



## Understanding anthropogenic pressures on freshwater ecosystems: recent trends and emerging issues (2019-2023)

Análise das pressões antrópicas sobre ecossistemas de água doce: tendências atuais e desafios emergentes (2019-2023)

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**Abstract: Aim:** To identify and analyze the most frequently investigated anthropogenic pressures and emerging research themes in freshwater ecosystem studies recently published (between 2019 and 2023). **Methods:** A bibliometric literature review was conducted using the Web of Science and Scopus databases. Articles were selected based on predefined search strings related to freshwater systems and human impacts. A total of 5,549 peer-reviewed articles in English were analyzed using the Bibliometrix package in R<sup>®</sup>, focusing on abstracts and author keywords to detect trends in stressors, contaminants, ecosystem types, and research collaboration networks. **Results:** Rivers were the most frequently studied ecosystems (4,848 records; 90%), followed by lakes (621; 11%) and wetlands (337; 6%). Agriculture (35%), urbanization (28%), and mining (11%) were the top referenced drivers. Mentions of emerging pollutants grew sharply, with microplastics rising from 19 in 2019 to 198 in 2023, surpassing nutrients and pharmaceuticals. China (3,089), the United States (1,207), Canada (353), and Brazil (309) led in research output, with increasing international collaborations and adoption of advanced tools such as machine learning and remote sensing. **Conclusions:** The literature reveals a growing interest in understanding complex human pressures on freshwater ecosystems. Strengthening international cooperation and integrating policy-oriented research emerge as frequently highlighted strategies in the literature to address these challenges.

**Keywords:** freshwater ecosystems; bibliometric analysis; anthropogenic stressors; emerging pollutants; scientific collaboration.

**Resumo: Objetivo:** Identificar e analisar as pressões antrópicas mais frequentemente investigadas e os temas de pesquisa emergentes em estudos de ecossistemas de água doce publicados recentemente (entre 2019 e 2023). **Métodos:** Uma revisão bibliométrica da literatura foi conduzida utilizando as bases de dados Web of Science e Scopus. Os artigos foram selecionados com base em sequências de busca predefinidas relacionadas a sistemas de água doce e impactos humanos. Um total de 5.549 artigos revisados por pares em inglês foram analisados utilizando o pacote Bibliometrix R<sup>®</sup>, com foco em resumos e palavras-chave dos autores para detectar tendências em estressores, contaminantes, tipos de ecossistemas e redes de colaboração em pesquisa. **Resultados:** Rios foram os ecossistemas



mais frequentemente estudados (4.848 registros; 90%), seguidos por lagos (621; 11%) e áreas úmidas (337; 6%). Agricultura (35%), urbanização (28%) e mineração (11%) foram os principais fatores referenciados. As menções a poluentes emergentes aumentaram acentuadamente, com os microplásticos subindo de 19 em 2019 para 198 em 2023, ultrapassando nutrientes e produtos farmacêuticos. China (3.089), Estados Unidos (1.207), Canadá (353) e Brasil (309) lideraram a produção de pesquisas, com crescentes colaborações internacionais e adoção de ferramentas avançadas, como aprendizado de máquina e sensoriamento remoto. **Conclusões:** A literatura revela um interesse crescente em compreender as complexas pressões humanas sobre os ecossistemas de água doce. O fortalecimento da cooperação internacional e a integração de pesquisas orientadas a políticas públicas surgem como estratégias frequentemente destacadas na literatura para enfrentar esses desafios.

**Palavras-chave:** ecossistemas de água doce; análise bibliométrica; estressores antropogênicos; poluentes emergentes; colaboração científica.

## 1. Introduction

Freshwater ecosystems, encompassing rivers, lakes, reservoirs, and wetlands, are essential components of the Earth's environment, providing vital ecological and socio-economic services (Lynch et al., 2023; Talampas et al., 2025). They serve as reservoirs of biodiversity, support agriculture and fisheries, contribute to the global hydrological cycle, nutrient cycling, carbon sequestration, and water purification, and influence local and global climates (Rinke et al., 2019). Thus, these ecosystems play a crucial role in maintaining ecological balance and supporting human lives (Qadri & Bhat, 2020). Nevertheless, they are increasingly described in literature as being vulnerable to the effects of human activities (Dudgeon et al., 2006; Culhane et al., 2019).

