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Review

Geomorphological Mapping Global Trends and Applications

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Abstract: This study conducts a bibliometric analysis of 735 research papers on geomorphological mapping published in English between 2000 and 2021 using the Web of Science database. The analysis focuses on key metrics such as annual publication rates, journal distribution, common keywords, and frequently cited papers. The results demonstrate sustained investment in geomorphological mapping research over the past two decades, driven by advancements in data analysis, GIS technologies, and cross-institutional and cross-country collaboration. While European universities and research centers lead the field, researchers from Latin America and Asia are also making noteworthy contributions. However, research concentration remains largely in Europe, particularly at low altitudes. The study highlights the vital importance of investment in geomorphological mapping research and the benefits of collaboration to advance understanding and knowledge production. It also emphasizes the need for greater geographic and cultural diversity among researchers to ensure a more comprehensive and inclusive approach to research in this field.

Keywords: geomorphological mapping; bibliometric analysis; data analysis; GIS technologies; cross-institutional collaboration; research concentration

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1. Introduction

Geomorphological mapping is a fundamental component of Earth Science that has gained increasing importance in recent years [1,2]. Geomorphology is the scientific study of landforms and the processes that shape them, including erosion, weathering, and tectonic activity [3,4]. The process of geomorphological mapping involves the identification, classification, and description of processes and landforms using a combination of field observations, remote sensing data, and topographic maps [5,6].

Geomorphological mapping is essential for understanding the Earth's surface and the processes that shape it [7,8]. It provides valuable information for a range of scientific disciplines, including geology, geography, hydrology, ecology, and archaeology [9,10]. Geomorphological maps can be used to identify potential natural hazards, such as landslides, volcanic eruptions, and floods, and to create strategies for management and mitigation of their associated risks [11–15]. Moreover, geomorphological mapping is crucial for the exploration and management of natural resources. It provides valuable information on the distribution, composition, and structure of geological formations, including mineral deposits, oil and gas reservoirs, and groundwater aquifers [16–18]. This information is essential for making informed decisions about natural resources extraction, conservation, and management [19–21].

In recent years, advances in remote sensing technology and digital mapping techniques have revolutionized the field of geomorphological mapping, enabling scientists to generate highly detailed and accurate maps of the Earth's surface [22–25]. These advances have opened new opportunities for interdisciplinary research and collaboration, as well as for the development of innovative solutions to global challenges such as climate change and environmental degradation [26–28]. Given the importance of geomorphological mapping in Earth Science, it is essential that we continue to invest in this field, supporting

research, education, and technological development [29–31]. By doing so, we can deepen our understanding of the Earth's surface, its processes, and its resources, and develop sustainable strategies for managing and conserving our planet [32–34].

Geomorphological mapping research has shown significant growth in the past two decades, with advances in data analysis, GIS technologies, and global collaboration contributing to increased knowledge production. However, research concentration remains largely in Europe, and there is a need for greater geographic and cultural diversity among researchers to ensure a more comprehensive and inclusive approach to research in this field [35–38]. The study aim is to perform a bibliometric analysis of geomorphological mapping studies published in English between 2000 and 2021 to classify its key trends and applications. Specifically, the study aims to assess annual publication rates, journal distribution, common keywords, frequently cited papers, and geographic and cultural diversity among researchers.

The study's findings may have significant implications for the future of geomorphological mapping research. The sustained growth of research in this field demonstrates the importance of continued investment and collaboration to advance understanding and knowledge production. However, the concentration of research in Europe highlights the need for greater geographic and cultural diversity among researchers to ensure a more comprehensive and inclusive approach to research. This study may help to inform future research strategies and funding priorities to promote more equitable and collaborative research in geomorphological mapping.

2. Materials and Methods

We conducted a bibliometric analysis of geomorphological mapping research papers published in English between 2000 and 2021. The analysis used the Web of Science (WoS) database using the Advanced search function [39–41]. We used the search terms "geomorphology" and "geomorphological" in combination with "mapping". We excluded planetary geomorphology papers, as our focus was solely on terrestrial studies. The search included all papers published until the end of 2021 (Figure 1). Using the WoS database to recognize cartographic products tends to underestimate the results of geomorphological mapping worldwide, as an increasing amount of these maps support public administration planning and may not be published in WoS-classified journals.

