particularly concerning hydrogeomorphic responses, has grown in recent decades. However, a comprehensive understanding of this field remains crucial for grasping the trends and developments in the evolving body of studies. Our study aims to perform a bibliometric analysis of the existing research on flash floods using a hydrogeomorphic approach to understand the development of themes in this field, as multiple potentially dangerous involved. The search was carried out in Scopus and Web of Science (WoS) databases. We focus on publications years, author keywords, countries where research has been conducted, collaboration networks among institutions and authors, journals in the area, and the application of hydrogeomorphic perspective to flash floods.

2. Materials and methods

2.1 Data selection and collection

The selection of data was conducted using the WoS and Scopus databases, covering the period from 1973 to 2024. These databases are widely recognized as essential tools for bibliometric analyses (Pranckutė, 2021; Visser *et al.*, 2021). The term "flash floods" is relevant across multiple disciplines within Environmental Sciences, Geography, and Earth Sciences (Czigány *et al.*, 2009; Kuksina & Golosov, 2020). To ensure comprehensive coverage, various keyword combinations related to hydrogeomorphology were employed. In the initial search, we used the terms "hydrogeomorphology" to assess general publications trends. Subsequently, the terms "hydrogeomorphological" and "hydrogeomorphic" were combined with keywords such as "flash-floods" to explore their relationships with these disciplines and hydrogeomorphic processes. All articles were read based on their titles, abstracts, and keywords. To start tracing each flash flood through hydrogeomorphic processes, articles were first selected by year of publication and then related to specific words associated with flash floods. Second, the specific words related to hydrogeomorphic processes with the highest frequencies allowed us to identify the variation in trends between flash floods and hydrogeomorphic aspects. Given the limited results from searches in Spanish (e.g., "hidrogeomorfología"; yielded only 14 publications), we focused exclusively on indexed articles in English. Other types of publications, such as books, book

chapters, and scientific reports were excluded. We acknowledge that using only two databases may underestimate the total number of relevant articles; nevertheless, the selected data provide a representative sample of scientific studies analyzed flash floods through a hydrogeomorphic approach.

To eliminate duplicated articles between databases, we used the "Revtools" R package in version 4.2.2 (Hui, 2018; Westgate, 2019), resulting in a single consolidated database. The database included the following information: (a) year of publication, (b) countries with the most publications, (c) author affiliations, (d) a network of co-occurrence keywords, and (e) the most frequent words used per year.

2.2 Data processing and analysis

We evaluated the trends of publication data through a Mann-Kendall (k) test ("MannKendall", "boot" R package) with a confidence level of 95%. This test is used to describe trends in time series data (Mann, 1945; McLeod, 2022). As the k statistics values, the z-value is used to test for the existence of a trend and p-value determines whether the k statistic is statistically significant. A significant trend was indicated if the computed p-value was less than 0.05. An exponential model was fitted in R to graphically represent the observed trend (McLeod, 2005; Yue *et al.*, 2002). We also analyzed the most frequently used words (q), focusing on those with a frequency greater than ten. These words were extracted from articles titles, abstracts, and keywords to identify the connections between topics and related terms. In this section, we mentioned the year of the first and second articles related to hydrogeomorphic processes. Then, we analyzed the collaboration networks between institutions and countries, wich were analyzed using VOSviewer software (van Eck and Waltman, 2023). Author affiliations were used to determine the corresponding countries (Van Den Besselaar and Heimeriks, 2006; Donthu *et al.*, 2021). In the maps, each node represents a country, with the distances between nodes indicating the degree of collaboration. Clusters of nodes represent collaborative networks (Chen, 2017). For the keyword network map, relationships between words were assumed, although some words may appear in multiple contexts; broad terms such as "water," "classification," and "area" were excluded to enhance clarity (Romanelli *et al.*, 2021).

To examine the temporal evolution of frequently used words, we focused on those with a frequency greater than thirty. This analysis allowed us to identify the years when various topics were integrated into research studies. The ggplot2 package in R version 4.1.2 (Team, 2020) was used for visualization.

To visualize the global distribution of publications, we mapped the locations of investigation sites and their relationship with climate conditions using Köppen's classification system (FAO, 2006).

