Rockfall Research: A Bibliometric Analysis and Future Trends

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Abstract: Rockfall is one of the main phenomena in mountainous environments due to its fast and high speed of movement, its unpredictability, and, therefore, the difficulty of identifying signs of instability and detachment of the blocks. Compared to other types of sliding, the proportion of rockfall research is smaller and sometimes little known, but, in the last five years, rapid growth in this area has been shown. Therefore, this research aimed to review the intellectual structure of rockfall, through analysis of scientific production using bibliometric techniques that allow its analysis, knowledge, global evolution, and future trends in rockfall. The research methodology consists of three steps: (1) data compilation, (2) software and data cleaning, and (3) analysis, interpretation, and visualization. This analysis focuses on the period from 1975 to 2019. For the data, a total of 811 academic publications were retrieved from the Scopus database. The results indicate an increasing trend of annual publications on rockfall. This analysis reveals the main topics, countries, and most influential institutions in the world that have carried out relevant research in scientific publications; it also shows the journals that have the most publications. VOSviewer software was adopted to evaluate the co-occurrence of author keywords. Currently, the hotspots rockfall issues mainly include: hazard-risk assessment, remote sensing, and rockfall monitoring. Finally, this article analyzes the limitations of current research and proposes a future direction for the development of new research.

Keywords: bibliometric analysis; co-occurrence; future trend; rockfall; VOSviewer

1. Introduction

Rockfall is the most frequent natural event in mountainous areas. Rockfalls are classified as a type of landslide that consists of the detachment of a rock block (or several individual rocks) from a vertical or sub-vertical cliff followed by rapid down-slope motion characterized by free-falling, bouncing, rolling, and sliding phases [1,2]. Cruden [3] and Zabota [4] complement this definition by stating that a rockfall is a fragmented rock or block that has detached from a surface slope or cliff by falling, sliding, toppling, bouncing, or rolling. Rockfall, commonly, is a relatively small limited sliding to the

removal of individual and surface rocks from a cliff [5,6]. Rockfall can generate massive large-scale movements of solid material, but these processes are defined as rockfall or rock avalanches [3,7,8]. A common approach to explaining rockfall is to analyze the environmental conditions that promote the occurrence of rocks and those factors that initiate movement [9,10]. Detachment mechanisms include natural climatic conditions, such as freeze-thaw [11], lithology, morphology [12], slope gradient [13], faults, and seismic activities [14,15].

Compared to other types of landslides, the proportion of rockfall research is small [2,16]. However, driven by the demand for civil works construction in mountainous areas, rockfall research is increasingly attracting the attention of academics and researchers [17,18]. Rockfall not only threatens the environment but also generates a severe loss of life within its area of influence because it behaves suddenly, frequently, and randomly [19–21]. Every year, blocks ranging from a few kilograms to tens of tons cause traffic interruptions, damage to structures and vehicles, and sometimes fatalities [22]. These natural disasters have been a subject of intensive research due to their significant destructive power: (i) Gotthard Tunnel in Switzerland: on 31 May 2006, a major rockfall (5000 m^3) killed two tourists on the main highway crossing the Alps through the Gotthard Tunnel [23], and (ii) ski resort Whistler, Vancouver, Canada: during the night of 29 July 2008, a rockfall blocked the highway Sea to Sky joining Vancouver to the ski resort Whistler [24].

Protecting people and infrastructure against rockfall phenomena is one of the most challenging tasks [25–27]. For this purpose, risk assessment procedures play a crucial role [20,28–31]. Therefore, rockfall-related studies are of great importance to prevent and reduce risk and to improve disaster mitigation and preparedness capabilities. During the past four decades, numerous studies have elucidated the various perspectives of rockfall hazards. In the scientific literature for evaluating hazard and risk from falling rocks, various qualitative and quantitative approaches have been proposed (e.g., References [32–37]). The choice between qualitative and quantitative hazard methodology is strictly related to the available dataset and does not depend on the complexity of the methods that are used to define the hazard [38]. Due to qualitative methods are based on the qualitative classification of the attributes of the rock surface, quantitative approaches require a significant amount of site-specific data [39,40].

For the protection and prevention of risks that a rockfall can cause are the construction of specialized structures or the maintenance and creation of green areas, for example, by building capture or barrier fences and containment networks [41], but these measures are expensive and deteriorate over time [42]. In some cases, maintaining forest stands with an explicit protection function, or a protection forest is profitable and more sustainable [43,44]. Therefore, studies related to rockfalls are of great importance to prevent and reduce risk and to improve disaster mitigation and preparedness capabilities.

The monitoring and early warning of rockfall hazards in mountainous areas are also necessary. Commonly used technologies of rockfall monitoring include light detection and ranging (LiDAR), laser scanning, geographical information systems (GISs), and video image recognition [45,46]. In addition, researchers usually combine LiDAR, laser scanning, and GIS technology to establish a three-dimensional numerical model of a rockfall and to analyze the spatiotemporal characteristics of rockfall hazards [47–49].

Over the past four decades, some researchers have submitted revisions and diverse perspectives of the risks of rockfalls in geo-environmental and geosciences science. Dorren [9] summarized existing rockfall models and proposed modifications to make them suitable for predicting rockfall on a regional scale; Volkwein et al. [50] and Ferrari et al. [39] provided an overview of both rockfall modeling, as well as hazard zoning and protective measures. These investigations have provided valuable information within the topic; therefore, it is necessary to carry out a systematic review, as well as bibliometric analysis for the integration of all the studies carried out.

The corresponding research results have been published by authors from all over the world in a large number of journals. To summarize global rockfall research trends and provide a potential guide for future research, a bibliometric analysis was applied to rockfall-related articles from Scopus

databases during the period 1975–2019. This will allow us to integrate knowledge, understanding the evolution and trends in a field of research. On this, we pose the following question: Is it possible to evaluate the evolution and trends related to research on the Rockfall theme through bibliometric analysis that allows a better understanding of the topic and that serves as a guide for future research?

Given these antecedents and what is stated in the research question, the scientific work aimed to review the intellectual structure of Rockfall, through analysis of scientific production using bibliometric techniques that allow its analysis, knowledge, its global evolution, and future trend lines about Rockfall. In this research work, three sections are presented: (i) Literary review on the subject and explanation of the methodology used, (ii) presentation of quantitative and qualitative results on the scientific production on Rockfall, and (iii) bibliometric analysis of the results, their discussion, conclusion and presentation of future research trends.

2. Materials and Methods

The literature review is an essential contribution to research progress by providing a systematic procedure that seeks to minimize potential biases and errors when selecting studies in a given area of knowledge, as well as an in-depth description of independent research efforts to identify potential gaps and highlight the limits of knowledge [51–53]. In this regard, Rowley and Slack [54] recommend a comprehensive methodology to structure a literature review, where bibliometric analyzes contemplate a similar systematic process [55].

Bibliometric studies consider a scientific field that uses quantitative analysis to describe, evaluate, and monitor scientific publications in a field of science and identify its main trends [56–58], allowing the analysis of the structure of a scientific research field [59,60]. This type of analysis was introduced in the academy by Eugene Garfield in the mid-20th century [61], and today it has spread in various academic fields, such as management [62], environment [63], and Earth Sciences. This last field has allowed the study of some disciplines, such as seismology [64], marine hazards [65], hydrogeology [66], landslides [67,68], remote sensing [69], oil industry [70], and geotourism [71], among others. In bibliometric analysis, a topic called bibliometric mapping is presented, which allows a visual understanding of the structure and behavior of the scientific field by observing the connections in its structure represented by units of analysis, such as documents, countries, or authors [72].

The proposed methodology for this bibliometric study is structured and comprises three phases: (1) Data compilation, (2) software and data cleaning, and (3) analysis, interpretation and visualization; to identify the most influential studies, in order to determine the thematic areas of research and provide information on current research interests. A summary of the application of the methodology shown in Figure 1.

2.1. Data Compilation

In bibliometric studies, the first step is the selection of an adequate and reliable database that allows the analysis to be carried out [73]. Currently, there is a debate on the comparability and stability of the statistical data obtained according to the two primary databases: Web of Science (WoS) and Scopus [74]. For this analysis, we chose the Scopus scientific database, which belongs to Elsevier, for our bibliometric analysis [75]. According to Elsevier, Scopus is the largest database of citations and summaries of peer-reviewed literature that has been used by various researchers for bibliometric analysis in various areas of research [76,77]. Scopus is a multidisciplinary database that has more than 69 million records; also, it has more indexed journals than the WoS [78,79].

