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Review

The Impact of Climate Change on the Failure of Water Supply Infrastructure: A Bibliometric Analysis of the Current State of Knowledge

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Abstract: With ongoing climate change, new threats appear to the operation of water supply systems (WSSs), which are related to the amount of available drinking water resources, its quality, the operation of existing water supply infrastructure and changes in consumer behavior. The paper presents a bibliometric analysis of the state of knowledge on the impact of climate change on the failure of water supply infrastructure. The bibliometric analysis was performed based on the VOSviewer program. The results of the analysis indicate current research trends in this area around the world and allow the identification of strengths and weaknesses. Most research concerns the identification of factors related to the impact of climate on the failure rate of water distribution systems. A popular research topic was also the prediction of water supply network failures, taking into account the impact of climatic factors. The main research gap is determining the impact of climate change on water quality. The acquired knowledge can be used by water companies, policy-makers and other researchers to plan adaptation strategies to climate change, which pose new challenges for the operation of water supply systems. The conducted bibliometric analysis also allowed for identifying research gaps.

Keywords: bibliometric analysis; climate change; water supply

Citation: Żywiec, J.; Szpak, D.; Wartalska, K.; Grzegorzek, M. The Impact of Climate Change on the Failure of Water Supply Infrastructure: A Bibliometric Analysis of the Current State of Knowledge. *Water* **2024**, *16*, 1043. https://doi.org/10.3390/w16071043

Academic Editor: Marco Franchini

Received: 13 March 2024
Revised: 25 March 2024
Accepted: 2 April 2024
Published: 4 April 2024

1. Introduction

Reliable operation of the water supply system (WSS) is required for ensuring continuous access to safe and clean drinking water, which is one of the basic human rights [1]. Identification of threats to the operation of WSS should include both natural and civilization factors. In general, it can be assumed that a threat is any potentially dangerous factor that probably leads to an accident involving the loss of human health or life, as well as loss of property [2]. Threats (virtual entities) may be activated in the form of dangerous events, i.e., circumstances in which people, property or the environment are exposed to one or several threats [3–5]. Climate change directly affects the operation of water supply infrastructure. Climate change poses a threat to both water quantity (decrease in water resources and extreme weather phenomena) and water quality (deterioration of water quality caused by global warming).

This work focused on determining the current state of knowledge regarding the impact of climate change on the failure of water supply infrastructure. This is consistent with the Sustainable Development Goals (SDGs) established by the United Nations (UN) [6].

The SDG strategy aims to build a greener, fairer and better world by 2030. Among the 17 identified SDGs, SDG 6 "Clean water and sanitation" and SDG 13 "Climate action" were distinguished. In terms of ensuring common and equal access to safe drinking water for the population, it is necessary to link these two goals. Climatic factors are identified as one of the biggest problems that the water supply industry will have to face in the near future [7]. Climate change poses threats to the operation of WSS already at the level of water resources. Over the last 5 years, surface water bodies, such as lakes, rivers and reservoirs have been subject to rapid global changes, with one in five river basins experiencing high fluctuations in surface water levels [8]. The water stress will be observed in the coming decades, affecting regions of the world where water resources are insufficient or where water quality does not meet the basic environmental or health requirements [9]. It is predicted that by 2050, 1.7–2.4 billion people will live in areas exposed to water scarcity [8]. Limiting global warming to 1.5 °C compared to 2 °C (above pre-industrial levels) would reduce the number of people experiencing water shortages by up to 50%, depending on the region [8]. Climate change affects not only the amount of available freshwater resources, but also its quality. As the temperature increases, new threats for water quality appear, such as the eutrophication of water reservoirs or the presence of emerging pollutants, e.g., antibiotics, medicinal substances, hormones or microplastics [10]. Water treatment plants must deal with new contaminants that cannot always be removed using existing infrastructure. Finally, the impact of climate change is also observed in the water distribution subsystem, where the seasonality of the impact of weather factors is observed, or the intensification of the impact of extreme weather phenomena that cause interruptions in the water supply due to failures of pipelines or other water supply infrastructure [7,11,12]. Climate change also affects water-use patterns, which increase with increasing temperatures [13]. Therefore, the work load on the water supply infrastructure increases, which in its existing state may not be able to cope with the growing demand for water production and distribution. WSS operation under long-term overload may result in faster infrastructure aging and more frequent failures [13].

The aim of the work was to review articles dealing with the problem of climate change and its impact on the failure of water supply infrastructure and to assess the possibilities of water supply system development facing the new challenges. The conducted systematic review and bibliometric analysis focuses on issues related to operational problems in water supply systems. The need to conduct this research results from the fact that climate change has a significant impact on water supply infrastructure. The process of water supply and distribution depends, to a significant extent, on climatic factors, e.g., high temperature, precipitation and extreme weather events, including flash floods. For this reason, it is necessary to recognize the current state of research in this area, identify research gaps and define adaptation actions to climate change in water supply systems. The work presents a comprehensive look on the research topic, taking into account research related to the impact of climate on each stage of the water supply process to the consumer and the accompanying infrastructure, starting from water resources (quantitative aspects), through water treatment technologies (qualitative aspects), then water distribution systems, as well as changes in water demand patterns (user behavior). The conclusions based on the analysis carried out present the current state of knowledge regarding the impact of climate change on the failure of water supply infrastructure. The acquired knowledge may constitute the basis for water supply companies and policy-makers to update guidelines or legal acts with the challenges related to ongoing climate change. The information obtained may also contribute to changing current views on the impact of climate change on the failure of water supply infrastructure and indicate directions for new research to other researchers.

