GeoHazards

Review

Worldwide Research Trends and Networks on Flood Early Warning Systems

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Abstract: This review paper examined the global landscape of research on continental flood early warning systems (EWS), shedding light on key trends, geographic disparities, and research priorities. Continental floods stand as one of the most pervasive and devastating disasters worldwide, necessitating proactive measures to mitigate their impact. Drawing upon a comprehensive analysis of the scholarly literature indexed in the Web of Science repository, this study unveiled significant patterns in EWS research. While the emphasis on flooding is evident, a considerable portion of research focuses on precipitation as a variable and modeling approaches. Furthermore, the influence of climate change emerges as a prominent theme, though distinguishing between climate change and variability remains a crucial area for exploration. Geographically, Europe, particularly England and Italy, dominates research efforts in flood related EWS. Conversely, the limited representation of Central America and other regions such as Asia and Oceania, underscores the need for greater attention to regions facing significant flood risks. Importantly, the concept of total link strength emerges as a valuable metric, highlighting collaborative networks established by European countries and the United States. Based on these findings, recommendations are proposed to enhance the inclusivity and effectiveness of flood related EWS research, including a broader consideration of socio-economic factors, fostering collaboration among researchers from diverse regions, and prioritizing initiatives to strengthen research capacities in vulnerable areas. Ultimately, this study provides valuable insights for policymakers, researchers, and practitioners seeking to advance flood risk management strategies on a global scale.

Keywords: floods; network analysis; bibliometric analysis; precipitation; research trends; early warning systems

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1. Introduction

Continental floods stand as one of the most prevalent and devastating natural disasters globally, inflicting profound impacts on both human lives and infrastructure [1,2]. Throughout history, this type of flood has consistently emerged as a primary contributor to loss of life, displacement of populations, and economic disruption [3,4]. Their indiscriminate nature, coupled with the increasing frequency and intensity attributed to climate change, renders floods as a paramount concern for communities worldwide [5,6]. Understanding the dynamics, trends, and responses to continental floods is imperative for mitigating their adverse effects and fostering resilience in vulnerable regions [7–9].

In the face of escalating flood risks, the implementation of effective early warning systems (EWS) emerges as a critical strategy for disaster preparedness and response [10]. EWS serve as proactive mechanisms to detect, monitor, and forecast impending flood events, thereby providing valuable lead time for communities to enact mitigation measures, evacuate residents, and safeguard vital infrastructure [11,12]. By leveraging advancements in technology, data analytics, and communication networks, EWS not only enhance the capacity to anticipate flood events but also empower stakeholders to make informed decisions, ultimately reducing the associated socio-economic toll [13].

The proliferation of bibliometric studies within the realms of Earth and social sciences has profoundly influenced our understanding of disaster risk management and policy formulation [14]. By systematically analyzing the scholarly literature, bibliometric studies unveiled underlying patterns, emerging trends, and research priorities pertaining to flood-related EWS [15]. These insights offer invaluable guidance to policymakers, emergency responders, and stakeholders, facilitating evidence-based decision-making and resource allocation [16]. Moreover, bibliometric analyses serve as a catalyst for interdisciplinary collaboration, fostering knowledge exchange and innovation in the pursuit of resilient communities.

This study endeavored to explore the trajectory of research trends surrounding EWS with a specific focus on continental floods. By harnessing the vast repository of scholarly publications indexed in the Web of Science, the hypothesis of this paper posited that there exists a discernible roadmap delineating the evolution, priorities, and geographic distribution of research in this domain. Particular attention was paid to Author Keywords, Keywords Plus, and Country for the integral analysis. Through rigorous analysis and synthesis of bibliometric data, the aim of this research was to elucidate the leading countries spearheading advancements in flood-related EWS and identify key thematic areas warranting further investigation. Ultimately, the positive implications of this study extend beyond academia, informing policy discourse, enhancing disaster preparedness, and fostering resilience on a global scale.

2. Methods

A descriptive approach regarding which trends were present in the development of networks about EWS with emphasis on continental floods was developed [17]. This work focused on understanding the research trends, thoughts, and global experiences about EWS on continental floods, therefore, insights that are not actually understood could be obtained.

According to [18], basic research was developed in which new research fields were sought. This was a longitudinal work because this paper focused on the evolution of EWS on continental floods, but it was also a descriptive study because it explained EWS with an emphasis on continental floods from their scientific knowledge contexts and used previous studies and their development trends [19,20]. The exploratory research methodology developed in this work can be consulted on Figure 1:

