

Article

Three Decades of Groundwater Drought Research: Evolution and Trends

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Abstract: In most parts of the world, groundwater is the main source of their water supply, particularly during periods of drought when surface water is scarce. As a result, groundwater drought is among the most worrying problems of our time. In order to shed light on the diversity of scientific productions related to this theme, this analysis was conducted on 151 publications, 76 sources, and 469 authors using version 4.3.1 of Rstudio's Bibliometrix tool. The clusters and keyword occurrence analysis reveals a research trend towards the use of advanced technologies and a more holistic approach that takes into account the complexity of hydrological systems. The use of drought indices to characterize and monitor groundwater drought, as well as satellite products and their assimilation into Land Surface Models are among the adopted solutions. This was endorsed through a summary of the five most cited publications in this field. The results also highlighted the performance of Chinese institutions in analyzing the various aspects related to this topic, as well as a lack of international collaboration between research structures. In conclusion, this study has enabled us to present the evolution and trends in scientific research and helped to specify the main emerging themes and future areas of research related to groundwater drought.

Keywords: advanced technologies; Bibliometrix; drought indices; emerging themes; groundwater drought; trends



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1. Introduction

Drought is a global scourge often associated with enormous economic and social repercussions, particularly in drought-prone regions where the impact is even more devastating [1]. In many parts of the world, groundwater is increasingly used for their drinking-water supply and irrigation [2,3]. It constitutes a primary or alternative source of water, particularly during periods of drought when surface water is less frequent, which leads to water table depletion and its long-term deterioration [4]. In order to acquire more knowledge of this phenomenon, numerous authors have conducted research on groundwater drought. According to Van Lanen and Peters, groundwater drought is defined as a drop in groundwater levels below a well-defined threshold over a given period [5]. It was defined by Mishra and Singh as a decrease in groundwater flow and storage [6], whereas Goodarzi et al. defined it as a distinct category of drought resulting from decreasing recharge [7]. According to other authors, groundwater drought is generated through the propagation of meteorological drought through the hydrological system [8–12]. Thus, during the early stages of drought, groundwater sources exhibit considerable resilience, while they are highly vulnerable when drought episodes are relatively persistent or prolonged, possibly worsening as a result of climate change [13,14].

In order to strengthen the resilience of groundwater to drought events, it is necessary to adopt responsible and sustainable management strategies that include monitoring and surveillance systems capable of identifying and tracking long-term patterns [15]. As these techniques are mostly expensive and require very advanced human and technological resources [16,17], the contribution of scientific research is crucial in developing cost-effective alternatives that can provide early warnings and proactive measures to prevent the depletion and overexploitation of this vital resource [18,19]. Throughout time, numerous innovative methods have been adopted to tackle this challenge on both local and international levels. As a result, decision-makers and scholars might face challenges stemming from the breadth and rapid pace of scientific development, which makes the mapping of science a demanding and complex task, especially since it often involves a range of expensive and sophisticated tools [20]. In response, a bibliometric analysis was carried out on existing studies to evaluate the present body of literature and aid in the bibliographic compilation of information within this area.

As defined by Rostaing, bibliometrics is a quantitative analysis based on the application of various mathematical and statistical methods to bibliographic references [21]. It uses indicators such as the number of publications, the number of citations, H-index, and g-index, to measure the volume of research and identify trends [22]. It can be used to identify key authors and journals, reference keywords, as well as leading countries and institutions in a given field [23]. Hence, employing bibliometrics in this research is based on their capability to create a clear, uniform, and reproducible evaluation framework anchored in the statistical evaluation of science, researchers, or scientific endeavors [24]. It also has the distinctive feature of providing an overview of the existing research, facilitating the systematic examination of a vast collection of data. It facilitates the identification of patterns and trends over time, the recognition of popular themes, the detection of changes in academic field boundaries, and the pinpointing of leading institutions and scholars [25].

Groundwater and drought research have been examined independently in a number of bibliometric studies. Several issues related to drought were covered using bibliometric analysis, such as drought monitoring [26,27], as well as drought indices, risks and forecasts as components of drought early-warning systems [28,29]. Bibliometric research on groundwater has covered several areas such as submarine discharges [30] and pollution and groundwater salinization in coastal and inland regions [22,23]. However, to our knowledge, no bibliometric study has been conducted specifically on the subject of groundwater drought. In addition to emphasizing the quantitative performance and features of published works, authors, sources, and keywords, this research also connects institutional affiliations, keywords, and countries, which creates a synthetic picture of scientific output. Additionally, it includes an exhaustive examination of the methods used by researchers in investigating groundwater drought. The aim is also to illustrate the relationship among the most critical topics pertinent to the subject, showcasing the evolution of scholarly discourse and identifying key research directions, which represent the foremost emerging topics. In order to direct academic efforts toward important problems, foster innovation, and contribute to the advancement of knowledge in this mostly unexplored subject, this approach aims to uncover insights within the literature and investigate prospective research paths relevant to groundwater drought.

2. Materials and Methods

The methodological framework used to perform a bibliometric analysis, as outlined by numerous writers, consists of many critical components [31,32]. Initially, it starts with collecting data from online bibliographic databases that provide essential metadata about scientific works, like Web of Science, Scopus, Google Scholar, or Science Direct [33]. To ensure consistent and high-quality results, preliminary processing and data cleaning are essential. This step aims to correct inconsistencies such as duplicated publications and variations in the spelling of authors' names, which are common in bibliometric data despite their overall reliability [34]. The data are then formatted in accordance with the

specifications of the bibliometric instruments in use. This stage of analysis encompasses descriptive assessments as well as the development of networks that shed light on the interconnections among different attributes within the database. For instance, it involves establishing connections between authors and journals, as well as correlating keywords with publication dates [35]. Bipartite networks, which are commonly represented as rectangular matrices [36], result from these relationships. Networks are subsequently constructed by analyzing the citations between publications, which allows for the assessment of the influence of different bibliometric entities. For the purpose of optimizing the interconnections among nodes in these networks, a normalization process is executed, utilizing statistical measures such as the Pearson correlation and Jaccard coefficient [37]. Methods to reduce dimensionality, such as principal component analysis, factor analysis, multiple correspondence analysis, and clustering algorithms, may be employed in order to facilitate the interpretation of intricate datasets [24]. The culmination of these analyses is the creation of scientific maps, which visually depict the structures and dynamics of the field under study.