2. Materials and Methods

2.1. Bibliometric Analysis Tools

Bibliometric analysis is one of the basic tools for examining scientific trends in a given field, identifying trending topics, journals, scientists or research centers with the greatest influence in a given research area [14–18]. The results of such an analysis are characterized by reduced bias compared to classic literature reviews, due to the conclusions being based on bibliometric statistics [19]. This research technique has recently become very popular in the area of research related to environmental engineering [19–23].

In recent years, specialized computer programs, e.g., VOSviewer, Bibliometrix and CiteSpace, are increasingly used for bibliometric analysis [14–18]. With their help, you can present the results of bibliometric analysis in the form of maps. The science mapping allows for the analysis of connections between individual publications, journals, topics, keywords, scientists and science institutions [14].

In this work, the VOSviewer program developed at Leiden University [24] was used for bibliometric analysis. The program uses bibliographical data collected in scientific databases (e.g., Scopus and Web of Science) and then creates a graphical interpretation of the analysis results in the form of connection networks, overlay visualizations and density visualizations. This allows the results of bibliographic analysis to be presented in a transparent easy-to-understand form [24].

The VOSviewer program uses an indicator called association strength [14–18] as the basis for calculations. This indicator is used to build a similarity matrix based on the co-occurrence matrix. Then, a map is constructed by applying the VOS mapping technique to the similarity matrix. In the next step, the map is translated, rotated and reflected. This indicator is determined from the formula [14]

$$s_{xy} = \frac{c_{xy}}{n_x \times n_y} \quad (1)$$

where

c_{xy} is the number of co-occurrences of items x and y;
n_x is the total number of occurrences of items x;
n_y is the total number of occurrences of items y.

For the bibliometric analysis, the indicator of the average number of citations per year (ACPY) for publications in the examined topic was also used, determined from the Equation (2), which describes changes in interest in the examined topic over the years:

$$ACPY = \frac{\sum c}{p \cdot t} \quad (2)$$

where:

$\sum c$ is the sum of citation number for publications in one year;
p is the number of publications in one year;
t is the number of years of publications availability.

2.2. Bibliographic Data Collection and Preparation

The Scopus scientific database, which is one of the most recognizable databases, was used as a source of bibliographic data. The articles were found based on the analysis of the title, abstract and keywords. A basic search query was formulated as “water AND pipe OR system OR network AND climate OR climatic AND failure OR failures OR reliability”. The data were obtained on 13 February 2024. After the first stage of searching for bibliographic data, 2944 items were found. Then, a secondary search query was formulated, limited to a precise search in the Article Title field and in the Keywords field. This allowed us to significantly narrow down the search results. When preparing bibliographic data, non-English items were rejected. Single papers published before 2000 were also rejected (due to their low relevance to the topic). As a result of filtering, the number of publications was limited to 526. The last stage of data preparation was the manual analysis of titles, abstracts and keywords and their relevance. During the manual analysis of the publications’ relevance, those related to agriculture, hydrology, medicine, social sciences and economics and those related to systems other than water supply (e.g., sewage and energy) were rejected. Only articles that were precisely related to the impact of climatic factors on water supply infrastructure or the water supply process were chosen to build the database for analysis. Finally, the bibliographical database for this analysis was limited to 45 literature items. Figure 1 shows the diagram according to which the database for bibliometric analysis was prepared. The database was also used to conduct the systematic review in the research field.