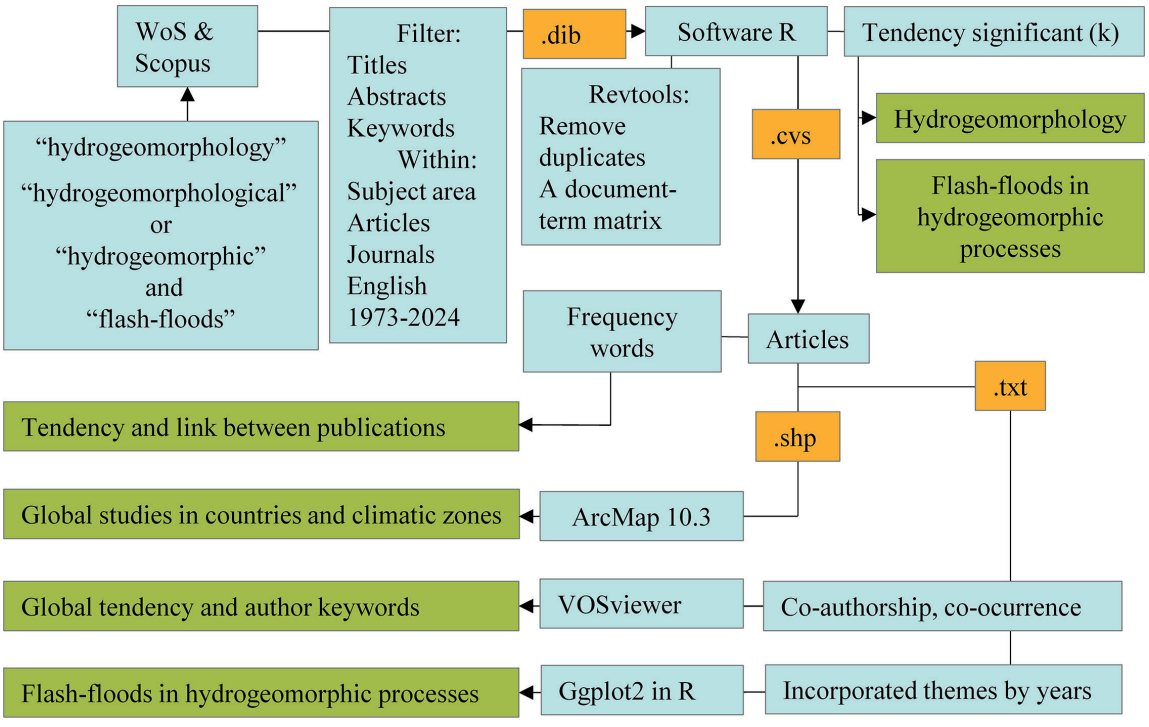

Figure 1. Methodological diagram for bibliometric analysis. Blue represents the analysis and data processing, orange means the format type, and green is the output.

3. Results and discussion

3.1 Publication trends

Figure 2 illustrates the publication trend in hydrogeomorphology over the 1973-2024 period. The first paper on this topic appeared in 1973, with a notable increase in publications beginning in 1998, and the number of publications decreased to 20 before the year 2000. The year 2021 recorded the highest number of hydrogeomorphology-related publications, with 99 articles, which accounts for 8% of the overall output. Over the last decades, 764 papers have been published in this field, representing 58% of the total publications and highlight the growing significance of hydrogeomorphic research internationally. Among these, 212 publications on flash floods using a hydrogeomorphic approach; with 202 released between 2000 and 2024, representing 95% of the flash flood literature. Trend analysis also shows a steady increase in publications for both hydrogeomorphology and flash floods with a hydrogeomorphic approach, both were significant ($p<0.0001$) as seem in Table 1. This analysis shows that hydrogeomorphic analysis is an emerging trend. However, we detected a trend in hydrogeomorphology publications toward groundwater topics, while others focused on hazard management associated with multiple interacting processes. For example, hydrogeomorphic analysis has enabled the characterization of debris flows and floods, contributing to efforts in impact reduction (Jakob *et al.*, 2017). The analysis of superficial and sub-superficial conditions -such as lithology, geo-structural guidelines, erosion, and flood zoning- has enhanced our understanding of infiltration and runoff processes (Narayana *et al.*, 1996). Additionally, Camarasa-Belmonte and Soriano-García (2012) and Tichavský *et al.* (2017) have emphasized that studies using hydrogeomorphic and dendrogeomorphological approaches prioritize spatiotemporal analysis and adopt a multidisciplinary approach to flash flood research.

Scheidegger (1973) authored publications integrating hydrology and geomorphology to understand the morphological effects of water. Sidle *et al.* (2000), and Sidle and Onda (2004) significantly contributed to establishing hydrogeomorphology as an interdisciplinary science, emphasizing spatial and temporal dimensions of hydrological components. Given the complexity of isolating and studying each process individually, some research has explored interactions among multiple hydrogeomorphic processes (Sidle *et al.*, 2017). For instance, Wilford *et al.* (2005) examined debris flows, debris floods, and floods; Diodato (2004) investigated erosion, landslides, flash floods, and

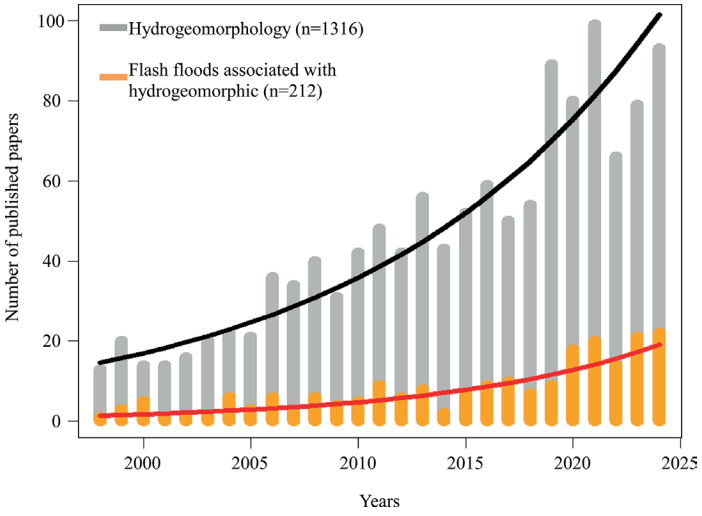

Figure 2. Publication trends in hydrogeomorphology and flash floods using a hydrogeomorphic approach. Red and black lines represent the publication trends.

Table 1. Value of Mann-Kendall trend test.

Series	Value	
	z-value	p-value
Hydrogeomorphology	6.143	<0.0001
Flash floods associated with hydrogeomorphic approach	5.024	<0.0001

river flooding; and Sakals *et al.* (2006) studied flooding, debris flows, snow avalanches, and rockfall. We theorize that studies on these topics have been conducted through a hydrogeomorphic approach, which accounts for the high volume of publications across various issues with in the discipline.

3.2 Global distribution of publications on flash floods

Publications on flash floods using a hydrogeomorphic approach have been distributed across 40 countries, including regions in South America, South Africa, and southern Asia (Figure 3). The United States (n=22), Spain (n=20), and Italy (n=19) had the highest number of publications during the study period, totaling 61 publications (29% of the total). In this context, two types of publications on flash flood studies were identified (see **appendix in supplementary data**): (i) studies referring to methods or theories (n=17; 8%) and (ii) publications related to hydrogeomorphic topics (n=196), such as fracture zones, tectonics, lineaments, riparian vegetation, floodplains, flash floods, floods, debris flows, landslides, and erosion. This last group includes publications considering multiple hydrogeomorphic processes (Table 2).

