

## Article

# Flood Models: An Exploratory Analysis and Research Trends

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**Abstract:** Floods can be caused by heavy rainfall and the consequent overflow of rivers, causing low-lying areas to be affected. Populated regions close to riverbeds are the sectors most affected by these disasters, which requires modelling studies to generate different scenarios. The work focuses on the bibliometric analysis of the search for topics such as flood modelling focused on the research, risk, and assessment of these catastrophes, aiming to determine new trends and tools for their application in the prevention of these natural disasters. The methodology consists of: (i) search criteria and database selection, (ii) pre-processing of the selected data and software, and (iii) analysis and interpretation of the results. The results show a wide range of studies for dimensional analysis in different flood scenarios, which greatly benefit the development of flood prevention and risk strategies. In addition, this work provides insight into the different types of software and modelling for flood analysis and simulation and the various trends and applications for future modelling.

**Keywords:** flood; inundation; bibliometric analysis; co-occurrences analysis; bibliometric



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## 1. Introduction

Floods resulting from overflowing rivers, canals and high rainfall have caused various socio-economic and environmental problems and loss of life throughout history, as in the case of Thailand [1], Ganges (India) [2,3], Magdalena river (Colombia) [4], Niger (Niger and Nigeria) [5,6], and Elba (Italy) [7].

Due to the frequency and damage to life and ecosystem, and as mentioned by Lim and Foo [8], these events are one of the most devastating natural disasters worldwide (40% of the total), affecting more than 4.2 billion people and economic damages exceeding 2.97 trillion dollars in the last 20 years. These effects cause the displacement of populations to more protected areas, as in Africa [9]. There are also alterations in the different ecosystems or natural heritage sites protected by UNESCO. Arrighi [10] highlights that out of 1121 sites, 35% of natural areas and 21% of mixed (cultural and natural) sites are exposed to flooding, especially in Europe, North America, and Asia-Pacific.

These areas also experience the so-called monsoons, strong winds that cause rainfall at any time of the year, causing drastic changes in the climate and extending several kilometers, as is the case in the western North Pacific [11]. Moreover, these events can occur

abnormally, which directly affects the ecosystem, inhabitants and the productive sector in times of drought and floods [12,13], encouraging the prediction of these events using different tools such as remote sensing [14].

Another factor involved in flooding is climate change, one of the main influences on sea-level rise, with the rate of inundation increasing over time, as does the demographic of the population [15,16]. Studies such as Johnston et al. [17], highlighting the effects of flooding on the coasts of the United States caused by storm surges, sea level and land subsidence due to overexploitation of aquifers, predict a significant increase of 61% in the risk of flooding for their inhabitants. In addition, this factor influences the proliferation of other natural phenomena such as the South American monsoon system [18] and the El Niño phenomenon, one of the natural events that contributes considerably to the generation of floods and damages thousands of victims [19].

Due to various factors, the majority of floods can be in different types, such as (i) fluvial floods, mainly by the overflowing of rivers caused by heavy rains or upstream dams [20,21]; (ii) pluvial floods, which occurs in highly saturated or impermeabilized terrain (e.g., urban areas), due to heavy rains even in the summer season by to monsoon winds [22–24]; (iii) flash floods, caused by the sudden increase in the intensity of the rains and the influence of groundwater recharge and the release of water stored in dikes or dams (natural or artificial), destroying the natural and anthropogenic environment due to the speed and force of water [25–27]; and (iv) coastal floods, generally caused by the action of the wind in the waves of the sea and the seismic movement under it (e.g., tsunami), causing flooding on the coastal edges of the continent [28,29]. These events affect coastal areas, which are the most densely populated and developed places globally, and the most intensely impacted by marine and river flooding [30].

The overflowing of canals, rivers and dykes due to high rainfall is one of the leading causes of flooding [31]. For this reason, different studies have been carried out to reduce their impact, such as the construction of a lateral flood overflow channel [32], allowing the recovery of river habitat and influencing the environmental impacts caused by hydropower dams [33]. Likewise, heavy rainfall and collapse of the sewage and stormwater systems in urban areas are the leading causes of flooding, and failures in the storage capacity of wastewater treatment plants, leading to environmental pollution due to overflowing [34,35].

In general, periodic flooding causes environmental and socio-economic problems in a given sector; however, it is considered part of a natural cycle that can generate environmental and social benefits in areas with water scarcity [36]. Therefore, it is necessary to generate models to prevent damage caused by floods and to encourage water management as a solution to drought problems [37].

To achieve this aspiration, and according to the systematic review by Teng et al. [36], several studies and method types of modelling have been carried out for decades about floods (see Table 1). These simulations require various inputs such as the use of DEMs [38,39], analysis of extreme rainfall events [40], geomorphic catchment parameters (soil type and storage porosity [41–44], land use variability, roughness [45]), satellite rainfall estimation [46], and combination of geometric, and hydrodynamic aspects [47,48].

**Table 1.** Classification of methods and models by their main characteristics [36].

Methods and Models	Main Characteristics
Empirical methods	Easy to implement and supports other modelling methods (calibration and data validation).
Hydrodynamic models	Focuses on simulating the movement of the flow in 1D, 2D and 3D through mathematical models.
Simplified conceptual models	It is efficient from a mathematical approach, does not require precision in the flow dynamics and has a low computational cost.

In general, all these studies contribute efficiently to the present field. However, limited research has aimed to compile information through publishing statistics about on flood modelling analysis, and risk assessment. Therefore, one way to compile previous experiences and analyse their internal structure is using a bibliometric analysis, which allows observing the behavior of different disciplines within a given field of study. This way, one can assess multidisciplinary scientific production, explore potential research areas, and determine potential trends [49].

In this context, review and bibliometric work has been carried out, focusing on (Table 2):

**Table 2.** Reviews and bibliometrics in the area of flood research.

Title	Database	Objective	Sources
Flood Risk Analysis and Assessment, Applications and Uncertainties: A Bibliometric Review	Web of Science (WoS) (FRAn * > 9800 records) (FRAs ** > 7100 records)	To assess the historical development of Flood Risk Analysis and Assessment (FRA) and the prospects of emerging fields of application.	[50]
Multidimensional flood risk management under climate changes: Bibliometric analysis, trends and strategic guidelines for decision-making in urban dynamics	Web of Science (WoS) and Scopus (Elsevier) (52 documents)	Floods in the face of climate change and their impact on more frequent and more extensive flooding.	[51]
Flood inundation modelling: A review of methods, recent advances and uncertainty analysis	It does not present a database	Review state-of-the-art flood models to explore their advantages and limitations and discuss future approaches.	[36]
GLOFs in the WOS: bibliometrics, geographies and global trends of research on glacial lake outburst floods (Web of Science, 1979–2016)	Web of Science (WoS) (892 documents)	Glacial lake outburst flood research, global bibliometrics, geography and trends review.	[52]

\* FRAn: Flood Risk Analysis; \*\* FRAs: Flood Risk Assessment.

