DOI 10.7343/as-2025-883

ACQUE SOTTERRANEE
Italian Journal of Groundwater

2025-AS54-883: 53 - 64

journal homepage: https://www.acquesotterranee.net/

The state of the art on groundwater quality studies: a bibliometric analysis of the topic at a global level

Lo stato dell'arte sugli studi sulla qualità delle acque sotterranee: un'analisi bibliometrica del tema a livello globale

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ARTICLE INFO

Ricevuto/*Received*: 2 April 2025
Accettato/*Accepted*: 2 September 2025
Pubblicato online/*Published online*: 30 September 2025

Handling Editor:
Iacopo Borsi

Citation:
Antunes Collares, M.F., Pereira Rosa, A. (2025). The state of the art on groundwater quality studies: a bibliometric analysis of the topic at a global level.
Acque Sotterranee - *Italian Journal of Groundwater*, 14(3), 53 - 64
https://doi.org/10.7343/as-2025-883

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Keywords:
hydrogeochemistry, environmental monitoring, geospatial analysis, sustainable water management.

Parole chiave:
idrogeochimica, monitoraggio ambientale, analisi geospaziale, gestione sostenibile delle acque.

Abstract

Groundwater is a critical freshwater resource, particularly in regions where surface water availability is limited. This study presents a comprehensive systematic review of global groundwater quality research, aiming to map and analyze the most prevalent and emerging themes. A bibliometric analysis was conducted on articles published in English over the last 25 years (2000–2024) using the Scopus database. The analysis, performed with RStudio and the Bibliometrix package, initially included 1686 publications. A clear upward trend in scientific production was observed, with the highest annual growth rate (60.9%) occurring in 2020 (140 articles). Before 2018, less than 60 articles were published annually. The leading journals in the field were Science of the Total Environment, Water, and Journal of Hydrology, with 80, 70, and 63 publications, respectively. The top contributing countries were China (1,201), India (1,006), the United States (572), and Iran (533), with Iran having the highest international collaboration rate (MCP_Ratio = 0.42) and the greatest groundwater consumption. Cluster analysis and Sankey diagrams showed a significant increase in keywords linking "machine learning," "groundwater," and "water quality" after 2014. Prior to this, research focused primarily on the physicochemical characterization of groundwater and its environmental impacts. The results indicate a shift towards interdisciplinary methods, integrating geoprocessing, hydrological modeling, and statistical analysis, alongside growing connections to climate change, water management, and artificial intelligence.

Riassunto

Le acque sotterranee rappresentano un'importante risorsa idrica, in particolare nelle regioni in cui la disponibilità di acqua superficiale è limitata. Questo studio presenta una revisione sistematica e completa, su scala globale, della bibliografia scientifica sulla qualità delle acque sotterranee, con l'obiettivo di mappare e analizzare i temi più diffusi ed emergenti nella letteratura scientifica. L'analisi bibliometrica è stata condotta su articoli pubblicati in inglese negli ultimi 25 anni (2000-2024) utilizzando il database Scopus. L'analisi dei dati, eseguita con RStudio e il pacchetto Bibliometrix, ha incluso inizialmente 1686 pubblicazioni. È stata osservata una chiara tendenza all'aumento della produzione scientifica, con il tasso di crescita annuale più elevato (60.9%) registrato nel 2020 (140 articoli). Prima del 2018 venivano pubblicati meno di 60 articoli all'anno. Le principali riviste del settore sono state Science of the Total Environment, Water e Journal of Hydrology, rispettivamente con 80, 70 e 63 pubblicazioni. I paesi che hanno contribuito maggiormente sono stati la Cina (1.201), l'India (1.006), gli Stati Uniti (572) e l'Iran (533), con l'Iran che ha il più alto tasso di collaborazione internazionale (MCP_Ratio = 0,42) e, al tempo stesso, il maggior consumo di acque sotterranee. L'analisi dei cluster e i diagrammi di Sankey hanno mostrato un aumento significativo delle parole chiave che considerano assieme i concetti di "machine learning", "groundwater" e "water quality", dopo il 2014. Prima del 2014, la ricerca scientifica si è concentrata principalmente sulla caratterizzazione fisico-chimica delle acque sotterranee e sui suoi impatti sull'ambiente. I risultati indicano una tendenza verso l'adozione di metodi interdisciplinari, che integrano discipline come il geoprocessing, la modellazione idrologica e l'analisi statistica, insieme a crescenti connessioni con il cambiamento climatico, la gestione dell'acqua e l'intelligenza artificiale.

Introduction

Water is an essential resource for sustaining life and socioeconomic development, found in various natural reservoirs such as rivers, lakes, aquifers, and glaciers. However, surface water quality can vary significantly depending on its source and exposure to environmental and anthropogenic factors, due to its direct exposure to human activities, including effluent discharge, the use of agrochemicals, and accidental chemical spills (Vliet et al., 2021). In contrast, groundwater typically exhibits greater chemical and biological stability over time due to its limited exposure to external contaminants. Despite this relative protection, aquifers can still be impacted by anthropogenic activities, particularly in areas with intensive fertilizer use, improper disposal of industrial waste, and unregulated land occupation. Studies indicate that groundwater contamination, although slower, can have persistent and difficult-to-remediate effects, impacting large areas and compromising water quality for extended periods (Chegbeleh et al., 2020).

Given the growing dependence on groundwater as a water supply source, both in rural and urban areas, it is essential to understand contamination patterns and the factors influencing its quality. In addition to its importance as a potable water source, aquifers play a crucial role in maintaining ecological flows and recharging surface water systems (Bose et al., 2023; Oiro et al., 2020). Groundwater exploitation depends on locational aspects and geological formations, requiring geophysical investigations, which require the use of equipment and complex studies integrating various factors (geological, geomorphological, pedological, topographical, among others). Despite the practical limitations in determining groundwater quality, efforts must be made to promote monitoring of this resource, particularly to prevent contamination from anthropogenic sources (Oiro et al., 2020).

The growing concern about groundwater quality has driven the use of innovative analytical approaches. Recent studies have applied techniques such as multivariate statistical analysis, including Principal Component Analysis (PCA) (Riboli & Lindino, 2023), Hierarchical Cluster Analysis (HCA) (Chotpantarat et al., 2020; Wisitthammasri et al., 2020), and spatiotemporal analyses based on Geographic Information Systems (GIS) and remote sensing (Sinha et al., 2021). These approaches enable the identification of contamination patterns and the assessment of groundwater contamination risk, by integrating the intrinsic vulnerability of aquifers with the spatial distribution and intensity of anthropogenic pressure.