The next step is the choice of the search parameter, which consists of a guide that avoids extensive results, which opens the door to literature that is not related to the area of knowledge and too limited results that leave out the scientific literature. important in the field [56,80,81]. In this investigation, the documents were considered relevant, in which our search argument appears only in the title [82–84]. The search argument is: (TITLE ("Rock-fall*") OR TITLE ("Rockfall*")), search carried out in April 2020, obtaining 1590 documents.
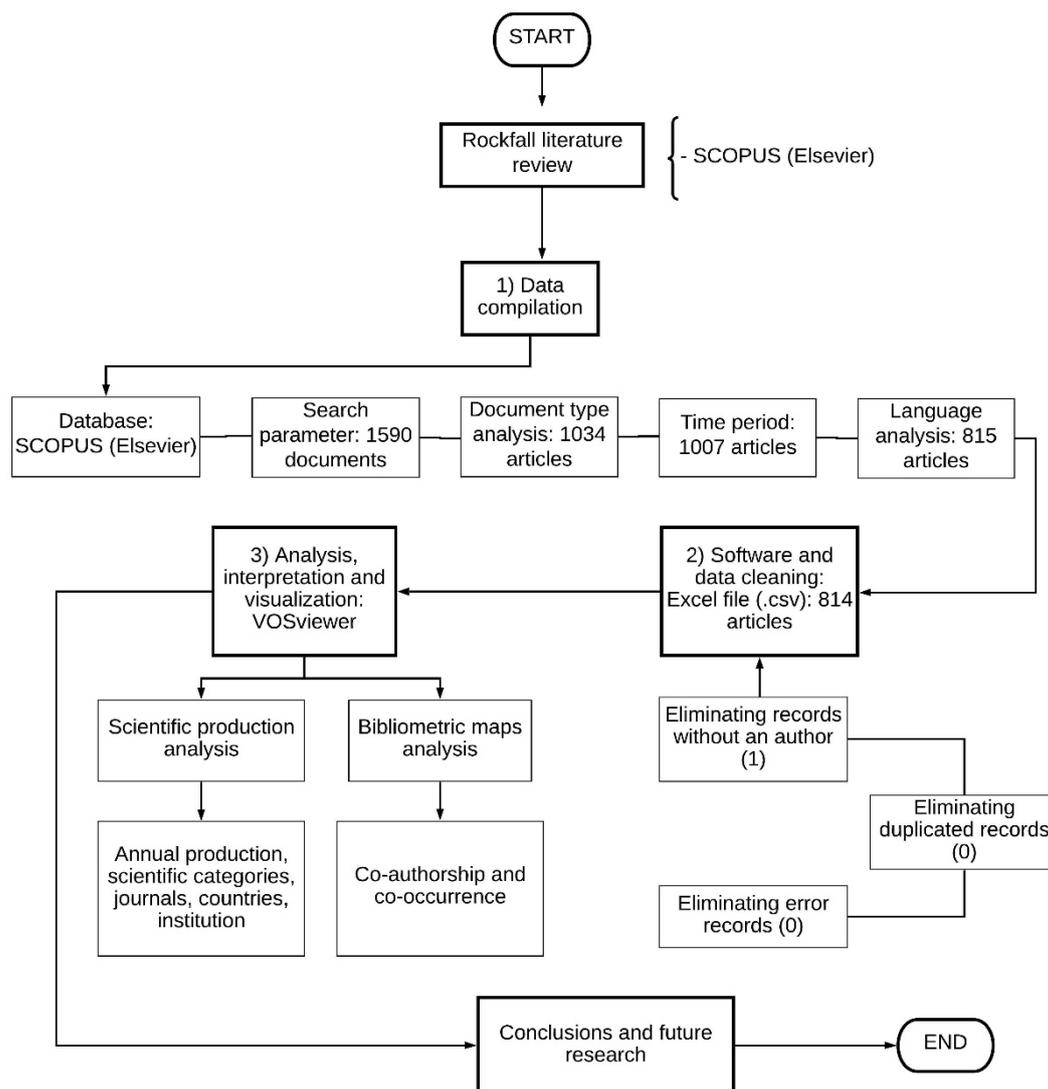
Figure 1. Summary of the application of the methodology in this research.

The study source was limited to the analysis of only published articles, which guarantees the academic quality of the publications and the homogenization of the results [85]. Indexed journals ensure academic quality, which is backed by a blind peer review [86]. With this search parameter, publications are obtained between 1942 and 2020; with the latter being this year, we exclude it because the totality of documents would not be available.

Finally, we considered an additional parameter related to language, in that only those written in English were analyzed because this language dominates scientific production in most scientific areas and is one of the most used restrictions in articles that use the bibliometric analysis [87,88]. With this last limitation, the final search argument was as follows: (TITLE ("Rock-fall*") OR TITLE ("Rockfall*")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (EXCLUDE (PUBYEAR, 2020)) AND (LIMIT-TO (LANGUAGE, "English")).

2.2. Software and Data Cleaning

The obtained information was exported to an Excel spreadsheet for analysis and organization [68,89]. Our database had a variety of parameters, in which the following are highlighted: the author's details (name/s and affiliation/s), the title of the article, the title of the journal, keywords used, the abstract, and the dating count. The reference collection needed to be reviewed and debugged by making the following adjustments: (i) delete records without an author, (ii) delete duplicate files,

and (iii) delete error records. We reviewed the database, and only the first adjustment reported inconsistency in an article; therefore, our database was reduced to 814 scientific articles.

2.3. Analysis, Interpretation and Visualization

Among the most widely used, leading and educational free access software based on its excellent results and data processing, we have the VOSviewer [90]. VOSviewer software is a tool popularly used in bibliometric literature and its analysis in different areas of knowledge [62,91–93]. This software was developed for the construction and visualization of bibliometric maps, which show the structure and networks of authors, magazines, universities, and countries [94]. VOSviewer is used to build author or journal maps based on co-citation data or to make keyword maps based on co-occurrence data [95,96].

3. Results

This section has been divided into two parts. In the first, scientific production based on its performance is evaluated. This allows us to examine the journals and subject areas that have been presented, as well as the contribution of the countries and institutions that have promoted the research and their authors. In the second part, the intellectual structure of Rockfall is analyzed by considering its evolution using bibliometric network maps based on author keywords.

3.1. Scientific Production Analysis

3.1.1. Scientific Production Period

Examining the chosen period (1942–2019), significant gaps were observed between years; for example, between 1943–1964, there are no documents on this subject, as well as the periods 1966–1968 and 1970–1974. Between the period 1942–1974, there are only three documents: (i) in 1942 titled Coal mine rock falls [97], (ii) in 1965 titled Rockfall-avalanche and rockslide-avalanche deposits at Sawtooth Ridge, Montana [98], and (iii) in 1969 titled Determination of the statistical characteristics of rock falls on the periphery of an unsupported underground working [99]. Therefore, our research period was between 1975–2019.

Therefore, a total of 811 publications meet all the criteria and are analyzed. The first publication in this period was recorded in 1975 and titled Surge effects in a lake as a consequence of rockfalls. Model tests to predict the effects of avalanches of rock on the Walensee [100]; and the latest publication was titled Economic valuation of ecosystem-based rockfall risk reduction considering disturbances and comparison to structural measures [101].

Figure 2 shows the number of scientific publications per year, from 1975 to 2019. We have divided them into three time periods, such as introduction (1975–2001), growth (2002–2016), and maturity (2017–2019).

Phase I: Introduction (1975–2001).—This period has 108 published articles, representing 13.32% of the total and an average of 4.00 documents/year. The study on the subject was starting, with few publications per year, but growing. The year with most papers is 1999 with 11 documents. This phase stands out because its publications were the foundations that refer to the valuation of rockfall danger [102,103], consideration of external factors that induce rockfall [104,105], and studies on structural damage and its geomorphology [106,107]. The amount of citations is 4398, equivalent to 25.35% of the total. In this group, there are 16 documents (14.81% of the 108 documents) without any citation. The article entitled Design of rockfall restraining nets from a discrete element modeling [108] closes this phase.

