Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Review Article
Acta Limnologica Brasiliensia, 2023, vol. 35, e17
https://doi.org/10.1590/S2179-975X0223
ISSN 2179-975X on-line version

Impacts of extreme precipitation events in water quality: a scientometric analysis in global scale

Impactos de eventos extremos de precipitação na qualidade da água: uma análise cienciométrica em escala global

Caio Vitor Matos Moreira[1*], Mariana Rodrigues Amaral da Costa[2,3] and Vanessa Becker[1,4]

[1]Programa de Pós-graduação em Engenharia Sanitária e Ambiental, Centro de Tecnologia, Universidade Federal do Rio Grande do Norte – UFRN, Av. Senador Salgado Filho, 3000, Campus Universitário, 59078-900, Natal, RN, Brasil

[2]Programa de Pós-graduação em Ecologia, Centro de Biociências, Universidade Federal do Rio Grande do Norte – UFRN, Av. Senador Salgado Filho, 3000, Campus Universitário, 59078-970, Natal, RN, Brasil

[3]ELKH-PE Limnoecology Research Group, Egyetem u. 10, 8200, Veszprem, Hungary

[4]Laboratório de Recursos Hídricos e Saneamento Ambiental, Departamento de Engenharia Civil e Ambiental, Universidade Federal do Rio Grande do Norte – UFRN, Av. Senador Salgado Filho, 3000, Campus Universitário, 59078-900, Natal, RN, Brasil

*e-mail: caiovitormatos@gmail.com

Cite as: Moreira, C.V.M., Costa, M.R.A. and Becker, V. Impacts of extreme precipitation events in water quality: a scientometric analysis in global scale. *Acta Limnologica Brasiliensia*, 2023, vol. 35, e17.

Abstract: Aim: This study aims to evaluate temporal patterns of extreme events related to precipitation on a global scale, identifying their main impacts and if there are climatic zones more susceptible to these phenomena using a scientometric approach. **Methods:** A systematic review was conducted on scientific papers published between 1991 and July 2020, obtained from the *Scopus* and *Thomson ISI Web of Science* databases. Keywords related to precipitation extreme events and their effects on planktonic communities and freshwater ecosystems' water quality were used in the search. **Results:** The analysis revealed a significant increase in publications, particularly from 2014 onwards, following the release of reports by the Intergovernmental Panel on Climate Change (IPCC) and the American Meteorological Society (AMS). These reports highlighted the increasing frequency of these climatic events and their potential for causing damage to humanity. In this review, we focused on extreme weather events related to precipitation such as droughts, rains, and floods. These events, due to their sudden volumetric changes, lead to immediate physical and chemical alterations in the water column. The main impacts of these extreme events on aquatic ecosystems include increased nutrient concentrations (mainly phosphorus and nitrogen), contamination by micropollutants, cyanobacteria blooms, and loss of biodiversity. **Conclusions:** The scientometric analysis indicates that extreme weather events associated with precipitation have a detrimental effect on water quality and aquatic biodiversity, exacerbating the eutrophication process in freshwater systems.

Keywords: climate change; drought; storms; rainfall; eutrophication.

Resumo: Objetivo: Encontrar padrões temporais dos eventos extremos relacionados a precipitação em escala global, assim identificar os principais impactos e se há zonas climáticas suscetíveis a esses fenômenos em uma abordagem cienciométrica. **Métodos:** Realizamos uma revisão sistemática investigando trabalhos científicos publicados entre 1991 até julho de 2020 nas bases de dados *Scopus*