Human economic development, while improving living standards, has led to unintended consequences for freshwater ecosystems (Wolfram et al., 2021). Land-use changes, such as urbanization and agriculture, have led to habitat degradation, increased sedimentation, and nutrient runoff (Almeida et al., 2019; Lacher et al., 2019). Urbanization often results in the replacement of natural landscapes with impermeable or compacted surfaces, increasing runoff and reducing the infiltration of water into the ground, which exacerbates flooding and erosion issues (Capps et al., 2016). Agriculture, while essential for food production, frequently involves the use of fertilizers and pesticides that can leach into water bodies, causing eutrophication and harmful algal blooms (Moss, 2008). Over-extraction of water for agricultural irrigation can lower water levels in rivers and lakes, reducing habitat availability for aquatic organisms and concentrating pollutants (Postel et al., 1996).

The construction of dams, industrial exploitation, and mining activities have profoundly altered

aquatic ecosystems, fragmenting habitats, blocking migratory species movements, disrupting sediment transport dynamics, and introducing pollutants such as heavy metals and chemicals, leading to ecosystem degradation and severe biodiversity loss (Cui et al., 2020; Prince et al., 2020). These disturbances cascade through food webs, with nutrient pollution altering plankton communities and triggering effects on fish and higher trophic levels (Su et al., 2021). Moreover, declining water quality and availability undermines essential ecosystem services, causing reduced agricultural productivity, threats to food security, and conflicts over water resources (Dinar et al., 2019; Barrett, 2020; Din et al., 2022). In communities heavily reliant on freshwater for drinking, irrigation, and fishing, these impacts exacerbate economic instability, health risks, and social tensions, reducing both ecosystem and societal resilience (Reid et al., 2019; Tzanakakis et al., 2020; Fonseca et al., 2022).

While numerous studies have documented the impacts of economic activities on freshwater ecosystems, recent literature points to new sources of concern (Xabadia et al., 2021). Interest in emerging contaminants, defined as chemicals or materials that have been detected in the environment but are not commonly monitored or regulated, is increasing. However, their effects on ecosystems and human health are still not well understood (Wilkinson et al., 2022).

The concept of emerging contaminants has gained prominence due to their growing potential environmental impact (Gavrilescu et al., 2015) this category includes pharmaceuticals, personal care products, endocrine-disrupting chemicals, and microplastics (Schwarzenbach et al., 2006; Wright & Kelly, 2017). For instance, recent works increasingly mention the presence of microplastics in aquatic environments, often raising concerns

about potential threats to biodiversity and human health (Bucci et al., 2020; Hale et al., 2020).

Given the critical importance of freshwater ecosystems and the increasing pressures they face from human economic activities, it is essential to conduct comprehensive studies that identify and analyze how these pressures are represented in the literature, while also recognizing the gaps and emerging research needs (Reid et al., 2019). Scientometrics, a field dedicated to the quantitative analysis of scientific publications, provides powerful tools for examining large volumes of literature. By applying statistical and computational methods, scientometric approaches allow researchers to identify trends, research gaps, collaboration patterns, and emerging areas of interest within a specific field (Oyewola & Dada 2022). In this study, scientometric methods were employed through the Bibliometrix/Biblioshiny platform to systematically analyze the recent literature on anthropogenic impacts on freshwater ecosystems (published between 2019 and 2023). By leveraging these tools, this study focuses on analyzing recent scientific research (2019-2023) on freshwater ecosystems, a timeframe chosen to ensure the inclusion of the most relevant studies, reflecting contemporary challenges and advancements. This period strikes a balance between capturing sufficient data to observe meaningful trends and maintaining the relevance of the findings. The analysis aims to identify what topics the scientific community has been recently addressing regarding the human-driven pressures on freshwater waters and whether new patterns, such as a focus on specific ecosystem types, stressors, and emerging topics—are becoming prominent. Additionally, it will examine global research productivity and collaborations. Thus, we discuss how anthropogenic activities are portrayed in literature, the trends that emerge from recent research, and their implications for understanding global freshwater challenges.

## 2. Methods

### 2.1. Selection of databases

We conducted our search on the Web of Science (WOS) and Scopus platforms. These databases were chosen due to their comprehensive coverage of peer-reviewed literature and their prominence in environmental science research (Mongeon & Paul-Hus, 2016). WOS and Scopus are known for their extensive indexing, which includes a wide range of high-impact journals (Zhu & Liu, 2020). This

ensures that the search captures the most relevant and high-quality studies in the field.