All those reports were focused on floods, their analysis, and risk prevention. However, little is known about the interrelationship of conceptual and empirical models as optimal tools to evaluate flood risk. Hence, what are the issues, tools, and trends of flood modelling research through bibliometric analysis and mapping?

For this reason, this research aims to determine trends and tools of flood modelling through analysis and bibliometric mapping across the Scopus and Web of Science (WoS) databases, to implement methods, tools, and solutions to these natural disasters.

The content of this research consists of (i) a brief introduction of the topic of interest, its content and achievements throughout time, (ii) a description of the materials, computational tools and methods applied for data selection, downloading and processing, (iii) results and discussions of the findings, and (iv) concluding remarks.

## 2. Materials and Methods

Exploratory analysis of a field of study can occur through systematic reviews [53]. These studies make it possible to analyse the intellectual structure of an entire topic of interest and present reliable information on the most representative findings and recent studies [54,55]. Bibliometric studies have a rigorous and formal analysis similar to the systematic (traditional way), allowing the exploration of different areas of knowledge and determining research trends [49]. Thus, the study focuses on this latter.

### 2.1. Research Approach: Bibliometric Analysis

A bibliometric analysis involves implementing optimal tools or software for the management of an extensive database, which holds the bibliographic data of the thousands of documents linked to this area of study [56]. Furthermore, considering quantitative

research due to the use of numerical data, based on statistics and content analysis of the interrelated documents, a cumulative knowledge system or network can be constructed by showing the themes, theories, methods, groups and research trends within a field of interest [57,58]. These studies are of most interest in various subject areas [59–62].

2.2. Research Method

To carry out the objective of this article, a methodological process consisting of three phases was established (Figure 1): (i) search and selection of data, (ii) pre-processing of data and software, and (iii) analysis and interpretation of results.

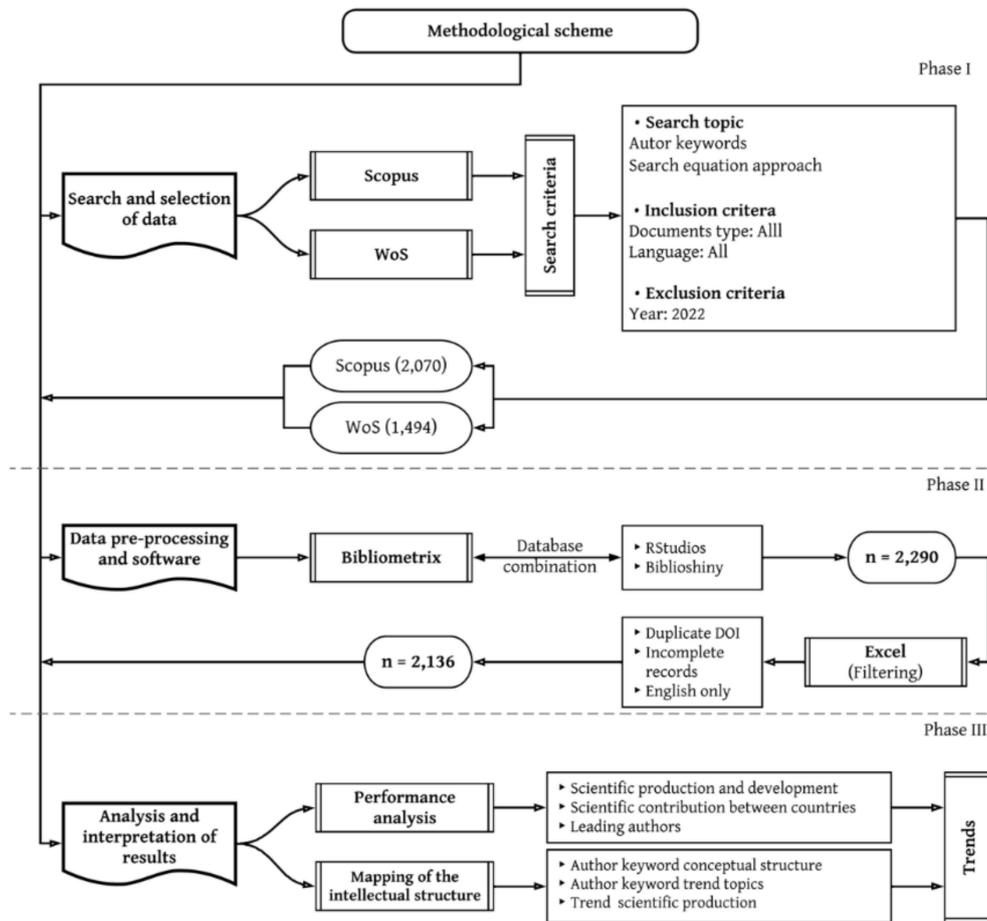


Figure 1. Methodological outline for bibliometric analysis and mapping of the research field.

2.2.1. Phase I. Search and Selection of Data

The quest for appropriate terms for the bibliometric study focuses on keywords associated with flood modelling using a bibliographic review and expert elicitation. The work carried out in the present theme (Table 2) allowed us to determine terms such as “flood” [50,52], “inundation” [36] and “flooding” [51], to which we added the term “model” and its synonyms to refer to the study of flood modelling. Furthermore, similar to the study by Díez-Herrero and Garrote [50], the search adjusted with the terms “risk”, “analysis”, and “assessment” with the objective of FRAs, which focus on reducing probability, risk and vulnerability to floods [63].

Researchers can download academic information from different databases like Google Scholar, Microsoft Academic, Scopus, Dimensions, Web of Science (WoS), and COCI from OpenCitations, multidisciplinary platforms with many documents commonly cited [64]. Therefore, based on the bibliographic review (Table 2), this study focuses on analyzing the data collected from Scopus and WoS. This decision is because those are multidisciplinary

databases covering most internationally reputed peer-reviewed articles and journals [65–67]; they have an extensive field of analysis and are the most widely used within statistical automated literature review [68,69].