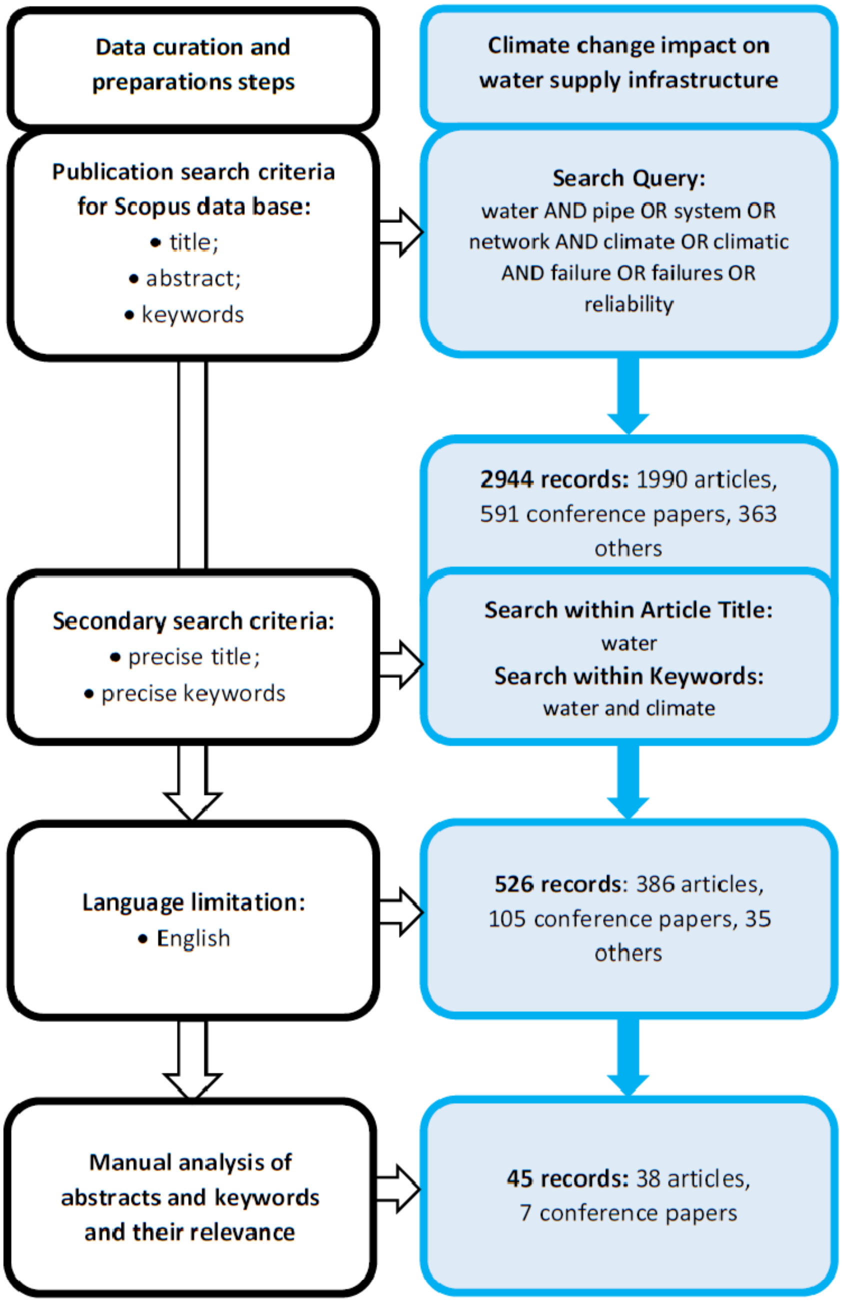

Figure 1. Steps of preparing a database for bibliometric analysis.

3. Results and Discussion

3.1. Systematic Review of the Current State of Knowledge

3.1.1. Climate Change as a Failure Factor

An increase in the research interest of the impact of climate on water supply infrastructure began to be visible in 2005. One of the first publications [25,26] concerned the identification of factors influencing the failure of water supply mains made of asbestos cement in the city of Regina, Canada. The research results indicated that the climate and soil conditions had the greatest critical impact on the failure rate of water supply pipes. In 2010, another work [27] appeared, presenting research on the relationship between the failure rates of main water supply networks in the UK and climatic factors. A large number of papers concerning the identification of factors influencing pipeline failures, which are related to the impact of climate, was published in 2010–2020 [28–35]. These analyses took into account pipe materials, pipe diameters, weather factors (temperature, precipitation, snow cover, wind and humidity) and soil settlement. In recent years, research is continued to identify factors related to the impact of climate that influences the failure of water supply networks such as temperature fluctuations or sea level rises [7,12,36–39].

3.1.2. Failure Prediction Models Based on Climate Change

Another group of research papers focused on predictive analysis for water distribution network failures related to the seasonal impact of climatic factors [40–46]. These research papers indicate that climatic factors such as temperature, precipitation or frost-depth have a significant impact on the formation of failure rates. Researchers recommended that the seasonal impact of climate should be taken into account when creating failure predictive models. Climate change may also have a positive effect on water infrastructure. The works [47,48] present the changes in the number of water pipe failures taking into account climate change scenarios in which a decrease in the number of failures related to climate warming will be observed for regions with a cold climate. In recent years, research has continued to forecast water supply network failures using Monte Carlo or machine learning methods [49,50].

3.1.3. Changes in Water Demand Due to Climate Change

Research on changes in water demand is also an important aspect in assessing the impact of climate on water supply infrastructure [13,51]. With climate change, water demand is expected to rise with decreasing available water resources, requiring people to adapt existing infrastructure to new conditions.

3.1.4. Impact of Climate Change on Water Quality

The quality of drinking water may also be affected by climate change [10,52,53]. This influence is seen through the aggravation of eutrophication; changes in the flow, hydrological and thermal conditions; and the destruction of ecosystems and biodiversity. Research in this direction provides information on the proper planning of the operation, use and protection of water resources and the adaptation of water treatment technologies to new climatic conditions.