Despite advancements in groundwater quality research, there is a limited number of systematic review and bibliometric articles in the literature compared to studies on surface waters (Adeniyi and Giwa, 2021; Barrett et al., 1999; Devic et al., 2014; Foster et al., 2013; Graham & Polizzotto, 2013; Katz et al., 2011; Loftis, 1996). Furthermore, recent studies, such as those by Kannazarova et al. (2024), indicate an increase in research on the use of groundwater for irrigation. However, these analyses are still limited to regional contexts, such as the countries of the Commonwealth of Independent States (CIS). This gap highlights the need for studies that systematically compile and organize information on groundwater quality at a global scale, considering both the evolution of research and the methodologies employed (Li et al., 2019; Zhang et al., 2017; Zhou et al., 2020; Zyoud & Fuchs-Hanusch, 2017).

In this context, bibliometric analysis emerges as a promising tool to identify cognitive structures and intellectual relationships in the field of groundwater quality. This approach allows for the examination of publication patterns, collaboration between researchers and institutions, and emerging themes in the literature (Donthu et al., 2021). Thus, this study aimed to conduct a systematic review of the literature on groundwater quality at a global level, with specific objectives: (i) to map and examine the most prevalent and emerging themes in groundwater quality publications; (ii) to detect knowledge gaps and suggest directions for future research that can contribute to a more comprehensive understanding of the topic; (iii) to identify the leading authors, institutions, and countries involved in groundwater quality research, analyzing co-authorship networks and patterns of international collaboration.

By integrating these elements, this study provides a comprehensive overview of the evolution of groundwater quality research, contributing to the development of sustainable management and protection strategies for this essential resource.

Materials and Methods

Database and Techniques for Article Selection

The search for scientific articles for the bibliometric analysis on groundwater quality was conducted in the Scopus database (https://www-scopus.ez35.periodicos.capes.gov.br/home.uri). Scopus is widely recognized as the largest database of abstracts and citations of peer-reviewed literature, covering a broad range of publications, such as scientific journals, books, and conference proceedings (Baas et al., 2020; Kannazarova et al., 2024).

The search was conducted using the following keywords and term combinations: "groundwater" AND "machine learning"; "groundwater quality" AND "machine learning"; "groundwater quality" AND "prediction"; "groundwater quality" AND "classification"; "groundwater quality index" AND "machine learning"; "underground water quality" AND "remote sensing"; "groundwater quality" AND "landsat"; "groundwater quality" AND "sentinel". The search query was constructed as follows: (("groundwater" AND "machine learning") OR ("groundwater quality" AND "machine learning") OR ("groundwater quality" AND "prediction") OR ("groundwater quality" AND "classification") OR ("groundwater quality index" AND "machine learning") OR ("underground water quality" AND "remote sensing") OR ("groundwater quality" AND "landsat") OR ("groundwater quality" AND "sentinel")). The search considered publications from the years 2000 to 2024. Initially, the search resulted in 2,524 potentially relevant

publications, covering various studies on groundwater quality and its estimates under different conditions, including the use of machine learning techniques and remote sensing. To refine the results, additional filters were applied, considering only articles published in English, between 2000 and 2024, and classified as "articles." After this filtering, 1,686 articles were selected for a more detailed analysis.

The bibliometric analysis was conducted based on the methodology adapted from Bose et al. (2023), which structures the evaluation of the articles into two main axes: (i) domain and (ii) structure. In the domain axis, the articles were examined for: (i) source types; (ii) document aspects; and (iii) origins and relevance of the authors. In the structure axis, the analysis covered: (i) intellectual aspects; (ii) conceptual aspects; and (iii) social aspects, with an emphasis on the countries of origin of the research on groundwater quality (Fig. 1).

The analyses were conducted using RStudio software and the Bibliometrix package, which allowed for the extraction of information on sources, authors, and documents, providing insights into the domain and structure of the articles. For the keyword co-occurrence analysis (conceptual aspect), VOSviewer software was used, enabling the visualization of relationships between the main terms found in the analyzed literature.

Results and discussion

Overview of Groundwater Publications

The bibliometric analysis revealed that, over the past 24 years, a total of 1,686 articles on groundwater have been published. Of these, 26 were written by individual authors, while the others resulted from collaborations among multiple researchers. On average, the published articles had more than four authors and received at least 22 citations each.

It is observed that the scientific interest in groundwater quality began to intensify in the late 20th century, coinciding with the increase in the global population and irrigation. This growth was largely driven by concerns about the deterioration of groundwater quality, as recently pointed out by Singh et al. (2024). However, since the 2000s, research on groundwater has increasingly integrated with other areas of knowledge, such as climate sciences (Rahaman et al., 2024), agricultural sciences (Sakthipriya et al., 2024), environmental chemistry (Abba et al., 2024), computer sciences (Ren et al., 2024), and geosciences/remote sensing (Inam Ullah et al., 2024), expanding the perspectives and research approaches.

Figure 2 illustrates the number of articles published on groundwater quality over the analyzed period. A clear trend of continuous growth in scientific production is evident, with a highlight in 2020, which saw the highest annual growth rate (60.92%), totaling 140 published articles. This accelerated growth can be interpreted as a response to the increasing demand for solutions to the challenges of groundwater management and preservation, especially in the face of climate change and the expansion of agricultural activities. It is worth noting that, until 2018, the number of publications on the topic did not exceed 60 articles per year, reflecting a substantial increase in interest and relevance of the topic in recent decades.

In addition to the increase in the number of publications over the years, an important aspect to evaluate the impact of research on groundwater quality is the average number of

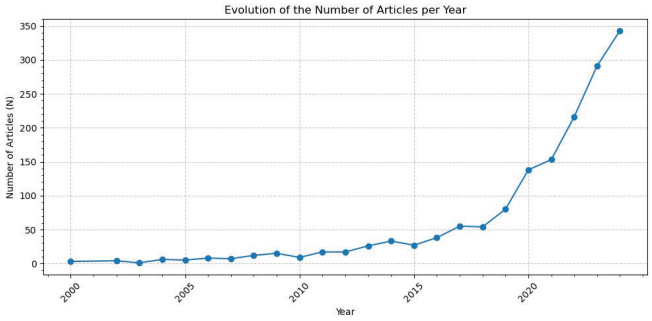

Fig. 2 - Number of articles published related to groundwater quality during the study period (2000–2025).