We looked for papers with explicit indications of a place in the abstract. Papers that did not include any reference to a specific geographic location were excluded from the analysis. In total, our search yielded 735 results that met our inclusion criteria (see Supplementary Information). All papers were in English and were research papers. By exclusively utilizing English papers, we aimed to maximize the quality, accessibility, and efficiency of our analysis, while maintaining consistency and reaching a wider audience in the scientific community. To ensure the accuracy of our analysis, we used the citation and publication data provided by the Web of Science database. Our bibliometric analysis focused on several metrics, including the number of papers published each year, the distribution of papers by journal, the most common keywords used in the papers, and the most frequently cited papers in the dataset. By conducting this analysis, we aim to give lines into the state of the art of research on geomorphological mapping and foresee potential areas for future research.

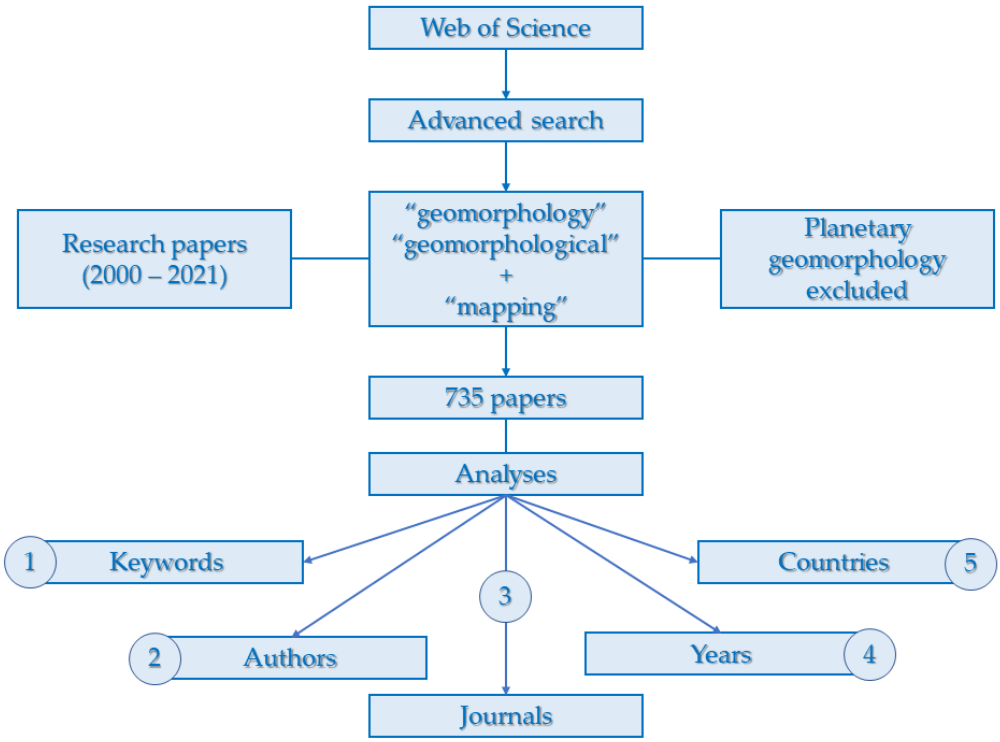

Figure 1. Schematic plot of the employed bibliometric method in geomorphological mapping.

3. Results and Discussion

This study aimed to conduct a bibliometric analysis of global publications about geomorphology, with the goal of mapping their locations and establishing a frequency index to identify hotspots. The study utilized a range of factors to inform its analysis, including the time gap between publications, the source of the publication, the authors of the publication, the country where the study was conducted, the country affiliation of the authors, and the keywords that appeared in the articles. The analysis revealed a serious lack of growth or incipient growth in the number of papers about geomorphological mapping between the years 2000 and 2010. However, during the next decade, from 2011 to 2021, there was a significant increase in the quantity of papers published about geomorphological mapping. This increment was particularly consistent and pronounced in the last few years of the decade.