Phase II: Growth (2002–2016).—This period has 497 published articles, representing 61.28% of the total and an average of 33.13 documents/year. The number of documents began to fluctuate in growth. Rockfall global study began about during this period. Possibly the reason for the presence of this increase due to advances in new research methodologies. The year with most papers is 2012, with 60 documents. In this phase, the papers of analysis of numerical models [109,110], susceptibility

analysis to risk [111,112], and interaction between rockfall-forest protection [113,114] stand out. The amount of citations is 12,064, equivalent to 69.55% of the total. In this group, there are 40 documents (8.05% of the 497 documents) without any registered citation. The last one published in this phase was Earthquake-induced rockfall hazard zoning [115]. The main funding sponsors in this period are National Natural Science Foundation of China (14 documents), Seventh Framework Program (European Union, 7 documents), and European Commission (European Union, 6 documents).
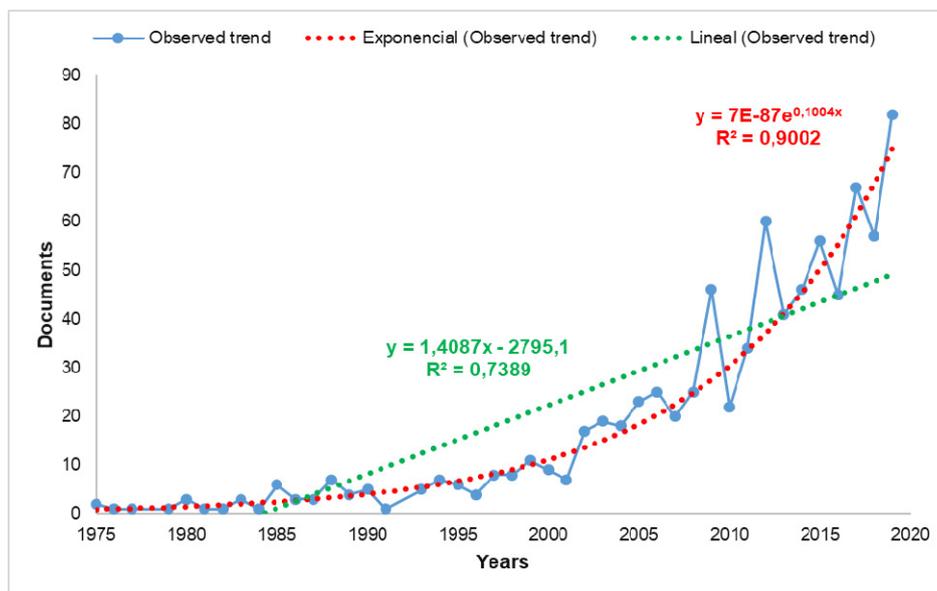

Figure 2. Scientific production of rockfall articles. Linear and exponential trend adjustments for the number of publications.

Phase III: Maturation (2017–2019).—This trend is marked from 2017; it can be considered that this topic is calling the attention of scientists since, in this short period of 3 years (until 2019), it has 206 publications, representing 25.40% of the total and with an average of 68.67 documents/years. The number of documents is increasing rapidly. The year of greatest publication is 2019 with 82 documents. This phase stands out because its publications have incorporated new technological trends for remote monitoring. The most outstanding are: (i) UAV-based mapping, back analysis, and trajectory modeling of a co-seismic rockfall in Lefkada island, Greece [116], (ii) A Spatial Ensemble Model for Rockfall Source Identification from High-Resolution LiDAR Data and GIS [117], and (iii) Managing rockfall risk through baseline monitoring of precursors using a terrestrial laser scanner [118]. The number of citations is 884, equivalent to 5.10% of the total. In this group, there are 57 documents (27.67% of the 206 documents) without any citation. The main funding sponsors in this period are National Natural Science Foundation of China (28 documents), Natural Sciences and Engineering Research Council of Canada (9 documents), and Agence Nationale de la Recherche (France, 7 documents), and State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (China, 7 documents).

Table 1 is a summary of the detail of the phases analyzed.

Table 1. Main characteristics of the phases.

Phase	Period	TP	%TP	TP/Year	TC	%TC	TC/Year	TC/TP	DC	%DC
I	1975–2001	108	13.32%	4.00	4398	25.35%	162.89	40.72	16	14.81%
II	2002–2016	497	61.28%	33.13	12,064	69.55%	804.27	24.27	40	8.05%
III	2017–2019	206	25.40%	68.67	884	5.10%	294.67	4.29	57	27.67%

TP: Number of publications; TC: Number of citations; DC: Number of documents without citations.

Additionally, we consider using a bibliometric indicator to evaluate scientific production using Price's Law [71,119]. This indicator allows analyzing the productivity of a certain field of knowledge, by using an essential element of scientific production, which is its exponential growth. We built two trend models (Figure 2). The first of linear trend ($y = 1.4087x - 2795.1$; $R^2 = 0.7389$; green color) and, second, an exponential model ($y = 7 E - 87 e^{0.1004x}$; $R^2 = 0.9002$; red color) based on data on the number of publications. The exponential trend line provided a better fit (measured by R^2), obtaining better evidence of exponential growth in the number of articles during the study period.

3.1.2. Journals and Subject Areas

The analysis of the journals allows to obtain an overview of the topic under study in the various academic fields [62]. In Table 2, we present the top 15 of the journals that record the most significant number of publications on the subject; additionally, the number of citations received, the impact factor (CiteScore 2018), and the Scimago Journal Ranking (SJR) are exposed. This group of journals represents 5.60% of the total with 368 articles (45.21%), receiving 9616 (55.30%) of the total citations (17,388). The first journal is Natural Hazards and Earth System Sciences (76 articles; Citescore: 3.07; SJR: 1.024), followed by Landslides (54 articles; Citescore: 4.53; SJR: 1.638), Geomorphology (41 articles: Citescore: 3.88; SJR: 1.454), Engineering Geology (29 articles; Citescore: 4.70; SJR: 2.209), and Rock Mechanics and Rock Engineering (27 articles; Citescore: 5.06; SJR: 2.334).

Table 2. Scientific production for the top 15 journals.

Journal	TP	TP%	TC	TC%	TC/TP	Citescore 2018	SJR
Natural Hazards and Earth System Sciences	76	9.34%	2687	15.45%	35.36	3.07	1.024
Landslides	54	6.63%	909	5.23%	16.83	4.53	1.638
Geomorphology	41	5.04%	1567	9.01%	38.22	3.88	1.454
Engineering Geology	29	3.56%	780	4.49%	26.90	4.70	2.209
Rock Mechanics and Rock Engineering	27	3.32%	874	5.03%	32.37	5.06	2.334
Natural Hazards	26	3.19%	401	2.31%	15.42	2.64	0.88
International Journal of Rock Mechanics and Mining Sciences	21	2.58%	896	5.15%	42.67	5.27	2.185
Bulletin of Engineering Geology and the Environment	17	2.09%	117	0.67%	6.88	2.37	0.839
Environmental Earth Sciences	17	2.09%	152	0.87%	8.94	2.12	0.625
Australian Geomechanics Journal	11	1.35%	16	0.09%	1.45	0.49	0.348
Canadian Geotechnical Journal	10	1.23%	747	4.30%	74.70	3.00	1.753
Engineering Structures	10	1.23%	103	0.59%	10.30	3.77	1.628
Environmental and Engineering Geoscience	10	1.23%	91	0.52%	9.10	0.80	0.289
Rendiconti Online Societa Geologica Italiana	10	1.23%	34	0.20%	3.40	0.55	0.395
Earth Surface Processes and Landforms	9	1.11%	242	1.39%	26.89	3.97	1.358

TP: Number of publications; TC: Number of citations; TC/TP: average citations per publication.

This information, related to the journals, leads us to some reflections. The journal Natural Hazards and Earth System Sciences has the highest production on the subject (76), as well as the number of citations (2687), but its Citescore indicator places it in the 8th position. The International Journal of Rock Mechanics and Mining Sciences presents the highest Citescore and Natural Hazards the highest SJR.

The research, in Rockfall, covered 19 subject areas identified by our database. The five most common categories were Earth and Planetary Sciences (52.13%), Environmental Science (13.86%), Engineering (13.23%), Agricultural and Biological Sciences (6.14%), and Social Sciences (5.98%). Figure 3 presents the scientific production, in percentage, by subject area. It can be seen that this topic (rockfall) is investigated in different research fields. Indeed, depending on the field of research, the habits of researchers are different, therefore, depending on the field of research, or researcher publishing more or less.