### 2.2. Search query design

The search query used was (“Freshwater\*” OR “River\*” OR “Lake\*” OR “Stream\*” OR “Wetland\*” OR “Pond\*” NOT “Sea\*” NOT “Ocean\*” NOT “Marine\*”) AND (“Human Impact\*” OR “Anthropogenic Stress\*” OR “Human Activity\*” OR “Anthropogenic Pressure\*” OR “Human-Induced Change\*” OR “Anthropogenic Effect\*”). The terms “Freshwater,” “River,” and “Lake” were included to focus on studies related to freshwater ecosystems. The terms “Sea,” “Ocean,” and “Marine” were excluded to ensure that the search results pertained specifically to freshwater environments, avoiding any marine studies which are outside the scope of this analysis. The inclusion of terms like “Human Impacts,” “Anthropogenic Stresses,” and “Human Activities” ensured that the search targeted research addressing the effects of human activities on freshwater ecosystems.

It is important to acknowledge that the use of explicit anthropogenic-related terms in the search string may have excluded some studies that are relevant to the topic but do not mention those terms directly. For example, papers addressing eutrophication, microplastics, or water quality impacts may have been missed if they did not frame their research within the context of “human activities” or “anthropogenic stressors.” As such, the results presented here reflect research themes explicitly framed in the literature under anthropogenic terms during the search period. However, this also means that our analysis identifies only whether such themes were mentioned in abstracts or keywords, not whether the studies confirmed or rejected their ecological impacts. This cut in the search should not impose any analytical bias in the evaluation but highlights the main topics of interest being assessed.

### 2.3. Search results

The initial search returned 6059 articles from WOS and 2422 articles from Scopus bases.

### 2.4. Screening of retrieved articles

#### 2.4.1. Data export and unification

The bibliographic information from each database was exported in a format compatible with R<sup>\*</sup> software (version 4.3.3). This step involved downloading the citation data in BibTeX or CSV format. The exported data from WOS and Scopus were combined into a single data set using R<sup>®</sup>. This unification process was

conducted using the Bibliometrix package, which automatically standardizes bibliographic records and removes duplicates based on title, DOI, and other metadata fields. This ensures that each publication is represented only once in the final data set, avoiding bias due to overlapping entries between the two databases.

#### 2.4.2. Filter criteria

To screen the retrieved articles, we applied several filter criteria. Only articles published between 2019 and 2023 and written in English were selected to maintain consistency and ease of analysis, as English is the predominant language of scientific publications. Only peer-reviewed journal articles were included to ensure data reliability and scientific rigor. While this criterion ensured consistency in the analysis and reflects the dominant language of international scientific communication, we acknowledge that it may have excluded regionally relevant studies published in other languages, representing a potential linguistic bias.

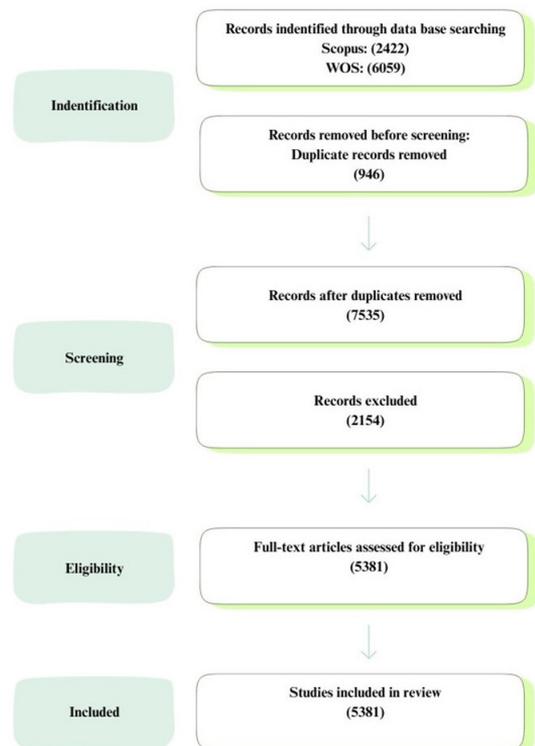
Additionally, we excluded articles primarily focused on estuaries and marshes. Although these ecosystems are often ecologically connected to continental waters and were initially considered due to their transitional nature (Junk et al., 1989; Mitsch & Gosselink, 2015), they are not strictly freshwater environments. Estuaries are characterized by variable salinity and are generally classified as brackish systems (Bianchi, 2007), while marshes may include freshwater, brackish, or saline types. To preserve ecological consistency within our freshwater scope, we focus exclusively on inland freshwater environments. These screening steps and exclusions are summarized in the PRISMA flow diagram (Figure 1), which illustrates the full methodological pathway from identification to inclusion.