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e *Thomson ISI Web of Science*. Buscamos por palavras-chave relacionadas a eventos extremos de precipitação e efeitos sobre a comunidade planctônica e a qualidade da água de ecossistemas aquáticos continentais. **Resultados:** Observamos um aumento expressivo de publicações, especialmente a partir de 2014 após a publicação de relatórios do Painel Intergovernamental sobre Mudanças Climáticas (IPCC) e Sociedade Americana de Meteorologia (AMS), apontando a tendência de crescimento de frequência desses eventos climáticos e o potencial de danos a humanidade. Nesta revisão escolhemos os eventos climáticos extremos relacionados à precipitação (secas, chuvas e inundações), que promovem uma variação volumétrica abrupta que imediatamente causa alterações físicas e químicas na coluna d'água. Como principais impactos desses eventos extremos nos ecossistemas aquáticos encontramos aumento da concentração de nutrientes (principalmente fósforo e nitrogênio), contaminação por micropoluentes, florações de cianobactérias e perda de biodiversidade. **Conclusões:** A análise cienciométrica revelou que eventos climáticos extremos relacionados à precipitação geram impactos negativos na qualidade da água e na biodiversidade aquática, intensificando o processo de eutrofização em sistemas aquáticos continentais.

Palavras-chave: mudanças climáticas; secas; tempestades; chuvas; eutrofização.

1. Introduction

Extreme weather events (EWEs) are climatic events that can have significant impacts on natural and human-altered environments. Examples include heat waves, storms, droughts, blizzards, and floods. There are two ways to characterize these events: frequency and/or magnitude (Peterson et al., 2012). Analyzing the occurrence frequency curve is a common method to determine if a climatic event is extreme. This involves examining the frequency distribution of the event over a specific period. Frequency is calculated by counting the number of times the event surpasses or crosses a predefined threshold value (IPCC, 2012; Peterson et al., 2012). By employing this method, we can objectively assess the severity of climatic events, leading to a better understanding, monitoring, and prediction of extreme weather phenomena. It also helps evaluate the potential impacts of such events and design appropriate adaptation and mitigation strategies.

Another approach is the classification based on the magnitude of the impact caused by these events. This approach establishes specific limits for parameters that quantify the intensity of the impact, such as temperature thresholds for heat waves or flow and precipitation values for extreme rainfall and floods. These limits are location-specific, as an event of the same magnitude can be considered extreme in one region and typical in another (Peterson et al., 2012).

The sixth report of the Intergovernmental Panel on Climate Change (IPCC) highlighted an increase in extreme events compared to the previous report (AR5). Global projections indicate an increase in extreme rainfall, droughts, heat waves, frosts, and hurricanes (IPCC, 2022). Regarding the specific climate zones most affected by the heightened occurrence of extreme weather events (EWEs), there is currently no scientific consensus. The IPCC report (2022) indicates that there are indications of intensified extreme precipitation events, particularly in tropical regions. However, there is insufficient research to make definitive claims. In terms of temperature-related EWEs, the same report suggests that these events are likely to become more pronounced.

Furthermore, extreme weather events (EWEs) are increasingly becoming more intense and prolonged, as reported by the Intergovernmental Panel on Climate Change (IPCC, 2022). These phenomena pose a significant threat to human life and biodiversity, particularly in freshwater environments (Marengo et al., 2009; Stockwell et al., 2020; IPCC, 2022). EWEs associated with precipitation, such as severe droughts and extreme rainfall (e.g., storms, floods, hurricanes), have substantial impacts on water quality in freshwater systems. It is therefore essential to comprehend the consequences of EWEs on water quality and how they will affect aquatic biodiversity.

Freshwater ecosystems are particularly sensitive to precipitation events due to the substantial fluctuations in water volume caused by these phenomena (Woodward et al., 2010; Hrdinka et al., 2012; Domis et al., 2013; Mosley, 2015). During storms, increased surface runoff accelerates erosive processes, leading to sediment transport into surface water bodies. The specific contaminants carried into the water source depend on the land use and occupation within the basin (Nobre et al., 2020; Stockwell et al., 2020). In drought events, the reduction in water volume leads to higher concentrations of nutrients and contaminants, potentially exceeding safe consumption limits during severe droughts (Rocha Junior et al., 2018; Santos et al., 2021; Cortez et al., 2022). The drastic changes in water volume trigger alterations in various physical and chemical parameters, such as suspended solids and nutrient concentrations, turbidity, transparency, temperature, and pH (Stockwell et al., 2020; Mosley, 2015; Marengo et al., 2018; Santos et al., 2021). These changes in light and nutrient conditions directly impact the phytoplankton community, thereby influencing trophic dynamics and overall ecosystem functioning (Guo et al., 2018; Ji & Havens, 2019; Lisboa et al., 2020).