The locations of the publications were categorized into different climates: cold-temperate climates (n=46), dry-temperate (n=14), and dry-tropical (n=10). The locations distribution highlights a research gap in intertropical climates, particularly in countries in South America, South Africa, and southern Asia. These results agree with authors who study natural hazards as a complex systems, especially in areas with climatic seasonality (Quesada-Roman, 2023; Rogelis & Werner, 2018; Sidle *et al.*, 2017). These regions have suffered significant human and economic losses resulting from the intensity of tropical cyclones between 1975 and 2016 (Hu *et al.*, 2018). In areas such as Latin America, Africa, and Indonesia, the scarcity of meteorological and runoff data poses challenges in implementing effective modeling methods for estimating flood magnitudes (Eccles *et al.*, 2019). Identifying study locations by climatic zones is essential to target areas that require research activities (Rogelis &

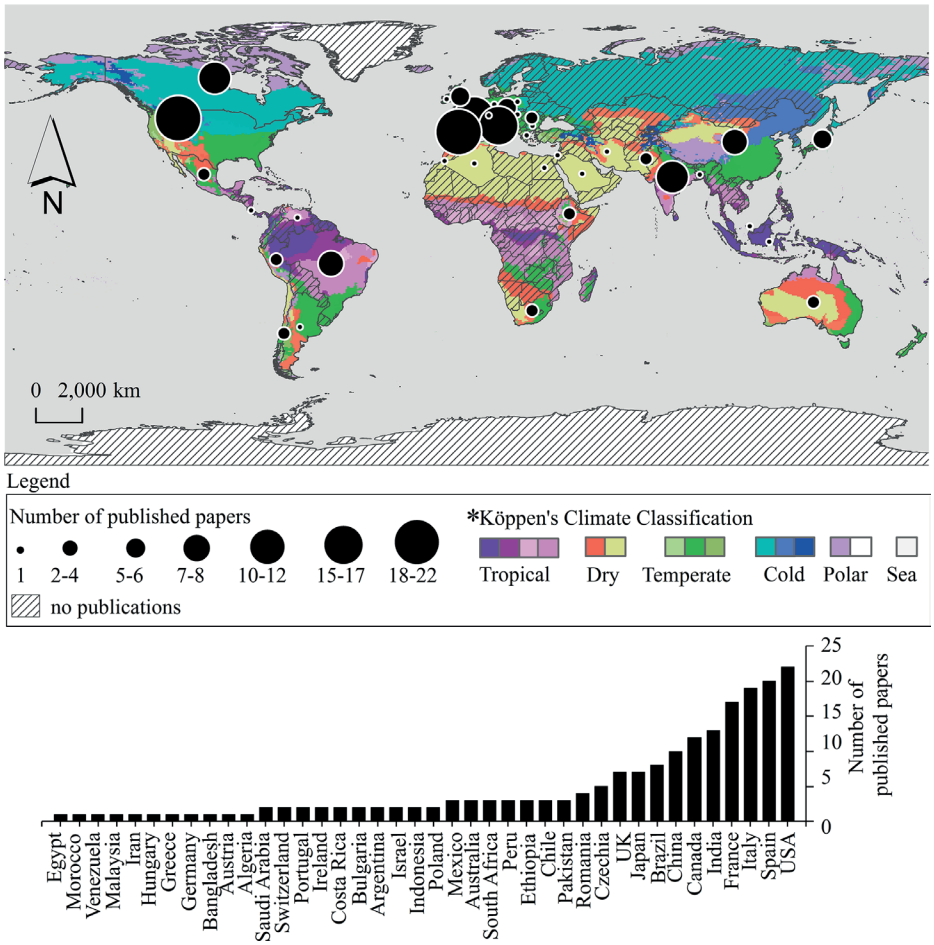

Figure 3. Global distribution of publications on flash floods using a hydrogeomorphic approach. (*) Climate distribution (FAO, 2006).

Table 2. Number of publications on flash floods by region and their relationship to relevant topics.

Countries and regions	Topics
Europe (n=32)	F, FF, E, DF, LD, T, I, RV, FP
Italy, Czech Republic, Greece, Spain, France, United Kingdom, Germany, Poland, Austria, Hungary, Romania.	
America (n=18)	F, FF, E, RV, T, DF, FP, LD
United States, Canada, Costa Rica, Brazil, Peru, Chile.	
Asia (n=15)	DF, LD, F, FF
Japan, Israel, China, Pakistan, Indonesia, Saudi Arabia, Ethiopia, India.	
Africa (n=5)	
South Africa, Algeria, Morocco, Bangladesh, Egypt	F, FF, E, T, LD, FP

F, floods; FF, flash floods; DF, debris flows; LD, landslides; E, erosion; T, tectonic; I, infiltrations; RV, riparian vegetation; FP, floodplains.

Werner, 2018). Studying flash floods under extreme precipitation conditions using a hydrogeomorphic approach can enhance the management of these hazardous events (Ballesteros-Cánovas *et al.*, 2015a). However, such studies are currently limited (Ballesteros-Cánovas *et al.*, 2015b; Stoffel & Wilford, 2012). The variability of geographical and physical parameters of basins, coupled with the difficulties in accessing meteorological data, complicates the understanding of hydrogeomorphic processes (Galia *et al.*, 2018; Šilhán *et al.*, 2018). Research conducted in diverse climatic settings contributes significantly to discussion regarding the variability and importance of extreme precipitation and threshold values in flash flood analysis (Eccles *et al.*, 2019). Additionally, the increase in high-intensity rainfall, driven by climate change, heightens the risk of flash floods, both globally and regionally (Beniston, 2009; Giorgi *et al.*, 2011). Therefore, collaboration among organizations, sectors, and nations is crucial (Hu *et al.*, 2020).