From a total of 8481 records identified in Scopus and Web of Science, 946 duplicates were removed. Of the remaining 7535 records screened by title and abstract, 2154 were excluded due to thematic irrelevance, lack of anthropogenic focus, or focus on transitional aquatic environments (e.g., estuaries, mangroves, marshes). The final data set consisted of 5381 peer-reviewed articles (published between 2019 and 2023) related to anthropogenic pressures on strictly freshwater ecosystems.

#### 2.4.3. Search for terms in abstracts and author's keywords

The search for terms for analysis was conducted in the abstracts of the articles in our database.

Abstracts provide a concise summary of the research objectives, methods, results, and conclusions. Analyzing the abstracts ensures that the focus remains on the core content and main findings of the articles, making it a robust method for capturing the essence of the research without being diluted by less relevant details that may be present in other sections of the articles. Additionally, examining the author's keywords is equally important and relevant since they reflect the most critical concepts and topics of their research. These keywords often highlight the primary focus and unique aspects of the study, making them an essential component for identifying trends, common themes, and emerging areas of interest within a specific field. By including the author's keywords in the analysis, we ensure a comprehensive understanding of the research landscape, capturing both the synthesized summaries from the abstracts and thematic elements emphasized by the researchers.



**Figure 1.** PRISMA flow diagram summarizing the identification, screening, eligibility assessment, and inclusion of articles analyzed in this bibliometric review. A total of 7535 articles remained after duplicate removal. Following the application of exclusion criteria (e.g., publication type, language, and ecosystem scope), 5381 articles were deemed eligible and included in the final analysis. No additional exclusions were made after full-text assessment, as all remaining records met the inclusion criteria.

This dual approach enhances the robustness of bibliographic analysis, providing deeper insights into the significant areas of study and the evolution of research topics over time.

It is important to note that the presence of specific terms in abstracts or keywords was interpreted only as an indication that the topic was mentioned, not as confirmation that a parameter was measured, nor whether the study confirmed or refuted a particular impact. Our results reflect trends in how the literature frames anthropogenic pressures, not verified ecological outcomes. Evaluating the magnitude of such impacts would bring interesting and important information, but it would rely on a different data collecting approach and analysis such as meta-analysis techniques.

This methodological approach inherently limits our ability to infer causal relationships between stressors and ecosystem responses; instead, it provides a robust overview of research interests and thematic priorities expressed in recent literature.

### 2.5. Data analysis

The extraction and frequency analysis of terms were conducted using the Biblioshiny web interface of the Bibliometrix package in R<sup>®</sup> (Aria & Cuccurullo, 2017). Both abstracts and author keywords were processed through automated text-mining functions. For term frequency analysis, we adopted a binary counting approach—each term was counted only once per article, regardless of how many times it appeared in the abstract. This approach prevented overrepresentation of terms due to repetition within a single study and ensured equal weight across all documents. The results were

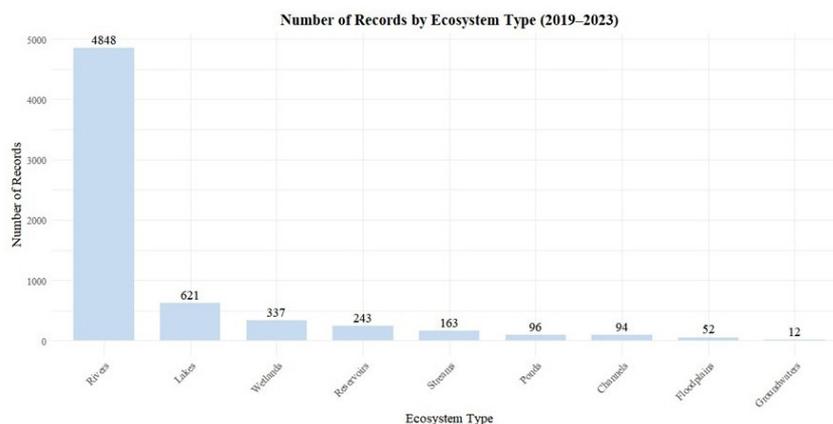
used to generate visual representations such as a Sankey diagram, which illustrates the evolution and co-occurrence of key topics across the study period. Although Bibliometrix provides tools for citation and co-citation analyses, these were not included in this study, as our focus was specifically on thematic trends and anthropogenic stressors represented in textual content.