Scientometric studies focusing on aquatic systems provide a valuable framework for investigating variations in water quality patterns and understanding the underlying mechanisms that govern the responses of water bodies (Costa et al., 2018; Stockwell et al., 2020). By analyzing scientific publications and related metrics in this field, these studies contribute to the accumulation of knowledge and insights regarding aquatic ecosystems (Costa et al., 2018). Scientometric studies allows for the identification of spatial and temporal patterns, enabling the detection of any increases in the frequency of extreme events and the identification of specific regional factors that amplify or mitigate impacts on aquatic ecosystems (Zitt & Bassecoulard, 2008; Stockwell et al., 2020). Such knowledge is essential for evidence-based decision-making, effective management strategies, and the conservation of our valuable water resources.

By conducting a scientometric review, we aim to gain a global and temporal understanding of how extreme weather events and their impacts on water quality have been studied. This framework of information will allow us to address several key questions: i) What are the specific impacts of precipitation-related extreme weather events on water quality ii) What methodologies have been employed in these studies iii) Which types of studies and parameters are most commonly utilized in this research iv) Has there been an increase in the number of publications on this topic? v) How do precipitation-related extreme weather events affect ecological communities? vi) Are these studies evenly distributed across different climatic regions?

This study aimed to assess the impacts of extreme weather events related to precipitation through a systematic review of nearly three decades of scientific studies. The objective was to evaluate the spatial and temporal patterns of these events on a global scale, while identifying the primary impacts and climates zones most vulnerable to such climatic events.

2. Material and Methods

We conducted a systematic review of scientific articles published between 1991 and July 2020, focusing on extreme weather events (EWEs) and their impact on water quality and planktonic communities in continental aquatic ecosystems. The search was performed in the *Scopus* database (up to July 3, 2020) and *Thomson ISI Web of Science* database (up to May 17, 2020). The search keywords included "extreme event" to represent extreme weather events, along with terms such as "water quality," "freshwater," and "limnol*" to represent continental water bodies and water quality. Duplicate articles found in both databases were eliminated from the analysis. Two screening processes were conducted to ensure that the articles addressed EWEs related to precipitation events and their effects on continental aquatic environments. Information from the selected scientific articles was extracted according to Table 1.

The data obtained from the review were analyzed from two perspectives: i) bibliometric data, including the year of publication, climate zones, methodologies used, and types of ecosystems studied; and ii) data on the effects on planktonic communities and water quality. The justification for selecting each parameter is provided in Table 1. The screening process was detailed in the supplementary material, available in SciELO Data (https://doi.org/10.48331/scielodata.QCGJEB), where there is also a table with the Digital Object Identifier (DOI) of all papers analyzed in this study.

3. Results

The selected set of keywords generated a total of 1649 scientific papers, with 1105 papers found in the Thomson ISI Web of Science database and 544 articles in the Scopus database. After removing duplicate articles (n = 287), the remaining database consisted of 1362 papers. However, upon further analysis based on the study criteria (specifically focusing on extreme precipitation events in freshwater ecosystems), the database was further narrowed down to 279 scientific papers, which were used for temporal analysis. Additionally, to specifically evaluate the response of biological communities to changes in water quality, studies that conducted reviews of extreme weather events (EWEs) were excluded, resulting in a final dataset of 254 articles.

Table 1. Categories of data extracted from the analyzed scientific papers (from 1991 to July 2020) available in the *Thomson ISI Web of Science* and *Scopus* databases, with acronyms used and rationale for each category analyzed.