To fulfil the objective of this study, the search equation based on titles, abstracts and keywords exposed with the inclusion of Boolean operators: (TITLE-ABS-KEY (“flood model\*”) OR TITLE-ABS-KEY (“flood modelling\*”) OR TITLE-ABS-KEY (“inundation model\*”) OR TITLE-ABS-KEY (“inundation modelling\*”) OR TITLE-ABS-KEY (“flood inundation modelling\*”)) AND (TITLE-ABS-KEY (“assessment\*”) OR TITLE-ABS-KEY (“risk\*”) OR TITLE-ABS-KEY (“analysis\*”)).

Table 3 shows the number of publications for each keyword:

**Table 3.** List of keywords and number of documents.

Keywords	Results	
	Scopus	Web of Science (WoS)
“flood model”	2164	1102
“flood modelling”	747	367
“inundation model”	1084	664
“inundation modelling”	257	133
“flood inundation modelling”	199	67
(“flood model” OR “flood modelling” OR “inundation model” OR “inundation modelling” OR “overflow flood model*”) OR “overflow flood modelling” OR “flood inundation modelling”) AND (“assessment” OR “risk” OR “analysis”)	2070	1494
<b>Scopus AND Web of Science (WoS)</b>		
(“flood model” OR “flood modelling” OR “inundation model” OR “inundation modelling” OR “overflow flood model*”) OR “overflow flood modelling” OR “flood inundation modelling”) AND (“assessment” OR “risk” OR “analysis”)		2290

The search was carried out for all types of documents in April 2022 (albeit up to December 2021) and obtained 2070 publications in Scopus and 1494 in WoS, with their respective year of publication.

### 2.2.2. Phase II. Pre-Processing of Data and Software

From phase I, a resulting text file format (.txt) consolidated the information from Scopus and WoS. It contains the data of each publication, such as authors’ names, references, affiliations, number of citations, title and year of publication, which are necessary for a bibliometric analysis [70,71]. Nevertheless, this information requires pre-processing in different programs before bibliometric analysis, such as:

- A combination of databases, was carried out through Bibliometrix 3.1 in RStudio programming language (version 4.1.2), obtaining a single record of the entire study area and using it for the bibliometric analysis [72].
- Data cleaning, Microsoft Excel software (version 2021) used to read and modify the extracted “.xls” file, adjusting its content and eliminating non-useful information such as publications without authors and duplicate doi. In addition, this analysis focuses on publications in English because this language represents 92% of the entire database [73,74].
- Bibliometric mapping, performed in Biblioshiny. It is a bibliometrix interface that allows the inclusion of bibliographic information from various databases such as Scopus, WoS, Dimensions, PubMed, and Cochrane [75]. This very recent package is also part of the R language, used for bibliometric and scientometric research [72,76–78].

### 2.2.3. Phase III. Analysis and Interpretation of Results

This paper examines the interactive graphics that represent the two main pillars of this bibliometric analysis:

- (1) Performance analysis focuses on the evolution of the research field according to the publications reported within a defined period (i.e., 1972–2021), determining its current domain, most relevant documents and, in general, any further analysis based on the extracted bibliography [79,80]; and
- (2) Mapping its intangible and non-visible intellectual structure within the field of interest determines the existing interconnections between publications, authors and countries, which allows us to know the direction or trends of research [81,82].

### 3. Results

There were 2290 publications coming from the Scopus and WoS databases, where 1274 documents represented the combined database (Figure 2). To improve the quality of the information, this file was filtered in Microsoft Excel, excluding publications that either were not in English, with duplicate doi, or with missing information as authors, keywords, title, doi and abstract. Moreover, Figure 3 shows the content or contribution of each database, resulting in 2136 used publications.

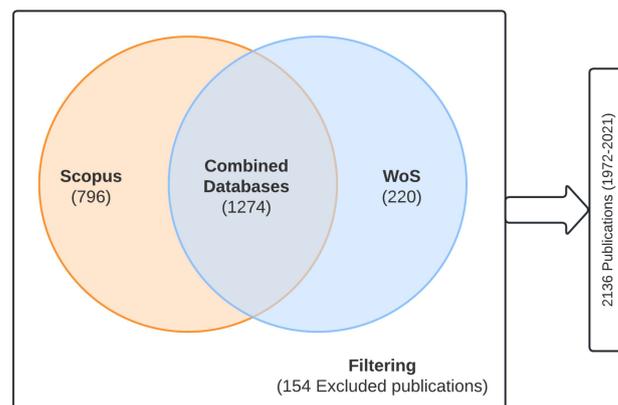


Figure 2. Distribution of publishing sources about floods.

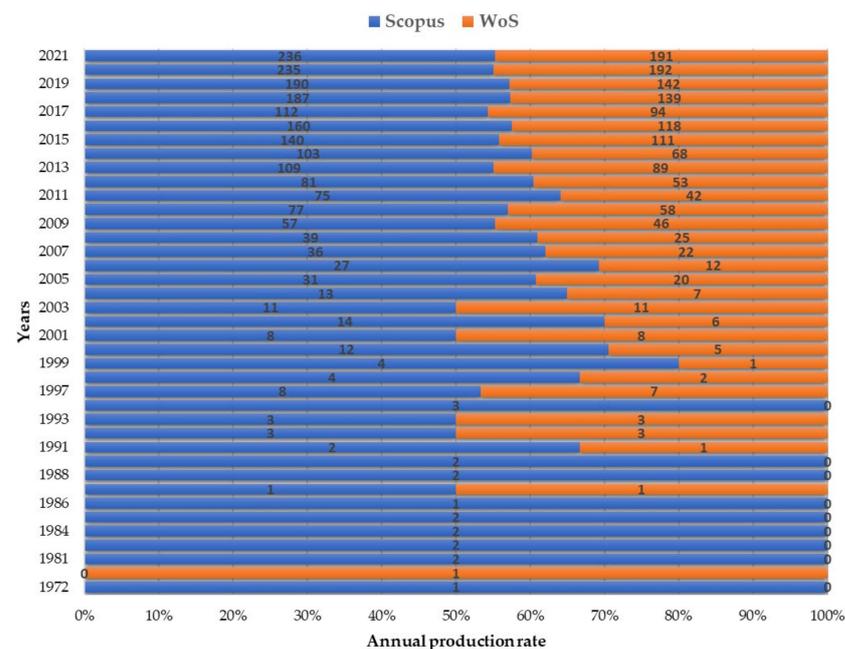


Figure 3. Contribution of databases (Scopus and WoS).

Table 4 presents the general information from the two databases used to analyse the two bibliometric approaches (performance analysis and mapping of the intellectual structure).