The key steps in developing this analysis are summarized in Figure 1. The study was carried out on published scientific documents listed in the Scopus database. Developed by the scientific publisher Elsevier in collaboration with several research institutions, researchers, and librarians, this database offers abstracts and full citations with full-text links covering a wide range of disciplines [38]. The data used in this analysis was retrieved on 5 August 2023, through a search using the keyword “Groundwater drought”, and applying the search filter “Title, abstract, keyword”. The references selected for this study are “Articles, Conference papers and Book chapters” published between 1989 and the database extraction date. This indicates that the search engine scans the titles, abstracts, and keywords of the specified scientific documents in the Scopus database to locate the term “Groundwater drought”. Up to 98% of the documents resulting from our research are published in English. Therefore, English was adopted as well as a search criterion to ensure uniformity in the language of the keywords.

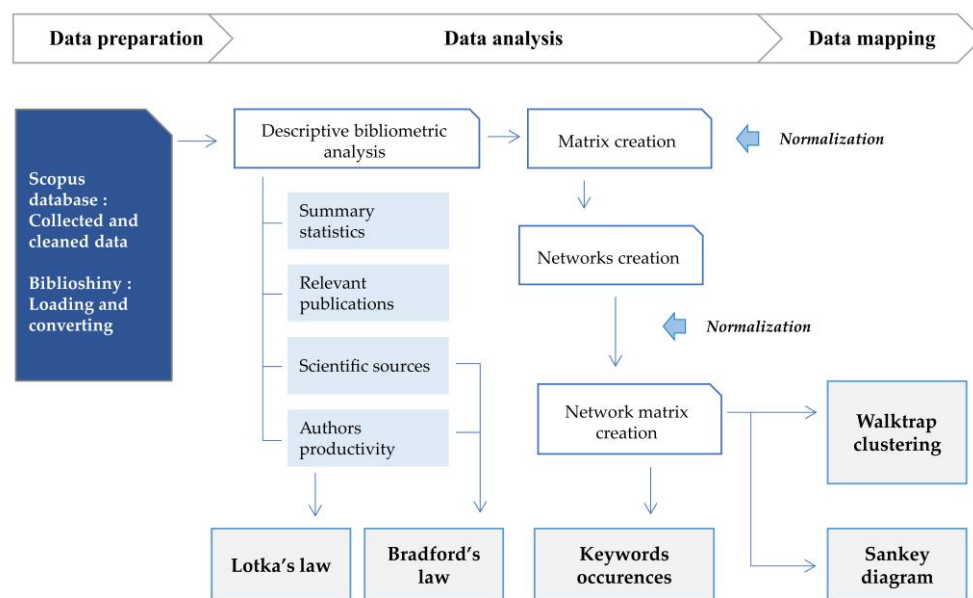


Figure 1. Methodology used for scientific mapping of groundwater drought.

A pre-processing operation was carried out to check and correct aberrations and redundancies in the database. As a result, a single duplicate was removed. The database, extracted in CSV format, finally comprises 151 publications, 76 sources, and 469 authors.

The data was analyzed using Biblioshiny, a web interface from the Bibliometrix package provided by Rstudio. This open-source tool, launched in 2017 by Aria and Cuccurullo [24], is widely used to perform bibliometric analyses and measure the performance and interaction of scientific work [39]. The number of publications is the most frequently

used measure of production, while the number of citations, which is a measurable aspect of quality, is commonly used as an impact indicator [40]. Bibliometrix is also used to quantify content through the literature keywords analysis, which helps to reveal the hot topics in a field of research [41]. The choice of this tool was based on its ability to provide customizable matrices that offer high-resolution mapping, as well as the development of numerous data reduction techniques such as network analysis and multiple correspondence analysis [42].

To ensure greater consistency in this analysis, it was necessary to harmonize the keywords in order to prevent the same word from being written differently and then counted multiple times as a distinct keyword. Biblioshiny was updated with a list of keyword synonyms to be incorporated into the processing of subsequent sections of the research.

The present study started with an examination of the synthetic statistics and the progressive development of scientific output throughout the years. Then, it has identified the main sources that best define groundwater drought research using Bradford's law. This method classifies sources into "zones" of decreasing productivity, according to the proportion of articles dealing with the studied subject [21]. The law thus divides sources into three roughly equal zones or groups [42]. The first zone is the core, which is highly productive in terms of the number of relevant articles. The second zone, is moderately productive, while the third zone has the lowest productivity [43]. As Bradford's law indicates, the quantity of journals within each zone increases as the productivity declines.

In terms of author productivity, the contribution of researchers to the scientific literature was analyzed using Lotka's law. This method helps to assess author productivity, identify the most influential authors and examine the concentration of scientific production [44]. Lotka's law establishes a correlation between authors and their number of contributions following an inverse square distribution [45]. In other words, the law states that most publications come from a small number of authors, while a larger number of authors have a much smaller number of publications [46].

In a bibliometric analysis carried out by Biblioshiny, keywords can be classified into four categories: Author Keywords, Keywords Plus, Title Keywords, and Abstract Keywords. The focus of this study was on the Author Keywords, as they represent the most relevant terms selected and used by authors. Their interconnections were then grouped into clusters using the Walktrap algorithm and depicted in a network to offer readily understandable information. Each defined cluster is represented by a color. Terms with a high frequency and density are represented by brighter characters and nodes [47]. The distance between the nodes represents the degree of thematic similarity between the keywords [48]. In other words, when the distance between the keywords is significant, their relationship is weak [49]. The thickness of the links reflects the strength of the associations between the words [50], i.e., as the thickness of the links increases, the association between words and their frequency of occurrence in the same publication becomes stronger, and vice versa.