3.3 Collaboration network among major countries

The collaboration networks in this topic were developed by 173 authors and 121 institutions (Figure 4). Notably, only 13 authors published individually, indicating that 90% of the articles were produced by research groups with two or more co-authors. The most significant collaboration groups, differentiated by color, are as follows. The red cluster includes the United States and England, which collaborated with 12 other countries. The green cluster comprises of Italy and India, with the most publications and connections to nine countries. However, the collaboration between Italy and India is less strong than that between Israel and Italy. Additionally, countries such as Spain, France, Germany, and Portugal collaborate with nations in tropical regions, including Israel, Mexico, and South Africa. Countries in intertropical regions have produced a limited of research publications. In India, most studies adopt a hydrogeomorphic approach (n=13). However, we identified a weak connection of India with other countries, which may be attributed to a sparse collaboration network, resulting in fewer chances for joint problem solving. The emphasis on collaboration with countries such as Spain and the United States highlights the significance of these connections for the international exchange of knowledge. International collaborations are essential for developing methods, conceptual frameworks, and theories that enhance the quality of research (Guan *et al.*, 2017).

3.4 How are the hydrogeomorphic aspects in the developed topics related to flash floods?

In our analysis of annual publications, we identified 425 frequent words, and nine of total topics related to flash floods studies. The two main emerging topics are riparian vegetation (q=74; 17%) and floods (q=53; 12%), which saw increased mentions from 2012 and 2018. We also observed a rise in discussions about landslides (q=38; 9%) and debris flows (q=35; 8%) in 2019. Additionally, erosion emerged as a significant topic (q=30; 7%), increasing since 2015. This distribution of keywords underscores the need to recognize flash floods as complex systems (Figure 5). Our research found that erosion and infiltration had been considered before 1990, with a peak in 2018. This corresponds to the application of erosion studies

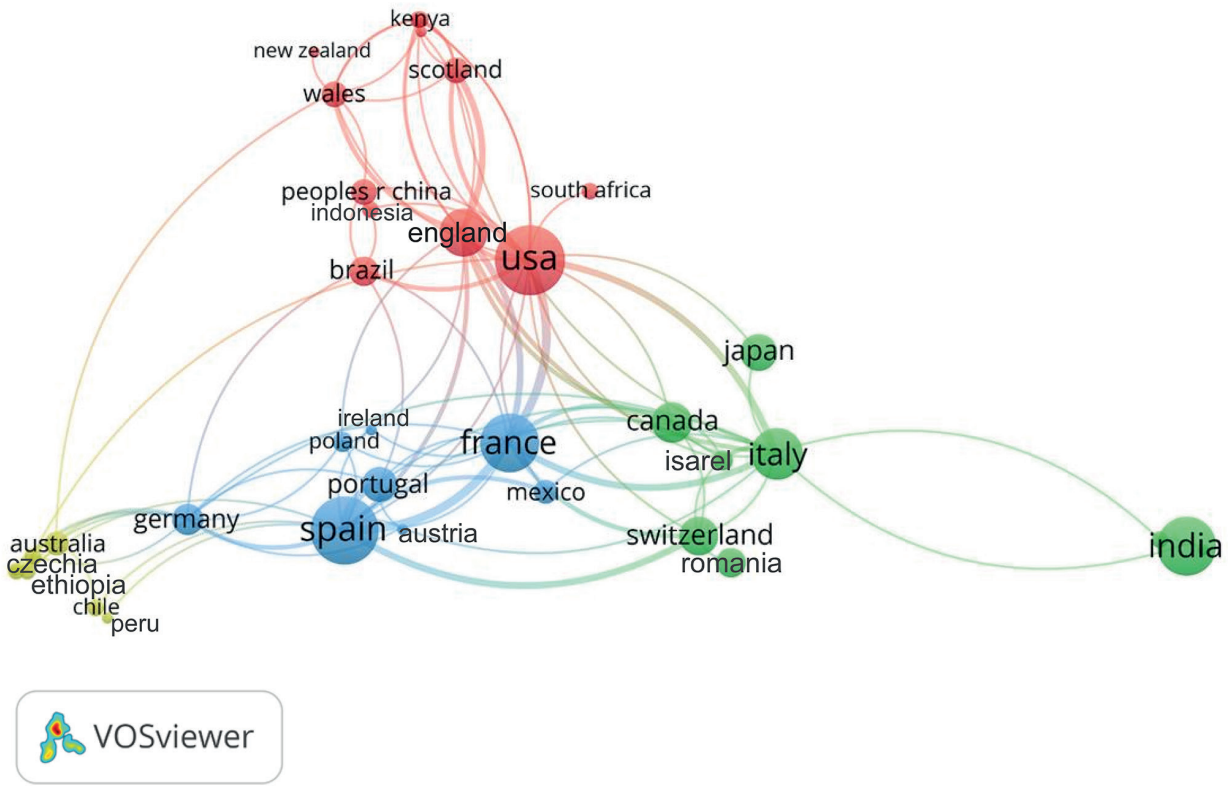

Figure 4. Collaboration network for studies on flash floods using a hydrogeomorphic approach.