Fig. 2 - Numero di articoli pubblicati relativi alla qualità delle acque sotterranee durante il periodo studiato (2000-2025).

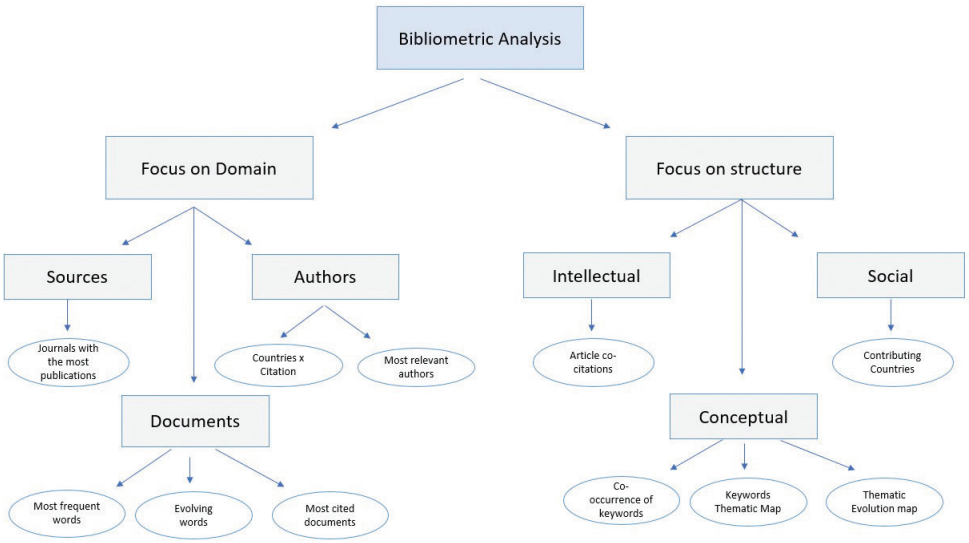

Fig. 1 - Diagram reporting the aspects considered in the bibliometric analysis.

Fig. 1 - Diagramma raffigurante gli elementi considerati nell'analisi bibliometrica.

citations per published article (MeanTCperArt), as shown in Figure 3. It is observed that older articles generally have a higher average number of citations, such as those from 2006, which recorded an average of 61.12 citations per article. This behavior was expected, as articles published earlier have more opportunities to be cited. However, when analyzing the average citations per year (MeanTCperYear), it is observed that the impact of more recent scientific production has been significant, with a peak in 2020 (9.63 citations per year), followed by a downward trend in the subsequent years.

This decline can be explained by the maturation time required for newly published articles to consolidate in the literature and become more widely cited. Starting from 2021, for example, the average citations per article gradually decreased, reaching 1.73 in 2024, reflecting the short time window available for citation accumulation. Therefore, the interpretation of these indicators should consider both the total number of citations accumulated over the years and the annual growth rate of citations.

Another relevant aspect is the relationship between interdisciplinarity and scientific impact. The increasing integration of groundwater quality research with areas such as climate change, water resource management, and artificial intelligence has broadened the scope of these studies and potentially accelerated their recognition within the scientific community. This phenomenon may explain the peak in citations per year observed in 2020, possibly driven by the growing global interest in water security and the application of new technologies in the field.

Dynamics of Publications in Scientific Journals and Authorship

The analysis of the publication sources of groundwater quality studies allows for the identification of the main scientific outlets disseminating research on this topic. Identifying the most relevant journals not only indicates where the scientific community has focused its efforts but also reveals editorial trends and areas of greatest impact within the field.

Table 1 presents a list of the scientific journals that have published most of the articles on the topic of groundwater quality. The results show that Science of the Total Environment stands out as the leading journal in terms of the number of publications, with a total of 80 articles, followed by Water (Switzerland) with 70, and Journal of Hydrology with 63 publications. In general, these journals have a broad scope covering environmental studies, water management, and applied hydrology, which explains their relevance for the dissemination of research on groundwater quality.

Tab. 1 - Journals with most of the publications on groundwater quality between 2000 and 2024.

Tab. 1 - Riviste che hanno pubblicato la maggioranza degli articoli riguardanti la qualità delle acque sotterranee, fra il 2000 e il 2024.

Position	Journal (ISSN)	Number of Published Articles
1	Science of the Total Environment (0048-9697)	80
2	Water (Switzerland) (2073-4441)	70
3	Journal of Hydrology (0022-1694)	63
4	Environmental Earth Sciences (1866-6299)	53
5	Environmental Science and Pollution Research (0944-1344)	46
6	Environmental Monitoring and Assessment (1573-2959)	43
7	Groundwater for Sustainable Development (2352-801X)	39
8	Remote Sensing (2072-4292)	26
9	Water Resources Management (0920-4741)	26
10	Arabian Journal of Geosciences (1866-7511)	24

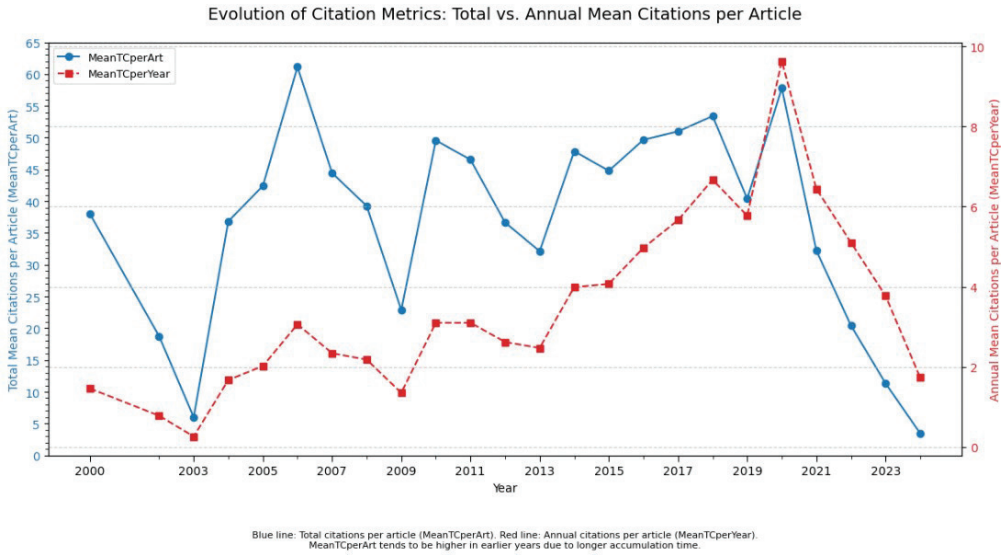

Fig. 3 - Evolution of the average number of citations per published article and per year in publications related to groundwater quality.