3.1.3. Countries and Institutions Contributions

The research collaboration allows to link knowledge and skills in search of a common goal, becoming essential for the progress of scientific research [120,121]. The contribution to the study area has been developed by 54 countries. Table 3 represents the scientific production of the 15

leading countries that represent 83.95%. As can be seen, Italy leads the group with 135 publications (13.21%) within the study period, followed by Switzerland, China, the United States, and France, with 110 (10.76%), 101 (9.88%), 93 (9.10%), and 86 (8.41%), respectively.
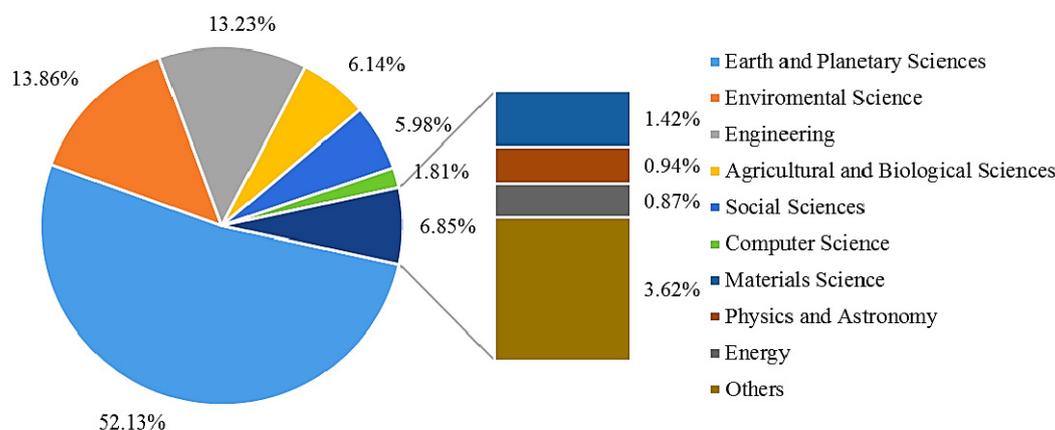

Figure 3. Scientific production by subject area.

Table 3. Scientific production for the top 15 contributing countries.

Country	TP	TC	TC/TP
Italy	135	3239	23.99
Switzerland	110	3355	30.50
China	101	1311	12.98
United States	93	1980	21.29
France	86	2335	27.15
Canada	50	1567	31.34
Australia	46	473	10.28
Spain	45	1347	29.93
Germany	39	638	16.36
United Kingdom	38	1114	29.32
Austria	33	401	12.15
Japan	30	625	20.83
New Zealand	19	342	18.00
Turkey	17	222	13.06
Greece	16	260	16.25

TP: Number of publications; TC: Number of citations; TC/TP: average citations per publication.

We note that the number of citations is consistent with the number of articles published, except for China; that is, its citations numbers are low compared to the countries below it, such as Canada and Spain. According to our TP/TC (Number of publications/Number of citations) relationship in Table 3, Switzerland with 30.50 citations/document is the most cited country, while Australia presents the lowest record with 10.28 citations/document.

These country-level contributions can be visualized using a co-authored network map (Figure 4). The nodes represent the countries that collaborate on Rockfall, and their size is proportional to the number of articles they collaborate on. The lines that interconnect these nodes show the strength of the collaboration. The map was achieved using the VOSviewer software (University of Leiden, Leiden, The Netherlands). A remarkable scientific link can be seen in this field between Switzerland with France and Italy, similarly between the United States with Australia and New Zealand. A greater closeness between the countries is an indicator of how close the collaboration is between them; this is the case of the European countries, where a high affinity of collaboration is observed between them (Switzerland-Italy-France-Spain-Germany-United Kingdom), while other countries, like China and

Japan, present very few works with the cooperation of researchers from other countries; therefore, its remoteness, as shown in Figure 4.
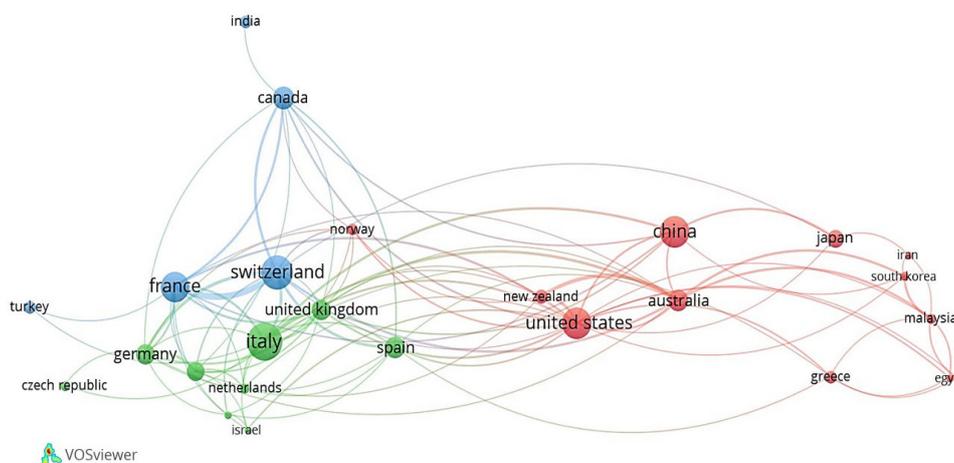

Figure 4. Collaborative network between countries in Rockfall research.

Table 4 shows the top ten institutions with the highest scientific production. First is the Universite Grenoble Alpes (35), followed by INRAE (National Research Institute for Agriculture, Food and Environment of France) (34), Chinese Academy of Sciences (32), CNRS Center National de la Recherche Scientifique (26), and the United States Geological Survey (26). These institutions (top ten) accumulate 270 articles, equivalent to 33.29% of total publications. Institutions, in Table 4, are from Europe, Asia, and America, having a total of eight, one, and one, respectively.

Table 4. The 10 most productive institutions internationally.

Institution	Country	TP
Universite Grenoble Alpes	France	35
INRAE	France	34
Chinese Academy of Sciences	China	32
CNRS Centre National de la Recherche Scientifique	France	26
United States Geological Survey	United States	26
Université de Genève	Switzerland	25
Consiglio Nazionale delle Ricerche	Italy	25
University of Bern	Switzerland	23
Politecnico di Torino	Italy	22
Laboratoire des Écosystèmes et des Sociétés en Montagne	France	22

TP: Number of publications.

3.1.4. Analysis of Papers and Authors

Citation is the most common method used as a measure of the influence of an author, journal or article because it allows the rapid identification of essential works in the field [122,123]. This measure is necessary because not all scientific documents have the same relevance in an academic area. Table 5 analyzes the structure of citations in the proposed field of study. Within this, three articles stand out for being cited more than 250 times, and these are: Catastrophic debris streams (sturzstroms) generated by rockfalls [124], The assessment of rockfall hazard at the base of talus slopes [32], and Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia [125]; with 589, 270, and 259 citations, respectively.

Table 6 shows the main ten cited publications on the subject and other characteristics considered by the authors of this research. The period of the most cited articles is between 1975–2009, but it also marks the trend of the articles with lower and higher citations per year with 8.00 and 17.91, respectively.

Table 5. General citation structure in Rockfall.

Number of Citations	TP	%TP
≥250 citations	3	0.37%
≥100 citations	29	3.56%
≥50 citations	64	7.86%
≥20 citations	146	17.94%
≥5 citations	274	33.66%
<5 citations	298	36.61%

TP: Number of publications; % TP: Percentage of TP.

Table 6. Most cited papers [9,11,32,109,110,124–128].