3.1. Keywords

The study of geomorphological mapping relies heavily on the use of keywords to establish the main subject of investigation and set the direction for inquiry. This approach allows researchers to obtain a deeper understanding of the field by analyzing the trends and insights gleaned from the keywords utilized in publications on geomorphological mapping.

The use of GIS (Geographical Information Systems) technologies in modeling, visualizing, and representing these processes is also emphasized in the study. The analysis of keywords provides valuable insights into the patterns and trends into geomorphological mapping (Table 1). By understanding the most studied topics and technologies, researchers can benefit with fresh knowledge of the current state of geomorphological mapping worldwide. Thus, the use of keywords is essential to furthering our understanding of geomorphological cartography and to identifying new areas for research and exploration. With explicit use of those keywords, the present study compared the number of publications. Table 1 represents the weight of the most used keywords by their frequency.

Table 1. Top nineteen keywords most used in geomophological mapping papers.

Rank	Keyword	NP
1	Geomorphology	141
2	Geomorphological mapping	82
3	Glacial geomorphology	52
4	Remote sensing	48
5	GIS	39
6	DEM	33
7	Lidar	28
8	Landslides	25
9	Fluvial geomorphology	20
10	Mapping	20
11	Holocene	15
12	Karst	15
13	Landslide	15
14	Coastal geomorphology	14
15	Quaternary	13
16	Tectonic Geomorphology	13
17	Palaeohydrology	12
18	Geomorphometry	11
19	Landscape evolution	11

NP: number of publications. This table shows the most frequent keywords in all geomorphological mapping articles.

One of the most frequently cited keywords in this analysis is "Geomorphology" (in 141 times). This indicates the vital role played by the broader field of geomorphology in shaping research in its direct mapping. Other commonly cited keywords include "geomorphological mapping", "glacial geomorphology", "Remote Sensing", "Light Detection and Ranging (LiDAR)", "Geographic Information Systems (GIS)", "DEM", and "Landslides". The prominence of GIS technologies and hydrometeorological events in the study is noteworthy.

The combination of remote sensing, LiDAR, DEM, and GIS allows for a synergistic approach to geomorphological mapping. Remote sensing provides broad-scale data acquisition capabilities, LiDAR offers detailed and accurate elevation information, while DEM and GIS serve as robust platforms for data integration, analysis, and visualization. Moreover, digital representation contributes to increasing the typology, quality, quantity of manageable and representable geomorphological information. Moreover, it excels in seamless integration with diverse themes across processing scales and conforms easily to international standards. This integration enhances our understanding of landscape dynamics, landform evolution, and the underlying processes shaping the Earth's surface. Consequently, these keywords have become common in the study of geomorphological mapping due to their instrumental role in advancing the field's capabilities and insights.

The analysis suggests that a significant focus has been placed on understanding the relationship between geomorphological processes and environmental phenomena such as floods, landslides, and erosion. Landslides, because of excessive water recharge in basins or any other system, can lead to gravitational processes, such as debris flow, rock falls, and other related events that are triggered by the impact of floods.

3.2. Authors

The contributions of authors are a critical factor in understanding the evolution of geomorphological mapping. This study identified the authors who have made significant contributions to the field by analyzing the number of publications focused on geomorphological cartography.

The results reveal that David J.A. Evans, from University of Durham of United Kingdom, is the author with the highest number of investigations, with 16 papers published about geomorphological mapping. Following closely is Francisco Gutiérrez from University of Zaragoza (13), then Professor Enrico Miccadei of the University G. d'Annunzio of Chieti

Pescara with 12 publications. Xu, SY, from China, has 11 studies related to geomorphological mapping. Additionally, Frank Lehmkuhl, from Germany, Tommaso Piacentini from the University of Chieti Pescara, and the professor Mauro Soldati from the University of Modena and Reggio Emilia are also important contributors, as is Arjen P. Stroeven, professor at the University of Stockholm, who also has nine publications. Moreover, there are other key authors that are noted in Table 2. Notably, the study finds a predominance of European authors among the most prolific contributors to the field of geomorphological mapping. However, there is also significant research output from Asia, Oceania, and America (and especially Latin America) on this topic, indicating a growing interest and investment in the field of geomorphological mapping across the globe. The impact of collaborations can be seen into the plurality of people from the country of the investigation and overseas.