	Acronyms used	Rationale
Type of extreme event	Extreme rain (R), extreme drought (D), floods (F), rain and wind extreme events (RW), hurricane (H)	Climate event addressed by the study. The type of EWEs will influence, direct and indirectly, in their effects on water quality and biological communities.
Climate zone	Tropical, Subtropical, Temperate, Continental and Polar	Related to the climatic zone in which the studied area is located. Relevant to understand the relationship of possible impacts with climate zones, identifying susceptible areas and how EWEs are distributed in the globe.
Approach	Monitoring, Case of Study, Modeling and Experimental.	Methodology used to develop the study. Understand how EWEs and their impacts on water bodies have been studied over time and space.
Ecosystem	River, Lake/lagoon, Reservoir, Basin, Mesocosms, Estuary and Wetlands.	Type of freshwater related to EWEs. Understanding the susceptibility of aquatic ecosystem types to EWEs.
Type of parameter studied	Physical, chemical and biological parameters.	Parameters used by the studies and their possible combinations. Understand how the water quality of these ecosystems under the influence of EWEs has been studied.
Type of biological parameter	Phytoplankton, zooplankton, macrophytes, macroinvertebrates and fishes.	Evaluate which biological community are being studied related to EWEs. Helps to understand effects of EWEs on ecosystem functioning and biodiversity.
Impact in the main parameter	Positive, Negative, Mixed or Neutral.	Evaluate direction of the effects of the response in the main parameter (abiotic or biotic factor) observed in the study.
Impact on water quality	Positive, negative, mixed or neutral.	Using the main parameter studied to interpret the variations (if occurred). Important to understand the direction of the effects observed on the water quality parameters.

3.1. Bibliometric and spatial-temporal information

We observed a consistent increase in the number of scientific articles focusing on the effects of precipitation-related EWEs on water quality throughout the analyzed years, as depicted in Figure 1. The publication of scientific articles on EWEs began in 1992, and a notable rise in publications per year was observed after 2014 (Figure 1A). This growth is also evident in the cumulative articles per year graph (Figure 1B).

In terms of specific event types, extreme rainfall events were the most frequently studied, with a total of 128 analyzed papers. Studies investigating precipitation-related floods contributed 81 papers, while papers addressing extreme droughts accounted for 86 studies. Additionally, there were 17 papers that focused on rainfall and wind extremes (Figure 2A). It is important to note that the total number of articles exceeds the sum of these amounts because some articles addressed more than one type of event. Consequently, research on extreme rainfall events, including extreme rainfall, storms, and floods, represented 72% of the total number of articles, while droughts constituted only 28% of the studies.

Regarding the distribution of studies across climatic zones, the temperate region had the highest number of publications (n = 124), followed by the subtropical region (n = 92), and the tropical region (n = 36). There was only one paper developed in a polar climate, and five papers did not provide information on the climatic region or their research did not pertain to specific climatic zones (Figure 2B).

Rivers were the most extensively studied type of freshwater ecosystems in relation to EWEs, with a total of 102 studies. Estuaries, lakes, and reservoirs accounted for a similar number of studies, with 40 each (Figure 2C).

Monitoring studies constituted the majority of the analyzed papers, totaling 176. Additionally, 77 papers utilized modeling approaches to generate their results. Other approaches explored in the research included case studies and experimental papers, which were represented by 10 publications each (Figure 2D).