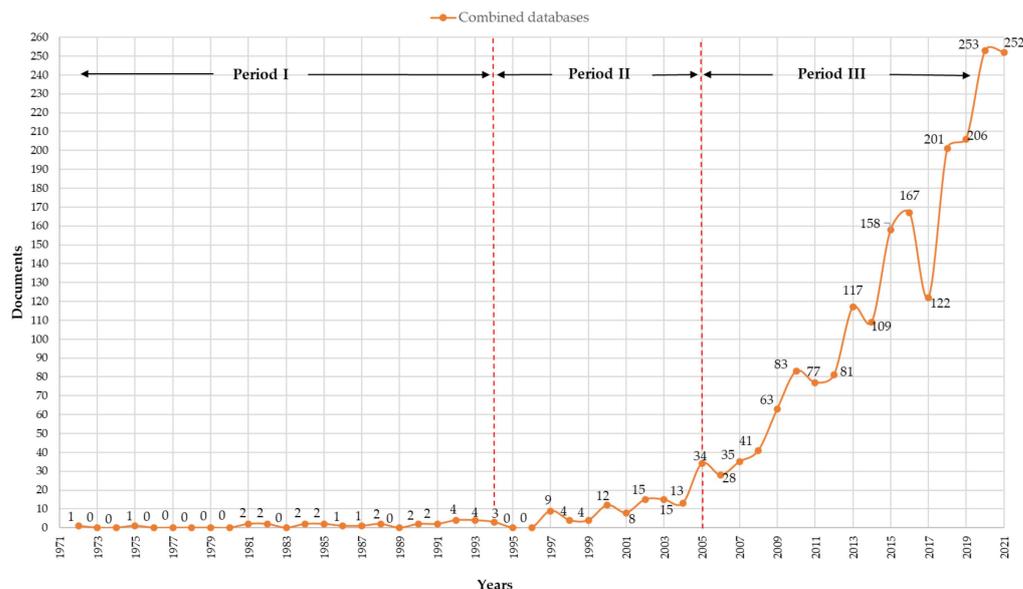
**Table 4.** Main data of the combined database.

Main Information	Results
Documents production	
Sources (Journals, Books, among others)	775
Documents	2136
Average years from publication	7.06
Average citations per documents	18.73
Average citations per year per doc	2.302
References	60,637
Document contents	
Keywords	4598
Authors	5649
Author appearances	8903
Authors of single-authored documents	107
Authors of multi-authored documents	5542
Authors collaboration	
Single-authored documents	118
Documents per Author	0.378
Authors per Document	2.64
Co-Authors per Documents	4.17
Collaboration Index	2.75

### 3.1. Performance Analysis

#### 3.1.1. Scientific Production and Development

Figure 4 shows the exponential growth of scientific production from 1972 to 2021. In that regard, according to Price’s Law [83], it can be established that this field of this study has promising research potential. During the period 2005–2021 there is a remarkable increase in production.



**Figure 4.** The annual production of the study field from flood modelling.

The study reviews 50 years of historical record; thus, the analysis focused on three critical periods strategically distributed according to the change in visible curvatures (Figure 4):

- Period I (1972–1994) has negligible growth due to only 29 publications in the first 23 years of study, referring to a nearly constant introduction and production stage, focusing on the generation of stochastic models based on mathematical and probabilistic formulations applied to the principle of continuity [84,85]. These models initiated the flood risk analysis, using extreme values of rainfall and runoff and associating them to a return period through methods such as Poisson's [86,87]. However, in discrete models, Bayesian methods were used for better accuracy of the results, to avoid a linear relationship between the calculations and the input parameters [88,89];
- Period II (1995–2005) has 114 publications and linear growth during the following eleven years of study. It focuses on a phase of development and evolution of modelling, focusing on urban areas and 1D-2D hydrodynamic simulations [90,91], allowing for analysis of their effects and establishing prevention measures [92]. Since this period, different computational tools and devices have been used, which facilitate the collection and resolution of data for better accuracy of the simulations, for example, the use of Light Detection And Ranging (LIDAR) [93,94], essential for the optical resolution and digital construction of the terrain; and
- Period III (2006–2021) has an exponential growth due to the development of 1993 publications in the last 16 years, focusing on the development of mathematical, distributed and hydraulic modelling. These models at the beginning of the study and this stage relates to 1D and 2D (fluvial and coastal) shallow flood simulations [95], risk analysis, socio-economic consequences and morphological and hydrological data of the watersheds [96], further including 3D analysis in coastal systems and estuarine environments [97,98]. Furthermore, this period highlights the technological growth and the use of remote sensing in a more progressive way than in the previous period, with more powerful computational tools and modelling methods used for a better quality of results [36,99], as well as media as data sources [100,101]. In this context, significant advances have been made over the last decade, highlighting its impact on society worldwide [102,103], focusing mainly on the analysis and assessment of flood risks caused by climate change [104]. These are addressed through flood mapping to identify the most susceptible areas (local/global) and provide guidelines for forecasting and future risk assessment [105,106].

### 3.1.2. Cross-Country Scientific Contribution

The interrelationship between countries provides insight into knowledge development through collaboration between authors globally [107]. In this field of interest, 95 countries have collaborated in this field of research. From those, 50 countries have at least five articles in collaboration with others. In Figure 5, contributions appear in a range of colors (from deep blue to light blue).

The main contributor are institutions from the United States (USA), with 797 publications. In addition, the USA has collaborated with 51 countries in different topics such as the application of new methods for urban flood modelling [108], large-scale forecasting [109] and improvement of the spatio-temporal resolution of data [110]. Among these countries, participation with the United Kingdom, China, and Italy in various research studies such as coastal flood risk is noteworthy [111].

The second-largest contributor is the United Kingdom (UK), with 596 publications. They have cooperated with 38 countries on a wide range of research, including remote tool evaluation and resolution improvement in urban areas [112,113], as well as continental and global scale forecasting [109,114]. However, like the USA and China (third contributor with 455 publications), there is a similar interest in climate change and flood propagation [115]. In addition, China has collaborated with 34 countries, focusing on topics such as the assessment of flooding under extreme historical rainfall conditions [116], the recording

of historical data for use and corroboration of results [117], and the evaluation of global modelling through satellite information [118].