Year	Authors	Title	Journal	TC	TC/Year
1975	Hsü K.J. [124]	Catastrophic debris streams (sturzstroms) generated by rockfalls	Bulletin of the Geological Society of America	589	13.09
1993	Evans S.G., Hungr O. [32]	The assessment of rockfall hazard at the base of talus slopes	Canadian Geotechnical Journal	270	10.00
1999	Hungr O., Evans S.G., Hazzard J. [125]	Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia	Canadian Geotechnical Journal	259	12.33
2003	Dorren L.K.A. [9]	A review of rockfall mechanics and modeling approaches	Progress in Physical Geography	219	12.88
2002	Chau K.T., Wong R.H.C., Wu J.J. [126]	Coefficient of restitution and rotational motions of rockfall impacts	International Journal of Rock Mechanics and Mining Sciences	208	11.55
2002	Guzzetti F., Crosta G., Detti R., Agliardi F. [109]	STONE: A computer program for the three-dimensional simulation of rock-falls	Computers and Geosciences	199	11.05
2009	Abellán A., Jaboyedoff M., Oppikofer T., Vilaplana J.M. [127]	Detection of millimetric deformation using a terrestrial laser scanner: Experiment and application to a rockfall event	Natural Hazards and Earth System Science	197	17.91
2003	Agliardi F., Crosta G.B. [110]	High resolution three-dimensional numerical modeling of rockfalls	International Journal of Rock Mechanics and Mining Sciences	183	10.76
1999	Matsuoka N., Sakai H. [11]	Rockfall activity from an alpine cliff during thawing periods	Geomorphology	179	8.52
1998	Dade W.B., Huppert H.E. [128]	Long-runout rockfalls	Geology	176	8.00

TC: Number of citations; TC/year: Citations per year.

The 811 publications have been written by 1293 authors. Table 7 shows the 10 main authors with the highest production of articles in the study area. This group has published a total of 151 documents, representing 18.55%. The author who has published the most in the subject is Stoffel, M., with 27 articles. In Table 8, in the total citations (TC) column, Stoffel, M. appears again, with 973 as first. TC/TP has also been added, allowing us to see the performance of each author. The most prominent author is Dorren, L.K.A., who has a throughput of 69.42 citations per published article, followed by Crosta, G. B. and Jaboyedoff, M. with 51.64 and 39.76, respectively.

Table 7. Main authors in Rockfall publications.

Author	Country	TP	TC	TC/TP	H-Index
Stoffel, M.	Switzerland	27	973	36.04	54
Bourrier, F.	France	21	280	13.33	16
Jaboyedoff, M.	Switzerland	17	676	39.76	35
Giacomini, A.	Australia	16	422	26.38	17
Peila, D.	Italy	15	413	27.53	21
Dorren, L.K.A	Switzerland	12	833	69.42	18
Berger, F.	France	11	229	20.82	16
Corona, C.	France	11	129	11.73	23
Crosta, G. B.	Italy	11	568	51.64	47
Lambert, S.	France	10	113	11.30	13

TP: Number of publications; TC: Number of citations; TC/TP: average citations per publication.

Table 8. Author keywords co-occurrence.

Keyword	Occurrences	Total Link Strength
Rockfall	362	372
Hazard	58	105
Landslide	29	52
Risk Assessment	28	49
GIS	25	62
Numerical Simulation	24	33
Natural Hazard	23	40
Dendrogeomorphology	21	42
LiDAR	20	47
Impact Force	18	19
Protection Forest	18	26
Earthquake	13	22
Monitoring	13	21
Modeling	12	28
Alps	11	18

Table 7 provides the H-index, which is a score that quantifies the result of an individual's scientific research by comparing documents and citations [129], in this case, all the documents and citations given by the Scopus database, where Stoffel, M. is the author with the highest index with 54. Having a higher H-index means an estimate of the impact of the contributions made by a researcher but does not necessarily mean that the impact is more significant in the fields of rockfall since there are researchers who are interested in several topics.

3.2. Bibliometric Maps Analysis

Keyword Co-Occurrence Analysis

This type of analysis is used to determine the cognitive structure and the important topics of the academic field studied by using visual maps of semantics based on the content analysis technique [56,130]. The VOSviewer software was used for the construction of the co-occurrence bibliometric map, using the author's keywords from the database obtained from Rockfall. A total of 1598 keywords was obtained, provided by the authors of 811 publications. Only 298 keywords appear more than once, which means 18.65%; also, 35 keywords appeared more than five times, 17 more than ten times, and only eight appeared more than twenty times. The fact that a large number of author keywords appear once shows lack of continuity and divergence in research [131], while the keywords that have a greater number of repetitions allow identifying the topics most used in the research field and determining of their structure [71,132]. These keywords are used by the authors to describe the same concept, so it is necessary to establish a standard for consistency in its structure, requiring adjusting the terms found in plural to singular and synonyms before the construction of the network map [133].

Table 8 shows the fifteen most used author keywords in the subject. Rockfall is the most recurring keyword (362), followed by Hazard (58), Landslide (29), Risk Assessment (28), and GIS (25). Additionally, the table shows information related to Total Link Strength, which denotes the importance of a keyword in the field, since a higher value means that it has been linked with others and many times [91].

The co-occurrence analysis was divided into three time periods (Stage I: 1990–1999; Stage II: 2000–2009; and Stage III: 2010–2019). This division allows some advantages: (1) greater clarity in the presentation of the results; (2) you can get patterns of evolution of the structure, and (3) compare the bibliometric maps constructed and the different conceptions of the authors involved in the field of study [134,135].

Figures 5–7 show the author keyword co-occurrence maps for each period. These network maps are made up of nodes and links. The nodes represent the keywords, and their size is related to the number of times the author keyword appears. Links indicate the relationships between nodes and the strength of their relationship [136].
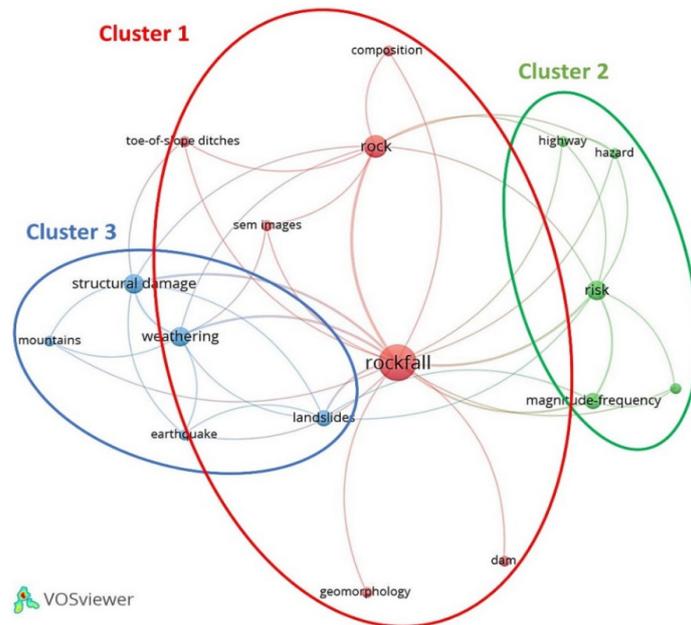

Figure 5. Co-occurrence network of keywords (1990–1999). Cluster analysis.
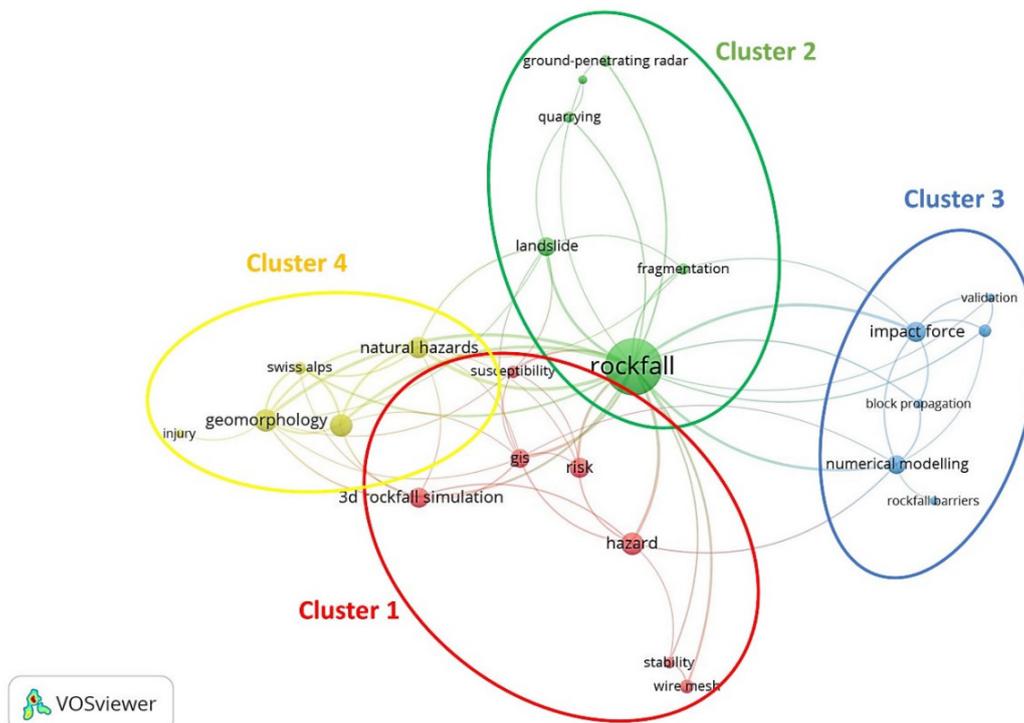