Table 2. Top fifteen authors ranked by their number of publications (NP) in geomorphological mapping.

Rank	Authors	AT	AF	CO	HI
1	Evans, D.J.A.	16	Durham University	UK	57
2	Gutierrez, F.	13	Zaragoza University	Spain	52
3	Miccadei, E.	12	Università degli Studi "G. d'Annunzio" di Chieti Pescara	Italy	28
4	Xu, S.Y.	11	Beijing Geosciences University	China	ND
5	Lovell, H.	10	Portsmouth University	UK	18
6	Lehmkuhl, F.	9	RWTH Aachen University	Germany	54
7	Piacentini, T.	9	Università degli Studi "G. d'Annunzio" di Chieti Pescara	Italy	22
8	Soldati, M.	9	Università di Modena e Reggio Emilia	Italy	33
9	Stroeven, A.P.	9	Stockholm University	Sweden	42
10	Glasser, N.F.	8	Aberystwyth University	England	64
11	Jansson, K.N.	8	Stockholm University	Sweden	54
12	Quesada-Román, A.	8	Universidad de Costa Rica	Costa Rica	26
13	Stokes, C.R.	8	Durham University	UK	58
14	Boston, C.M.	7	Portsmouth University	UK	15
15	Cofaigh, C.O.	7	Durham University	UK	59

Abbreviations: AT = Articles; AF = Affiliations; Co = Country; HI = H-Index, ND = No Data.

Therefore, the analysis of the contributions of authors provides valuable insights into the patterns and trends within the field of geomorphology (Table 2). The table presents the impact of the most productive authors, taking into consideration more than six papers related to geomorphological mapping as the initial factor. It is worth noting that while European authors currently dominate the field, research and publications in geomorphological mapping are not exclusive to Europe. Other regions, such as North America, Asia, and Oceania, also contribute significantly to the field and have their own influential authors and institutions. However, the higher concentration of publications from Europe, accounting for three-quarters of the production, contributes to the prominence of European authors in the field of geomorphological mapping.

3.3. Journals

In geomorphological mapping, the choice of the journal for publication is crucial in determining the reach and impact of research findings. This study identified the journals that have published the highest number of papers, revealing some interesting insights. The analysis reveals that *Geomorphology* by Elsevier (Amsterdam, The Netherlands) is the most significant journal about the discipline. It has existed since 1987, and it is a peer review journal about geomorphological topics and investigations with an H-index of 171. The scope of this journal includes geomorphic themes, tectonics, glacial processes and landforms, mass movements, slopes, weathering and soil erosion, quantitative geomorphology, and GIS applications. Moreover, it includes geomorphic hazards, planetary geomorphology, and vulcanology. The number of publications can be above and over 400 per year, showing a great production of knowledge whose intention is to provide the information to

analyze the processes and the changes of landforms to a better understanding of surface Earth dynamics.

Journal of Maps is also an important house of publishing, with an H-index factor of 40, the publisher of which is Taylor and Francis, located in the United Kingdom. It has been publishing since 2005, producing more than a hundred papers annually, concerning social and physical processes that take place on a geographical scale. Furthermore, the study found that several other journals have also made significant contributions to the field of geomorphological mapping, but with less impact. *Quaternary Science Review*, *Earth Surface, Processes and Landforms*, and *Geografia Fisica e Dinamica Quaternaria* have each published several papers on geomorphological mapping topics, demonstrating a diverse range of outlets for researchers to publish their findings.

The study findings highlight the value of journal selection in shaping the reach and impact of research in the field of geomorphology (Table 3). While some journals dominate in terms of the number of papers published, there are also several other journals that have made notable contributions to the field. By identifying the most prolific journals, researchers can gain a better understanding of where to focus their efforts for maximum impact and visibility. As the results show, Geomorphology and the Journal of Maps lead the number of publications about geomorphological research worldwide by a large margin compared to the rest of geomorphological mapping related journals.