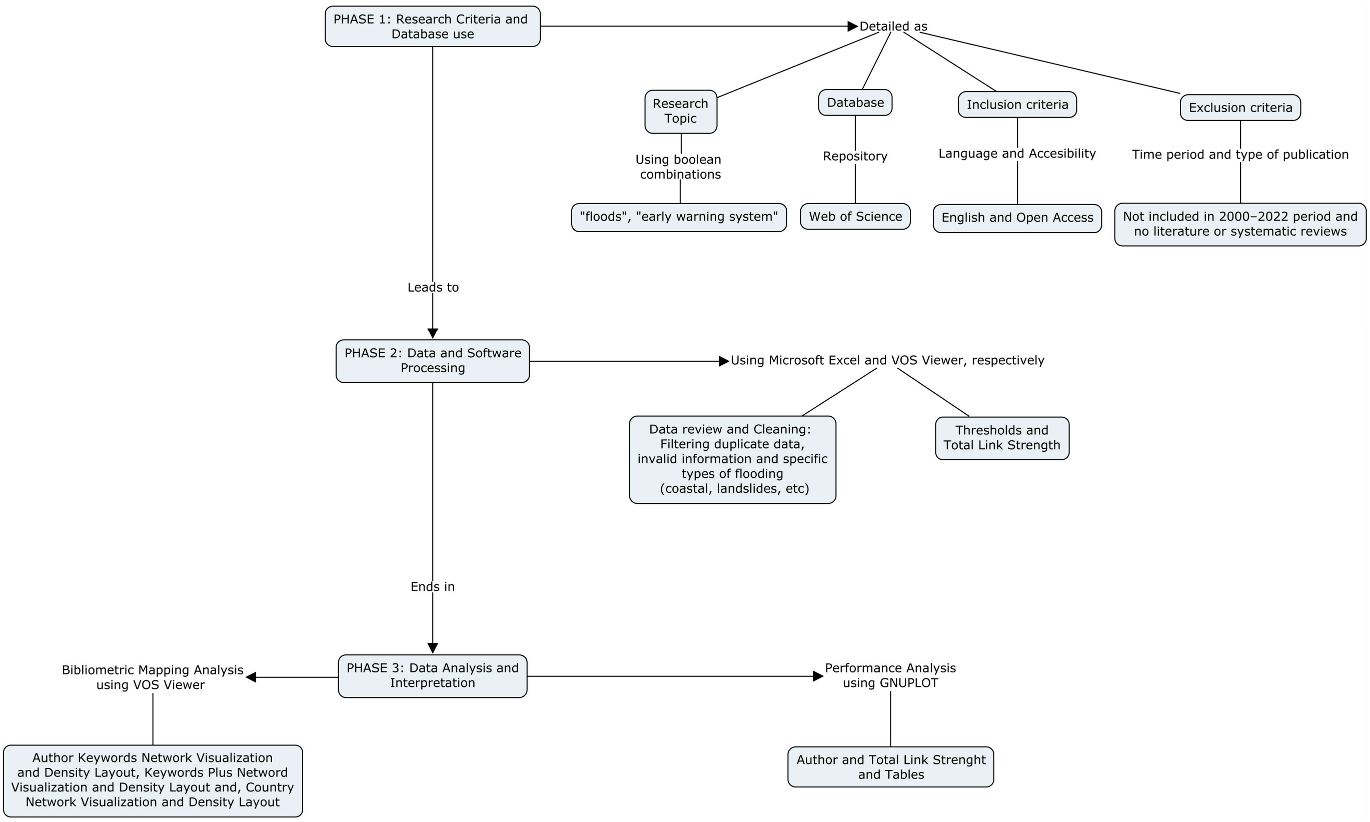

Figure 1. Research methodology applied in this study based on [21–23].

The units of research were journal studies, therefore, information was obtained from the Web of Science (WoS) repository (https://www.webofscience.com accessed on 21 June 2024). A search focused on journal articles and conference papers from 2000 up to 2022 was performed using the keywords floods and early warning system. The choice of the period was made because in previous years, the bibliography compiled focused more on theoretical aspects on the basis of EWS in a general perspective and were not specific for continental floods. A total of 320 documents were recovered after the usage of a Boolean combination including the operator "AND". The query used to recover these documents is shown in (1):

$$=((TS = (floods)) \text{ AND } TS = (\text{"early warning system"})) \quad (1)$$

Once the 320 papers were retrieved, filtered by title and related keywords (these filters discarded other types of EWS or floods such as glacier floods, tsunamis, and coastal floods), open access and review status were applied. The last filter consisted of discard papers that were systematic reviews or literature reviews. Figure 2 shows the detail of the different filters applied. At first glance, 126 papers were selected by title; in this filter, only papers that indicated in their title that they were about EWS for floods were considered. A second filter by keywords was applied. This filter selected papers in which Author Keywords (the ones chosen by the original authors) included descriptors such as early warning system (and its plural and variants) and flood (and its plural and variants) at the same time. It is important to consider that there was another way to classify keywords, named Keyword Plus. This category included keywords derived from the titles of cited references that were related with words that commonly appeared in these titles and were not necessarily listed by the authors [24].

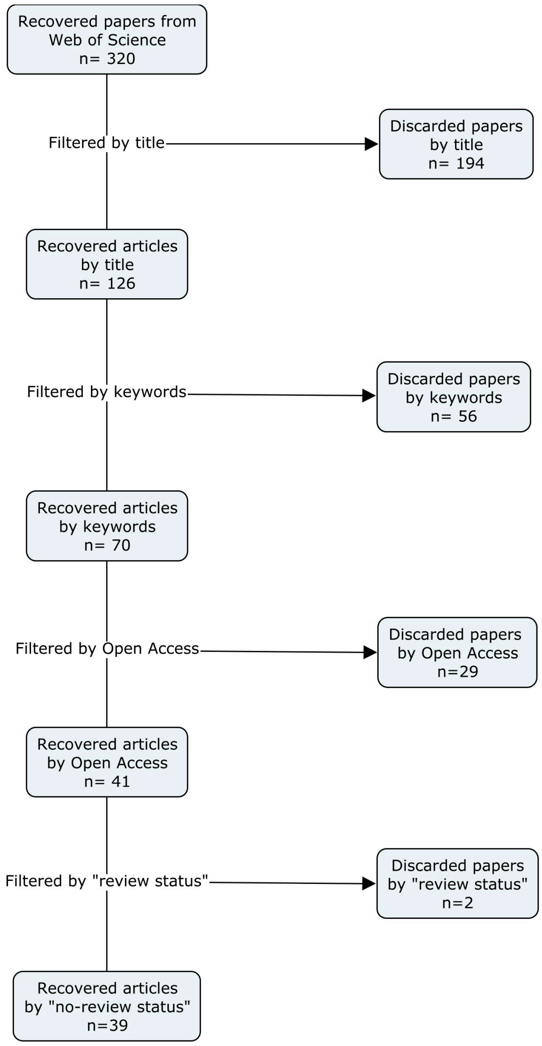

Figure 2. Flow diagram of the article filtering and selection process.

Once this filter was applied, only 70 papers fitted this criterion. As a third step, we considered only papers that could be consulted via open access. This meant that 29 papers were discarded and only 41 were retrieved. As a last step, papers derived from a research process were considered, so literature reviews or systematic reviews were not included. This last filter discarded two papers, so we achieved a final sample of 39 papers. These 39 papers represent 12% of the recovered papers from WoS according to the minimum recommended for a descriptive and qualitative analysis in this type of study [25].