3.1.5. Reliability and Risk Assessment of Water Supply in Aspects of Climate Change

Another topic discussed in [54] was research on the impact of climate on water supply systems in the Netherlands, where a flexible approach for planning and the redesign of water supply facilities and infrastructure adapted to the ongoing climate changes was recommended. It was one of the first research studies on the reliability of the water supply infrastructure in the aspects of climate change. At the beginning of the second decade, few publications appeared in the field of risk assessment in the aspect of climate impact on water supply infrastructure [55,56]. The conclusions drawn from these studies indicate that the design of water supply infrastructure should take into account the long-term effects of climate change, which are characterized by high uncertainty. The future goal should be to ensure the reliable operation of the designed systems. Researchers also raised the topic of the resilience and reliability of water supply systems to climatic factors in works [57–60]. In recent years, research has been continued on the perception of risks to the operation of water supply systems resulting from climate impacts, such as weather risk, flood risk and operational risk [61–64].

3.2. Bibliometric Analysis of Current State of Knowledge

Figure 2 shows the number of publications in the period of 2005–2024 related to the impact of climate change on water supply infrastructure and the average number of citations per year (ACPY). The number of publications in the analyzed period has an increasing trend. The increasing climate awareness of people in recent years and the emerging new threats to the operation of water supply systems related to climate change result in an increase in the interest of scientists in this research topic. According to the authors, this trend will continue in the coming years, and as the number of publications increases, an increase in the number of citations will be observed. Table 1 presents selected most frequently cited publications in the period of 2005–2024, including publications cited more than 30 times (number of citations as of 13 February 2024).

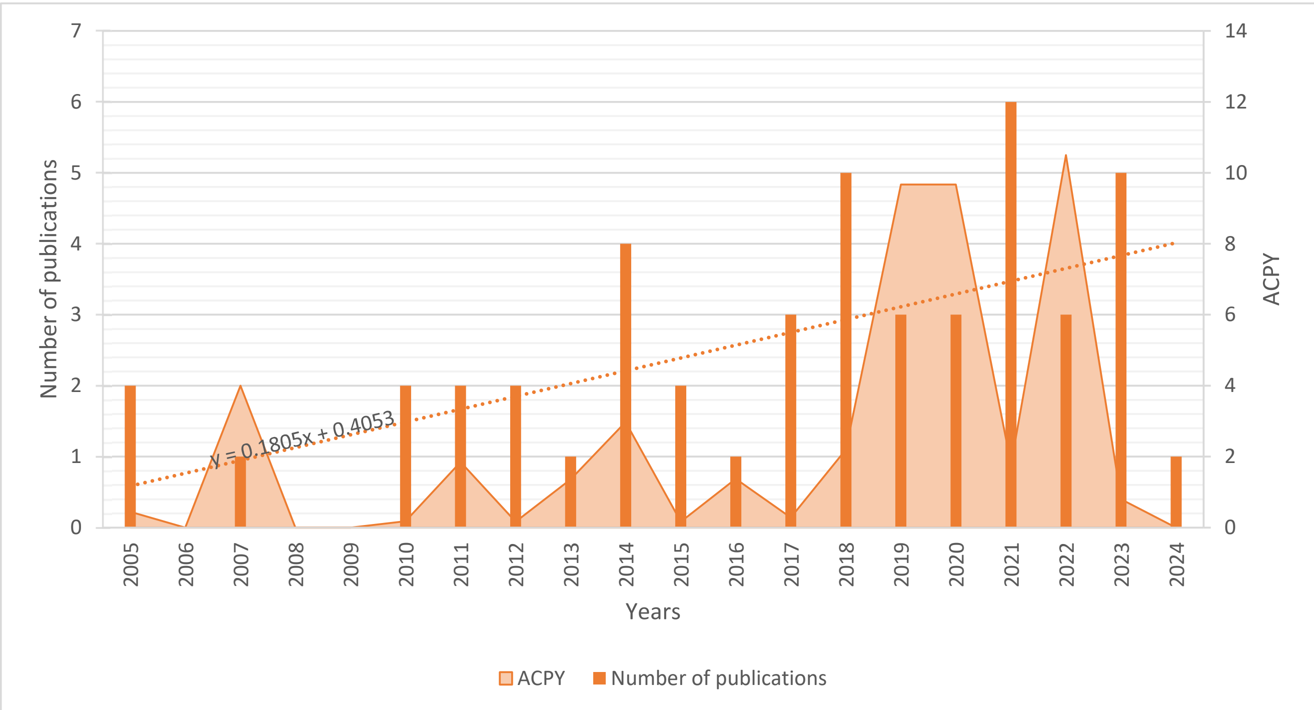

Figure 2. Number of publications and average citation per year in the analyzed topic.

Table 1. Most cited research in the analyzed topic.