Table 3. Top twenty journals ranked by total number of publications (NP) in geomorphological mapping.

Rank	Journal	NP
1	*Geomorphology*	231
2	*Journal of Maps*	126
3	*Quaternary Science Reviews*	17
4	*Earth Surface Processes and Landforms*	15
5	*Geografia Fisica e Dinamica Quaternaria*	13
6	*Journal of Coastal Research*	9
7	*Zeitschrift Fur Geomorphologie*	8
8	*Geosciences*	7
9	*Marine Geology*	7
10	*Catena*	6
11	*Journal of South American Earth Sciences*	6
12	*Natural Hazards*	6
13	*Quaterly Journal of Engineering Geology and Hydrogeology*	6
14	*Remote Sensing*	6
15	*Arabian Journal of Geosciences*	5
16	*Bulletin of the Seismological Society of America*	5
17	*Geografiska Annaler Series A- Physical Geography*	5
18	*Landslides*	5
19	*Natural Harzards and Earth System Sciences*	5
20	*Water*	5

These journals exhibit a specialized focus on geomorphology, making them highly attractive to researchers specializing in the field and seeking to contribute to the advancement of knowledge in geomorphological mapping. Renowned for their strong reputation and wide recognition within the geomorphology community, these journals maintain rigorous peer-review processes and uphold high standards for publishing scientific research. Their consistent demonstration of high impact factors signifies their influence and prominence in the scientific community. Moreover, the selection of these journals may also reflect the geographic breadth of published research in geomorphological mapping, as this field often intersects with other disciplines like geology, geography, environmental sciences, and remote sensing. The interdisciplinary nature of geomorphological mapping research is thus supported by these chosen journals, fostering collaboration, and facilitating the exchange of knowledge across diverse disciplines.

3.4. Country (Publication and Affiliation)

Research on geomorphological mapping is carried out worldwide, but it is highly concentrated in certain areas, with Europe leading the way as the region with the highest number of studies (74.5%), followed by America (12.5%), Asia (9.5%), Oceania (2%), and Africa (1.5%). Italy, Spain, and China are the top three countries with the most extensive research on geomorphological mapping (Figure 2). Interestingly, while Italy tops the list in number of studies, the number of times a paper is cited does not necessarily align with the number of studies produced by a country. For instance, Italy is the most important country in terms of citation, but England, Spain, and Germany follow closely behind. It indicates that the linkage between research production and affiliation is not conclusive, and other factors may come into play, such as funding opportunities or availability of resources.

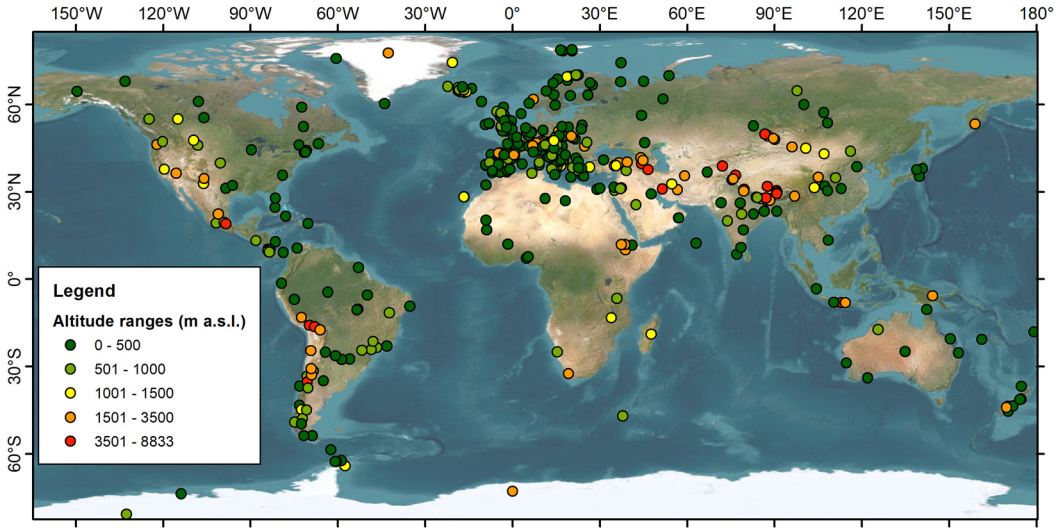

Figure 2. Global geographical distribution of geomorphological mapping studies based on altitude.