during the 1960s to 1970s to estimate long-term average soil loss and to explore its relationship with debris flow material release (Kinnell, 2019; Tichavský & Šilhán, 2016). In addition, evaluation of cycles of terrain moisture of the late Quaternary is necessary to explain hillslope sediment transport (Estrany *et al.*, 2020). Similarly, our results indicate a link between landslide and tectonic lineaments has been considered since 2000; the link rose in 2010 and has remained steady since then. Authors, such as Viles *et al.* (2008), and Stoffel and Wilford (2012) have demonstrated that the structure and composition of riparian vegetation influence hydrogeomorphic processes including floods and debris flows. Some authors such as Dykes and Welford (2007) and Sidle *et al.* (2017) have recognized the importance of these themes in flood, debris flood, and hyperconcentrated flash flood for a quantitative investigation of flood frequency research. Finally, the themes such as riparian vegetation and flood have been rising since 2015. From 1950 to 2015, Wang *et al.* (2021) studied 32,473 flash floods in China, analyzing 68% of the recorded data. They found that although the number of flash flood events has increased from 2010 to 2015, this trend has been short-lived. In the last decade, research on flash floods from a hydrogeomorphic perspective, particularly concerning hazard evaluation, has gradually advanced (Guo *et al.*, 2024). Ghosh and Guchhait (2014), and Yousif *et al.* (2024) evaluated some hydrogeomorphic parameters to define the flash floods effects and the quality of water in the Kopai river and the Suez Gulf. The main topics with more than ten publications cover (a) infiltration, (b) tectonics, (c) landslides, (d) debris flows, (e) flash floods, (f) erosion, (g) floodplains, (h) floods, and (i) riparian vegetation. However, this study focuses on hydrogeomorphic approach related to flash floods, such as erosion, debris flows, landslides, and floods. The following subsections elaborate on these components in greater detail.

3.4.1 Floods

Flooding has caused significant loss of life and economic damage worldwide, although it also provides ecosystem services (Ballesteros-Cánovas *et al.*, 2015b). A total of 79 publications related to flash floods and flooding have emerged over the years. The first publication was by Baker (1976) in the United States, who proposed hydrogeomorphic methods for the regional evaluating flooding hazards. This was followed by Baker (1977), who analyzed flash floods specifically in the southeastern United States and made notable contributions to the field. Between 1978 and 2006 publications were sporadic; however, from 2006 to 2016, one paper was published each year. In contrast, between 2017 and 2024, the output increased significantly to

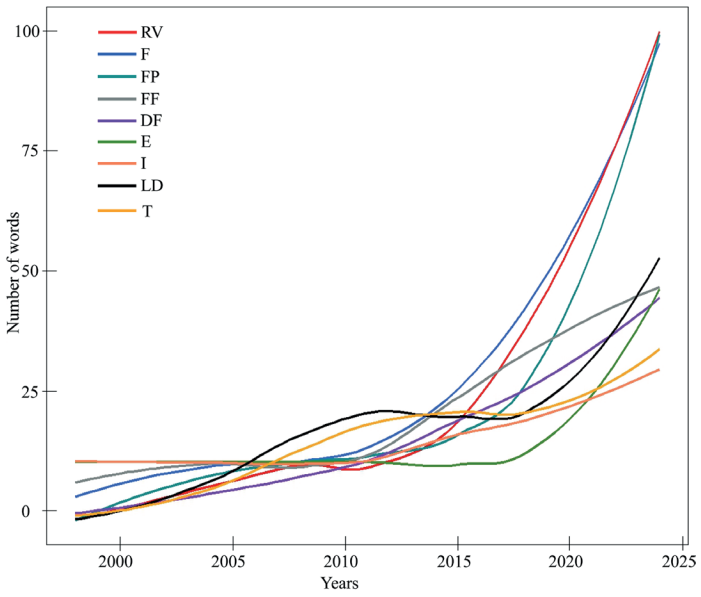

Figure 5. Most frequently used keywords in publications related to flash floods from a hydrogeomorphic approach F, floods; FF, flash floods; DF, debris flows; LD, landslides; E, erosion; T, tectonic; I, infiltrations; RV, riparian vegetation; FP, floodplains.

an average of seven papers per year. Ballesteros Cánovas *et al.* (2017) modeled the multidecadal variation of floods using dendrogeomorphic methods in India. They incorporated data on historical maximum discharges and their relationship with flash floods. The same study highlighted that flood hazards in the region have been previously underestimated, emphasizing the need for return period analysis and a deeper understanding of hydrogeomorphic processes.

3.4.2 Erosion

Some investigations have referenced two pioneering papers from Japan, authored by Okunishi *et al.* (1974, 1991), but these papers were not available in Scopus or WoS. A total of 30 publications focusing on erosion were recorded. One of the first significant studies on this topic was conducted by Arnaez-Vadillo and Larrea (1994). They examined the linked between erosion in mountain road cuts and their hydrogeomorphic functioning, demonstrating that these cuts are associated with runoff regimes. Their research contributed to understand the relationship between erosion and surface runoff in sloped areas during high-magnitude rainfall events (55 mm per year) that occur infrequently (once every 45 years) is crucial. Shortly after, Cerdà (1998) analyzed hydrogeomorphic processes at the pedon scale to evaluate soil's hydrological and erosive behavior, emphasizing the need to relate slope to erosion rates during extreme drought conditions. DeLong *et al.* (2014) studied the effects of erosion in southern Arizona, focusing on shallow subsurface runoff. They reported that flash floods and landscape changes significantly impact the removal of soil particles in basin headwater drains. Overall, between 1998 and 2014, one article on this topic was published annually. This rate subsequently increased to two articles per year.

3.4.3 Debris flows

Debris flows on steep slopes are significant hydrogeomorphic events often associated with flooding (Galia *et al.*, 2018). Our research identified a total of 34 publications on the topic of debris flows. The first article was written by Wilford *et al.* (2004) in Canada and aimed to differentiate between debris flows, debris floods, and floods. They emphasized the importance of morphometric parameters in studying hydrogeomorphic processes. Then, Benda *et al.* (2005) discussed the morphometric concepts related to watersheds headwaters, noting that these areas can contain sediments and wood, which can be released sporadically, leading to debris flows and flash floods. They also highlighted how varying types of debris flows and flash flood materials can influence the morphology of downriver streams. Furthermore, Imaizumi *et al.* (2006) evaluated the morphological and sedimentological aspects of multiple debris flows in Japan, linking these events to both saturated and unsaturated processes of upstream sediments. Corti *et al.* (2024) compared the 2022 event, which involved shallow landslide, debris flow, and erosion with other relevant events from the past to evaluate the peak discharge using two physically-based models based on channel processes and catchment scale. The authors of that

study highlighted the importance of hazard management across different scales in catchment landscape (Corti *et al.*, 2024). According to the database, one article on debris was published each year between 2005 and 2014. Subsequently, the number of publications increased to three articles per year.