Years	Title	Journal	Authors	Research Summary	Citations
2007	Factors contributing to the failure of asbestos cement water mains	Canadian Journal of Civil Engineering	Hu and Hubble [26]	In this paper, water main pipe failure data from the City of Regina (Canada) were correlated with few failure factors, including type of soil, quality of water, climate, construction quality and maintenance practices.	68
2011	Seasonal factors influencing the failure of buried water reticulation pipes	Water Science and Technology	Gould et al. [40]	The paper presents the impact of climate change and various soil settlement patterns on the failure rate of water pipes in regions with a warm climate.	39

Table 1. *Cont.*

Years	Title	Journal	Authors	Research Summary	Citations
2014	Study on relationships between climate-related covariates and pipe bursts using evolutionary-based modelling	Journal of Hydroinformatics	Laucelli et al. [28]	The paper examines the relationships between climate data (i.e., temperature and precipitation) and pipe failures recorded in Scarborough (UK) in a 24-year period. For this purpose, The Evolutionary Polynomial Regression modelling paradigm was used.	41
2014	Modelling the effect of climate change induced soil settling on drinking water distribution pipes	Computers and Geotechnics	Wols and van Thienen [30]	The paper presents a forecasting method (Monte Carlo simulation) for water supply network failures related to soil settlement associated with lowering the groundwater level resulting from climate change.	36
2019	Improving pipe failure predictions: Factors effecting pipe failure in drinking water networks	Water Research	Barton et al. [34]	The publication identified factors influencing the failure rate of water pipes, including climate change as one of the environmental factors related to the impact of weather.	107
2020	A Method for Predicting Long-Term Municipal Water Demands Under Climate Change	Water Resources Management	Zubaidi et al. [51]	The paper examines the relationship between monthly climate factors and municipal water consumption and presents the long-term prediction of monthly water demands using the artificial neural network (ANN) algorithms.	86
2022	Machine learning based water pipe failure prediction: The effects of engineering, geology, climate and socio-economic factors	Reliability Engineering and System Safety	Fan et al. [50]	This study presents the application of data-driven machine learning (ML) models to predict water pipe failures based on the historical pipe break dataset, soil type dataset, topographical dataset, climate dataset and residents number dataset.	52

Figure 3 shows the results of the bibliometric analysis performed in the VOSviewer software (version 1.6.20). It contains a mapping of a keyword co-occurrence network on the topic of climate change impact on water supply infrastructure. Individual keywords are represented by circles, and the larger the circle, the more important a given position is. They have been divided into two clusters marked with red (#1) and green (#2). The smaller the distance between individual nodes, the more closely related the keywords are [21]. There are also lines in the drawings that reflect the connections between keywords. The thicker it is, the greater the frequency of the occurrence of two keywords in publications [21]. The division into clusters, the year of occurrence, and the average number of citations are presented in Figure 3.

Table 2 shows the most important statistics for keywords in the network shown in Figure 3. Due to the large number of keywords in the manually selected positions (595 keywords), those that appeared in at least four publications were included in the analysis, limiting the set to 22 keywords.