Italy, Spain, and China are among the leading countries in the production of geomorphological mapping research papers for several reasons. Firstly, Italy and Spain are countries with a rich geological and geomorphological heritage, with a diverse range of landscapes, geological formations, and landforms. This natural diversity and complexity of the terrain provides researchers with a wide range of subjects for study and investigation. Furthermore, Italy and Spain have a long tradition of research in the field of geology and geomorphology, with well-established research institutions and universities that are active in this field. This has created a favorable environment for the growth of research and scientific collaboration, increasing geomorphological mapping publications. Similarly, China has a vast territory with diverse geographical landscapes, including high mountains, deserts, and plains, providing abundant resources for geomorphological mapping research. The country has invested heavily in research and development, including in the field of geosciences, which is linked with more publications in recent years. Moreover, the advancement of technology with the large application of Geographic Information Systems (GIS) and Remote Sensing, has enhanced the accessibility to remote areas and increased the accuracy and precision of research in the field of geomorphological mapping, which has benefited all countries. The natural diversity of the terrain, the long tradition of research, the investment in research and development, and the advancements in technology have contributed to the leadership of Italy, Spain, and China in the production of geomorphological cartography investigations.

To better understand the distribution of geomorphology studies, we mapped these sites worldwide, classified by altitude (Table 4). The map reveals that most of the studies have been conducted principally in Europe, below 2000 m above sea level (Figure 2). They were carried out on diverse topics such as glacial or paleoglacial geomorphology,

fluvial geomorphology, coastal geomorphology, and environmental sciences. Europe offers a diverse range of landforms and geomorphological features within this elevation range, making it an ideal location for studying various aspects of geomorphology and environmental sciences. Additionally, Europe has a long history of scientific research and well-established academic institutions, which may have contributed to the concentration of studies in this region [3]. Then, in Southern Asia, those works have been conducted at different altitude ranges, in eolian and fluvial geomorphology, but in the United States roughly all the studies were conducted at low altitude with regard to fluvial, glacial, and coastal geomorphology. In South America, most of the studies are in Brazil, primarily at low altitudes and centered on environmental sciences, dendrogeomorphology, and sedimentary formations, while in the Andes chain of mountains, there are more studies across all altitude ranges. In Central and North America, the variety of studies diminishes, but the number of investigations is still significant. Surprisingly, even in the polar regions, where environmental conditions can be extreme and challenging to conduct research, there are a few studies. As a result, this information provides valuable insights into the distribution of geomorphology studies worldwide, highlighting areas where research is concentrated and underscoring the need for further investigation in other regions. Moreover, it is important to acknowledge the need for further research in other regions and at higher elevations to obtain a more comprehensive understanding of global geomorphological processes and their implications.

Table 4. Number of geomorphological mapping studies based on its altitude.

Altitude Range (m a.s.l.)	NP	Percentage (%)
0 to 1000	431	69.4
1000 to 2000	102	16.4
2000 to 3000	54	8.7
3000 to 4000	15	2.4
4000 to 8833	19	3
Total = 621		100

The difference between the country of the study and the country affiliation is the source of the funding for the investigation, the institution that leads the study. As Figure 3 demonstrates, the importance of country of affiliation is not always related to the countries where investigation takes place. For example, China is in the top 3 countries by number of studies. However, by country of affiliation, it is located in 10th place. Brazil and Argentina, recognized as developing countries, figure as 6th and 9th, respectively, in number of studies; thus, in country of affiliation they are 7th and 20th. Norway is another great example; the country ranks 4th in terms of studies due to its abundance of glacial knowledge and other geomorphological formations found in its landforms, but its affiliation is far from being significant, in 18th place. Germany also invests significant amounts in geomorphological mapping studies, being the 4th country in terms of affiliation, but it does not have many studies on its territory.