To provide a contextual understanding of the keywords and their mutual links, a bibliographic summary was compiled for the top five most cited publications related to groundwater drought.

Finally, the Sankey diagram was used to evaluate the interconnection between 'institutional affiliations', 'author keywords', and 'countries', in order to identify the affiliations and countries that had most contributed to enriching and improving understanding of the subject.

3. Results

This chapter compiles the results of the bibliometric analysis carried out on 151 documents relating to the groundwater drought research field. These documents were published in 76 sources, mainly scientific journals.

The average annual growth rate of publications indicates a satisfactory increase in scientific production related to this topic (Table 1). The average age of the documents indicates that research in this field covers recent subjects. The average citations per document indicates that the articles are well-cited. The corpus was extensively documented with

7586 references. Several types of keywords can be found in Scopus documents, including Author Keywords and Keywords Plus [41]. For this study, 1085 Keywords Plus and 385 Author Keywords were identified. The results also revealed the number of unique authors contributing to this field of research. In total, 7 authors out of 469 made contributions by publishing a single-authored paper each, while an average of 4.01 co-authors contributed to the remaining papers. Furthermore, only 22.52% of scientific publications involved authors of different nationalities.

Table 1. Summary statistics.

Description	Results
Timespan	1989 to 5 August 2023
Sources (Journals, Books, etc.)	76
Documents	151
Annual Growth Rate %	7.01
Document Average Age	5.41
Average Citations Per Doc	22.38
References	7586
Keywords Plus	1085
Author's Keywords	385
Authors	469
Authors of Single-Authored Docs	7
Single-Authored Docs	7
Co-Authors Per Doc	4.01
International Co-Authorships %	22.52

In regard to published materials concerning groundwater drought, articles represent 91% of the total, while conference papers and book chapters represent only 11% and 2%, respectively.

Figure 2 shows the evolution of annual scientific production and average annual citations between 1989 and the database extraction date. The graph illustrates a general upward trend in research related to groundwater drought. From 1989 to 2014, authors' interest in publications concerning groundwater drought was relatively low. There were only 5 in the early 2000s, rising to a total of 141 by 2022. The highest average number of citations in 2013 involved three articles. The most cited paper is "Analysis of groundwater drought building on the standardized precipitation index approach" by J. P. Bloomfield and B. P. Marchant.

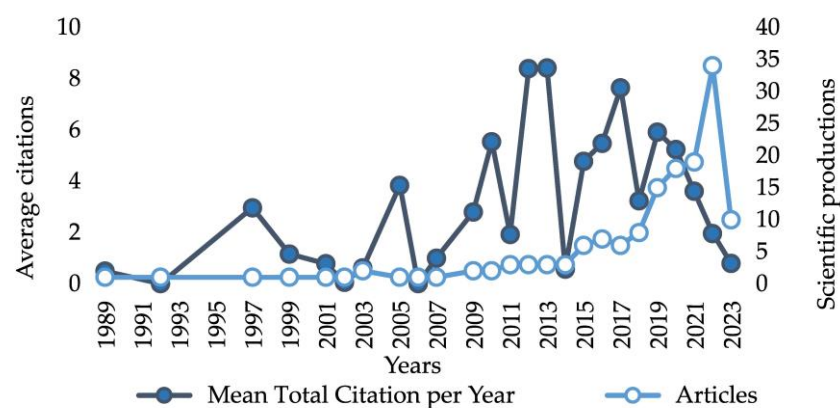


Figure 2. Scientific production and citation evolution per year.

3.1. Bradford's Law

As Bradford's law indicates, the number of journals in each zone increases as productivity decreases. The core zone, which is highly productive, accounts for 34% of publications for only 7% of all analyzed sources. The second zone, moderately productive, represents

34% of publications for 28% of the total number of analyzed sources. The third zone, with low productivity, represents 32% of publications for 64% of all analyzed sources (Figure 3).

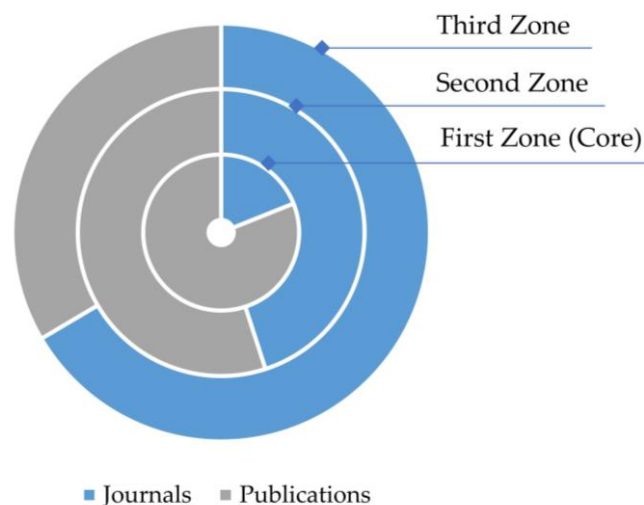


Figure 3. Zones defined by Bradford's law.

For this study, the main sources of research that form the core of the first zone are of the order of six, and are listed in Table 2. *Hydrology and Earth System Sciences* is the most influential journal in the field. It has the highest h-index and number of citations for only 13 publications related to groundwater drought. *The Journal of Hydrology* ranks second. The other journals, such as *Sustainability* (Switzerland), *Water Resources Management*, and *Water* (Switzerland), have fewer citations and publications related to groundwater drought, but show promising profiles.

Table 2. Scientific journals in zone 1 defined by Bradford's law.