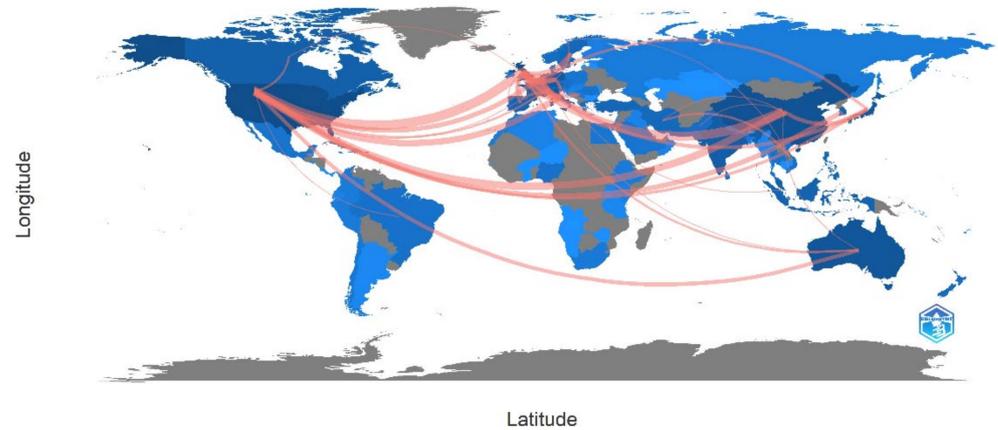


Figure 5. Country collaboration map.

In addition, Figure 6 shows the scientific collaboration in terms of citations. The United Kingdom presents 9305 citations due to the cooperation of its researchers with different academic institutions, followed by the United States and the Netherlands.

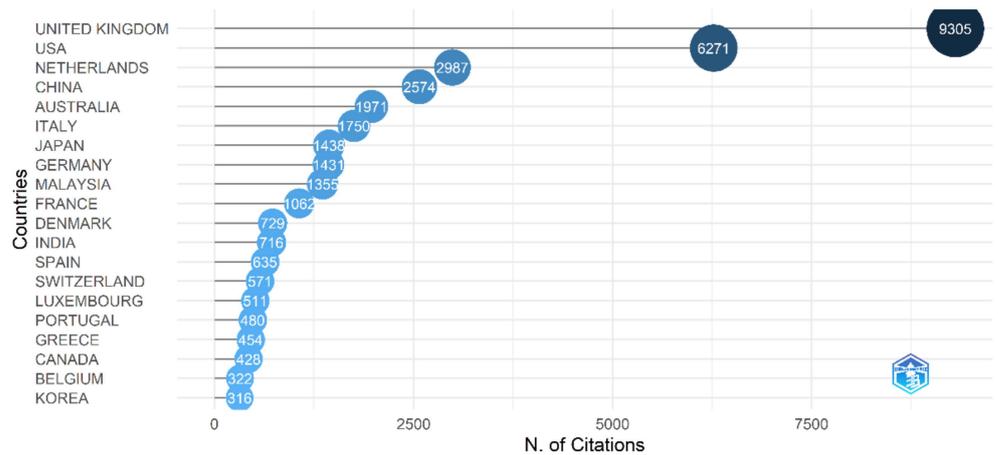


Figure 6. Top 20 countries by the number of citations.

### 3.1.3. Featured Authors

By means of this kind of analysis, it was possible to know individually the researchers who have provided valuable information through these studies [119,120], in which there is a total of 5649 authors. Figure 7 is a statistical graph over time, showing the ten most productive and cited authors during this study period.

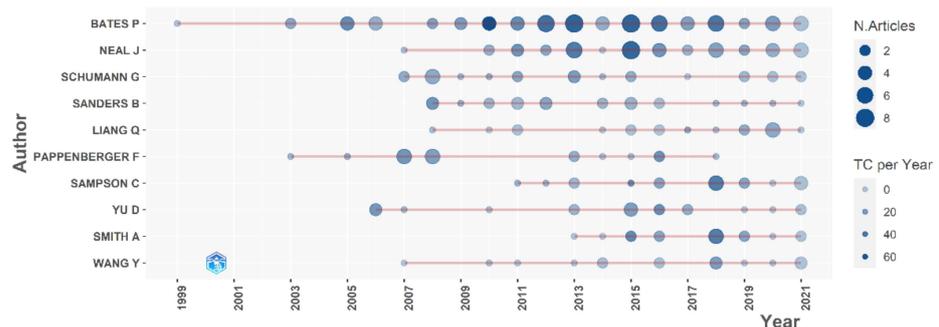


Figure 7. Top-Authors’ Production over time. Number (N) of articles y Totals Cites (TC) per year.

The top ten authors in this field have the following affiliations: University of Bristol (UK), University of California-Irvine (USA), Loughborough University (UK), European Centre for Medium-Range Weather Forecasts (UK), University of Science and Technology of China, University of Southampton (UK) y Ruhr-Universität Bochum (Germany).

Overall, this range of contributors dates from 1999 to 2021, with Bates P. making the most significant scientific contribution (79 papers) and 1181 citations. His contributions began with a focus on river flow dynamics and floodplain dynamics [121]. Over the last decade, he has developed equations for a two-dimensional model [95]. In addition, in collaboration with other authors, Bates identified key challenges such as global terrain data, extreme flow generation, global river network and geometry, flood defenses, computational hydraulic engine and automation framework [122] (p. 3). In addition, Neal J. (45 papers and 434 citations) and Schumann G. (24 papers and 242 citations) have had a near-constant output since 2007 and maintain collaboration with Bates.

Table 5 shows the ten researchers with the highest number of citations, focusing on publications related to this field of study. These authors belong to countries such as the United Kingdom and the United States, which have the highest number of publications and citations worldwide, corroborating the previous results. Finally, the H-Index shows the authors' impact, which corresponds to the ratio between the number of global citations and all the publications made, highlighting Beven K., Bates P. and Pappenberger F.

**Table 5.** Leading authors by the number of citations in flood modelling. Total Cites (TC) and Number of Publications (NP).

Authors	Affiliation	Country	TC	NP	H-Index (Scopus)	H-Index (WoS)
Bates P.	University of Bristol	United Kingdom	1181	79	84	82
Neal J.	University of Bristol	United Kingdom	434	45	41	38
Horritt M.	Horritt Consulting, Ross-on-Wye	United Kingdom	383	10	37	32
Fewtrell T.	Willis Towers Watson, London	United Kingdom	379	8	14	11
Sanders B.	University of California, Irvine	United States	267	23	41	41
Sampson Christopher C.	Fathom, Bristol	United Kingdom	246	19	21	21
Schumann G.	University of Bristol	United Kingdom	242	24	40	36
Schubert J.	University of California, Irvine	United States	238	14	17	18
Pappenberger F.	European Centre for Medium-Range Weather Forecasts	United Kingdom	233	19	56	56
Beven K.	Lancaster Environment Centre, Lancaster	United Kingdom	203	14	96	91

### 3.2. Mapping of the Intellectual Structure

#### 3.2.1. Author Keyword Conceptual Structure

A clustering method based on Callon’s centrality and density within a matrix [123] was applied, to perform in-depth exploration of the issues involved in flood modelling. In that context, four different quadrants were explored, focusing on: (i) important and developed themes with strong linkages (driving themes), (ii) isolated and high centrality themes, (iii) emerging or declining themes and (iv) core and cross-cutting themes [124].