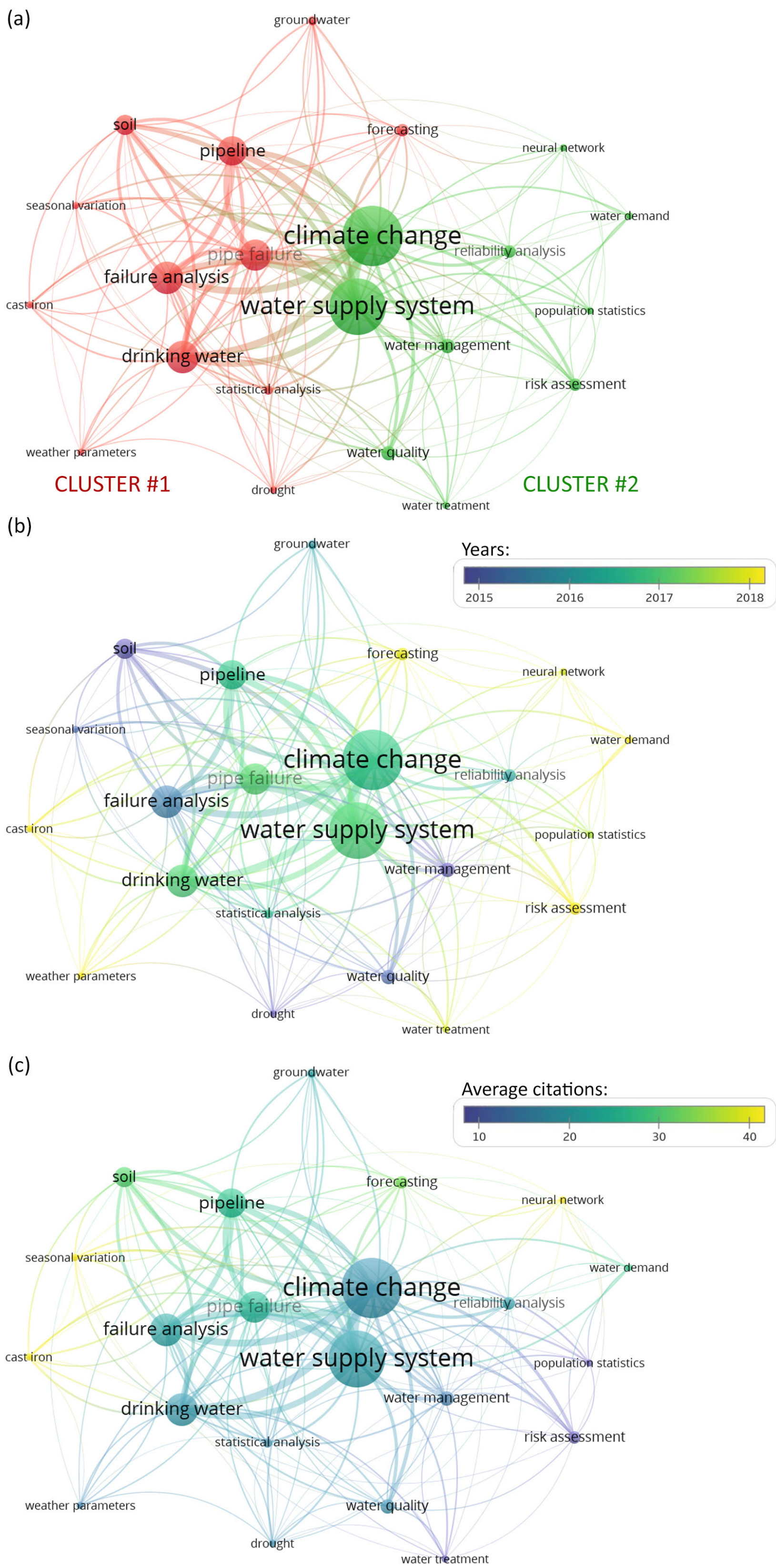

Figure 3. Keyword co-occurrence network map on the analyzed topic: (**a**) cluster division, (**b**) the years of occurrence and (**c**) the average number of citations.

Table 2. The most important keywords in the analyzed topic.

Cluster	No.	Keyword	Occurrences	Links	Total Link Strength	Average Citations
1	1	drinking water	18	18	101	18.6
	2	failure analysis	18	19	101	21.1
	3	pipe failure	17	19	105	24.7
	4	pipeline	16	19	92	26.1
	5	soil	11	15	67	30.1
	6	forecasting	7	16	37	32.1
	7	groundwater	5	10	28	21.0
	8	statistical analysis	5	14	31	17.2
	9	cast iron	4	11	28	41.5
	10	drought	4	16	31	17.0
	11	seasonal variation	4	12	27	45.8
	12	weather parameters	4	10	22	15.8
2	13	climate change	33	21	160	17.8
	14	water supply system	31	21	163	19.7
	15	water management	8	19	56	15.1
	16	water quality	8	15	43	17.3
	17	reliability analysis	7	15	30	20.0
	18	risk assessment	7	14	33	4.4
	19	neural network	4	11	17	40.5
	20	population statistics	4	12	22	6.3
	21	water demand	4	9	19	27.0
	22	water treatment	4	12	23	5.3

In cluster 1, the keyword “pipe failure” had the highest total link strength (105), which appeared in 17 publications and created 19 links. The most individual links (19), apart from the keyword “pipe failure”, had the keywords “failure analysis” and “pipeline”. The highest average number of citations in cluster 1 are for the keywords “seasonal variation”, “cast iron” and “forecasting”, for which the number of occurrences is small. The keywords collected within cluster 1 indicate the existence of a research direction aimed at identifying factors influencing the failure rate of water supply infrastructure that are sensitive to climate change and forecasting changes in failure rates. In cluster 2, the highest total link strength (163) had the keywords “water supply system” and “climate change” (160), which appeared in 31 and 33 publications, respectively, creating 21 links each. The keywords “neural networks”, “water demand” and “reliability analysis” have the highest average number of citations in cluster 2. Cluster 2 includes keywords related to the issues of managing the operation of the water supply system in relation to climate change, which is another direction of research.

The analysis of the average age of publications indicates that keywords such as “soil”, “seasonal variation”, “water management”, “drought”, “water quality” and “failure analysis” shaped the initial directions of research in the period of 2005–2024. Then, keywords such as “pipeline”, “pipe failure”, “drinking water”, “statistical analysis”, “reliability analysis” and “groundwater” appeared in the publications. The latest trends that have emerged in research in recent years include keywords such as “forecasting”, “neural network”, “water demand”, “population statistics”, “risk assessment”, “water treatment”, “weather parameters” and “cast iron.”

The keywords "cast iron", "seasonal variation" and "neural network" are characterized by the greatest interest in the research topic, described with the highest average number of citations. There is also great interest in the keywords "forecasting", "soil", "pipeline", "pipe failure" and "water demand". A smaller number of citations is observed for other keywords. The least interest is observed for the keywords "population statistics", "risk assessment" and "water treatment".

Figure 4 shows the worldwide distribution of research number on the topic of climate change impact on water supply infrastructure and the research teams' international cooperation. Most publications (10) were created in the USA and in the Netherlands (7). Interest in this topic was also observed in countries such as Canada (6), China (5), Australia (4), Canada (4), Poland (4), UK (4), UAE (2) and South Korea (2). Single publications have also been created in Norway, India, Italy, Iraq, Brazil, Qatar, Nigeria, Portugal and New Zealand. In the countries where the most research has been carried out (USA and the Netherlands), there is little interest in international cooperation. Most research in international teams was conducted in China and Canada.