3.2. Consequences of EWEs on biological communities

In evaluating studies related to the response of limnological parameters to EWEs, it was observed that

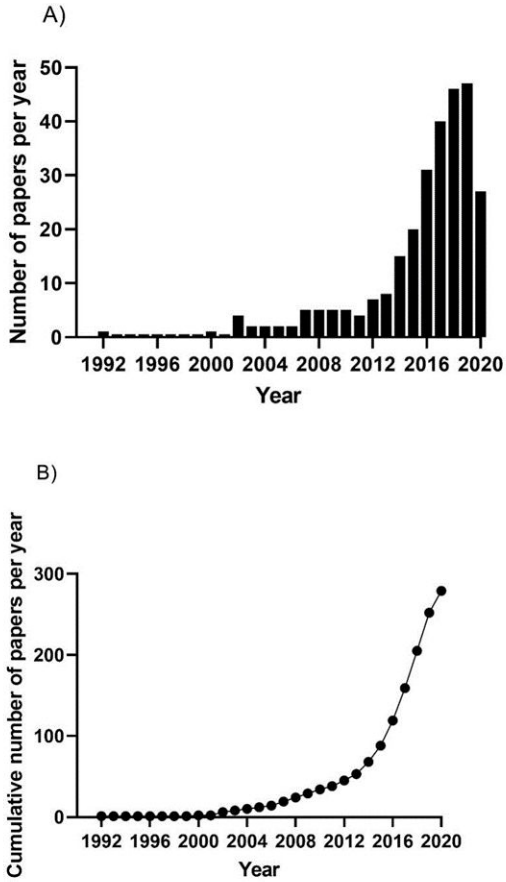

Figure 1. A) Number of published articles about the effects of precipitation-related EWEs on water quality over time. B) Cumulative number of published articles by year. Study period analized from 1992 to July 2020.

the majority of them focused on physical parameters (n = 222), followed by chemical parameters (n = 194), and biological parameters (n = 115) (Figure 3A).

Regarding the direction of the effects, the prevalence of papers indicated negative impacts on water quality following EWEs, accounting for 88% of the total articles studied (n = 224). Mixed impacts, involving both positive and negative effects, were observed in 19 studies, while 8 studies reported positive impacts on the analyzed parameters. Only one article showed no impact from the extreme weather event under investigation (Figure 3B).

Among the analyzed biological communities, the most extensively studied category was phytoplankton (n = 43), followed by macroinvertebrates (n = 24), fish (n = 17), zooplankton (n = 6), and macrophytes (n = 6) (Figure 3C).

4. Discussion

This scientometric study allowed us to evaluate the impacts of extreme precipitation events on the physical, chemical, and biological parameters of continental surface water bodies. Given the context of climate change, this topic is crucial for discussing future human water supply, as the majority of water consumed by communities comes from surface water sources on the continent (Yoshikawa et al., 2014; IPCC, 2022). Additionally, we identified patterns in scientific research on this subject, including the regions where most studies are conducted and the primary methods employed in these publications.

Our analysis revealed an increasing interest in the issue of climatic events, particularly with a notable surge in publications starting in 2010. There is also a strong focus on water quality and the impacts of extreme events on rivers, which constituted the majority of studies, with most publications reporting negative impacts associated with EWEs. This perspective underscores the importance of these studies and the necessity for such analyses to inform actions aimed at mitigating the effects of these phenomena. Changes in physical-chemical parameters ultimately affect the biological community, leading to alterations in aquatic ecosystems (Sharip et al., 2019; Stockwell et al., 2020), thereby compromising the assurance of multiple water uses, including public supply, irrigation, and ecosystem services (Barbosa et al., 2012).

There is not a concept that fully defines what extreme weather events are, but the most common approach to defining extreme weather events is by using historical data and climate expectations. Typically, events occurring in the lowest 5% of a frequency curve are considered extreme (Ji & Havens, 2019; Camuffo et al., 2020; Stockwell et al., 2020). This analysis requires at least 20 years of daily, continuous monitoring data from historical time-series (IPCC, 2012; Peterson et al., 2012; WMO, 2016). However, many countries lack programs for monitoring and managing extreme weather events, which further complicates the classification and study of their impacts (Peterson et al., 2012; WMO, 2016).

As a result, still remains a significant gap in the literature regarding the classification of extreme weather events, and many publications do not specify the method used for their classification due to data limitations or a lack of consensus on the threshold for an event to be considered extreme (Peterson et al., 2012; Camuffo et al., 2020; Stockwell et al., 2020).