After filtering, co-occurrence of author keywords and co-occurrence of key keywords networks and density layouts were performed using VOSviewer version 6.18. The purpose of doing this was to identify the main research trends that are present worldwide about EWS. Also, a co-occurrence network and a density layout of the main countries that worked on EWS on continental floods was obtained. All the used data is available in the Supplementary Materials.

The aim of this exercise consisted of studying the roadmap regarding the research trends on EWS with emphasis on continental floods and also, to consider which countries are taking the initiative on this topic in the twenty-first century. For future work, these trends can be considered to determine how EWS can be implemented more efficiently worldwide.

3. Results and Discussion

3.1. Analysis by Author Keywords

Figure 3 shows the network visualization of the Author Keywords from the selected papers. At first glance, this graph shows that the main research trend englobes a general topic that is early warning systems, but it includes a couple subtopics that are floods and flood forecasting.

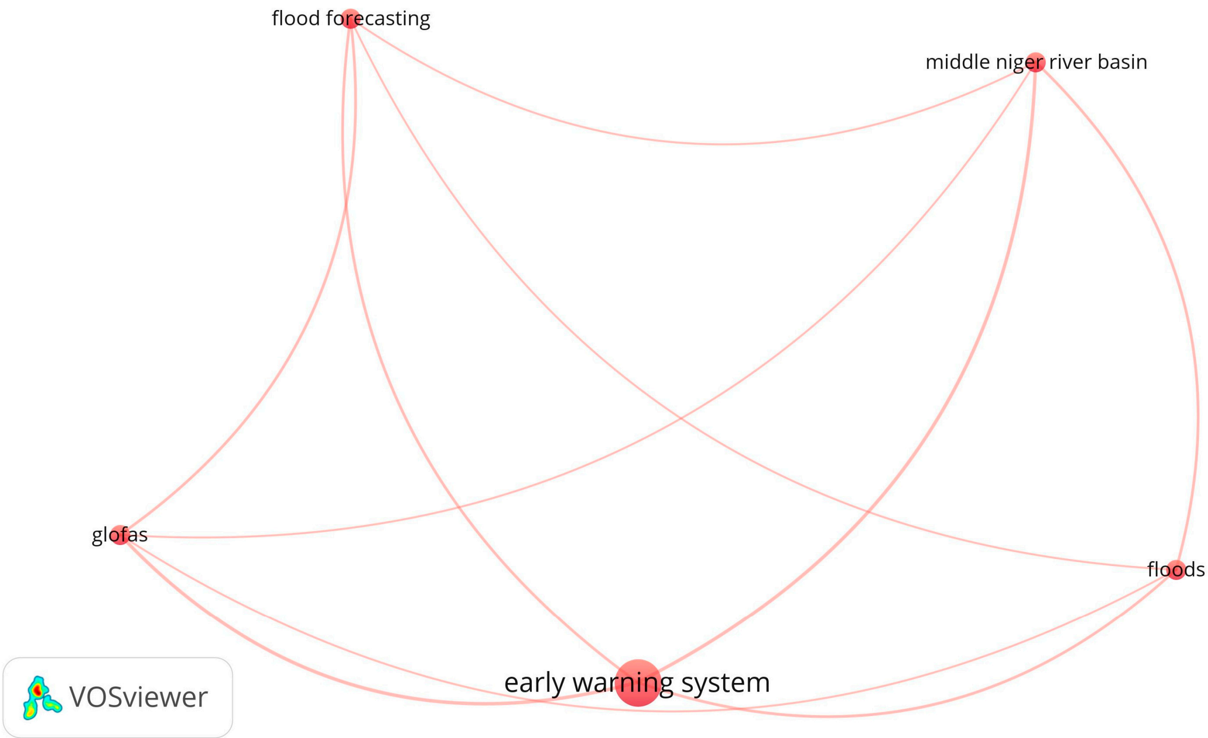

Figure 3. Network visualization of Author Keywords from selected papers.

Nodes labeled as *glofas* (acronym of Global Flood Awareness System [GloFAS]) [26] and *middle Niger river basin* appear with the same number of relationships as the other two. It is important to remember that this was a descriptive study, therefore, centrality measures such as centrality, betweenness, in-degree, out-degree, and other actor-network theory (ANT) measures as suggested by other authors such as [27] were not calculated; we obtained the total link strength only for the network visualization and density layout for countries. However, this study considered that the nodes which exhibited more (less) size and had darker (brighter) colors owned a higher (lower) degree value.

Figure 4 shows the density layout of the Author Keywords from selected papers. Again, the node labeled as *early warning system* has more presence in the layout structure and the other four nodes show a similar exhibition pattern between them. Even though no centrality measures were calculated, it is important to note that nodes *glofas* and *middle Niger river basin* are closer to the central node early warning system than the other two.

It is important to emphasize that in each network visualization and density layout, this research sought to optimize the thresholds of minimum relationships and co-occurrence patterns in the settings of each visualization. The purpose of this was because each node and relationship appeared only once in each network visualization and density layout.