## 3. Results

Our bibliometric analysis identified clear patterns in the literature between 2019 and 2023. Rivers were the most frequently mentioned freshwater ecosystem in the analyzed literature, followed by lakes and wetlands. Among anthropogenic stressors, agriculture, urbanization, and mining appeared as the most recurrent drivers. A noticeable increase was observed in references to emerging pollutants—particularly microplastics and pharmaceuticals, especially after 2021. In terms of geographic distribution, the United States, China, Canada, and Brazil were the most productive countries (Figure 2).

In the search for terms related to freshwater ecosystems, rivers emerge as the most frequently mentioned environment. Lakes are the second most cited type of ecosystem, followed by wetlands and reservoirs, which rank as the third and fourth most studied environments, respectively. (Figure 2).

Agriculture and food production emerged as the most frequently investigated impactful activities on the studied freshwater ecosystems, followed by industrial and energy-related activities, and finally, those associated with urbanization (Figure 3A).



**Figure 2.** Number of bibliometric records classified by ecosystem type. The figure presents the distribution of peer-reviewed articles (2019–2023) focused on strictly freshwater environments. Ecosystems such as estuaries, mangroves, lagoons, marshes, and peatlands were excluded due to their transitional or brackish nature, ensuring ecological consistency within the freshwater scope of this review. Rivers represent the most studied ecosystem, followed by lakes and wetlands.

When examining the types of pollutants affecting these ecosystems, nutrients such as Nitrogen (N) and Phosphorus (P) dominated the records, followed by pesticides and emerging contaminants like microplastics, personal care products, and pharmaceuticals. The literature revealed that references to microplastics, which were among the least frequent in 2019, sharply increased and, by 2022, surpassed nutrients as the most frequently mentioned potential contaminant in freshwater ecosystems (Figure 3B).

The Sankey diagram illustrates a progression and diversification of research themes reported in the literature. In the 2019-2020 period, the predominant themes include “Remote sensing”, “Erosion”, “Climate change”, “Biodiversity”, “Water quality”, “Groundwater”, and “Anthropogenic activities”. In 2021, there is a diversification of research themes. “Climate change” and “Water quality” remain relevant, while new themes emerge, such as “Holocene”, “Stable isotopes”, “Sediment transport”, “Sustainable development”, “Heavy metals”, “Ecosystem services”, and “Eutrophication”. In 2022, there is continuity in themes like “Water quality” and “Groundwater”, along with the introduction of “Human activities”, “Driving mechanism”, “Vulnerability”, “Wetland”, “Zooplankton” “Lake” and “Pollution.” In 2023, we observe a consolidation of persistent themes like “Climate change”, “Water quality”, “Groundwater”, and “Biodiversity”, along with the emergence of “Conservation”, “Google Earth Engine”, “Human activity”, “Eutrophication”, “Sediment”, “Ecosystem services”, and “Monitoring”. Themes like “Climate change” and “Water quality” are consolidated across all years, while others, such as

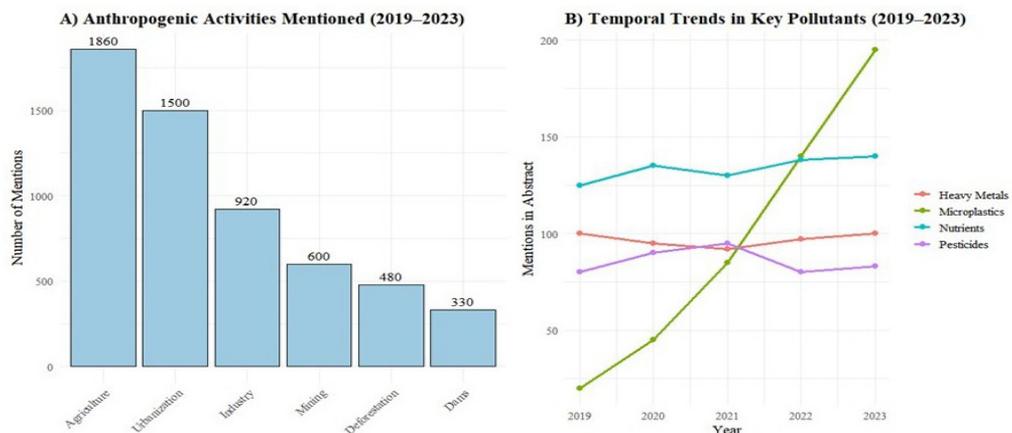
“Remote sensing” and “Sustainable development”, appear in multiple periods. Some themes, such as “Erosion” and “Heavy metals”, emerge briefly and disappear, reflecting shifts in research focus over time (Figure 4).