In 2012, the IPCC published a report focused on the risks of extreme weather events and the

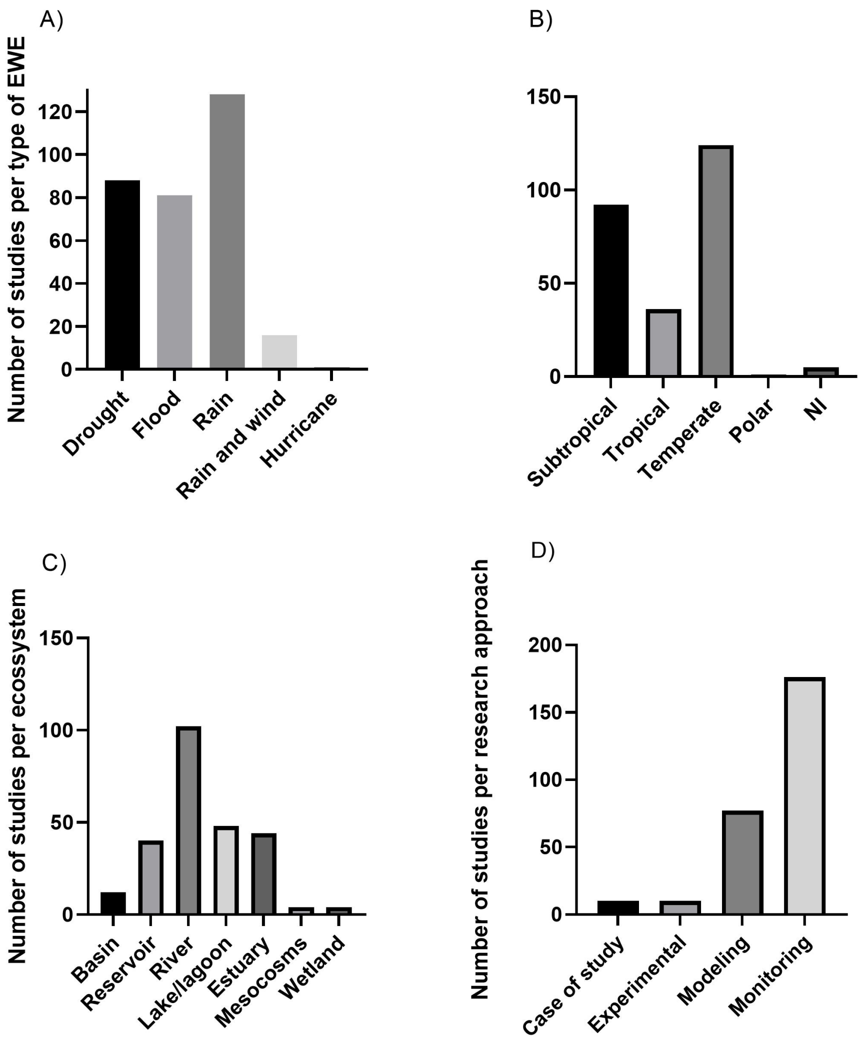

Figure 2. A) Number of papers published by type of extreme weather event. B) Number of articles published per climate zone. C) Number of articles by ecosystem type. D) Number of publications by methodological approach. Articles published from 1992 and June 2020. NI = not informed.