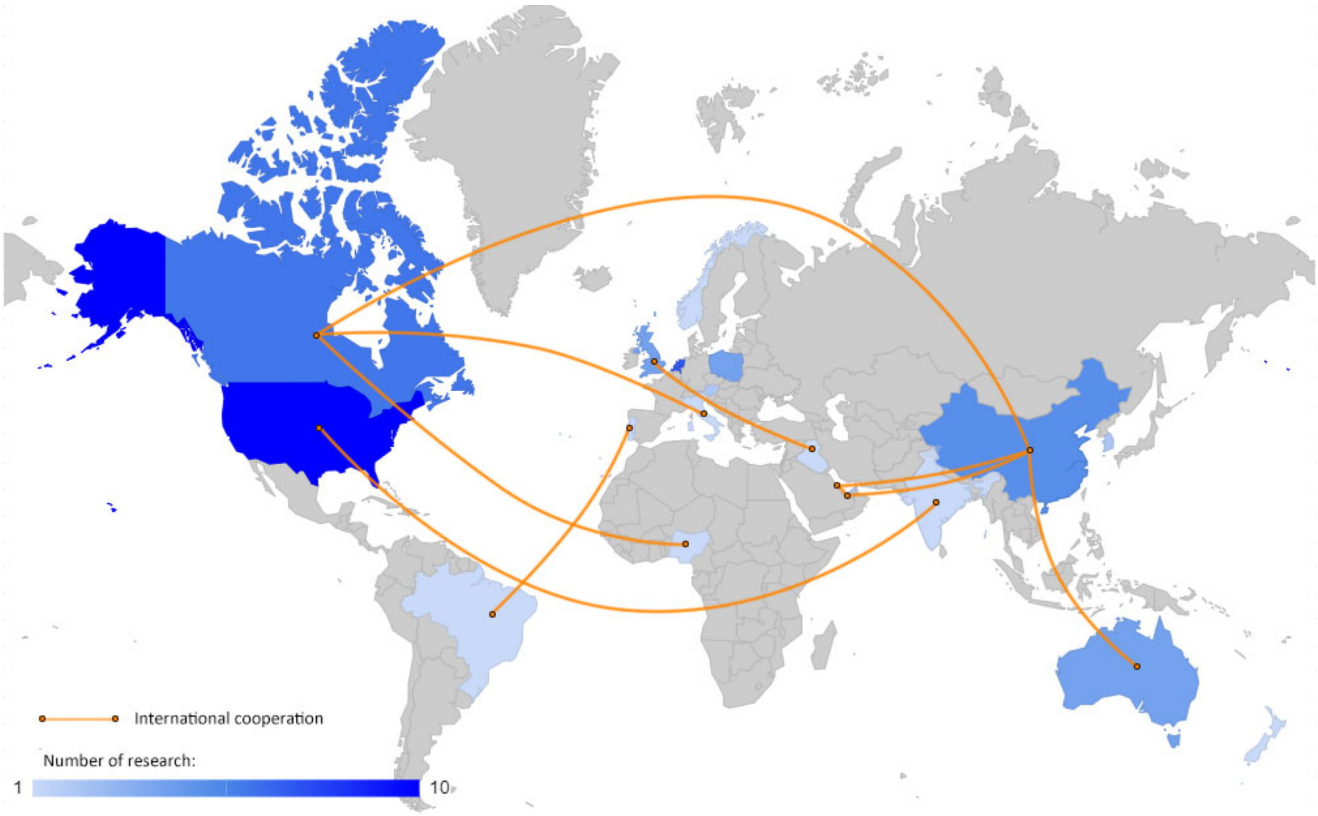

Figure 4. Global distribution of publication on the analyzed topic and countries' research team cooperation.

Table 3 presents selected publications from the last 3 years in the field under study. More than 30% of the analyzed publications come from this period. The most interesting research directions developed in recent years include research on the impact of climate change on water quality in water supply systems [10], research related to the increase in sea water levels and its impact on water supply infrastructure in coastal regions [39,64], and research on the impact of climate change on water demand [13]. Still, one of the most popular directions of research is the assessment of the impact of climatic factors on the failure rate of water pipes [7,37–39,51].

Table 3. Selected newest publications related to the analyzed topic.

Years	Title	Journal	Authors	Research Summary	Citations
2023	Assessment of the impacts of climate change on water supply system pipe failures	Scientific Reports	Fan et al. [37]	The paper presents climate-fragility failure rate models, and then the evaluation of the impact of climate change on the water systems. The prediction of the failure rate and the number of failures in the water systems in the years 2020 to 2100 was precedented, using different climate change scenarios.	0
2023	Emerging pollutants of water supplies and the effect of climate change	Environmental Reviews	Alshamsi et al. [10]	The article highlights the threats resulting from climate change for emerging pollutants in water supply systems, which may have an adverse impact on the water supply infrastructure.	3
2022	Effects of saltwater intrusion and sea level rise on aging and corrosion rates of iron pipes in water distribution and wastewater collection systems in coastal areas	Journal of Environmental Management	Tansel and Zhang [39]	In this paper, a quantitative assessment of forecasted changes in failure rates of iron pipes due to the intrusion of saltwater and the rise of sea level in coastal areas related to climate change was presented.	10
2021	Drivers of future water demand in Sydney, Australia: Examining the contribution from population and climate change	Journal of Water and Climate Change	Barker et al. [13]	The paper presents research on the impact of population increases and climate change on the future municipal water demand for Sydney, Australia. The increase in water demand may have a negative impact on the reliability of water supply infrastructure.	3