In addition to quantitative trends, an exploratory Sankey diagram (Figure 4) was used to visualize how author keywords evolved across the study period. This figure reveals thematic continuity (e.g., “climate change”, “biodiversity”, “water quality”) as well as the emergence of newer terms like “Google Earth Engine” and “random forest” in more recent years. While not a metric-based analysis, this visualization supports the identification of research transitions and complements the temporal trends quantitatively shown in Figure 3B.

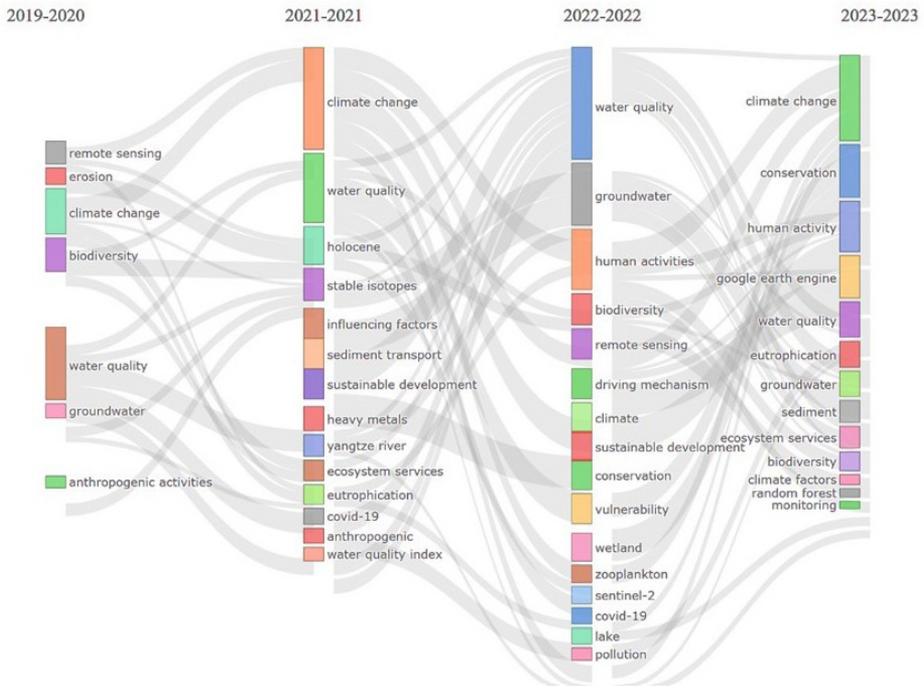
China stands out as the country with the highest scientific output on research addressing anthropogenic pressures on freshwater ecosystems studies during the 2019-2023 period. The United States, Canada, and Brazil follow in the ranking, with Brazil being the only Latin American country among the top contributors (Figure 5). These results highlight the prominence of countries with consolidated scientific infrastructure, while also revealing the significant role of emerging economies such as Brazil. The analysis also indicates differences in collaboration patterns, with some countries showing a high proportion of international co-authored publications.

#### 4. Discussion

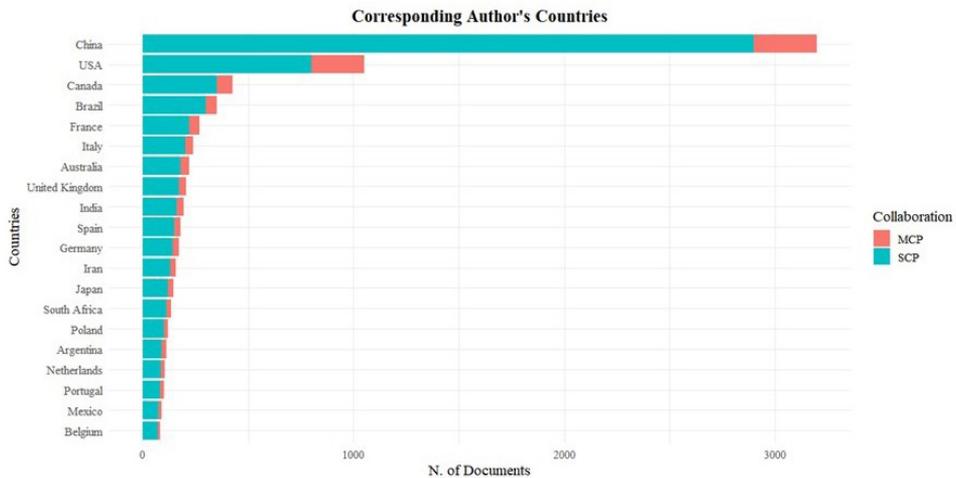
Freshwater ecosystems are increasingly affected by multiple anthropogenic stressors, and the literature reviewed between 2019 and 2023 reflects this concern. Our analysis identified clear patterns