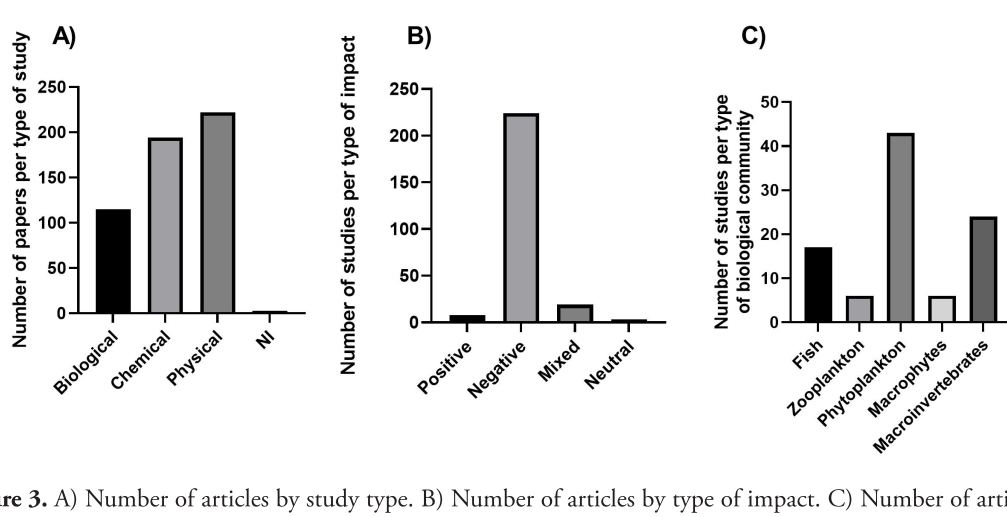

Figure 3. A) Number of articles by study type. B) Number of articles by type of impact. C) Number of articles by type of biological community. Articles published between 1992 and July 2020.

number of publications showed a significant increase after that year (IPCC, 2012). The increase of publications on this topic may be explained by the growing interest related to climate change.

Extreme droughts are more difficult to catalogue, as they require large databases, with long and continuous monitoring periods (WMO, 2016; IPCC, 2022). While storms systems last from hours to a few days, extreme droughts can last for years. Thus, tracking and identifying water quality impacts becomes more challenging in drought extreme events.

The publications selected by our study were more abundant in temperate climate regions, which can also be evidenced in the bibliometric analysis by Mehmood (2019), which showed that the five countries that published the most water-related articles in the period 2012-2017 were: the United States, China, Germany, the United Kingdom, and France. All these countries have most or all their territories in temperate climate zones. It is also worth to mention that these are reference countries in research funding, which may explain the amount of work done in this climate zone.

There is no consensus in climate science whether some regions are more prone to increased occurrence of precipitation-related EWEs due to climate change than others, but it is known that certain regions are more vulnerable to these events, whether due to social, political, or environmental issues (Lima & Bonetti, 2020). Places with less accumulated rainfall during the year and with high evapotranspiration rates are likely to be more affected by severe droughts. On the other hand, places with high urbanization and low vegetation cover are more vulnerable to the risks of extreme rainfall and flooding, since these watersheds produce higher surface runoff flows and, consequently, carry more allochthonous material to the water body (Mosley, 2015; Marengo et al., 2018; Nobre et al., 2020). These aspects, despite not being characteristic features of extreme events shape the level of impact of EWEs on freshwater ecosystems (rivers, lakes, reservoirs, and estuaries), have had a large difference in the number of publications. Yoshikawa et al. (2014) showed that rivers are the largest suppliers of water for irrigation worldwide, and these ecosystems already show signs of collapse, with the expectation that by 2050 they will not be able to meet the demand for irrigated agriculture. Thus, most publications have these environments as an area of study due to their importance as a source of water and the predictions of water shortages due to climate change (IPCC, 2022).