In period I, only the keyword “flood” is found as the driving theme that initiated this field of study. In contrast, in period II, its development or communication flow is integrated with other driving themes (Figure 8b), which would imply that research containing these words showed a more essential dominance in the study of that period. For example, the studies focused on land use change and the generation of digital terrain models (DEM) through LIDAR images, focusing on improving spatial resolution, determining the changes of that time, and predicting different events until the present. However, some themes had little influence and are almost in equilibrium between development and relevance degree (density and centrality). For example, since 2006, “remote sensing” (frequency: 74) and “gis” (69) have been integrated with “flood modelling” (361) (Figure 8c), which have moved from being essential to driving themes for monitoring satellite data and impact prediction [125,126]. Topics such as “flood” (240), “modelling” (46), “urban flood” (99) and “flood risk management” (42) show an increase in density together with several keywords from the previous period, raising their scientific interest from basic topics to the area close to the motor topics. Likewise, compared to the last period, there are topics such as “coastal flood” (45) that have decreased the degree of relevance, located in an isolated area of research with “sea-level rise” (30) and “storm surge” (30). Conversely, “flood risk” (94), “climate change” (76) and “flood hazard” (60) were found as emerging topics given their increased frequency and interest in different areas, providing research that focuses on atmospheric changes and their influence on floods.

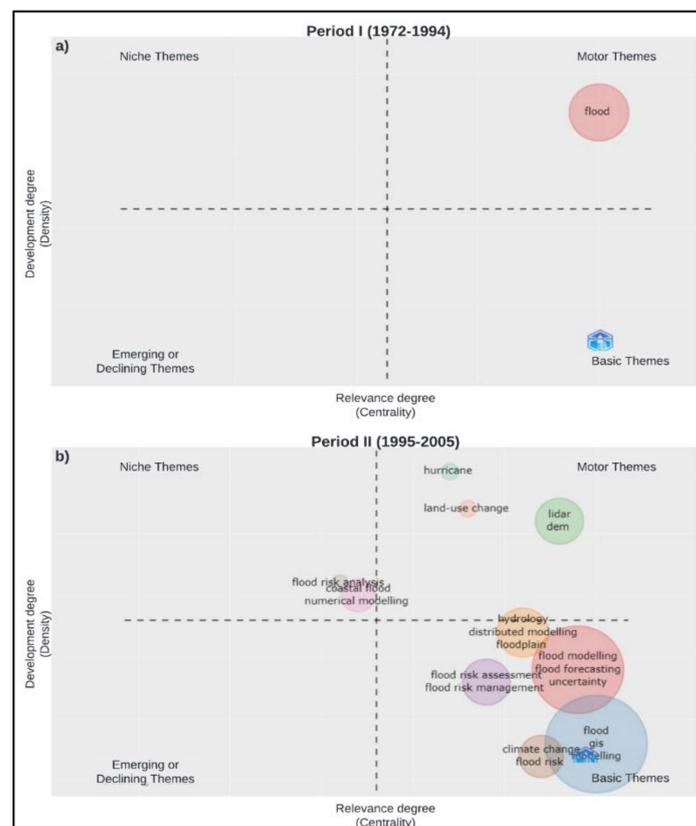
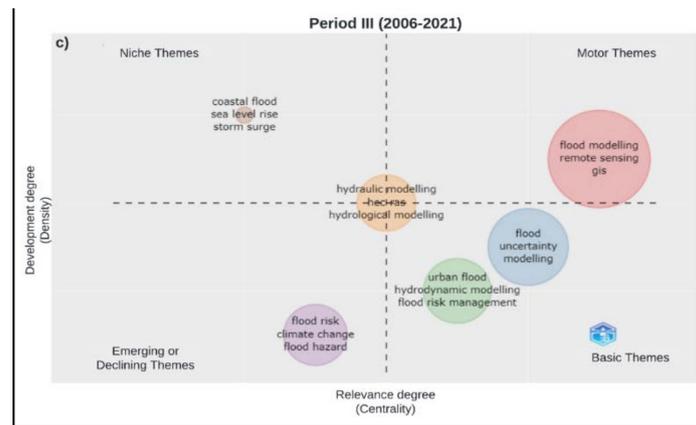


Figure 8. Cont.

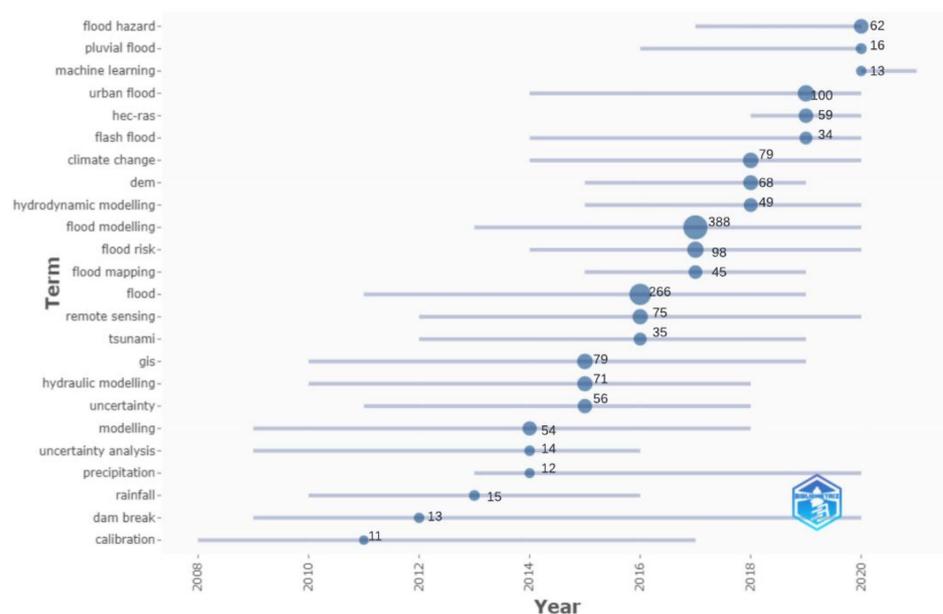


**Figure 8.** The conceptual structure of author’s keywords during the three periods analysed. (a) Grouping of keywords in the first study period (1972–1994); (b) Conceptual structure of period II (1995–2005); (c) Current conceptual structure of keywords (period III, 2006–2021).