4. Conclusions, Perspective and Limitations

Understanding and adapting to climate change in the context of operating water supply systems is a key challenge for water companies whose task is to provide safe drinking water to consumers. In addition to water supply companies, actions in this area should also be taken by policy-makers, because they are responsible for providing society with appropriate conditions for development and quality of life. These activities are consistent with the ideas of the 17 Sustainable Development Goals (SDGs) presented by the United Nations [6]. Among them, SDG 6 "Clean water and sanitation" and SDG 13 "Climate action" were distinguished, which, together, correspond to the issue of operating water supply infrastructure. Providing access to drinking water in the face of ongoing climate change is one of the most important strategies. This strategy is appropriate for all regions of the world, because it is predicted that water stress will not only be present in underdeveloped countries or with a dry climate but will also be observable in developed countries such as Spain, Italy, Greece, Germany or the USA [9]. The lack of proper management and investment in water supply infrastructure in the face of climate change will pose a threat to water resources, ecosystems and human health and life due to water-related diseases such as malaria and diarrhea [8].

The paper presents a bibliometric analysis of the state of knowledge on the impact of climate change on the failure of water supply infrastructure. Every stage of water supply is considered, starting from water resources and ending with the water use stage. Analysis of research development in the analyzed topic allows for the identification of strengths and weaknesses. The results of the analysis also indicate gaps in ongoing research, which may indicate research directions for other researchers. So far, most attention has been focused on issues related to the identification of factors related to the impact of climate on the failure rate of water distribution systems [7,12,28–39,49,50]. A popular research topic was also the prediction of water supply network failures, taking into account the impact of climatic factors [40–46]. These studies point out the weaknesses of existing water supply systems that can be improved, and then increase the resilience of water supply systems to the impact of climate change. The presented analysis made it possible to identify the main groups of threats to the functioning of water supply systems related to climate change, such as changes in the water quality in sources, changes in the amount of water in sources, extreme weather phenomena and their consequences (droughts and floods), sea level rises and changes in water demand. An opportunity to increase the number of studies and better understand the impact of climate change on the functioning of water supply systems is the exchange of information between international research organizations. So far, only about 20% of relevant publications have been created by international teams.

Despite the growing number of publications on the impact of climate change on water supply infrastructure, there are still some research gaps. There has been relatively little research conducted on the impact of climate change on water quality [10,52,53]. Emerging new water pollutants and their connection with climate change pose a significant threat to the effectiveness of existing water treatment systems and water recipients. The research in the field, both on the climate change impact on water supply infrastructure and emerging pollutants, began to be conducted at the beginning of the 21st century. The first publication combining these two issues was published in 2020. It is necessary to delve deeper into this topic in order to take actions aimed at minimizing the risk of threats, especially those to the health and life of water consumers. The behavior of water consumers and its change under the influence of climate changes has also been discussed in a small number of papers [13,51]. Variations in the patterns of water demand will shape water policy, especially in countries that will be affected by water stress in the near future. The research in this field will allow us to identify future problems and the possibilities of avoiding them by introducing appropriate models for managing the development of water supply systems and changing the law in this area. The impact of climate change on the operation of water supply infrastructure manifests itself in many aspects (e.g., qualitative, quantitative, technical and social), which may cause difficulties in conducting research in this area. The research in this field started 20 years ago, so this problem is only just being noticed, but its popularity is growing. In the following years, more and more extensive research will appear, closing existing research gaps, but also identifying new ones that have not yet been recognized. It is our duty to use available water resources and water supply infrastructure in such a way to guarantee access to safe and healthy water for future generations, which is why research in this area is so important and should be further developed.

Water supply companies and policy-makers, with the support of scientists, should focus their activities on limiting the negative effects of climate change on the water supply infrastructure and the water supply process. These activities will help implement the sustainable development strategy. It is necessary to adapt the water supply infrastructure to the changing climate, which will contribute to building a fair and better world, and, thus, give future generations a chance to live in decent conditions.

Author Contributions: Conceptualization, J.Ż.; methodology, J.Ż., D.S., K.W. and M.G.; validation, J.Ż., D.S., K.W. and M.G.; formal analysis, J.Ż.; investigation, J.Ż., D.S., K.W. and M.G.; resources, J.Ż., D.S., K.W. and M.G.; data curation, J.Ż.; writing—original draft preparation, J.Ż., D.S., K.W. and M.G; writing—review and editing, J.Ż., D.S., K.W. and M.G.; visualization, J.Ż.; supervision, K.W. and M.G.; project administration, J.Ż. and D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

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