Fig. 3 -Evoluzione temporale del numero medio di citazioni per anno per articolo pubblicato, considerando pubblicazioni relative alla qualità delle acque sotterranee.

It is important to note that the high number of publications in these journals does not necessarily imply a specific editorial commitment to the topic, but rather a convergence between the demands of the scientific community and the editorial focus of these publications. The recurrent presence of these journals reinforces that groundwater quality studies have found a priority space in journals dedicated to environmental science and hydrology. Furthermore, the analysis of the distribution of publications across journals may indicate the interdisciplinary nature of the topic, as groundwater quality studies are not confined to strictly hydrological journals but are also published in journals focused on geosciences, environmental sciences, and engineering. This diversity highlights the need for integrated approaches to understanding the challenges and solutions related to the sustainable management of groundwater resources.

Table 2 presents the group of authors who have made the most significant contributions to groundwater research, based on data obtained from the bibliometric analysis. The ranking was initially determined by the h-index, followed by Total Citations (TC).

Among the most influential researchers, Lee S. (South Korea) stands out for having the highest h-index (10), a metric that quantifies a researcher's productivity and impact, based on their most cited articles. Since 2019, his research has explored various innovative approaches in groundwater management and quality, with a particular focus on the use of artificial intelligence (AI) and machine learning to predict nitrate contamination susceptibility and model pollutant adsorption processes such as fluoride. His research also includes studies on the impacts of road transportation systems on groundwater quality, employing Explainable Artificial Intelligence (XAI), as well as modeling the suitability of groundwater for human consumption through neural networks and geospatial analysis (Lee et al., 2022). The author's research has been crucial in developing strategies and policies for the sustainable management of groundwater resources through the development and application of validated models to prevent environmental issues (Mallick et al., 2022), which were further enhanced by Jayasingle et al. (2021) to map suitable locations for groundwater extraction.

The author with the most cited works is Wu J. (China), who is the principal author of 9 articles published during the period, resulting in 967 citations, and has authored 16 articles. Among the highlighted researches, the author is a pioneer in publishing articles on groundwater, with his first publication in 2008, establishing himself as one of the most influential researchers in the field. Wu's contributions range from analyzing groundwater quality in urban and rural areas to modeling changes in water storage in large river basins, such as the Ordos Basin in China (Wu et al., 2024). Furthermore, Wu J. has been prominent in applying advanced techniques for modeling and predicting groundwater quality using machine learning (Wu et al., 2022) and investigating the relationship between water quality and land use patterns (Wu et al., 2020).

Tab. 2 - Identification of the most relevant researchers in publications related to groundwater quality.

Tab. 2 - Lista dei ricercatori più influenti, dal punto di vista delle metriche bibliografiche, riguardo al tema della qualità delle acque sotterranee.

Autores	h_{index}	g_{index}	m_{index}	TC	NP	PY_{start}
LEE S	10	13	1.429	700	13	2019
WU J	9	16	0.500	967	16	2008
PHAM BT	9	10	1.125	629	10	2018
MOSAVI A	9	9	1.500	574	9	2020
ISLAM ARMT	9	12	1.000	413	12	2017
LU W	9	13	1.000	179	13	2017
LI P	8	12	0.667	773	12	2014
PRADHAN B	8	9	1.000	653	9	2018
PRAKASH I	8	8	1.000	600	8	2018
PAL SC	8	12	1.333	290	12	2020

Legend: h_{index}: hirsch index, which measures the productivity and impact of an author's publications based on the number of citations received; g_{index}: egghe index, which gives more weight to highly cited publications, reflecting the global impact of the researcher; m_{index}: index that adjusts the h_{index} for the researcher's career length, allowing for fairer comparisons between researchers with different career durations; **TC (Total Citations)**: total number of citations received by the author's publications; **NP (Number of Publications)**: total number of the author's publications; PY_{start} **(Publication Year Start)**: year of the first publication registered in the analysis.

Another prominent researcher is Islam ARMT, who has published 12 articles since 2017 and received 413 citations. His research focuses on analyzing the variation in groundwater quality in response to climate change and land use, integrating statistical modeling and machine learning to predict the presence of pollutants. Lu W., also with 13 publications and an h-index of 9, has made significant contributions to the hydrochemical characterization of groundwater and the identification of contamination sources, employing geostatistical models and optimization algorithms for the sustainable management of aquifers. Among the researchers who have advanced the application of artificial intelligence in hydrogeology, Mosavi A. and Pham BT deserve special mention. Mosavi A., with 9 publications since 2020 and an h-index of 9, has led studies on the prediction of groundwater levels and aquifer recharge analysis, considering the impacts of climate change. Pham BT, with an h-index of 9 and 10 published articles since 2018, has specialized in the use of Explainable Artificial Intelligence (XAI) to enhance the interpretation of groundwater quality prediction models, contributing to more transparent and effective decision-making.

Other researchers, such as Li P. (h_{index} 8, 773 citations), Pal SC. (h_{index} 8, 290 citations), and Pradhan B. (h_{index} 8, 653 citations), also rank among the most influential, with significant contributions to groundwater quality modeling and the development of innovative methodologies for the management of groundwater resources. The increasing relevance of these researchers reflects the evolution of the field of hydrogeology and groundwater quality, with advances driven by the use of artificial intelligence, machine learning, and geostatistical modeling. Interdisciplinary collaboration

and the development of new approaches have been key to enhancing monitoring, prediction, and mitigation of environmental risks, ensuring the sustainability of groundwater resources for future generations.