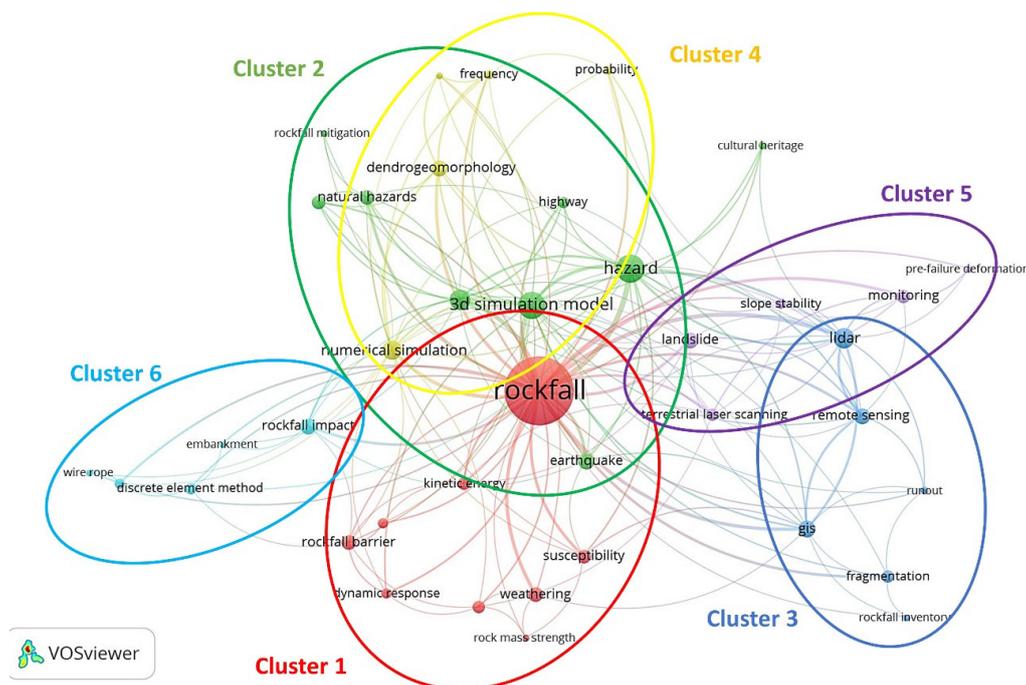**Figure 6.** Co-occurrence network of keywords (2000–2009). Cluster analysis.

Figure 7. Co-occurrence network of keywords (2010–2019). Cluster analysis.

Stage I (1990–1999): Table 9 shows the main lines of research, showing. Three research areas (or clusters): (i) rockfall-geomorphology (main keywords: "rockfall", "rock", "composition"; red circle); (ii) hazard-risk (main keywords: "risk", "magnitude-frequency", "coefficient of restitution"; green circle); (iii) natural hazards (main keywords: "weathering", "structural damage", "landslides"; blue circle). During this period, rockfall research was dominated by studies, examining the causes and effects that caused rockfall. Among the reasons, geomorphology of rock is highly analyzed, as well as natural hazards, such as weathering, landslides, and earthquakes. It is also proposed first mathematical simulations and models for their predictions [11,32,124,125].

Table 9. Cluster groups of the 1990–1999 keyword nodes.

ID	Cluster	Main Including Labels
1	rockfall-geomorphology	rockfall, rock, composition, dam, geomorphology, SEM images, toe-of-slope ditches
2	hazard-risk	risk, magnitude-frequency, coefficient of restitution, hazard, highway
3	natural hazards	weathering, structural damage, landslides, earthquake, mountains

Figure 5 presented the bibliometric map, where the three mentioned clusters are observed. It can be seen that the investigations between cluster 1 (rockfall-geomorphology) and cluster 2 (hazard-risk) are higher than between cluster 1 and cluster 3 (natural hazards), where there are also distant connections between clusters 2 and 3. In this stage I, the nodes are separated, which give an appearance of disconnection between clusters; thus, subfields are shown as independent research connected by critical terms (central). This arrangement and the distant connectivity between the groups reveals that the field of study is in an early phase.

Stage II (2000–2009): This stage was characterized by the increase of clusters to four (see Table 10): (1) hazard-risk (main keywords: "hazard", "3D rockfall simulation", "risk"; red circle); (2) rockfall monitoring (main keywords: "rockfall", "landslide", "fragmentation"; green circle); (3) numerical modeling (main keywords: "numerical modeling", "impact force", "rock mechanics"; blue circle); and (4) natural hazards (keywords: "geomorphology", "protection forest", "natural hazards"; yellow circle). At this stage, among the most cited articles, there is a tendency to monitor and predict rockfall hazards through detection techniques using the terrestrial laser scanner, numerical models, and computer

programs, such as GIS [9,109,114,127]. Hazard and risk assessment techniques are presented through an analysis of historical, statistical and geomorphological data. At this stage, the appearance of research related to forest-rockfall interaction stands out. Figure 6 presents the bibliometric map of co-occurrences of author keywords, where we observed the four clusters mentioned above. Figure 6 shows a better interaction between cluster 1 (hazard-risk), cluster 2 (rockfall monitoring), and cluster 4 (natural hazards), as they are closer to each other, unlike cluster 3 (numerical modeling), which is separate from the others; this was considered as a topic that developed with little interaction with the rest.

Table 10. Cluster groups of the 2000–2009 keyword nodes.

ID	Clusters	Main Including Labels
1	hazard-risk	hazard, 3D rockfall simulation, risk, GIS, wire mesh, susceptibility, stability
2	rockfall monitoring	rockfall, landslide, fragmentation, terrestrial laser scanner, ground-penetrating radar, quarrying, monitoring
3	numerical modeling	numerical modeling, impact force, rock mechanics, block propagation, rockfall barrier, validation
4	natural hazards	geomorphology, protection forest, natural hazards, swiss alps, injury

Stage III (2010–2019): Table 11 shows the six clusters obtained in the analysis of this stage: (1) rockfall monitoring (main keywords: "rockfall", "rockfall barrier", "weathering"; red circle); (2) 3D simulation model (main keywords: "3D simulation model", "hazard", "risk assessment"; green circle); (3) remote sensing (main keywords: "remote sensing", "LiDAR", "GIS"; blue circle); (4) numerical simulation (main keywords: "numerical simulation", "dendrogeomorphology", "frequency"; yellow circle); (5) slope stability (main keywords: "monitoring", "landslide", "terrestrial laser scanning"; purple circle); and (6) rockfall impact (main keywords: "rockfall impact", "discrete element method", "energy dissipation"; light blue circle).

Table 11. Cluster groups of the 2010–2019 keyword nodes.

ID	Clusters	Main Including Labels
1	rockfall monitoring	rockfall, rockfall barrier, weathering, susceptibility, failure mechanism, kinetic energy, coefficient of restitution, dynamic response, rock mass strength
2	3D simulation model	3D simulation model, hazard, risk assessment, earthquake, natural hazards, protection forest, highway, cultural heritage, rockfall mitigation
3	remote sensing	remote sensing, LiDAR, photogrammetry, GIS, fragmentation, runout, rockfall inventory
4	numerical modeling	numerical simulation, dendrogeomorphology, frequency, probability, mass movement
5	slope stability	monitoring, landslide, terrestrial laser scanning, slope stability, pre-failure deformation
6	rockfall impact	rockfall impact, discrete element method, energy dissipation, embankment, wire rope

At this stage, new techniques, such as the LiDAR device and photogrammetry (3D and 4D), have been performed and used for the spatial detection and prediction of rockfall and the evaluation and analysis of rockfall hazard in new case studies or previous case studies as a checking effect. The number of articles on natural hazards (especially earthquakes) and geomorphology as rockfall triggers have increased [137–139]. Among the new themes are some approximations using a model of discrete elements of rock fragmentation after the impact in the analysis of rockfall.