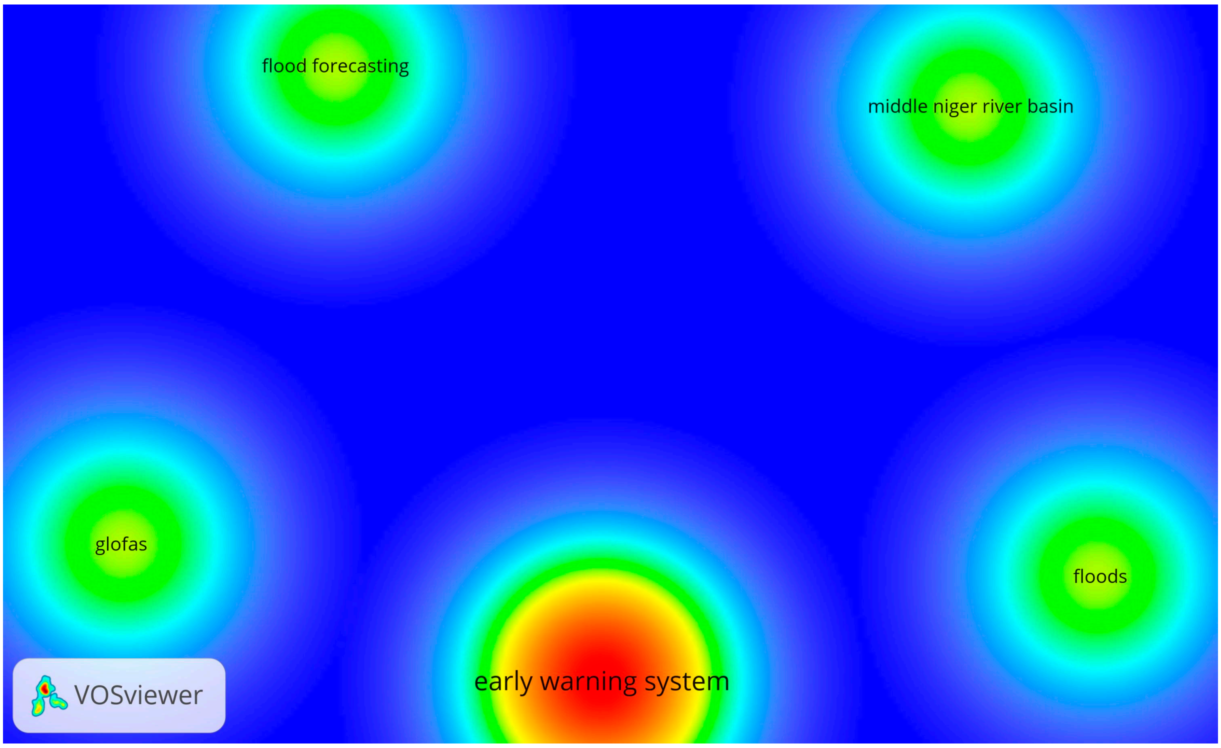

Figure 4. Density layout of Author Keywords from selected papers.

3.2. Analysis by Keywords Plus

Figure 5 shows the network visualization of Keywords Plus from select papers. At first sight it is possible to recognize two clusters, one at the left (red) and the other one at the right in green. It is also noticeable that the node labeled as *precipitation* is the one that has more relationships within the graph, followed by *model* and *rainfall* with three relationships each. Other nodes such as alert system and *climate change* only exhibit two relationships in this network.

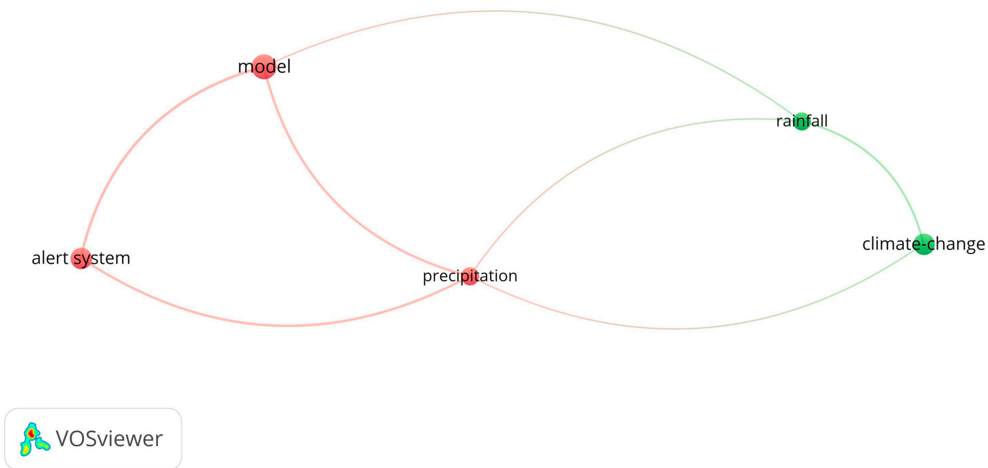

Figure 5. Network visualization of Keywords Plus from selected papers.

Nodes labeled as *precipitation* and *rainfall* can be considered as synonyms at a language label but, according to each publication, they can have a different context. One remarkable aspect is that the left cluster includes *model* and *alert system* nodes and this denotes the importance of the model chosen for the development of precipitation forecasts to be included in the EWS (Figure 5).

Despite the importance of climate change in world scientific and political agendas, at a research level on EWS with an emphasis on floods, *climate change* does not have a predominant role. Maybe it could be that climate change is not directly related with EWS because of the problem of predictability [28] which establishes that climate change is related with Type-2 predictability problems, and it depends on the definition of boundary conditions instead of initial conditions (e.g., soil moisture as an initial condition) (Type-1 predictability problem). *Rainfall* can be considered as a hazard, for example, the increase in heavy rainfall on a specific territory or an increase/decrease in the number of days of rainfall, therefore in these cases, adaptation measures can be implemented to prevent the impacts of extreme events related to these types of hazards.

The density layout of Keywords Plus of selected papers is shown on Figure 5. A remarkable feature of this layout is that *model* and *alert system* nodes have a higher color intensity than the others. This enhances the eligibility of the model to forecast precipitation characteristics (duration, intensity, and volume) that may lead to a flood as the most important topic trend in EWS research. The *model* node also exhibited a bigger size compared to the other nodes within the layout, therefore, the size of this node also supports the importance of the model chosen for the *alert system*.

As in the network visualization of Keywords Plus (Figure 5), *climate change* has no significant weight compared to the other nodes in the density layout. Again, this was a descriptive approach. Further steps should include the calculation of centrality measures to ensure this hypothesis.