Regarding scientific production on groundwater, there is a predominance of a limited number of countries (Figure 4), which may be related to the high demand for water resources in these nations, as well as the availability of funding for research on this topic. According to the data on scientific production by country, China (1,201 articles) and India (1,006 articles) lead the number of publications from 2000 to 2024, followed by the United States (572), Iran (533), and Saudi Arabia (163). Along with the scientific prominence of China and India in publications, it is important to note that these are the most populous countries in the world, and consequently, there is a high demand for water resources, particularly groundwater sources. As highlighted by the National Ground Water Association of China, the intense exploitation of these resources presents challenges that drive scientific research in search of solutions for the sustainable management of groundwater.

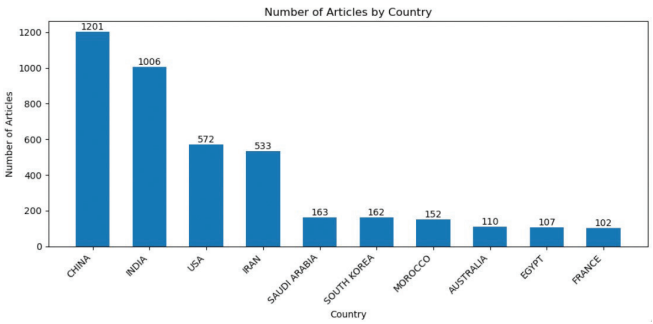

Fig. 4 - Scientific production by country in publications related to groundwater quality.

Fig. 4 - Produzione scientifica (numero di articoli pubblicati) per paese, sul tema della qualità delle acque sotterranee.

In addition to the number of publications, it is important to analyze the distribution of corresponding authors, which indicates scientific leadership and international collaboration. In this regard, China (356 articles), India (277), and the United States (230) also occupy the top positions (Table 3). However, while China and India have a higher number of publications with national collaboration, Iran stands out for its high rate of international collaboration (MCP_Ratio = 0.42), suggesting that its research often involves cooperation with foreign institutions. This metric represents the proportion of a country's publications involving international collaboration, calculated by dividing the number of multi-country publications (MCP) by the total number of the country's publications (Petermann et al., 2024). In the case of Iran, 42% of publications were produced in international collaboration, while China had a rate of 25.8%, indicating a greater focus on national scientific output. According to FAO data (AQUASTAT), Iran is among the countries with the highest consumption of groundwater, reinforcing the need for effective management strategies, thereby promoting international collaborations for the development of scientific based solutions.

Tab. 3 - Distribution of scientific publications and international collaboration by country in publications related to groundwater quality.

Tab. 3 - Distribuzione per paese degli indicatori di produzione scientifica, in termini di pubblicazioni sulla qualità delle acque sotterranee.

Country	Articles	SCP	MCP	Freq	MCP_{Ratio}
China	356	264	92	0.174	0.258
India	277	224	53	0.136	0.191
Usa	230	185	45	0.113	0.196
Iran	181	105	76	0.089	0.420
Australia	50	26	24	0.024	0.480
Korea	45	31	14	0.022	0.311
Germany	40	28	12	0.020	0.300
Canada	34	19	15	0.017	0.441
Italy	33	26	7	0.016	0.212

Legend: **SCP**: single country publication; **MCP**: multiple countries publication; **Freq**: represents the relative frequency of scientific publications from each country in relation to the total number of articles in the sample analyzed.

The bibliometric analysis also reveals a social structure within the research field, highlighting the contribution and collaboration among researchers and their institutions (Fig. 5). Among the collaborations established through co-authorships, notable joint publications include those between Iranian and American researchers (23 publications), Chinese and American researchers (22 publications), Indian and Iranian researchers (20 publications), and researchers from India, Bangladesh, and the United States, with 18 publications. These data highlight how collaboration among researchers influences the quality of research and contributes to the global advancement of scientific knowledge.

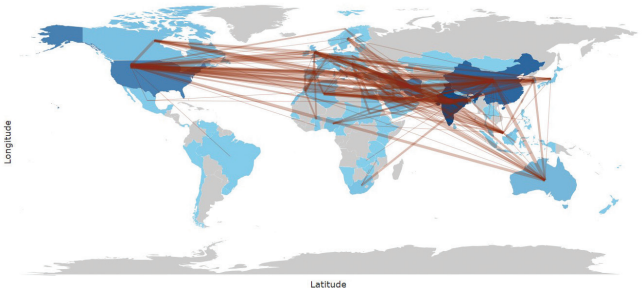

Fig. 5 - World map illustrating the collaboration of authors and institutions between countries in publications related to groundwater quality.

Fig. 5 - Carta globale che illustra la collaborazione di autori e istituzioni tra paesi in pubblicazioni relative alla qualità delle acque sotterranee.

Based on the survey of articles (1,342), the number of keywords counted in publications on groundwater quality exceeded 2,000. Figure 6 highlights the 30 more frequently used keywords; the most common term was "groundwater" (1,344 occurrences), followed by "water quality" (1,188 occurrences), "machine learning" (805 occurrences), and "groundwater pollution" (434 occurrences). Notably, there

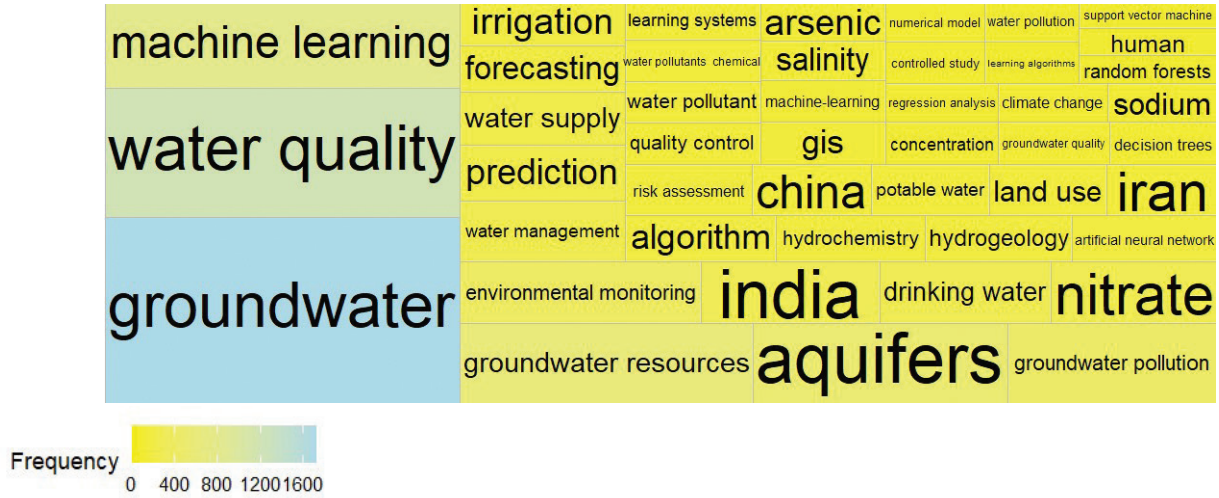

Fig. 6 - Most frequency keywords used in articles related to groundwater quality.