Element	Publisher	h_ Index	g_ Index	m_ Index	TC ¹	NP ²	PY_ Start ³
<i>Journal of Hydrology</i>	Elsevier	11	17	0.48	494	17	2001
<i>Hydrology and Earth System Sciences</i>	European Geosciences Union (EGU)	11	13	0.92	876	13	2012
<i>Hydrogeology Journal</i>	Springer	2	6	0.18	69	6	2013
<i>Sustainability</i> (Switzerland)	MDPI (Multidisciplinary Digital Publishing Institute)	5	5	0.83	65	5	2018
<i>Water</i> (Switzerland)	MDPI (Multidisciplinary Digital Publishing Institute)	4	5	0.5	58	5	2016
<i>Water Resources Management</i>	Springer	4	5	0.28	184	5	2010

Note: ¹ TC: Total citations; ² NP: number of publications; ³ PY_start: start of publication year.

3.2. Lotka's Law

As the law stipulates, Figure 4 shows that the vast majority of authors (82%) have published a single article, 12% of authors have published two articles, 4% of authors have published three articles, and 2% of authors have published four articles. Only two authors achieved 7 publications, while two other authors had 6 and 10 publications, respectively.

Based on the results of Lotka's law, Table 3 presents the five most prominent authors in terms of citations and scientific production in the research field of groundwater drought. Their studies related to groundwater drought started between 2001 and 2020. This relatively long period offers valuable insight into the progression of the scientific methodology concerning this particular subject. In addition, their research areas and topics show that they have varied research backgrounds, ranging from drought statistics and risks, to environmental sciences, hydrology, and hydrogeology. This variety of affiliations and scientific interests helps to broaden the perspectives of the multidisciplinary analysis of this topic and provides a complementarity that helps to better understand the subject.

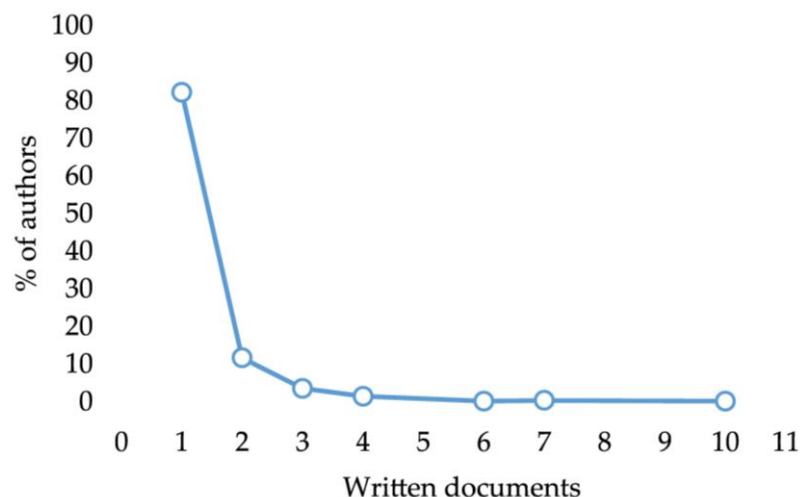


Figure 4. Authors' productivity based on Lotka's law.

Table 3. The five most influential authors in terms of citations and scientific production.

Rank	Authors	Field	Affiliation	h_Index	g_Index	m_Index	TC	NP	PY_Start
1	JP Bloomfield [8,14,51–53]	Groundwater science	British Geological Survey, Nottingham, United Kingdom.	8	10	0.381	473	10	2003
2	AF Van Loon [11,54–60]	Drought Risk	Institute for Environmental Studies, Vrije Universiteit Amsterdam, Netherlands.	6	7	0.5	438	7	2012
3	BP Marchant [61,62]	Statistics	British Geological Survey, Nottingham, United Kingdom.	5	7	0.455	396	7	2013
4	HAI Van Lanen [5,63]	Environmental Sciences	Wageningen University and Research.	5	6	0.217	329	6	2001
5	B Li ¹ [64–70]	Hydrological Sciences	Earth System Science Interdisciplinary Center, University of Maryland.	2	2	0.222	254	2	2015
	DM Hannah ² [71]	Physical geography	University of Birmingham, UK.	4	4	1	59	4	2020

Note: ¹ Rank based on total citations; ² rank based on number of publications.

For the first four authors, the ranking remains the same in terms of production and citations, whereas for the fifth position, the authors change according to the ranking criterion. At the top of the list is JP Bloomfield, with the highest number of publications and citations in the groundwater drought field. His research subjects particularly involve groundwater [8,14,51–53]. In second place comes AF Van Loon. She is known for her work in the field of hydrological modelling, drought risks, and climate change [11,54–60]. In third place is BP Marchant. As a statistician, his contribution to research in the earth sciences is valuable for data analysis and modelling [61,62]. In fourth position is HAI Van Lanen. His research covers aspects related to water resource management, modelling, hydrological and hydrogeological simulation, as well as climate change [5,63]. Based on the number of citations as a ranking criterion, fifth place goes to Li B, with 254 citations for just two articles related to groundwater drought, while based on the number of publications, fifth place goes to DM Hannah. Li B is among the pioneering researchers in the field of remote sensing and modelling of terrestrial water storage, as well as groundwater drought monitoring [64–70]. Her work and contributions are recognized for their originality and their spatial and temporal scope.

3.3. Word Occurrences and Walktrap Clustering Algorithm

As shown in Figure 5, only keywords with four or more occurrences are represented. It is not surprising that words like “Groundwater”, “Drought”, and “Groundwater drought” have a higher number of occurrences than other terms, since they are the main search terms in this analysis. As a result, the first word with the highest number of occurrences is “Standardized Groundwater Index”, followed by “Standardized Precipitation Index”. However, the words “Standardized Precipitation Evapotranspiration Index” and “Ggdi” have a lower occurrence.