A last observation of Keywords Plus density layout (Figure 6) shows that as in the network visualization, there are two defined clusters, one at the left that can be considered relevant for EWS with emphasis on continental floods (related to Type-1 predictability problem) and a second cluster related to climate change. Also, the second cluster distance from the node *precipitation* is larger than the one in the first cluster. This can be explained because of the type of predictability that is needed in the development of the EWS that were the subject of study of this research.

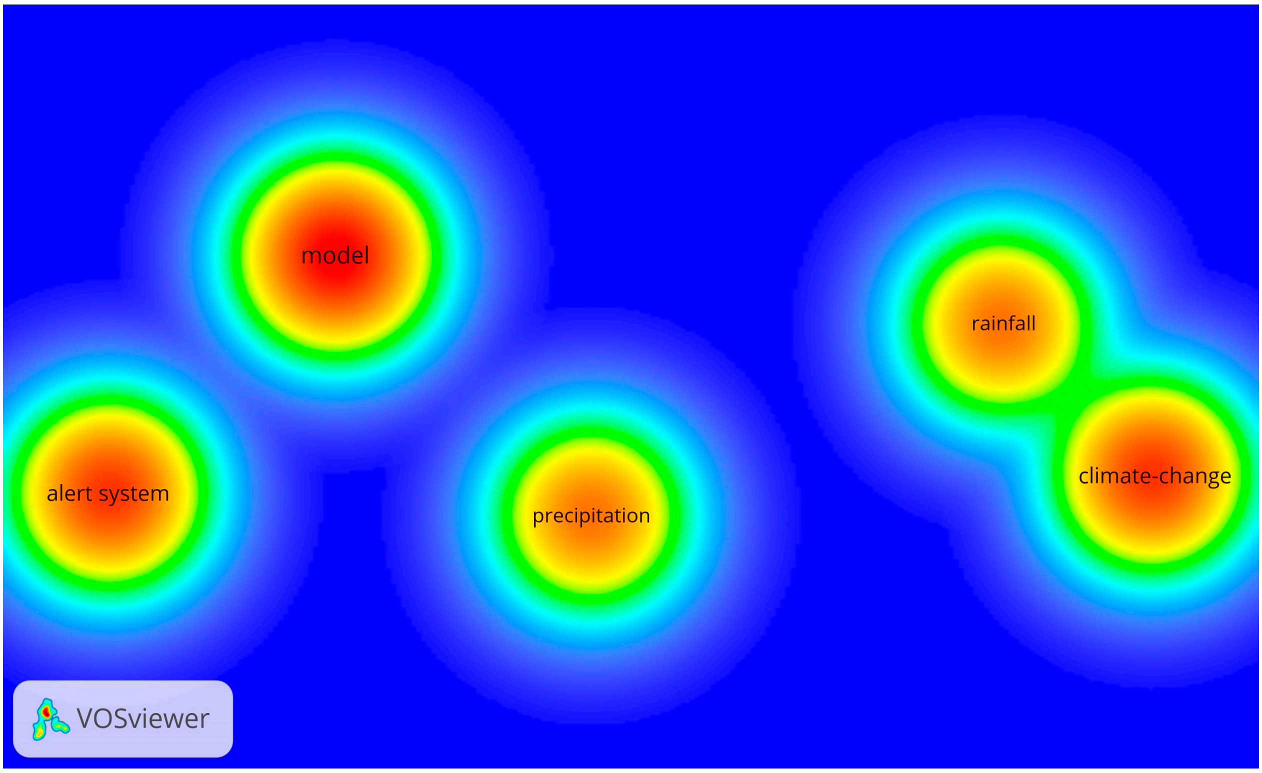

Figure 6. Density layout of Keywords Plus from selected papers.

3.3. Analysis by Country

The network visualization of the countries in which selected papers were developed is available on Figure 7. A first impression of this network shows that the lead countries that worked on EWS with an emphasis on flood are European, such as England and Italy. Both countries are the nodes with more links attached to them, with eight each. Also, at a first glance, six of the countries that lead this research trend are from Europe; three from America; and Australia, Africa and Asia have one country representing them in Figure 7.

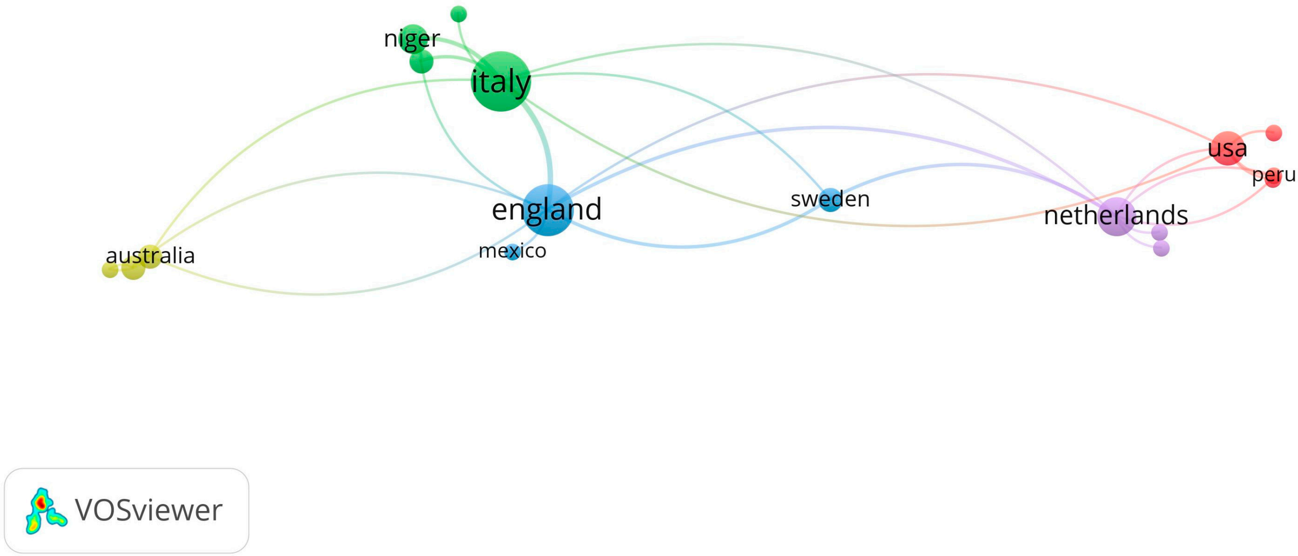

Figure 7. Network visualization of countries from selected papers.