**Figure 3.** (A) Most frequently mentioned anthropogenic activities; (B) Temporal trends of the most frequently mentioned pollutants in freshwater environments.



**Figure 4.** Sankey diagram depicting the temporal evolution of research themes in freshwater ecosystem studies from 2019 to 2023, based on author keywords. Node size reflects the frequency of each keyword in a given year, and the width of connecting lines represents thematic continuity between consecutive periods.



**Figure 5.** Scientific production by country on freshwater ecosystem impacts caused by anthropogenic activities (2019-2023), based on the corresponding author's affiliation. The bar colors distinguish between SCP (Single Country Publications) and MCP (Multiple Country Publications), indicating the extent of international collaboration.

in research priorities: (i) rivers as the most frequently studied ecosystems, (ii) agriculture, urbanization, and mining as dominant anthropogenic drivers, and (iii) microplastics and pharmaceuticals as emerging pollutants receiving growing attention. Below, we discuss the main themes highlighted in the literature, their regional distribution, and gaps that remain for future research.

#### 4.1. Rivers as the primary research focus

Rivers dominate freshwater studies, reflecting their ecological importance, accessibility, and direct connections to human populations (Meybeck, 2003). They play a central role in biogeochemical cycles (Pahl-Wostl, 2005) and are vulnerable to multiple stressors, from nutrient loading to plastic pollution (Vörösmarty et al., 2000). Their visibility

and immediate socio-economic relevance make them a natural research priority, as shown by their high frequency in the literature (Grill et al., 2019).

Although rivers dominate, lakes and wetlands also appeared as recurrent topics, though at lower frequency. Wetlands, for instance, remain underrepresented despite their crucial functions in biodiversity and carbon storage (Mammola et al., 2019; King et al., 2021). Encouraging greater attention to these ecosystems could broaden the scope of global freshwater research (Ramsar, 2018, 2021).

#### 4.2. *Human activities and pollutants impacting freshwater ecosystems*

Our results show that agriculture, urbanization, and mining are the most frequently referenced anthropogenic drivers. While case studies are abundant, here we summarize key impacts identified in the literature rather than detailing each example.

Agriculture remains a leading source of freshwater stress, frequently linked to nutrient enrichment and eutrophication (Carpenter et al., 1998; Smith et al., 1999). Fertilizers, pesticides, and sediment runoff contribute to biodiversity loss and long-term water quality decline (Carpenter et al., 1998; Smith et al., 1999; Dodds & Smith, 2016). Studies also emphasize indirect effects, such as deforestation for agricultural expansion, which alters hydrological cycles and ecosystem resilience (Foley et al., 2005; Davidson et al., 2012).

Urbanization is strongly associated with pollution from stormwater runoff, sewage, and impervious surfaces (Walsh et al., 2005). Literature frequently links urban expansion to increased nutrient and contaminant loads, shifts in microbial communities, and ecosystem health risks (Walsh et al., 2005; Paul & Meyer, 2001; Grimm et al., 2008). While negative impacts are well documented, some studies also highlight opportunities for mitigation, such as green infrastructure and bioremediation (Shuster et al., 2005; Fu et al., 2023).

Mining poses acute and long-lasting threats through sedimentation, heavy metal release, and acid mine drainage (Hudson-Edwards, 2003). Catastrophic dam failures in Brazil (Fundão 2015; Brumadinho 2019) stand out as emblematic cases of socio-ecological collapse, underscoring the vulnerability of river basins to poorly regulated extractive activities (Fernandes et al., 2016; Carmo et al., 2017).