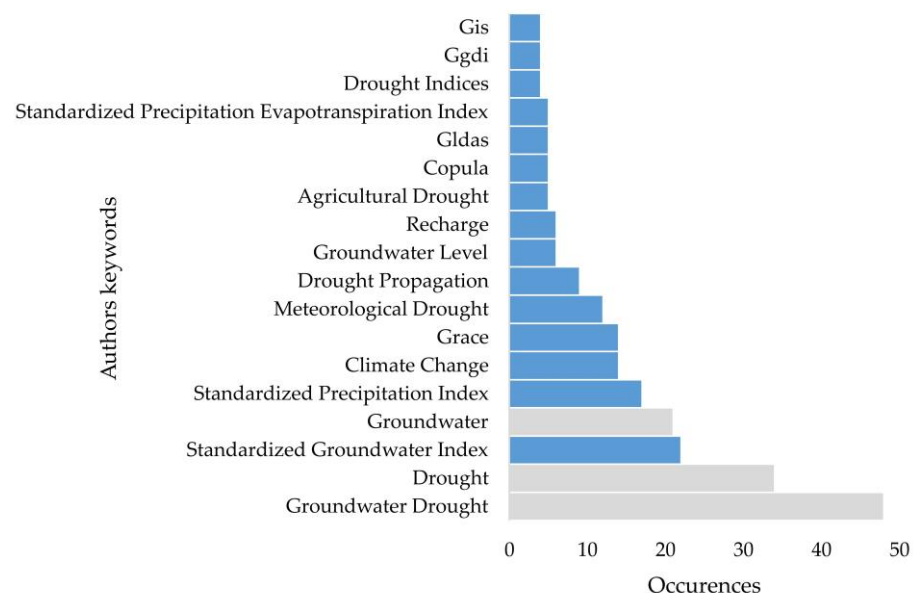


Figure 5. Authors’ keyword occurrences. (Grey denotes the main search terms. Blue refers to the main keywords generated by the bibliometric analysis).

The occurrence of the term “Climate Change” is succeeded by the keyword “GRACE”, which occurs more frequently than “GLDAS”, and following are the terms “Meteorological Drought”, “Drought Propagation”, “Groundwater Level”, “Recharge”, and “Agricultural Drought”. Finally, the use of words such as “Copula” and “GIS” is relatively limited in comparison to other words.

The “Groundwater Drought” cluster, denoted in red, is the most significant based on the node’s size and its associated characters (Figure 6). It has strong links with “Standardized Groundwater Index” and “Meteorological Drought”. This cluster also includes terms such as “Standardized Precipitation Index”, “Standardized Precipitation Evapotranspiration Index”, “Drought Indices”, and “Groundwater Monitoring”, which underline the usefulness of drought indices for characterizing and monitoring groundwater, as well as other types of drought such as meteorological and agricultural droughts. In addition, the characters of the words “Standardized Precipitation Index” are more prominent than the others, which means that this index is the most widely used in the groundwater drought studies. The occurrence of other keywords in this cluster, such as “Agricultural Drought”, “Hydrological Drought”, “Groundwater Propagation”, “Groundwater Level”, “Mann-kendal”, with less prominent characters, demonstrates that groundwater drought may be related to other types of drought, thus affecting groundwater level trends. Finally, the use of words such as “Copula” and “GIS” highlights the use of tools such as geographic information systems and statistics for data analysis, management, and modelling.

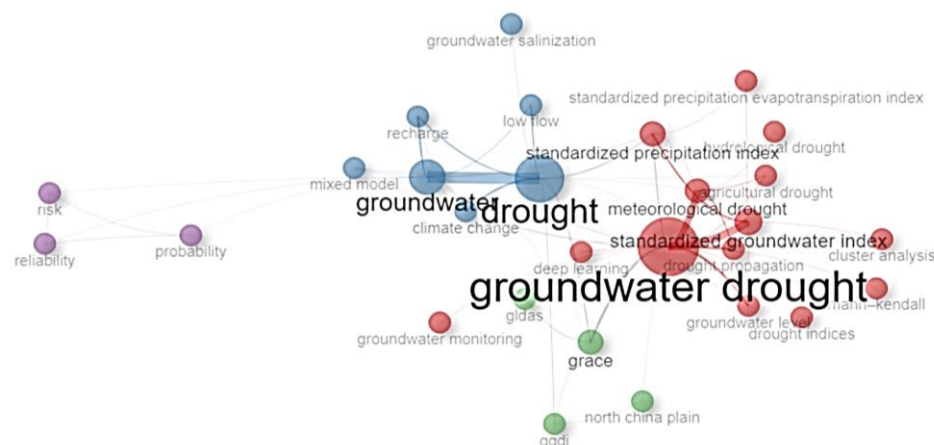


Figure 6. Authors' keywords co-occurrence network using Walktrap clustering algorithm.

The second cluster, 'Drought', represented in blue, is strongly linked to the word 'Groundwater' (Figure 6). It includes the words "Climate Change", "Recharge", "Low Flow", and "Groundwater Salinization". It highlights the impact of climate change and drought on groundwater recharge and quality, particularly in low-flow areas, which are known for their complexity and their limited availability of data [64].

The third cluster, represented in green, includes the words "GRACE", "GLDAS", and "GGDI". It is located between the two keywords "Groundwater Monitoring" and "Deep Learning" related to the first cluster. The occurrence of the word "North China Plain" in this cluster suggests that these products are mostly used to study groundwater drought in several regions of China.

The fourth cluster, less related to the first three, includes the words "Risk", "Probability", and "Reliability". It focuses on the notion of groundwater drought risk, which is commonly assessed in terms of reliability and probability, among other metrics [72]. Its distance from the other clusters shows that the co-occurrence of their related keywords is very low, which means that this cluster adopts a completely different approach to the first three.

3.4. Most Relevant Publications

Based on the total number of citations and the annual citation rate, the five highest-ranking publications, comprising works by the previously mentioned top five most cited authors, are listed in Table 4.