Fig. 6 - Parole chiave più frequenti negli articoli relativi alla qualità delle acque sotterranee.

is a significant relationship between keywords referencing methodological tools associated with statistical analysis aimed at understanding the impact of chemical and geological parameters on groundwater quality. Within this context, the terms "prediction" (237 occurrences) and "algorithm" (183 occurrences) stand out.

The selection of keywords reflects the focus of the research on aspects related to contamination, the presence of nitrates and salinity, land use changes, as well as the identification of hazardous substances. The frequency of the keywords also reveals the emphasis on statistical methods and other computational tools used in the research, such as machine learning (805), multivariate statistics (130), Geographic Information Systems (GIS) (225), and geostatistics (kriging) (64). In recent years, hydrogeological and hydrochemical aspects have been studied in conjunction with modern computational techniques, indicating a research trend within this field (Mohammed et al., 2024), as well as the use of advanced machine learning techniques and data mining (Varouchakis et al., 2023; Tian et al., 2024).

Complementarily, Figure 7 presents the evolution of the accumulated occurrence of the ten most frequently used keywords in scientific publications for the period from 2000 to 2024, based on the bibliometric analysis. From 2000 to 2012, the number of scientific articles was limited, with only 108 articles published (Figure 2), as well as the frequency of the keywords. However, after 2014, there was a significant increase in the number of publications, accompanied by a rapid shift in the use of specific keywords. In particular, there was a notable growth in the keywords "machine learning", "groundwater," and "water quality," which highlights the increasing use of predictive tools for simulating groundwater quality.

This trend aligns with the advancement of machine learning (ML) as an approach widely used in science, driven by increased computational capacity and the availability of large volumes of data starting in the 21st century (Fu et al., 2022 , Singha et al., 2021). Although traditional statistical techniques had already been applied in groundwater quality modeling, the use of ML began to gain greater relevance once the scientific community recognized its potential to handle

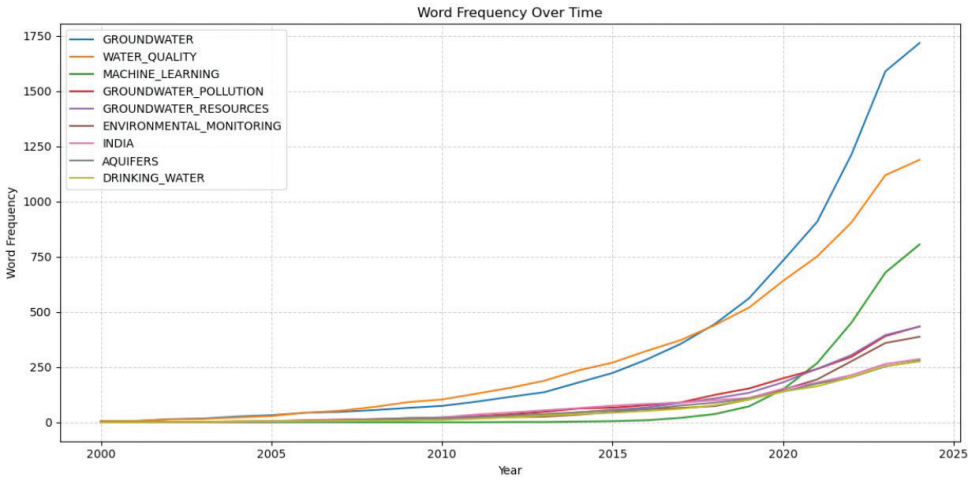

Fig. 7 - Evolution in the frequency of use of key keywords in articles on groundwater quality between 2000–2024.

Fig. 7 - Evoluzione della frequenza di utilizzo delle parole chiave negli articoli sulla qualità delle acque sotterranee tra il 2000 e il 2024.

complex and nonlinear patterns in environmental data (Hao et al., 2024, Li et al., 2023, Zhan et al., 2025). Thus, the adoption of machine learning in the field of hydrogeology was not immediate, but rather occurred as the technology became more established in other fields and more accessible. The progressive use of ML, particularly in the prediction of groundwater quality, supports decision-making for more sustainable resource management.

Table 4 presents the 10 most cited articles on groundwater quality for the analysis period. Among the most notable studies related to groundwater quality is the research of Podgorski & Berg (2020), who assess the impacts of arsenic contamination.

They employ advanced modeling techniques to map the potential risk in various regions of the world. This study provided an understanding of the risks associated with arsenic presence, particularly in areas facing water security challenges. Additionally, Naghibi et al. (2016) explored the mapping of groundwater potential in the Chaharmahal-e-Bakhtiari province of Iran, using machine learning models to produce accurate spring maps, which provided valuable insights for the sustainable management of these resources. Another significant study was conducted by Rodriguez-Galiano et al. (2014), who investigated the use of the Random Forest method in predictive modeling of nitrate pollution in groundwater. The authors demonstrated the effectiveness of this technique in identifying pollution sources and creating vulnerability maps, highlighting the potential of these approaches in water resource management.