Emerging pollutants such as microplastics and pharmaceuticals have seen a sharp rise in mentions, especially after 2021. Microplastics now appear in studies across all continents, with urbanization and

population density emerging as strong correlates, which agrees to our data as urbanization as one of the main impacting human activity (Windsor et al., 2019; Xu et al., 2021; Tibbetts et al., 2018). Although their ecological and health effects remain uncertain, the rising number of publications indicates increasing global concern (Ghosh et al., 2023). Pharmaceuticals are often studied alongside nutrient and pesticide contamination, highlighting cumulative stress on aquatic organisms (Kümmerer, 2008).

Overall, while the drivers differ in scale and mechanism, they share a common outcome: degradation of water quality and ecosystem function. By condensing the literature into these main categories, our analysis emphasizes how research efforts cluster around the most pressing global concerns.

#### 4.3. *Thematic evolution and emerging research tools*

Our Sankey analysis shows continuity of key themes such as climate change, biodiversity, and water quality, but also the rise of new keywords like Google Earth Engine, machine learning, and random forest. These reflect the incorporation of advanced computational approaches into freshwater studies (Gorelick et al., 2017; Lary et al., 2016).

The diversification of themes suggests a growing interdisciplinarity: ecological impacts are increasingly studied alongside socio-economic drivers, technological tools, and ecosystem services (Gorelick et al., 2017; Nasiri et al., 2022). However, our results also show a gap in the integration of limnological data with policy-oriented research. Despite abundant evidence of stressors, relatively few studies assess the effectiveness of management interventions. Strengthening this link is critical for translating knowledge into action (Shaad et al., 2022).

#### 4.4. *Geographical distribution of studies and international collaborations*

Research production remains concentrated in high-income countries—especially the United States, China, and Canada—driven by strong scientific infrastructure and investments (NSB, 2020; Zhang et al., 2022; Tollefson, 2018). Brazil also stands out as a leading contributor in the Global South, reflecting its ecological importance as a biodiversity hotspot and as a country that harbors some of the world's largest and most diverse freshwater ecosystems (Azevedo-Santos et al., 2019; Farjalla et al., 2021).

Nevertheless, budgetary constraints and policy fluctuations continue to limit Brazil's scientific

capacity (SBPC, 2023a, b). The recent COP30 in Belém (2025) highlights both the urgency and opportunity for greater investment in environmental research. Broader international collaboration is needed to reduce asymmetrical materials and ensure that regions facing the greatest ecological pressures are adequately represented (Dudgeon et al., 2006; Dudgeon & Strayer, 2025).

#### 4.5. Limitations and opportunities for future research

As with any bibliometric review, our findings reflect research attention, not measured impacts. The reliance on keywords and abstracts means some stressors (e.g., dams, deforestation) may be underrepresented if not explicitly tagged in the literature (Mongeon & Paul-Hus, 2016). Future reviews could address this limitation by combining bibliometric screening with meta-analytical approaches or systematic reviews of ecological outcomes, thereby linking research patterns more directly to evidence of environmental change (Donthu et al., 2021; Page et al., 2021).

Another important gap is the limited integration of socio-economic dimensions with ecological assessments. Although freshwater degradation is known to affect human health, livelihoods, and inequality, studies explicitly linking these dimensions remain scarce (Lertzman, 2010; Woods, 2022). Expanding interdisciplinary approaches that connect biogeochemical and ecological research with social sciences and policy frameworks could help align freshwater science more directly with societal priorities and management needs (Dudgeon et al., 2006; Kroll et al., 2019).

## 5. Conclusion

Our bibliometric review highlights how recent scientific literature has approached anthropogenic pressures on freshwater ecosystems between 2019 and 2023. Rivers were the most frequently studied ecosystems, followed by lakes and wetlands, while agriculture, urbanization, and mining were the most often referenced anthropogenic drivers. Emerging pollutants, especially microplastics and pharmaceuticals, have attracted growing attention in literature, reflecting increasing scientific concern for their potential ecological and health risks.

The results also show the prominence of countries such as the United States, China, Canada, and Brazil, with noticeable growth in international collaborations and the adoption of advanced analytical tools, including machine learning

and remote sensing. By mapping these thematic and geographical trends, our study provides a clearer picture of current research priorities and highlights gaps where future studies could better integrate ecological data, policy frameworks, and management strategies.

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## Data availability

The database used in this study, resulting from a bibliographic analysis, is not publicly available. However, it can be requested from the corresponding author, Layla Mayer Fonseca. For further information or to access the database, please contact the author directly.

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