At the top of the list is the article authored by Bloomfield and Marchant [8], considered to be, respectively, the first and third most cited authors in this field (Table 3). This article addresses a Standardized Groundwater Index (SGI) to characterize groundwater drought. This index is calculated from the non-parametric normal transformation of piezometric level time series at monthly intervals. It was calculated for 14 sites belonging to various aquifers, and then compared with the SPI for the same sites over different accumulation periods. The results show that there is a positive and constant linear correlation between the accumulation period of the SPI that leads to the strongest correlation between the SPI and the SGI ($q_{\max}$), and the autocorrelation range of the SGI for which the autocorrelation is statistically significant ($m_{\max}$). The findings also indicate that sites with a longer autocorrelation range of the SGI tend to experience more frequent and extended periods of groundwater drought. This is because the SGI defines the maximum duration of groundwater droughts as an increasing function of $m_{\max}$. The results also show that the autocorrelation of SGI depends on the intrinsic characteristics of the aquifer, such as discharge and storage. Given these results, SGI appears to be a robust indicator for characterizing groundwater drought, which must take into account the hydrogeological context of the aquifers.

Table 4. Top five most cited publications.

Rank	Title	Authors	Year	Source	Total Citations	TC per Year
1	"Analysis of Groundwater Drought Building on the Standardised Precipitation Index Approach." [8]	JP Bloomfield and BP Marchant	2013	<i>Hydrology and Earth System Sciences</i>	234	21.27
2	"A Process-Based Typology of Hydrological Drought." [54]	AF Van Loon and HAJ Van Lanen	2012	<i>Hydrology and Earth System Sciences</i>	222	18.50
3	"GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought." [10]	BF Thomas et al.	2017	<i>Remote Sensing of Environment</i>	162	23.14
4	"Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges." [64]	B Li et al.	2019	<i>Water Resources Research</i>	154	30.80
5	"Groundwater Drought in the Northwestern Districts of Bangladesh." [73]	S Shahid et M.K Hazarika	2010	<i>Water Resources Management</i>	154	11.00

The second most cited article is authored by Van Loon and Van Lanen [54], considered, respectively, to be the second and fourth most cited authors in the groundwater drought field (Table 3). This article proposes a typology of hydrological droughts based on the process of drought propagation at the catchment scale. This gradual process occurs when meteorological drought cascades through the hydrological cycle to give rise to hydrological drought, resulting in dry streamflows and groundwater. The analysis was based on observed and simulated data for five European river basins with contrasting climatic and hydrological characteristics. The HBV semi-distributed rainfall-runoff conceptual model was used because of its reliability in low-flow conditions, which is the case for all the studied catchments. The method used to define droughts is the threshold-level method. It indicates that a drought event begins when the studied variable falls below the predefined threshold, and the drought will continue until the threshold is exceeded again. As a result, the analysis of hydro-meteorological data time series revealed that the propagation of meteorological drought can give rise to six distinct types of hydrological droughts, each with very specific propagation characteristics: Classical rainfall deficit droughts, which are considered to be the most common type of hydrological drought in the studied catchments. Rain-to-snow-season droughts, which are manifested in catchments that had experienced a well-marked snow season. Wet-to-dry-season droughts, which are observed in catchments where the dry season were clearly established. Cold snow-season droughts occurred in catchments that had experienced considerable snow accumulation during an extremely cold winter. Warm snow-season droughts manifested in catchments that had temperatures close to or slightly below zero in winter. Composite droughts are produced in catchments with a slower response. The occurrence of these types of droughts depends on several parameters, including climate and catchment characteristics, as well as the duration and severity of drought episodes, together with propagation characteristics such as accumulation, lag, attenuation, and elongation.

The third most cited paper in the groundwater drought field is authored by Thomas et al. [10]. Despite their prominent rankings, none of the authors are among the five most-cited in this field. In order to assess the occurrence of groundwater drought in the Central Valley of California, the analysis focused on the calculation of two groundwater drought indices. The Groundwater Index (GWI) is based on in situ observation of groundwater storage changes, and the GRACE Groundwater Drought Index (GGDI) is calculated on the basis of normalized groundwater storage deviations derived from observations by

the GRACE (Gravity Recovery and Climate Experiment) satellite from NASA. The GGDI was then compared with other drought indices such as the SPI and the Palmer Drought Stress Index (PDSI), in order to highlight the drought propagation represented by temporal response lags. The results show a decrease in groundwater storage over time, which is highly dependent on soil moisture deficits. The results also show that the GGDI index clearly shows two periods of drought that overlap with previously documented drought conditions in the study area. In addition, a strong correlation was established between the GGDI and GWI. As for the comparison of the GGDI with the PDSI and SPI drought indices, a temporal response lag was observed. This lag was manifested by the propagation of the drought conditions identified using these two indices to give rise to groundwater drought. All these results suggest that the approach used by the authors is an effective way of characterizing groundwater drought.

The fourth most cited article is authored by Li et al. [64]. This paper holds significant influence within the field of groundwater drought as it exhibits the highest value of total citations per year in the present analysis (30.80). Furthermore, the first author of this paper is ranked among the top five most-cited authors in this particular area of study (Table 3). The aim of this article is to generate a groundwater storage time series that will be used to monitor drought on a global scale. To do so, a groundwater storage product derived from GRACE satellite observations, regularized and based on regional mass concentration functions (mascon), was assimilated into NASA's Catchment Land Surface Model (CLSM) on a global scale, using the improved ensemble Kalman smoother implemented in the NASA Land Information System (LIS). In situ data from nearly 4000 wells around the world were then used to evaluate this assimilation, as well as to understand the usefulness of large-scale GRACE data compared with small-scale model estimates. Low-flow data from the Global Runoff Data Center (GRDC) and global permeability data were also used for the same purpose. The use of this massive and varied amount of data helped to link the uncertainty in the simulated data to local environmental factors, such as climatic and hydrogeological conditions, which is the particularity of this work. Also, this study used GRACE data assimilation results to develop a global groundwater drought index (GWI) that was compared with other regional drought indices for different accumulation periods. The results show that the simulation of groundwater storage variations is improved with the assimilation of GRACE data compared with in situ measurements around the world, particularly in regions with high interannual variability. The relevance of the assimilation was also demonstrated by the improved correlation between simulated annual groundwater storage and GRDC low-flow discharge for the 27 stations studied. As for GWI, it is generally better correlated with SPI-12 for most regions, with shorter SPI accumulation periods for the tropics and much longer for cold high-latitude regions, reflecting the impact of environmental factors such as climate on the propagation of drought in groundwater.