Figure 7 shows the bibliometric map, where we observed the four mentioned clusters in Table 12. Cluster 2 (3D simulation model) and cluster 4 (numerical modeling) are closely related to each other, to such an extent that cluster 4 is almost entirely incorporated into cluster 2. In Figure 7, clusters 1, 2, 4, and 5 they are close to the center of the map. In contrast, clusters 3 (remote sensing) and 6 (rockfall impact) are distant, with very little interaction with the other clusters.

Table 12. Topic clusters of rockfall research 1975–2019.

Topic #	Clusters	Top 5 Terms	2010–2019		2000–2009		1990–1999	
			# Terms	Share	# Terms	Share	# Terms	Share
1	rockfall-geomorphology	rockfall, rock, composition, dam, geomorphology	0	0.00%	shifted to #5	0.00%	19	54.29%
2	hazard-risk	risk, magnitude-frequency, coefficient of restitution, hazard, highway	0	0.00%	shifted to #4	0.00%	8	22.86%
3	natural hazards	weathering, structural damage, landslides, earthquake, mountains	0	0.00%	shifted to #7	0.00%	8	22.86%
4	hazard-risk	hazard, 3D rockfall simulation, risk, GIS, wire mesh	shifted to #8 and #10	0.00%	51	23.83%	0	0.00%
5	rockfall monitoring	rockfall, landslide, fragmentation, terrestrial laser scanner, ground-penetrating radar	shifted to #8 and 10	0.00%	94	43.93%	0	0.00%
6	numerical modeling	numerical modeling, impact force, rock mechanics, block propagation, rockfall barrier	shifted to #11	0.00%	28	13.08%	0	0.00%
7	natural hazards	geomorphology, protection forest, natural hazards, swiss alps, injury	shifted to #9	0.00%	41	19.16%	0	0.00%
8	rockfall monitoring	rockfall, rockfall barrier, weathering, susceptibility, failure mechanism	348	47.80%	0	0.00%	0	0.00%
9	3D simulation model	3D simulation model, hazard, risk assessment, earthquake, natural hazards	174	23.90%	0	0.00%	0	0.00%
10	remote sensing	remote sensing, LiDAR, photogrammetry, GIS, fragmentation	73	10.03%	0	0.00%	0	0.00%
11	numerical modeling	numerical simulation, dendrogeomorphology, frequency, probability, mass movement	50	6.87%	0	0.00%	0	0.00%
12	slope stability	monitoring, landslide, terrestrial laser scanning, slope stability, pre-failure deformation	47	6.46%	0	0.00%	0	0.00%
13	rockfall impact	rockfall impact, discrete element method, energy dissipation, embankment, wire rope	36	4.95%	0	0.00%	0	0.00%
			728	100.00%	214	100%	35	100%

In total, there were 6 cluster topics in this period, out of a total of 13 that existed between 1975 and 2019 (see Table 12 and Figures 5–7). The rockfall monitoring topic has stabilized and captured a persistent engagement, albeit with a larger number of articles. Several very new topics that emerged in this period were: rockfall impact, remote sensing, and slope stability. There are no topics to weaken.

4. Discussion

This bibliometric analysis focused on determining the evolution and trend of the researches in terms of authors, citations, journals, and keywords.

Figure 2 shows the number of scientific publications per year, in rockfall-related articles, since 1975. This increase in production can be compared with the global increase in scientific papers in the most productive and outstanding subject areas in Figure 3. In Figure 8, it proceeds to compare, from the years 2000 and 2019, the production of articles in English (such as the search argument carried out in rockfall topic) of the most prominent subject areas. Noting that, the increase in rockfall-related articles is more notable (increases 9.11 times) than the increases in Earth and Planetary Sciences (increases 2.04 times), Environmental Science (increases 3.99 times), and Engineering (increases 2.93 times).

This bibliometric analysis identifies the authors with the most significant number of publications: Stoffel, M. (27), Bourrier, F. (21), Jaboyedoff, M. (17), and Giacomini, A. (16). All of them analyze the theme of rockfall from different perspectives; Stoffel, M. focuses more on the interaction between rockfall and tree ring activity and using Dendromorphology. Bourrier, F. and Giacomini, A. analyze the trajectory of rockfalls using 3D simulators, the efficiency of protective barriers against rockfall and determine danger zones. Finally, Jaboyedoff, M. explains risk zones using different techniques, such as terrestrial laser scanner, kinetic energy, and GIS-based parameter rating.

The analysis shows that the journals with the highest number of articles on the subject are Natural Hazards and Earth System Sciences with 76 publications and Landslides with 54 publications; Geomorphology follows with 41 publications. In the case of Natural Hazards and Earth System

Sciences and Landslides, contributions focused on rockfall susceptibility assessments using different scenarios. Finally, Geomorphology contributions aimed at modeling the mountain or slope for path prediction and rockfall hazard analysis.
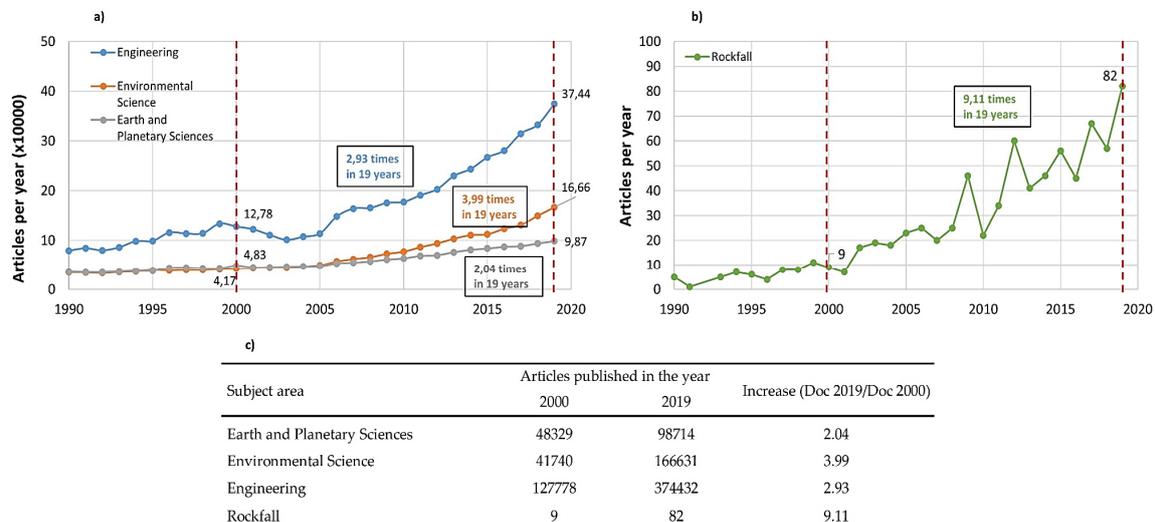

Figure 8. (**a**) Comparative analysis between the principal subject areas with Rockfall content; (**b**) Articles per year in the Rockfall theme; (**c**) Summary table of the data, based on Scopus, of articles in the principal subject areas with Rockfall content and the Rockfall theme in 2000 and 2019.

Subject area	Articles published in the year		Increase (Doc 2019/Doc 2000)
	2000	2019	
Earth and Planetary Sciences	48329	98714	2.04
Environmental Science	41740	166631	3.99
Engineering	127778	374432	2.93
Rockfall	9	82	9.11

From the analysis of scientific production in the countries, it was determined that Europe and Asia are the continents with the most research countries on this subject, with 39 of 54 states and their main contributors belong to Europe (8), Asia (3), America (2), and Oceania (2) (Table 3). It should be noted that the countries with the most significant number of publications have areas of mountain ranges on their territory, in some cases with high instability, for example, Italy, France and Switzerland share one of the best-known mountain ranges, the Alps. On the other hand, China, the United States, and Japan have mountainous areas in their territories, but these suffer as a consequence of earthquakes due to its proximity to the so-called Ring of Fire. These are reasons that we have considered to explain the interest in the subject by these countries.