It is essential to mention that the most current and representative topics of the evolution of this field of study are found in the last period. Hydrodynamic modelling is a fundamental topic linked to urban areas, so it is an appropriate method to simulate floods and analyze fluid dynamics, allowing better flood risk management in these sectors. This model method allows associating the movement of the flow in different dimensions (1D, 2D and 3D) through mathematical models for the prediction, analysis and simulation of various events. Hec-Ras (58) is a computational tool located in the center of the graph (Figure 8c), as well as “hydrological modelling” (43) and “hydraulic modelling” (63). Hec-Ras allows modelling floods; on the other hand, “hydrological modelling” and “hydraulic modelling”, due to the mentioned location, indicate that these issues are essential and are in force.

### 3.2.2. Author Keyword Trend Topics

This analysis makes it possible to know the field evolution of study according to the frequency of the main topics of interest [71]. Figure 9 shows the thematic development based on three keywords per year, located in the period with the most frequently developing research.



**Figure 9.** Trend topic of authors’ keywords.

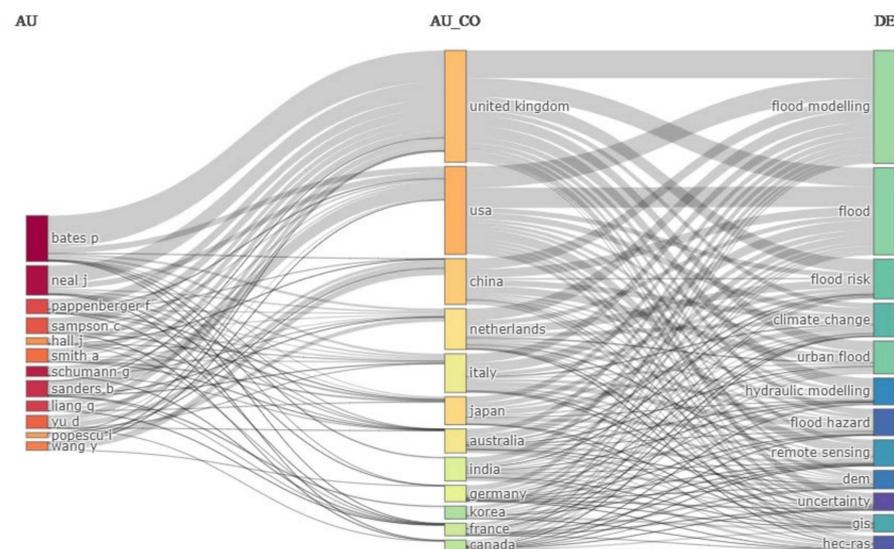
The topics with the most extended period correspond to studies related to dam break, “calibration” and the use of “gis”. In contrast, the issues with the shortest period represent recent studies such as “machine learning” and “hec-ras”.

In a nutshell, this analysis leads to the observed flood modelling (hydrodynamic and hydraulic) through various implements. Examples are the Digital Elevation Model (DEM) [127], Geographic Information Systems (GIS) [128] and remote sensing [36], as well as computational tools such as tools for risk and hazard analysis of these disasters that are being affected by climate change [129]. Moreover, machine learning is a computational method recently designed for this type of study [130]. As a result, different flood scenarios have been developed, and the suitable solutions for a given environment have been applied [131].

### 3.2.3. Trend Scientific Production

The Sankey diagram was utilized to understand the conceptual structure and evolution of the research area by preserving the flow of communication between the different fields [132]. In this way, based on a three-field plot, the interaction between three different categories and their communication flow (from left to right) was identified [71,133], showing the main themes of interest that link through 12 variables in each field established.

The authors visible in the AU column (Figure 10) collaborate with the United Kingdom (UK), where studies have focused on representative topics such as “flood modelling”, “flood risk”, “hydraulic modelling”, “urban flood” and “climate change”. Bates P. is the lead author of this field of study, collaborating with these countries except Korea and France.



**Figure 10.** Analysis of the Sankey diagram. Author–country–keyword intersection.

## 4. Discussion

The evaluation of 50 years of scientific production in Scopus and WoS (1972–2021) identified three periods of publications representing 2136 documents. In Periods I and II (1972–2005, see Figure 4), studies were conducted on urban flooding, especially in disaster management and prevention, using models that have evolved in different dimensional approaches [90–92]. Since 2006 (Period III), the technological growth and use of remote sensing [36,93,99,134] allowed scientific production to increase by 93%.

### 4.1. Scientific Contribution by Country

Ninety-five countries have participated in this research topic. The United States stood out on top of with 797 publications and collaborated with 51 countries (Figure 5). These numbers are in agreement with other bibliometric studies on flooding [50–52]. Publications from this country are mainly related to modelling using GIS applications [135], LIDAR

data [136] and high-resolution topography [137]. These have allowed the establishment of strategies for the management and prevention of floods that generate economic and human losses, especially in urban areas [138–140], and in different circumstances, such as tsunamis [141–143] and the effects of climate change [144–147]. In the impact analysis based on the number of citations (Figure 6), the United Kingdom is the country with the highest number (9305 in 596 publications) due to several studies such as the formulation of new equations for two-dimensional modelling [95], climate change and wetland loss [148], urban flood [134] and high-resolution hazard modelling at a global level [122].

#### 4.2. Scientific Contribution by Authors

An analysis by authors worldwide indicates that there are three influential authors (Figure 7), researchers from the University of Bristol (United Kingdom) who have a large number of publications: (i) Bates P. (79 publications and 1181 citations), has been cited since 1999 on topics such as the application, development and challenges encompassing flood models [89,95,122,149]; (ii) Neal J. (45 publications and 434 citations), has focused on similar topics as Bates such as the application of two-dimensional models and flood mapping [150,151]; while (iii) Schumann G. (24 publications and 242 citations) is related to the previous researchers in the modelling of large-scale forecasts, in collaboration with other countries such as the USA and China [151]. In contrast, a citation analysis (Table 5) shows the integration of other researchers, such as Horritt M. and Fewtrell T. They are involved in several research projects mentioned above by researchers from the University of Bristol (Bates P., Neal J. and Schumann G.).