The fifth most cited paper is authored by Shahid and Hazarika [73]. The study was carried out in three districts in north-west Bangladesh, where groundwater is the main source of irrigation. Due to overexploitation, groundwater has been suffering from prolonged drought in the range of shallow tube wells during the dry season for several years, resulting in incomplete replenishment during the recharge season. As a result, and in order to measure the severity and probable causes of groundwater droughts, the spatial distribution of groundwater droughts, hydrograph trends, and the relationship of groundwater to meteorological droughts were analyzed. The cumulative deficit (CD) approach was also used. The results show that until 1995, groundwater levels followed variations in rainfall, which was the main source of recharge. The results show that until 1995, groundwater levels followed variations in rainfall, which was the main source of recharge. In the following years, the level of the water table fell considerably as a result of the intensification of cultivation, the extension of agricultural land, recurrent climatic droughts, and cross-border anthropogenic interventions, creating an imbalance between groundwater recharge and withdrawal. Based on these results, the authors highlight the need to set up water conservation programs, regulate withdrawals, and direct research

towards a realistic and accurate estimate of recharge in order to maintain the proper functioning of the hydrological cycle and ensure the sustainability of groundwater.

3.5. Analysis of Sankey Diagram

Although all the publications included in this analysis are produced in English, they cover a wide spatial area. Several affiliations and countries have contributed to enriching and improving the understanding of this topic. China is the first country to have made a significant contribution to scientific production in this field, due to its large number of universities that are particularly interested in this subject (Figure 7). Xi'an University of Technology has the highest number of publications, followed by North China University of Water Resources And Electric Power.

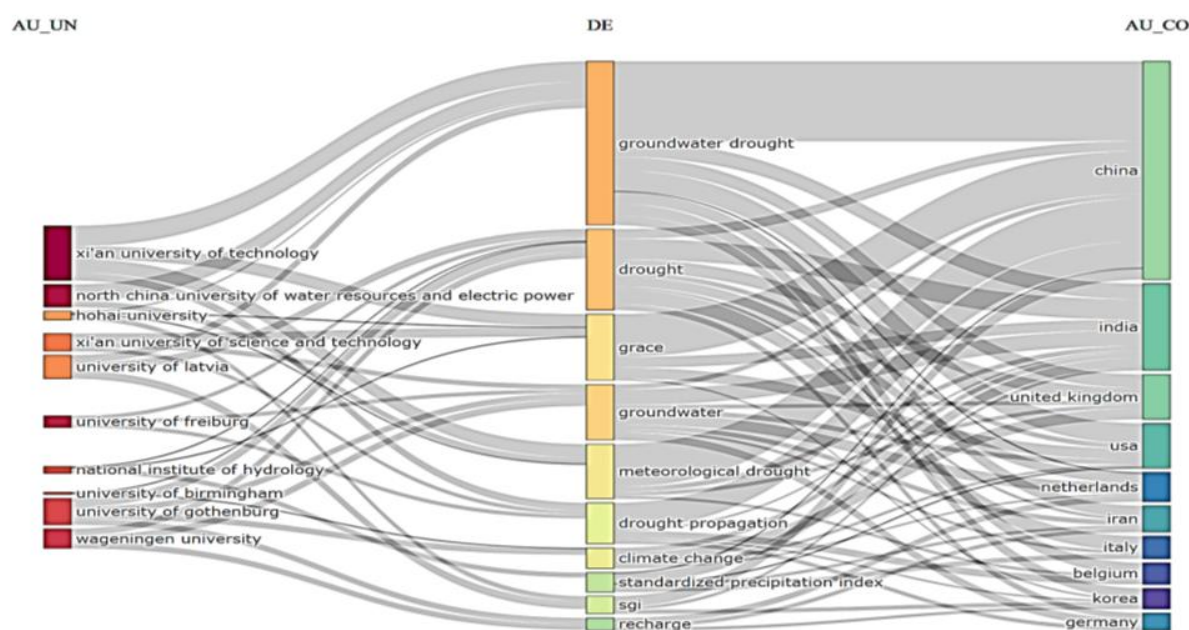


Figure 7. Three-field plot of the relationships among “institutional affiliations”, “author keywords”, and “country”.

According to the Sankey diagram (Figure 7), these two research institutes address all the aspects of groundwater drought analysis described by the authors’ keywords, such as “GRACE”, “meteorological drought”, “drought propagation”, “SGI”, “SPI”, etc. In addition to China, various institutions from countries including India, the United Kingdom, the United States, Germany, Latvia, etc., have also made contributions to the development of the subject. However, the number of corresponding publications from these countries is comparatively lower. The diagram shows that the most important collaborations are between the UK and the Netherlands, between China and the USA, and between India and the USA.

4. Discussion

Although groundwater drought is a significant global issue, it has historically received limited attention in the academic research. Until 2018, publications did not reach ten per year, which accounts for the comparatively limited number of publications that have been retrieved from the SCOPUS database (151). Moreover, a significant proportion of publications stem from a restricted group of authors, whereas the remaining authors have a considerably smaller number of publications. This may be due to the complexity and the specialized nature of this subject, which requires extensive expertise, as well as collaborative work between researchers with diverse scientific backgrounds [74]. The collaboration rate between institutions from different countries is also not commensurate with the severity of the issue. However, in the last few years, the increasing temperatures and the growing

impacts of recent climatic conditions have sparked interest in this topic as indicated by the documents' average age, which does not exceed 5 years. Indeed, the term "Climate Change" was first documented in the studied publications starting from 2003, emerging subsequently as one of the most frequently occurring keywords.