The scientific productivity of institutional collaboration (Table 4) shows that the greatest contribution corresponds to those of French nationality, unlike Table 4, where Italy is the leader. The first institute in Italy is in seventh (Consiglio Nazionale delle Ricerche), which has a production of almost 30% less than the institution located first (Universite Grenoble Alpes). In contrast to Table 4 with Table 5, there are no institutions in the top ten of countries like Canada, Australia, and Spain (sixth, seventh, and eighth, respectively). So, it suggests a variety of institutions in which these publications are distributed. From Table 4, it should also be highlighted that researchers report or register more than one affiliation (two or more institutions from the same country or another country); therefore, the institutions included in Table 4 may match in one or more papers.

Table 13 shows the evolution and variation of the top 15 author keywords in stage I (1990–1999), stage II (2000–2009) and stage III (2010–2019). Landslide, Rockfall, Risk, and Hazard were the author keywords that appear in all stages. The keywords "susceptibility", "risk", "hazard", and "risk assessment" are aspects of rockfall's susceptibility assessment. "Risk assessment" and "hazard" refer to a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of rock slides that exist or may occur in an area [9].

Table 13. Variation author keywords in 1990–1999, 2000–2009, and 2010–2019 stages.

Author Keyword 1990–1999	Co-Occurrence	Author Keyword 2000–2009	Co-Occurrence	Author Keyword 2010–2019	Co-Occurrence
rockfall	10	rockfall	75	rockfall	276
rock	4	geomorphology	12	hazard	46
risk	3	hazard	12	3D simulation model	45
structural damage	3	protection forest	12	risk assessment	26
weathering	3	natural hazards	11	LiDAR	25
landslides	2	3D rockfall simulation	10	numerical simulation	22
magnitude-frequency	2	impact force	10	GIS	17
coefficient of restitution	1	risk	9	earthquake	16
composition	1	GIS	8	landslide	16
dam	1	landslide	8	dendrogeomorphology	15
earthquake	1	numerical modeling	8	remote sensing	15
geomorphology	1	wire mesh	5	rockfall impact	15
hazard	1	rock mechanics	4	natural hazards	14
highway	1	susceptibility	4	rockfall barrier	14
mountains	1	swiss alps	4	weathering	14

Areas susceptible to rock landslides can be assessed and predicted using empirical methods, analytical methods or kinematic analysis. The need for this type of research caught the attention of researchers and engineers involved in rock landslide risk mitigation and infrastructure planning. The co-occurrence of "hazard" increased continuously, with 1 in 1990–1999 to 12 in 2000–2009 and 46 in 2010–2019; likewise, "risk assessment" ("risk"), with 3 in 1990–1999, to 9 in 2000–2009 and 26 in 2010–2019, suggesting that assessment of rock landslide susceptibility has remained an attractive research topic for the past three decades. "Rockfall" remained the most widely used keyword during the study period because this word was the search argument used in this study.

Rapid developments in remote sensing techniques, "GIS" and "LiDAR" tools made quantitative analysis of rock landslide assessment, analysis and monitoring are more feasible [117,140]. Recently, the availability of GIS and remote sensing data has provided many advantages in quantifying topographic attributes related to rock slides. These techniques are also used to create susceptibility maps and hazard and risk maps. "GIS" has undergone an advance since its appearance in the period 2000–2009; while, the term "LiDAR" only appears in this last decade (2010–2019), its co-occurrence has been very high. This pattern indicates that "remote sensing" has become an essential tool to process and analyze spatial data that facilitate the application of quantitative techniques in the evaluation of rockfall risk.

5. Conclusions and Future Trends

This article presents a review of the academic research carried out on Rockfall during the period 1975–2019, along five dimensions: annual production trends, scientific categories (subjects) and journals, author performance and geographic distribution, institution performance, and the temporal evolution of keyword frequencies. This bibliometric analysis will provide researchers involved in rockfall studies with necessary information about rockfall research, such as its main scientific categories (subjects), its main journals, its active countries/territories and institutions, its most productive authors, and its most used keywords from a historical perspective. With this information, researchers can identify the critical points and frontiers of rockfall investigation. A total of 811 publications were analyzed, involving 1293 authors, 267 journals, 54 countries, 158 institutions, and 1598 different keywords author.

Research on Rockfall has grown since 2002 (beginning of Stage II: Figure 2 and Table 1), and this increase demonstrates the interest of academics in the fields of Earth and Planetary Sciences, Environmental Science, and Engineering. Global geographical distribution of the authors in rockfall research was visualized cartographically, with important spatial groupings in the EE.UU., Europe, Asia, and Oceania. Developed countries, such as Italy, Switzerland, China, the United States, and France, are responsible for 64.73% of scientific publications in this field worldwide. The most productive institution in terms of publications is Universite Grenoble Alpes (Grenoble, France), with 35 publications, followed by INRAE (National Research Institute for Agriculture, Food and Environment of France) and Chinese Academy of Sciences. The leading journals, according to the number of publications, in this scientific field are Natural Hazards and Earth System Sciences, Landslides, and Geomorphology. Likewise, the

prominent authors are Stoffel, M., from the Université de Genève (Genève, Switzerland); Bourrier, F., from the Universite Grenoble Alpes (Grenoble, France), and Jaboyedoff, M., from the Université de Lausanne (Lausanne, Switzerland).

Bibliometry is presented as a suitable methodology for inductive approaches to the semantic limits of the conceptual structure of recently developed disciplines. In our case study on rockfall, we elucidate the multidisciplinary nature of this area of knowledge. The use of bibliometrics can improve our understanding and help researchers to better understand the conceptual structure of rockfall, as in any other scientific field.

A temporal evolution analysis of keyword frequencies was used to shed light on the general research directions and trends in rockfall and to provide reference for future study. In the most recent ten years (2010–2019), several author keywords (Table 13), such as "hazard", "3D simulation model", "risk assessment", "remote sensing", "numerical simulation", "earthquake", "rockfall barrier", "LiDAR", and "GIS", became the research hotspots in rockfall research, which were in the areas of regional susceptibility assessment, typical deformation monitoring and prediction, effective research technologies, and models. Moreover, two hot issue (hazard-risk assessment and 3D simulation model), one major triggering factor (earthquakes), three research technologies (GIS, LiDAR, and remote sensing), and one effective model (numerical simulation by a algorithms) received steadily increasing attention, indicating likely future rockfall-related research in these areas. From this we can highlight the following topics:

(i)   For development of a reliable and automatic rockfall monitoring system, remote sensing techniques, such as LiDAR or photogrammetry, have been combined with the development of innovative data processing methods (seismic measurements). Until now, the combination of remote sensing techniques with seismic measurements remains scarce. Therefore, additional calibration work is necessary to corroborate the utility of combining both methods.

(ii) For hazard-risk assessment, many machine learning algorithms, such as backpropagation neural network (BPNN), support vector machine (SVM), or using remote sensing (LiDAR, Terrestrial laser scanning-TLS, airborne LiDAR system-ALS, or UAV 3D Photogrammetry), have been widely used to perform the susceptibility assessment. In addition, in recent years, it has been carried out for the protection of Cultural Heritage. This in the frame of a quick protocol for a preliminary zonation, to ensure the safe and sustainable management of the sites.

(iii) To determine the trajectories, the potential runout, and impact energies, the use of numerical and models in 2D-3D simulations are being developed, such as: stochastic program (RockGIS) for rockfall fractal fragmentation model (RFFM) or simulation software uses the point-mass model (STONE, RockFall Analyst and PICSUS-ROCKnROLL). However, a greater number of parametric analyses and calibration exercises are required.

(iv) GIS-based techniques, physical-based approaches, and also new technologies (such as big-data analysis of monitoring systems) could play an important role in the future for the mitigation and management of rockfall events.

This study had its limitations and implications for future research. First, an opportunity to continue deepening knowledge of rockfall, as a discipline, could be to expand the study using other databases, such as Web of Science (WoS), or using different types of documents and other languages. Second, the research has used the citations provided by the Scopus database as the unit of analysis, so the implications of self-citations and citations should be considered in future research. These could complement the survey so that all the scientific production is considered and the conclusions are more rigorous and better reflect the evolution of disciplinary structures. Furthermore, it would be fascinating to approach the study of intellectual structure through the study of citation, bibliographic coupling, and co-citation because it is a part little explored by bibliometric studies, and it would be of the most significant interest to understand the complete structure of this scientific domain. This analysis of the intellectual structure would reflect the degree of internationalization of a discipline.

In addition, a comparative analysis of keyword co-occurrence can be suggested, and results can be compared based on keyword type selection. Here, whether or not taking all the keywords for the analysis could alter the results could be studied.

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