#### 4.3. Analysis of Issues, Tools and Trends

Topics such as “flood” and “modelling” are essential topics relevant over time (Figure 8b). However, when combined they link to “flood modelling” (especially during the last decade), generating important research (Figure 9). The application and analysis of flood modelling allows one to support and quantify the effects caused by these disasters, facilitating the study of floods for damage prevention [95,134,152]. This topic started as a basic theme in flood forecasting and uncertainty (Figure 8b), developing in recent years as a driving theme within this field of study (Figure 8c).

Among the different modelling approaches is “hydraulic modelling”, with an increase similar to “GIS” (Figure 9), which denotes its link to flooding and damage prevention issues [153–155]. Another theme is “hydrodynamic modelling”, highlighted in the last decade (Figure 9). This links with an in-depth analysis of dynamic factors in floods, achieving assessments in the large floodplain and riverine areas [21,127,156], where “hec-ras” is an essential hydrodynamic modelling tool for these analyses. Based on a similar study, Teng et al. [36] mentioned the importance of this modelling for assessing the impact of tsunamis, dam failures or flash floods.

The use of various tools allows the generation of models and simulations, such as “gis”, which allows the processing of the information collected on rainfall, elevations, slopes, land use and geology [135,152,157], managing to generate thematic maps that show the vulnerable areas according to the flood probability index [91,158]. This tool has a long period of study (Figure 9), evolving from a basic theme to a driving theme within this field (see Figure 8b,c). Another computational tool is “hec-ras”, in which floods can be simulated and analyzed from different perspectives (Figure 8c) [159], as well as bringing together different modelling approaches for flood hazard analysis (see Figure 8c) [160]. From the second decade of the 21st century, this software has gained relevance in research on modelling types for flood hazard and risk assessment [128,161–163]. In the case of hec-ras [164], this could be due to its ease of use, free-license nature, especially in developing countries, compared to commercial or other similar computational packages.

The term “calibration” has been a constant topic for almost ten years (Figure 9). This is an indispensable tool and a fundamental requirement for the successful application of inundation models [165], mainly to increase the degree of reliability of results in these

events (e.g., calibration of the Manning's coefficient [166,167]). On the other hand, remote sensing has improved the resolution and extent of models and further risk evaluation, generating susceptibility maps for flood triggers [152,168–170]. This growth has been most evident since 2012 (Figure 9) and the linkage with various countries (Figure 10).

Climate change is related to the spread and increase of natural disasters [145,171], which are caused by variations in sea level, cyclonic tides, precipitation [172–174] and the variability of extreme events [104,175,176]. Furthermore, this topic can be considered an emerging theme due to the increase in research on flood modelling since 2014 (Figure 9), as evidenced by the scientific interest of several countries and researchers (see Figure 10), and the linking of flood risk and hazard analysis to these natural changes (Figure 8c). Therefore, their study is essential for the management and development of preventive strategies, reducing their impact on populated and environmentally vulnerable areas [177–180].

In the last three years of study, the term “machine learning” (Figure 9) benefits and increases the knowledge of flood simulations in a more automated way [131]. Moreover, it generates greater profitability and efficiency in flood forecasting, providing the model with autonomous development through a database and a set of algorithms such as artificial neural networks [181]. Also, since 2014, terms such as “urban flood” and “flash flood” have emerged that are driven mainly by the extreme rainfall of “climate change”, highlighting the importance of flash flood analysis and prevention in urbanized areas, linking to the previous terms “dam break” [40,182], which have remained constant over time in this field of study (Figure 9). The latter has been reflected in the application of hydrodynamic modelling, as studied by Teng et al. [36].

## 5. Conclusions

This study shows the development and evolution of this field of research, which relates to floods from a modelling perspective. This topic is considered a means for risk analysis and developing strategies for managing and evolving these events. Scientific production increased from 2006 onwards by formulating new equations for 1D and 2D flood modelling. In general, there are several issues for flood modelling that are of interest to academia: (i) the causes of climate change; (ii) effects on wetland loss; (iii) mapping of susceptibility zones; and (iv) application of new computer modelling tools in affected areas (urban areas, flood plains, levees, among others).

The United States has the largest distribution of researchers (Figure 5), which shows collaboration with more than 50% of countries publishing in this field. In contrast, when looking at the analysis by citations, most researchers belong to the United Kingdom with more than 596 publications (Table 4). However, these publications have a relationship with authors from the USA.

Various computational tools allow the generation of flood models, focusing on hydrology, hydraulics and hydrodynamics, generating event simulation, strategy planning, management and damage prevention. However, in this study, it has been determined that hydrodynamic modelling has a broad scientific interest worldwide through several researchers due to the analysis of the fluid dynamics in these disasters, which allows to have results more in line with reality.

Global study trends focused on:

- Flash floods have a more significant impact on urban areas due to the speed of propagation, economic damage, loss of human lives and triggering factors such as tsunamis or dam failures;
- Flood risk and hazard are analysis subjects through modelling for management and preventive strategies;
- Dam failures, with a focus on the impacts on urban areas due to their economic impact on society;
- Climate change is an important issue linked to flood modelling due to changes in the nature and the increased frequency of extreme events;

- Hydraulic and hydrodynamic modelling. Modelling topics focus on the controlling factors and aspects that cause floods. They also focus on flow dynamics in urban areas and river floodplains; and
- Machine learning is applied to flood modelling using a set of state-of-the-art data drive and black box algorithms to obtain reliable and accurate results, competing with physically based and hybrid (gray box) models.
- The computer tools with the most significant application in this field of study are:
- Geographic Information Systems (GIS) allowing the processing and mapping of flood-prone areas through hydrological and hydraulic data in a given area;
- Hec-Ras as an open-access multidisciplinary computational tool with a broad domain in modelling issues due to its versatility, free cost, and application in different dimensional approaches; and
- Remote sensing is essential for obtaining information that is difficult to access, improving the quality of results and extending the study area. Among the main derived products are Digital Elevation Models (DEM), soil type and land use maps, which are essential in developing simulations and analyses on various topics such as flooding, widely used in computational packages such as GIS and Hec-Ras.

The contribution of this study focuses on: (i) the opportunity to learn about the scientific collaboration between countries and authors, allowing the identification of recognized researchers in flood modelling, (ii) the most widely used models in the prevention and analysis of these disasters, (iii) the identification of the most relevant trends or research topics in this field of study, and (iv) efficient computational tools for obtaining reliable and accurate results.

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