In spite of this, researchers investigating groundwater drought encounter numerous constraints that impede the increasing number of publications. The literature review revealed that most regions suffer from a lack of long-term data due to the high cost of monitoring and surveillance processes, which in most cases require extensive financial, human, and technological resources [16,17,64]. In addition, measurement data are in most cases able to adequately represent trends and variations in meteorological and hydrological conditions over a wide spatial and temporal range [1,75,76]. The significance of the reviewed publications lies in their ability to enhance comprehension and address the primary obstacles impeding research on groundwater drought, thereby facilitating the identification of potential solutions and alternatives.

The innovative studies listed in Table 4, as well as the previously stated findings, have demonstrated that the use of satellite products emerges as a highly relevant solution for drought monitoring at both regional and global scales. As the keywords occurrence show, the term "GRACE" occurs more frequently than "GLDAS", which suggests that GRACE is the most popular satellite product used in this research field. The particularity of this product is its ability to provide information on the Earth's gravity field, whose temporal variations depend on changes in the Earth's water mass [77]. Its use helps to deduce changes in total terrestrial water storage (TWS), which provides information on soil moisture and groundwater [78]. Recent studies have demonstrated the relevance of GRACE data assimilation into Land Surface Models (LSM), which helps improving the simulation of groundwater storage variations compared to in situ measurements at both regional and global scales [64,72,79–81]. They have also demonstrated their relevance in the definition of robust drought indices that allow groundwater drought assessment and monitoring such as GWI or GGDI [10,82–86]. The same studies tend to use other drought indices such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) in order to analyze the relationship between groundwater and other types of drought as defined by the propagation phenomenon. The keywords' occurrence analysis shows that SPEI is less widely used. In most cases, SPI succeeds in characterizing the groundwater drought index (GWI, GGDI or SGI) in time and space, showing similarities in the drought cascade's chronology, while displaying shifts in temporal response [66]. Therefore, enhancing comprehension of droughts' attributes such as duration and persistence of propagation enables the prediction and prevention of droughts, particularly those affecting groundwater.

Several affiliations and countries have contributed to enriching and improving the understanding of this topic. China has emerged as a pioneering nation making a substantial impact on scientific production in this field, primarily owing to its extensive array of universities that exhibit a particular interest in this subject. A cluster analysis also reveals that this country ranks among the nations with the highest utilization of satellite products. The contribution of other institutional affiliations from different countries of the world, despite having fewer publications compared to China, shows that groundwater drought is a serious problem that impacts all places regardless of their location, hydroclimatic context, or economic strength.

Within the attempt to map the complex landscape of groundwater drought research, the value of a nuanced analysis that exceeds broad generalizations is duly recognized. This analysis aims to contribute to uncovering the strengths, limitations, and development of different approaches. The progression of methods highlighted in this research reflects a trend towards leveraging advanced technologies and adopting a more holistic approach that considers the complexity of hydrological systems. While drought indices offer a robust quantitative method for drought analysis, employing cutting-edge technologies for extensive coverage and consistent comparability, their effectiveness may be limited by the

availability and resolution of data, as well as their ability to reflect the local specificities of aquifers. This underlines the need to contextualize these tools within the framework of local aquifer systems in order to improve their accuracy and relevance.

On the other hand, the integration of GRACE data into hydrological models represents a significant advancement in improving the accuracy of drought forecasts, though it demands high requirements in terms of modeling and data analysis. These approaches need to be carefully calibrated and validated with in situ data to overcome the challenges of spatial resolution and the uncertainties inherent in water storage estimates.

While each method has its strengths and weaknesses, it becomes evident that combining different approaches can provide a more complete and accurate picture of groundwater drought conditions. Moving towards integrated models and multifactorial drought indices appears to be a promising direction for enhancing the monitoring, prediction, and management of groundwater droughts.

5. Conclusions

This article provides a bibliometric analysis exploring scientific production in the groundwater drought field over the last 34 years, using Rstudio Bibliometix and Biblioshiny. The study covers 151 documents published by 469 authors in 76 sources, all arranged by the Scopus database.

This bibliometric analysis identified the scientific literature's trends in relation to groundwater drought. It also highlighted the differences, limitations, and similarities between the methods adopted by the authors. In addition, it provided an opportunity to highlight the reliability of the clustering and keywords occurrence through a summary of the most pertinent papers in the field. As for the analysis of the Sankey diagram, it reveals the existence of flagship countries such as China, whose pioneering institutions cover all the aspects of groundwater drought analysis previously described. Other countries are emerging, such as India, the United Kingdom, the United States, Germany, and Latvia, with a much smaller number of publications than China.

In conclusion, this analysis provides an overview of research on groundwater drought, highlighting the importance of integrating science into the implementation of public policies for the resilient and concerted management of water resources.

Despite the valuable information provided on publication trends and patterns in the field of groundwater drought, the bibliometric approach is not without inherent limitations. The relevance and scope of bibliometric analyses are strongly influenced by the selected databases as well as the available metadata, including titles, abstracts, keywords, and citations. These elements may not fully reflect the content or quality of the research. Inaccurate metadata may also compromise the precision of the analyses. Furthermore, bibliometric analyses tend to favor quantitative aspects, such as the volume of publications or the number of citations, as indicators of a study's impact or value. This focus can overlook the recognition of high-quality but less-cited research. Additionally, identifying emerging trends through bibliometric analyses can be a lengthy process, requiring the accumulation of a significant volume of publications and citations before these new directions become discernible using these methods.

One other limitation of our approach lies in the fact that we adopted a single database, hence the need for future analyses to integrate other databases such as Web of Science and Google Scholar.

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