3.4.4 Landslides

Landslides in mountainous regions accelerate the degradation and shaping of headwater watersheds (Tichavský, 2019). Landslide events increase the velocity of flash floods and alter floods paths (He *et al.*, 2012). A total of 22 publications have explored the impact of landslides on runoff processes. Since 1999, Japan has been assessing the recurrence of shallow landslides in headwaters. Iida (1999) identified that when the depth of saturated flow exceeds a critical threshold -the volume of liquid equivalent to the mass- it exposes the water table. Furthermore, Gomi *et al.* (2004) linked landslides and debris flows to sediment deposits found in fluvial channels and riparian vegetation structures of Alaska. They recognized triggering factors, such as storms that produce 24 hours of precipitation, which lead to accumulated landslides in coastal areas. Beginning in 2008, publications on landslides started appearing twice a year, and from 2022 to 2023, this frequency increased to three articles per year (Figure 5). Recently, Kotsi *et al.* (2023) defined areas susceptible to landslides using photogrammetry in the Mediterranean region, highlighting the synergy between hydrogeomorphic processes and the active tectonic deformations of rocks, which are significantly related to erosion and sedimentation. The study of landslides also includes the analysis of lineaments and fractures associated with tectonics, specifically concerning flash floods and hydrogeomorphology (Rashwan *et al.*, 2024).

3.5 Author keywords: co-occurrence network analysis

For the co-occurrence network analysis, we examined the relationship between flash floods and hydrogeomorphology through a spatial analysis (Figure 6). This analysis identified four distinct clusters. The central cluster, labeled "flash floods," is connected to three other clusters: "runoff" and "catchment" (green), "hydrogeomorphology" and "erosion" (red), and "rainfall" (blue). The distribution of the nodes is dispersed, with

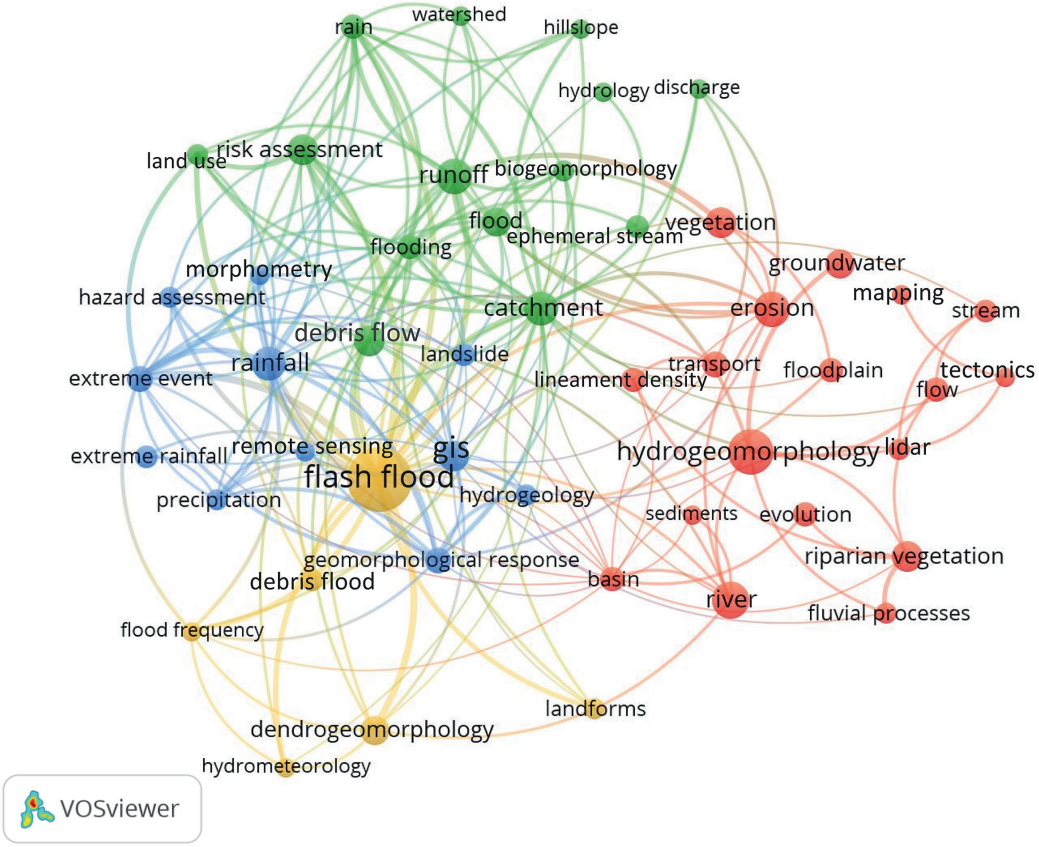

Figure 6. Network of co-occurrence author's keywords.

many represented as smaller nodes. This finding aligns with the publication by Patton and Baker (1976), who estimated hydrogeomorphic controls in regions prone to flash floods based on morphometric parameters in the United States. They identified two main types of hydrogeomorphic controls: (a) relief, drainage density, and roughness, and (b) storms, evaporation, and water storage capacity. These characteristics are related to landform dissection and relief (Wistuba *et al.*, 2015). The terms closest to "flash floods" include Geographic Information System (GIS), remote sensing, hydrogeology, and geomorphological response. In contrast, the nodes linked to "hydrogeomophology" feature terms such as LiDAR (Light Detection and Ranging), transport, sediments, and lineament density. For hydrogeomorphic processes, nodes associated with flash floods include debris flood, debris flows, landslide, and flood. The article by Ballesteros-Cánovas *et al.* (2015b) highlighted the challenges of estimating landscape changes caused by flash floods in Spain. However, the intensity of these events has been understood through post-event studies in ungauged basins using paleohydrology and dendrogeomorphology techniques (Bodoque *et al.*, 2015; Stoffel & Wilford, 2012).