3.5. Years

The analysis of the data reveals a marked growth in geomorphological mapping publications over the considered years. The data from 2001 to 2021 show that there is a clear trend of increase in the total number of publications. In the first decade, from 2001 to 2010, there was a relatively low production, with no more than 155 papers published during this period. However, in the following decade, from 2011 to 2021, there was a substantial proliferation in the research products, with a total of 580 papers published during this period.

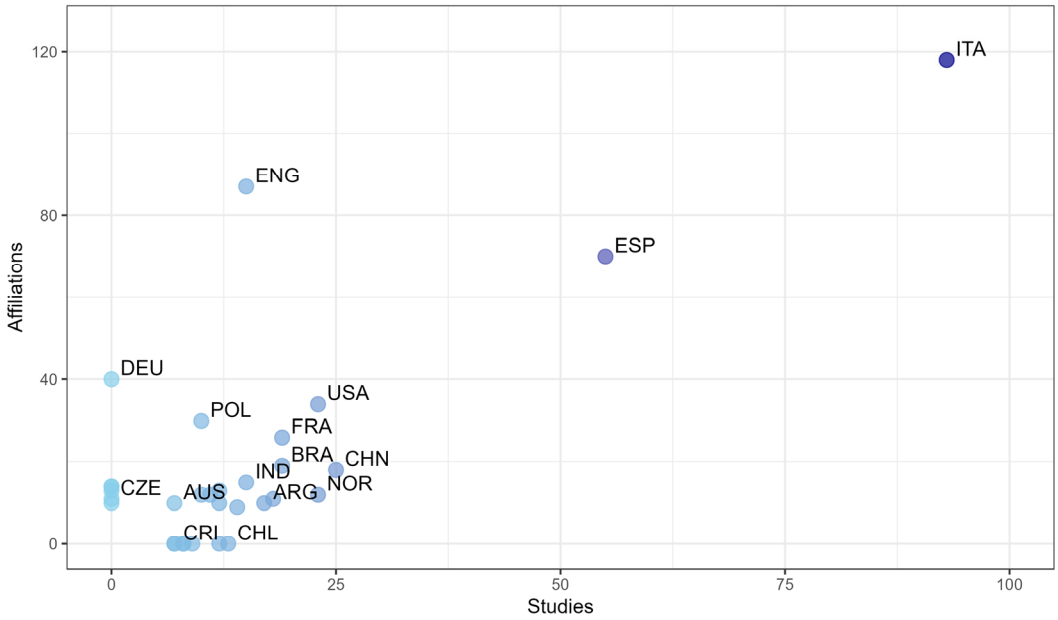

Figure 3. Number of published papers by country of affiliations and studies in geomorphological mapping.

This increase in the number of publications can be linked to several factors, comprising the impact of the technological revolution on GIS, cartography, and transportation, which has made it easier to access and explore remote sites. It is also likely that the increase in funding for research in this field has contributed to the growth in the number of publications. Despite the overall trend of growth, there have also been some periods of steadiness during the 2010 decade. For example, there was a brief period of growth between 2000 and 2004, followed by a period of stability until 2007, after which there was a marked growth in the number of articles published. However, in the following years, the number of publications remained stable at around 35 papers per year, perhaps associated with the 2008 crisis.

Towards the end of the decade, the number of publications on geomorphological mapping increased again, reaching a peak of 78 papers. Although there have been some periods of steadiness in the past, the data show that there has been a clear trend of growth in the number of publications on geomorphological mapping over the years. More specifically, between 2005 and 2007, 2008 and 2011, and 2013 and 2014 there were steadiness periods. However, between 2004 and 2005, there was a huge growth in the total published papers, as well as in the 2007 and 2008 period and the 2011 and 2012 period. Since 2015, the number of publications annually has been historically important, reaching 45 papers, and, excepting 2018, the number continuously increased until the last year of the study, reaching the peak level of 84 papers.