Two defined clusters can be appreciated in Figure 8. This figure shows the density layout of the countries that improve research processes on EWS related to continental floods. European countries lead both clusters, with Italy the strongest as it can be seen in the brightness and intensity of its yellow color on Figure 7. England has a secondary role on this cluster; it is possible that the closeness (closeness in this case should not be interpreted as a centrality measure) between both countries consists of a research relationship between both, as shown in the thickness of their link. Small nodes may be related with the territories of interest for the development of EWS or maybe initial research projects are being implemented in those countries.

The right cluster on Figure 8 shows a similarity pattern between the four nodes within this density layout. The brightness and size of the nodes that correspond to the United States and Netherlands indicate their importance in this cluster; both countries are used to facing flood consequences and have considerable resources that let them invest funds toward researching continental floods. This explains that the number of papers that each country produces is bigger than the rest of the others included in Figure 8.

A remarkable behavior is exhibited by the nodes corresponding to Australia and Sweden because they are alone in the density layout representation. A first approach can be related with an initial effort of both countries not only on the development of research projects regarding EWS and its relationship with continental floods, but on the attempts to establish this type of prevention tool. It is also important to consider that the node that represents Australia is brighter and bigger than the one of Sweden; this can be related to further steps taken on the topic of interest of this work by the first country.

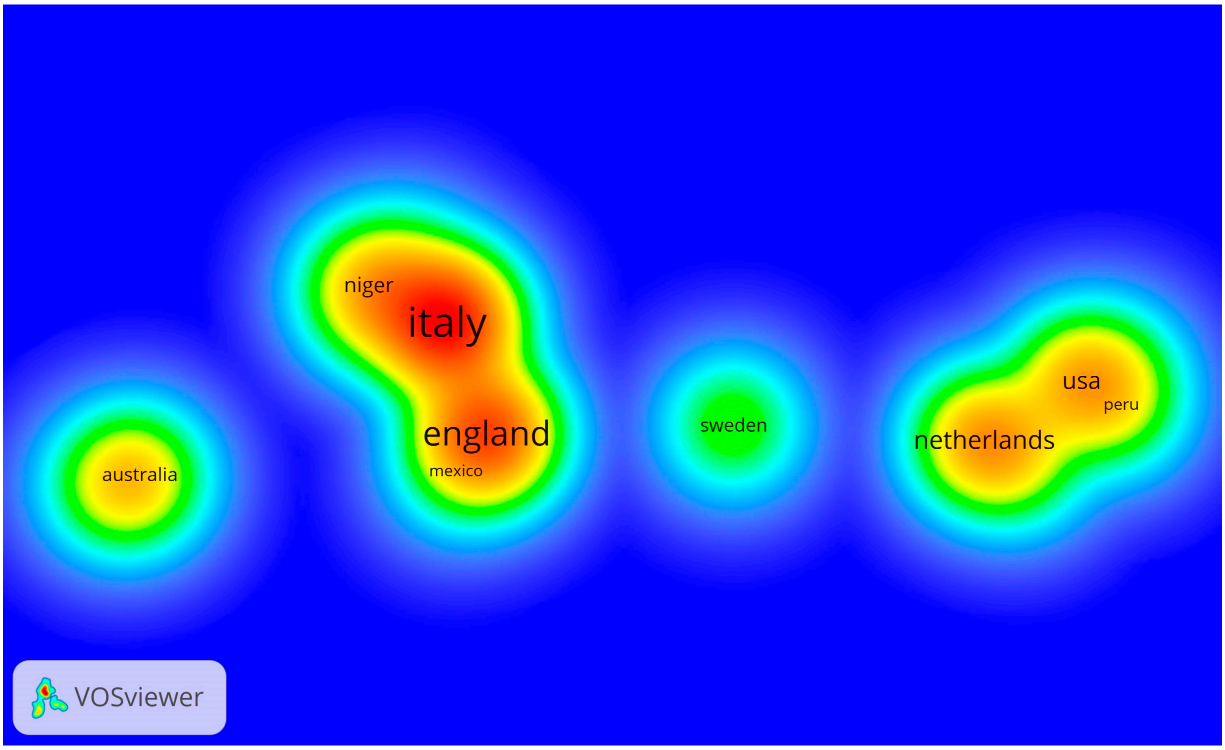

Figure 8. Density layout of countries from selected papers.

Two more aspects were analyzed in this research: the number of documents produced by country and, as an exploratory exercise, the gathering of the total link strength of the graph shown in Figure 7. Italy appears as the country with more documents produced on EWS with an emphasis on flood issues, followed by England, Netherlands, United States, Sweden, and Australia (Figure 9). This confirms the leadership and behavior of these countries as nodes in Figures 7 and 8.

Figure 9 also shows the Total Link Strength of the network visualization shown on Figure 7. It is important to denote that not all the countries that appear in Figure 9 are present in Figures 7 and 8 because a threshold was imposed. This threshold consisted of the condition that the Total Link Strength ≥ 3 were represented in both figures.

A noticeable fact of this condition is that there are countries such as Germany, Spain, and Czech Republic that despite producing research documents related to EWS with an emphasis on continental floods, they are not significant within the network because their research and collaborative relationships with other countries were not significant. Germany, Greece, and Indonesia had two or more documents, but they did not relate in a strong way with the other countries under the conditions of this research.