Regarding the tools utilized, Di Baldasarre *et al.* (2020) noted that using GIS enables the integration of physical-environmental data, such as information on riparian and erosion zones. GIS and statistical methods of bivariate regression are employed to calculate the magnitude of extreme flooding and flash floods (Clarke *et al.*, 2008; Ruidas *et al.*, 2022; Tariq *et al.*, 2023). Additionally, the analysis of LiDAR data for interpreting river morphodynamics and bank erosion has facilitated the detection of changes prior to the onset of flash floods (Betancourt-Suárez *et al.*, 2021; Buffin-Bélanger *et al.*, 2017).

3.6 Main authors according to the number of citations and journal related in the topics

The results indicate that Scopus records the highest number of citations among the databases. On average, the citation count in Scopus and WoS differ by about ±10 citations per article. We selected 15 key articles based on their citation counts, considering them the most relevant to this research topic. The journals publishing these articles have impact factors ranging from three to four (Table 3). The most cited article, with 469 citations, is by Sidle *et al.* (2006), published in Forest Ecology and Management journal. The article examined erosion and landslide processes in Indonesia, concluding that shallow water accumulation was a significant factor and the locations of trails and roads played a critical role in accelerating flow movement during storms. The second most cited article, with 418 citations is by Baker (1977), published in the Bulletin of the Geological Society of America. He evaluated the response of flood drains in the southeastern United States and found that high-magnitude flash floods are related to surface flows and the groundwater system. The third most cited article, with 416 citations, is by Sidle *et al.* (2000), published in Hydrological Processes. This study assessed headwater runoff in Japan under wet and dry conditions and concluded that runoff begins after shallow groundwater accumulation.

In intertropical zones, 27 articles (13%) have been published in recent decades. The most cited article was by Sidle *et al.* (2006), highlighting the importance of intertropical studies. The article by Frankl *et al.* (2011) has 101 citations and compares 60 historical photographs in Ethiopia, relating the profound effects of flash floods to channel alteration. They conclude that these effects are due to increased aridity, erosion, and vegetation elimination. In South America, Ettinger *et al.* (2016) received 70 citations for their work evaluating hydrogeomorphic hazards in constructed areas of Peru. They measured flash flood height marks without runoff data, focusing on factors such as proximity to drains and flood traces on buildings. Their research developed a hydrodynamic model using a logistic regression to estimate susceptibility to hydrogeomorphic hazards. Given these findings, it is increasingly important to understand the dynamics of flash floods in intertropical zones. Therefore, generating data on hydrogeomorphic characteristics in these areas is critical for constructing statistical models and implementing new techniques in natural hazard assessments (Sidle *et al.*, 2017; Quesada-Roman, 2023). However, we identified that the research in intertropical regions has not increased significantly in the last decades. Identifying the most cited publications allows us to determine whether specific characteristics should be incorporated in flash floods studies.

3.7 Citation registration in the bibliographic database

The citation record of an article reflects its connections to innovative content and references to prior works (Okubo, 1997). Generally, when comparing citation numbers between Scopus and WoS, we observed an increasing range of publications. However, discrepancies exist in how citations are registered on the two platforms (Aviv-Reuven & Rosenfeld, 2023). For instance, the journal Geography Compass has been indexed in Scopus since 2008 and includes the work of Sidle (2010), which investigates the hydrogeomorphic processes in temperate and intertropical forests; yet, this publication is not listed in WoS. Additionally, the journal Forest Snow and Landscape Research, indexed in Scopus since 2004, contains the publication by Sakals *et al.* (2006) that discusses hydrogeomorphic hazards, but is not in WoS. This emphasizes the importance of WoS for searching bibliographic sources and its complementary role to Scopus in accessing

Table 3. The fifteen most cited articles according to Scopus and WoS.

Author	Title	Journal	Scopus	WoS
Sidle *et al.* (2006).	Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia.	Forest Ecology and Management	469	404
Sidle *et al.* (2000).	Storm generation in steep forested headwaters: a linked hydrogeomorphic paradigm.	Hydrological Processes	418	390
Baker (1977).	Stream-channel response to floods, with examples from central Texas.	Bulletin of the Geological Society of America	416	347
Borga *et al.* (2014)	Hydrogeomorphic response to extreme rainfall in headwater systems flash floods and debris flows.	Journal of Hydrology	363	319
Patton and Baker (1976)	Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls.	Water Resources Research	248	208
Wilford *et al.* (2004)	Recognition of debris flow, debris flood and flood hazard through watershed morphometrics.	Landslide	234	211
Steiger *et al.* (2005)	Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: A review for the temperate zone.	River Research and Applications	226	200
Sidle and Bogaard (2016)	Dynamic earth system and ecological controls of rainfall-initiated landslides.	Earth-Science Reviews	220	204
Frankl *et al.* (2011)	Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia).	Geomorphology	101	97
Stoffel and Wilford (2012)	Hydrogeomorphic processes and vegetation: Disturbance, process histories, dependencies and interactions.	Earth Surface Processes and Landforms	89	87
Ruiz-Villanueva *et al.* (2013)	Reconstruction of a flash flood with large wood transport and its influence on hazard patterns in an ungauged mountain basin.	Hydrological Processes	75	72
Ettinger *et al.* (2016)	Building vulnerability to hydro-geomorphic hazards: Estimating damage probability from qualitative vulnerability assessment using logistic regression.	Journal of Hydrology	70	60
Ballesteros-Cánovas *et al.* (2015a)	Flash floods in the Tatra Mountain streams: Frequency and triggers.	Science of the Total Environment	63	58
Armon *et al.* (2018)	Synoptic-scale control over modern rainfall and flood patterns in the Levant drylands with implications for past climates.	Journal of Hydrometeorology	53	46
Ballesteros-Cánovas *et al.* (2015b)	Unravelling past flash flood activity in a forested mountain catchment of the Spanish Central System.	Journal of Hydrology	46	40