The main approach adopted in the papers on this theme was the monitoring. The difficulty of isolating the impact of extreme events from the various other factors that alter the dynamics of water quality is noteworthy, so these studies allow us to verify changes over time, but their results can be influenced by anthropic activities in watersheds and other environmental factors that should be considered (Costa et al., 2019; Stockwell et al., 2020). Therefore, experimental research, which presented little expression regarding the number of publications, plays an important role for this area, since in these studies it is possible to isolate the effects of EWEs and observe more clearly the impacts on water quality. The extreme events related to precipitation (rainfall, floods and extreme droughts) cause mostly negative impacts, and some effects on water quality common to these types of events include the increased concentration of suspended solids, nutrients, and micropollutants, favoring the eutrophication and loss of biodiversity (Havens et al., 2016; Rocha Junior et al., 2018; Costa et al., 2019; Nobre et al., 2020; Pham et al., 2021; Santos et al., 2021). As for the papers that showed positive impacts, on the other hand, there is a case of repeated flooding that resulted in phosphorus depletion in the watershed and phosphorus stock in the sediment (Zoboli et al., 2015).

Moreover, the EWEs of heavy rainfall (extreme rainfall and floods) were characterized by an initial effect of reduced primary productivity due to the high concentration of solids and low light conditions, but over time, the nutrients (phosphorus and nitrogen) brought along with these materials caused an increase in phytoplankton biomass, favoring the dominance of cyanobacteria (Outram et al., 2014; Havens et al., 2016; Pham et al., 2021). In events with thunderstorms and extreme rainfall, preliminary conditions such as water volume and watershed use/occupancy are very important factors to indicate the direction of impact (and its magnitude). Ecosystems in urbanized watersheds suffer greater and longer-lasting impacts than those in watersheds with natural vegetation. Basins that have most of the natural vegetation preserved are less prone to having these materials introduced into the water bodies they hold (Adame et al., 2019; Stockwell et al., 2020). In the case of severe droughts, the negative impacts are observed in several ways, from the decreased water transparency due to sediment becoming more susceptible to wind action (Luettich Junior et al., 1990; Jalil et al., 2019; Tang et al., 2020), to the increasing pollutant and nutrient concentrations due to reduced water volume, which favors eutrophication and cyanobacteria dominance. In reservoirs, severe droughts have an accentuated impact due to the increased water residence time, making them ideal environments for these blooms (Qiu et al., 2017; Rocha Junior et al., 2018; Nobre et al., 2020; Santos et al., 2021; Cortez et al., 2022). A study conducted in a semi-arid region indicates that reservoirs in the same region under the same drought period had different behavior regarding the dominance of cyanobacteria. While part of these reservoirs had an increase in phytoplankton biomass and dominance of the cyanobacteria group, others that were with lower water capacity showed relevant growth of the mixotrophic algae community (Costa et al., 2019).

This study highlights the significance of consolidating information to enhance our understanding of the impacts of extreme events. Additionally, our research raises crucial questions regarding the variations in ecosystem types across climate zones, the associated primary impacts, and how these characteristics can mitigate the effects of extreme weather events, particularly precipitation events. New studies are required to address these questions and ensure access to water in future climatic scenarios resulting from climate change. In conclusion, our scientometric analysis revealed that extreme weather events related to precipitation generate negative impacts on water quality and aquatic biodiversity, intensifying the eutrophication process in freshwater systems. Our findings show the need to track and study the impact of extreme events in a multidisciplinary and multi methodological way, so that we can better understand and eventually mitigate the expected impacts to our continental water bodies.

Acknowledgements

We are grateful to the Programa de Pós-Graduação em Engenharia e Saneamento Ambiental from Universidade Federal do Rio Grande do Norte (UFRN), and the Limnological Studies in the Semiarid Group (ELISA), especially Gabriel Nogueira Cunha and Luana Silvestre Fernandes for help in sorting the papers used in scientometric analysis. We would also like to thank Professor Juliana D. Dias for her support and guidance during the study. MRAC is grateful for the postdoctoral scholarship by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES), finance code 001. VB also acknowledges continuous funding through a Research Productivity Grant provided by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (process #308652/2019-3). The authors declare no conflict of interest.

Data availability

The entire dataset supporting the results of this study was made available in SciELO Data and can be accessed in https://doi.org/10.48331/scielodata.QCGJEB.

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Received: 10 January 2023
Accepted: 21 June 2023

Associate Editor: Victor Satoru Saito.