In addition, Naghibi et al. (2017) applied machine learning methods, such as Support Vector Machine (SVM), Random Forest (RF), and Genetic Algorithm-optimized Random Forest (RFGA), to map groundwater sources near springs. The study, conducted at 842 locations, indicated that RF and RFGA were more effective than SVM. The most influential variables in this process were altitude, the Topographic Wetness Index (TWI), and slope angle. This methodology proved to be promising for application in other regions with water scarcity. Subba (2006) also made a significant contribution by studying the seasonal variation in groundwater quality in an area of the Guntur district, Andhra Pradesh, India. The author analyzed water samples collected from 40 wells before and after the rainy season over three years, observing that most samples did not meet quality standards for either human consumption or irrigation, particularly in the post-rainy period, which was attributed to factors such as the semi-arid climate, water-rock interaction, and human activities. Finally, Sajedi-Hosseini et al. (2018) developed a new method using machine learning to assess the risk of nitrate contamination in groundwater in an arid region of Iran. Samples from 102 water wells were analyzed, and the results pointed to a high risk of nitrate pollution in the central region of the plain, emphasizing the importance of such studies for risk management in semi-arid areas.

Tab. 4 - List of the 10 most cited articles on the topic of groundwater for the evaluated period (2000–2024).

Tab. 4 - Elenco dei 10 articoli più citati sul tema delle acque sotterranee nel periodo esaminato (2000-2024).

Position	Title	Number of citations	Citation
1	Global threat of arsenic in groundwater	694	Podgorski & Berg (2020)
2	GIS-based groundwater potential mapping using boosted regression tree, classification and regression tree, and random forest machine learning models in Iran	490	Naghibi et al. (2017)
3	Predictive modeling of groundwater nitrate pollution using Random Forest and multisource variables related to intrinsic and specific vulnerability: A case study in an agricultural setting (Southern Spain)	316	Rodriguez-Galiano et al. (2014)
4	Application of Support Vector Machine, Random Forest, and Genetic Algorithm Optimized Random Forest Models in Groundwater Potential Mapping	313	Naghibi et al. (2017)
5	Seasonal variation of groundwater quality in a part of Guntur District, Andhra Pradesh, India	250	Subba (2006)
6	A novel machine learning-based approach for the risk assessment of nitrate groundwater contamination	248	Sajedi-Hosseini et al. (2018)
7	Machine learning algorithms for modeling groundwater level changes in agricultural regions of the United States	243	Sahoo et al. (2017)
8	GIS-based groundwater potential analysis using novel ensemble weights-of-evidence with logistic regression and functional tree models	235	Chen et al. (2018)
9	Origin and assessment of groundwater pollution and associated health risk: A case study in an industrial park, northwest China	223	Li et al. (2014)
10	Hydrogeochemistry for the assessment of groundwater quality in Varanasi: a fast-urbanizing center in Uttar Pradesh, India	217	Janardhana et al. (2011)

These studies highlight the relevance of using advanced modeling techniques and machine learning in the management and preservation of groundwater, particularly in regions vulnerable to contamination and water scarcity. The adoption of these approaches is crucial for the development of sustainable strategies that ensure the quality and availability of the resource.

Figure 8 presents a network diagram, obtained using the VOSviewer software, which is a tool used to construct and visualize bibliometric networks, such as term co-occurrence networks, citation networks, or co-authorship networks. In bibliometric analyses, a term refers to a word or expression that frequently appears in the analyzed literature, representing key concepts and thematic trends in the field. The co-occurrence of terms indicates how often they appear together in the same documents, helping to identify research patterns and emerging topics. At the center of the diagram, the terms "machine learning" and "groundwater" are prominently used, indicating that these are the most frequently mentioned concepts that come together in the literature. This suggests the emphasis of research on the use of machine learning techniques for the study and management of groundwater.

The different clusters are represented by distinct colors and indicate groups of terms that frequently appear together, reflecting specific research areas within the broader field of groundwater and machine learning. In this bibliometric analysis, the terms "groundwater" and "machine learning" are highlighted, reflecting the growing trend of applying machine learning techniques in the study and management of groundwater. Both terms are closely related to water quality, salinity, irrigation, and quantification methods such as artificial intelligence, prediction, and classification of chemical and geological parameters. Issues related to health, arsenic contamination, and salinity have emerged as consequences associated with the domain. This cluster illustrates the complexity and interconnectivity of groundwater research, highlighting the growing importance of machine learning techniques and artificial intelligence in the analysis, management, and optimization of groundwater resources. Each cluster reveals different subareas of focus, ranging from water quality and contamination to advanced modeling and mapping techniques.

The thematic evolution of keywords in articles published on groundwater quality from 2000 to 2024 (Fig. 9) is represented by a Sankey diagram, where the nodes correspond to the themes identified in different periods, and the arrows indicate the transition of these themes over time. The thickness of the arrows is proportional to the inclusion index, meaning that the greater the inclusion, the higher the similarity between the themes of different periods. Additionally, the area of the boxes represents the abundance of the theme in the literature, indicating its relevance within the field of study. To construct this analysis, a bibliometric approach was applied to track how specific research topics evolved over time. The co-occurrence of keywords in published studies was examined across different periods, revealing shifts in scientific focus. Keywords that frequently appeared together in older studies were compared to those in more recent periods, allowing the identification of emerging trends and methodological advances. This enables the visualization of how initial research topics, such as physicochemical characterization, gradually integrated new approaches like statistical modeling and, more recently, artificial intelligence techniques.

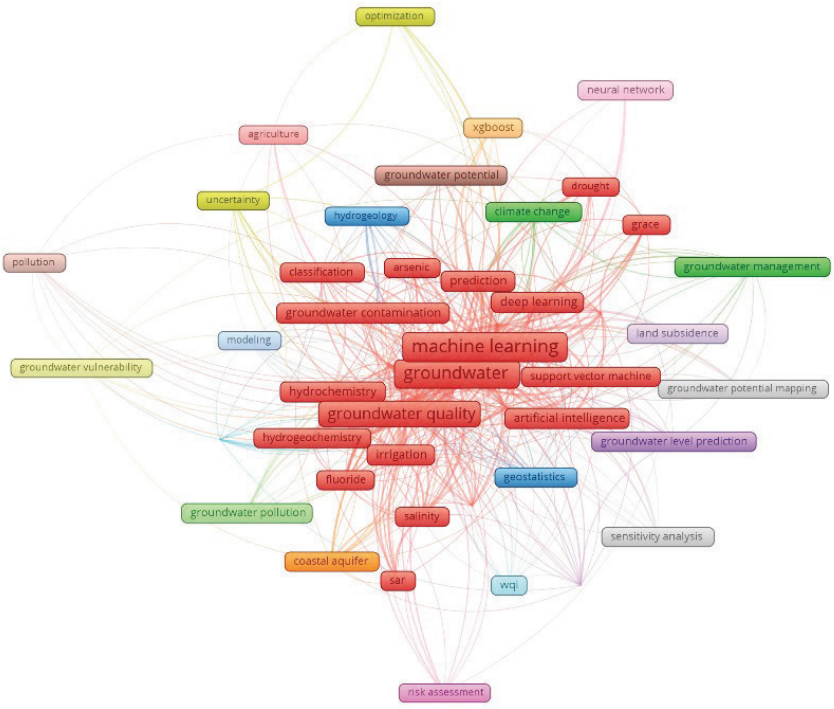

Fig. 8 - Network diagram showing a bibliometric analysis of terms related to groundwater research.