Another perceptible aspect that can be noticed in Figure 9 is that the Total Link Strength value is higher in all countries than the Number of Documents produced by each one and that the countries that produce more documents are the ones that have a bigger value of the Total Link Strength within the network. This behavior can be related to the position on the graph shown in Figure 7 and probably, with higher values of their centrality measures although this analysis is out of the scope of this study.

Despite review papers not being included as part of the sample, the obtained results were consistent with similar studies. The Niger Basin appears as an area of interest for the development of EWS with an emphasis on continental floods [29]. A correct choice of model can contribute to developing a robust and effective communication of flood warnings and communities that own an EWS can be prepared and will have an early response to a flood event [30].

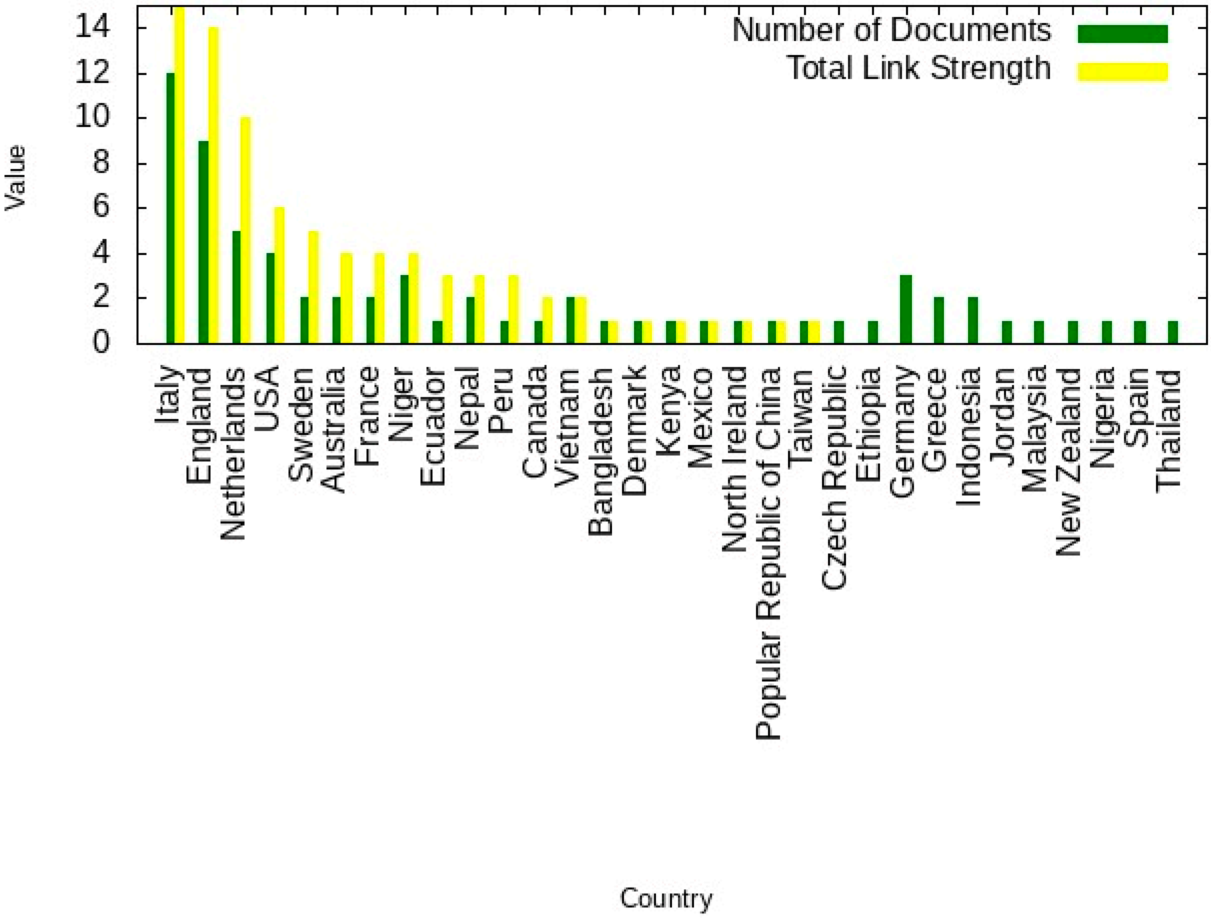

Figure 9. Number of documents and Total Link Strength of the network visualization of the countries from selected papers.

In a practical approach, these trends were identified in EWS in countries such as Vietnam and Nepal [31,32]. Also, European countries that established an EWS related to continental floods obtained a monetary benefit regarding damage costs (benefits of EUR 400 vs. EUR 1 invested) and avoided flood damages [33].

One important fact that is important to expose is that seven of the selected papers were published in the *Water* journal, this is approximately 18% of the total sample (Table 1). Four papers were published in *Sustainability* and the other four in the *Journal of Flood Risk Management*, which represent 20% of the total sample. A remarkable behavior on publishing about EWS with an emphasis on floods can be found in the *ISPRS International Journal of Geo-Information*, *Sensors*, and the *Journal of Hydrology* in which three papers were published on each one; this behavior represents 23% of the total sample. These behaviors can be related with the h-index, the i-10 index or other impact factor measures.

According to these results, EWS are composed of four pillars that are united between a chain. These pillars are, (i) disaster risk knowledge, which represent the basis of early warning; (ii) detection, observations, monitoring, analysis, and forecasting of hazards; (iii) warning dissemination and communication; and (iv) preparedness to respond. Worldwide initiatives are currently being implemented such as the Early Warning Systems for All effort of the United Nations (https://www.undrr.org/early-warnings-for-all, accessed on 21 June 2024).

At first glance, having knowledge of risk is important for designing a roadmap for the establishment of an EWS. In the case of continental floods, it is important to know the hazards relevant to the territory of interest; some are atmospheric such as an increase in wet days, an early onset of the rainy season, or a rising probability of days with frost. This statement is supported by [34] where these authors mentioned that continental floods affect not only the environment, but also social assets. Their study concluded that with the development of risk assessments and simulations, it is possible to design a flood management strategy that can reduce potential damages and risks associated with continental floods but not eliminate them.