citation counts, periodic citation records, titles, institutions, and countries. To demonstrate that the number of citations for an article does not always depend on its year of publication, we can compare two papers. The foundational work by Patton and Baker (1976) averages five citations per year, while the paper by Borga *et al.* (2014), published thirty-eight years later, averages 34 citations per year (Figure 7). Chang and Ho (2014), and Zhai and Ho (2018) evaluated the impact of a citation of articles, and they considered it essential to contemplate a broader timeframe than just the first year. They mentioned that a low citation count may indicate systematic changes in the research field, especially if the topic has gained popularity.

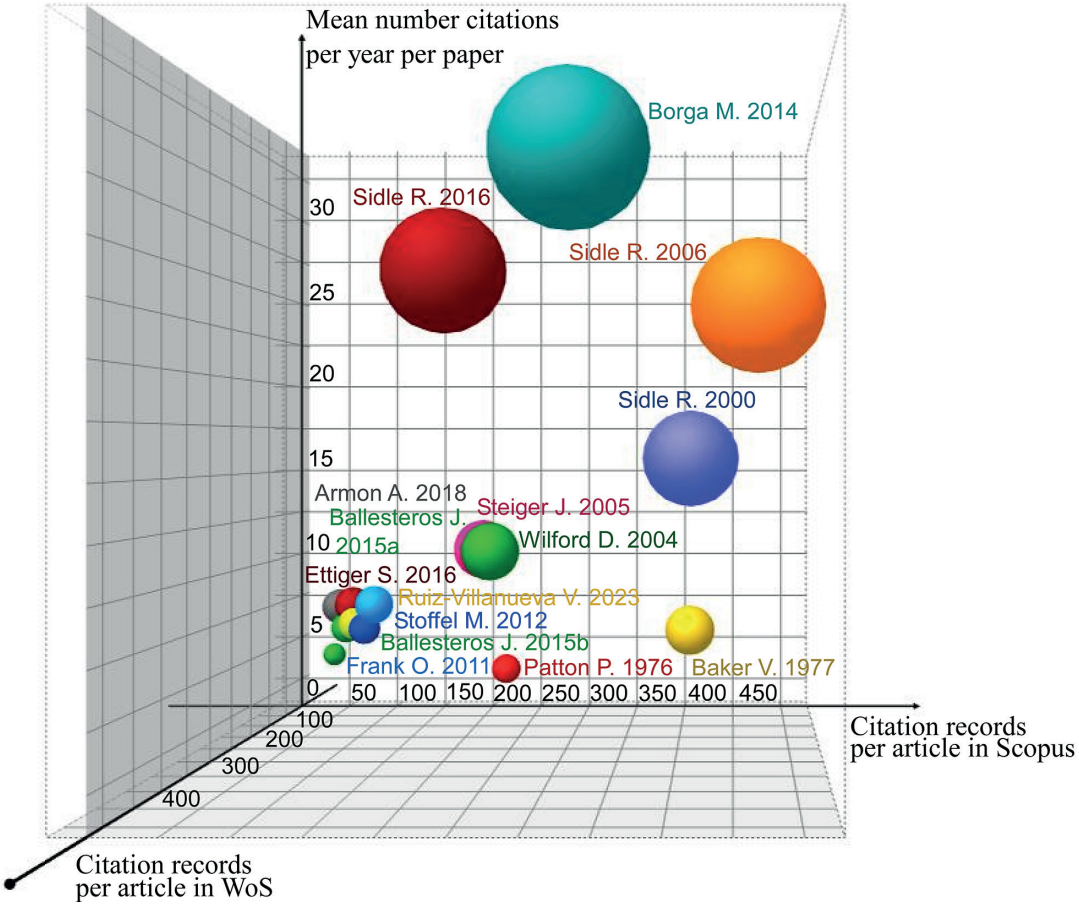

Figure 7. Mean number of citations per year for each paper in Scopus and WoS.

4. Conclusions

The bibliometric analysis conducted from 1973 to 2024 highlights a significant increase in publications over the last eleven years (2013-2024), indicating a trend in flash floods research using a hydrogeomorphic approach. The publications since 2013 represent a significant development in the field of science and an international interest. The analysis revealed that 40 countries in temperate zones have published studies on flash floods using a hydrogeomorphic approach. However, there is a recognized need to conduct research in intertropical environments, which are highly vulnerable to hydrogeomorphic hazards. The classification of publications revealed a continuous increase in nine themes over recent decades. The study themes indicated a development of interdisciplinary research models for analyzing flash floods with a hydrogeomorphic perspective. The limited consideration paid to infiltration and tectonic processes suggests a poor understanding of drainage dynamics, underscoring the need for a more in-depth study of complex geological structures and features from a hydrogeomorphic perspective. The collaborating network map expresses that some countries have created an international network, mainly in temperate climatic countries. We found that limited studies in flash flood research that incorporate multiple processes, such as flooding, debris flows, landslides, and erosion exits. Addressing this gap requires multiple processes approach that considers different spatiotemporal scales, as highlighted by hydrogeomorphology. We advocate for a hydrogeomorphic perspective when studying flash floods in intertropical environments, emphasizing the importance of integrating methodologies that utilize both frequency and magnitude data related to these processes.

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