Fig. 8 - Diagramma che mostra l'interconnessione dei termini usati nell'analisi bibliometrica relativi alla ricerca sulle acque sotterranee.

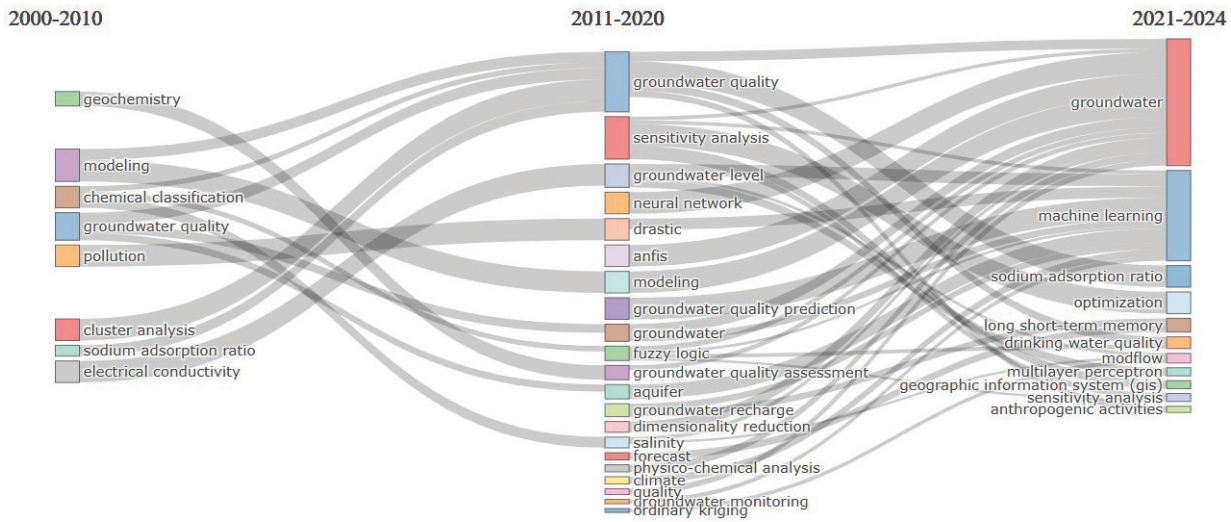

Fig. 9 - Thematic evolution of keywords in groundwater quality papers from 2000 to 2024.

Fig. 9 - Evoluzione dei temi delle parole chiave utilizzate nelle pubblicazioni sulla qualità delle acque sotterranee dal 2000 al 2024.

During the period from 2000 to 2010, topics such as "chemical classification," "electrical conductivity," "sodium absorption," and "pollutant contamination" were prominent, reflecting the initial concern with the physicochemical characterization of groundwater and its environmental impacts. In the following decade, there was a shift toward interdisciplinary methods, with an increased use of combined approaches involving geoprocessing, hydrological modeling, and statistical analyses. This period marks a maturation of research, with greater integration of different areas of knowledge.

In the last four years (2020–2024), the thematic evolution indicates a convergence toward the application of machine learning techniques and complex statistical tools in the assessment of groundwater quality. This trend suggests an enhancement of computationally advanced analyses, allowing greater accuracy in predicting contamination patterns, as well as in identifying critical factors for the sustainable management of water resources.

Conclusion

Since 2020, a notable increase has been observed in scientific production on groundwater quality, driven by global challenges such as population growth, climate change, and agricultural expansion, which exacerbate groundwater contamination and degradation issues. This trend reflects an intensification of interest in understanding and mitigating the threats that compromise the quality of these waters, particularly in countries with large populations or significant investments in science and technology, such as India, China, Iran, and the United States.

The bibliometric analysis reveals an important shift in research areas, with a growing focus on interdisciplinary approaches, such as the use of machine learning, geoprocessing, and hydrological modeling, which have deepened the understanding and resolution of problems related to groundwater quality. These technological and methodological advancements demonstrate a clear shift towards more integrated studies, utilizing innovative tools for water quality monitoring and management, going beyond traditional physicochemical characterization.

The rise of predictive methods and advanced tools, such as machine learning, not only improves the ability to predict changes in water quality but also indicates the maturation of research, which now embraces more complex and interdisciplinary solutions. Finally, the state of the art in groundwater research highlights the growing importance of international collaboration and the central role of new technologies in overcoming challenges related to the quality and management of this resource. The evolution of research reflects a robust response to contemporary challenges and a continued commitment to the sustainability and protection of groundwater, essential for human and environmental well-being.

Competing interest
The authors declare no competing interest.

Acknowledgments
This study was funded by the Coordination for the Improvement of Higher Educational Personnel (CAPES Finance Code 001), Brazilian National Research Council (CNPq) and the Minas Gerais State Research Foundation (FAPEMIG) (call n.003/2022 - FAPEMIG/IGAM APQ - 01011-22).

Author contributions
Conceptualisation, all; Collection of data, Antunes Collares; interpretation of results, all; data processing, Antunes Collares; all; writing-original draft preparation, all; writing-review and editing, all; visualization, all; supervision, all. All authors have read and agreed to the final version of the manuscript.

Funding source
This study was funded by the Coordination for the Improvement of Higher Educational Personnel (CAPES Finance Code 001), Brazilian National Research Council (CNPq) and the Minas Gerais State Research Foundation (FAPEMIG) (call n.003/2022 - FAPEMIG/IGAM APQ - 01011-22)."

Additional information
DOI: https://doi.org/10.7343/as-2025-883
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Publisher's note Associazione Acque Sotterranee remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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