Table 1. Frequency of publication in Journals of the selected papers.

Journal	Frequency
Water	7
Sustainability	4
Journal of Flood Risk Management	4
ISPRS International Journal of Geo-Information	3
Sensors	3
Journal of Hydrology	3
Geosciences	2
Remote Sensing	2
International Journal of Environmental Research and Public Health	1
Journal of Marine Science and Engineering	1
Journal of Engineering and Technological Sciences	1
Hydrology and Earth System Sciences	1
H_2O Open Journal	1
Environmental Research Letters	1
International Journal of Disaster Risk Reduction	1
Environmental Science & Policy	1
Climate	1
Natural Hazards	1
Journal of Hydroinformatics	1 [1]

[1] Source: Web of Science.

Once countries have considerable insight and knowledge of their risk, it is important to strengthen the capacities of the National Meteorological and Hydrological Services (NMHS). These efforts include the acquisition of meteorological stations (and the substitution of damaged and old conventional equipment), the implementation of IT infrastructure and training for technicians in the development of outputs from numerical weather prediction models, among others. One outstanding activity could be to develop a standard common protocol in which local and private organizations that own meteorological stations can join a national network; this protocol must establish the requirements that these stations must fit, so the national monitoring capacities will become more robust. These ideas can be seen as near-term opportunities and challenges in which NMHS can enable coordination mechanisms for an enhanced set of EWS and meteorological services. these entities can develop efforts to advance social equity and diversity to support the most vulnerable communities [35].

One of the most important pillars of all EWS is communication. People vulnerable to continental floods need to have access to precise alerts within a time gap that lets them take proper measures to deal with the possible negative impacts of continental floods, regarding their economic activities or living conditions. Most of the time, these people do not have access to communication channels or the education system. Sometimes they communicate in a local language or do not know how to interpret the information that is being delivered through the EWS structure. Previous studies indicated that information needs to allow the civil population to comprehend the severity of possible impacts of a hydrometeorological event [36]. To achieve this, governments and local authorities must invest in multiple communication channels that provide warning messages and impact-based forecasts at a local level.

Other authors refer that warnings must trigger decisions at a community level and, as mentioned above, outputs from the second pillar can be used to develop a framework for adopting it at a site-specific environment [37]. Therefore, each EWS (not only the ones related to continental floods) must ensure that the information and an easy and nontechnical interpretation can reach people in their local language via their preferred communication channel (for example, local radio programs or talks in a local committee) and in a way that respects their world and local point of view so they can take early decisions that mitigate possible negative impacts of continental floods.

The fourth pillar of EWS was out of the scope of this work because this research sought to emphasize prevention. The first three pillars are related with preventive actions and the results shown on the research trends that are being studied worldwide exhibits that there are plenty of opportunities to develop EWS with an emphasis on continental floods focusing on the development of prevention strategies and policies.

Finally, sustainability is the main feature an EWS must have and, in most of the cases, it will depend not only on infrastructure and technology but on community engagement [38]. Despite the fact of the EWS being developed or promoted by a first world country or being implemented in a vulnerable country, or even if there is a huge amount of research within the EWS, a strategy that sustains it on time is the key to the success of each system. The suggestion of this research is to seek a way to institutionalize the EWS. This could be at the national authority of disaster risk management, or maybe local organizations can have a local EWS that joins a national initiative or common framework to prevent negative impacts of continental floods. This could be the way in which meteorological and streamflow information is delivered using local resources and a popular language, so people that live and work in areas vulnerable to continental floods can be protected from this and other natural hazards.

4. Conclusions

The analysis of global research on continental flood EWS reveals several noteworthy trends and patterns. Firstly, despite the primary focus on flooding, a significant portion of EWS research revolves around precipitation as a variable in modeling approaches. Secondly, the influence of climate change emerges as a prominent theme in EWS research, although distinguishing between climate change and climate variability warrants further investigation. Thirdly, Europe, particularly England and Italy, dominates research efforts in flood-related EWS, with notable contributions also observed in the Niger Basin. Conversely, the limited representation of regions such as Central America, Asia, and Oceania in the literature underscores the need for greater attention to regions facing significant flood risks. Lastly, the concept of Total Link Strength emerges as a valuable metric, highlighting the collaborative networks established by European countries and the United States in advancing research on flood-related EWS.

Based on these findings, several recommendations can be proposed to enhance the effectiveness and inclusivity of research on continental floods EWS. Firstly, there is a need for greater diversity in research focus beyond precipitation and modeling, including a broader consideration of socio-economic factors and community resilience. Secondly, efforts to address the impacts of climate change on continental floods should include robust methodologies to differentiate between climate change and natural climate variability, ensuring more nuanced analyses and targeted interventions. Thirdly, fostering collaboration and knowledge-sharing among researchers from diverse geographic regions, particularly in underrepresented areas like Central America and other latitudes such as Asia and Oceania, can enrich the discourse and enhance the applicability of EWS solutions globally. Additionally, policymakers and funding agencies should prioritize initiatives aimed at strengthening research capacities in vulnerable regions, thereby fostering more equitable and comprehensive approaches to flood risk management.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geohazards5030030/s1, Table S1: Databases.

Author Contributions: Conceptualization, O.C.-S. and A.Q.-R.; methodology, O.C.-S. and A.Q.-R.; software, O.C.-S. and A.Q.-R.; validation, O.C.-S. and A.Q.-R.; formal analysis, O.C.-S. and A.Q.-R.;

investigation, O.C.-S. and A.Q.-R.; writing—original draft preparation, O.C.-S. and A.Q.-R.; writing—review and editing, O.C.-S. and A.Q.-R.; visualization, O.C.-S. and A.Q.-R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All the used data for this study is provided in the Supplementary Materials.

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Conflicts of Interest: The authors declare no conflicts of interest.

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