The data analysis shows a clear trend of growth in the number of publications on geomorphological mapping over the years (R^2 = 0.91), with some periods of steadiness (Figure 4). The increase in publications can be assigned to various aspects, which include technological advancements and increased funding for research. By unraveling these intricate patterns, researchers gain invaluable insights into the ever-evolving landscape of geomorphological mapping worldwide. This not only enriches our understanding of the subject but also uncovers potential research opportunities that lay the foundation for exciting scientific adventures yet to come.

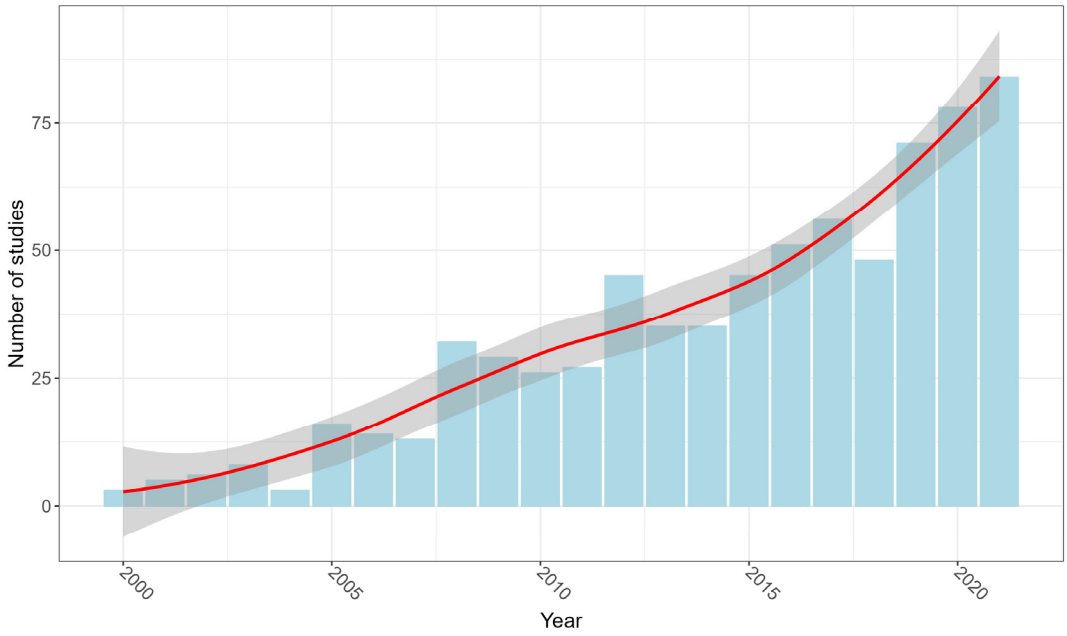

Figure 4. Number of publications per year on geomorphological mapping.

It is important to note that while Europe has a higher proportion of geomorphological mapping studies, valuable research is being conducted in other continents as well. The varying distribution is influenced by a combination of historical, geographic, infrastructural, and socio-economic factors. Promoting collaboration, knowledge sharing, and enhancing research infrastructure in regions with lower representation can help bridge the gap and foster a more equitable distribution of geomorphological mapping studies worldwide.

4. Conclusions

This study highlights the significant influence of investment in geomorphological mapping as a crucial factor in promoting research and knowledge production in Earth Sciences. Over the last two decades, there has been a continuous increase in geomorphological mapping research due to the impact of data analysis, collaboration between institutions and countries, and the rapid development of GIS technologies. These factors have justified the sustained investment in geomorphology cartography research by some countries. While most of the principal authors in this field are from European universities or research centers, there are also some notable researchers from Latin America and Asia who are contributing to geomorphological mapping. Furthermore, when examining the spatial and geographical distribution of research, it becomes clear that there is a concentration of research in Europe, particularly at low altitudes worldwide. Overall, this study demonstrates the vital importance of investment in geomorphological cartography research and the benefits of collaboration between institutions and countries to advance knowledge and understanding of this field. Additionally, it highlights the need for greater diversity in the geographic and cultural backgrounds of researchers in this field to ensure a more comprehensive and inclusive approach to research.

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