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REVIEW ARTICLE

Potentially toxic elements in groundwater: a hotspot research topic in environmental science and pollution research

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Abstract
A scientometric analysis based on the Scopus database was conducted to provide insight into research activities on the occurrence of potentially toxic elements (PTEs) (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, and Zn) in groundwater during 1970–2019. The selection of these PTEs was based on their significance concerning their reference frequency in environmental science and pollution research (ESPR) studies and their toxicity to living organisms. The analysis utilizes data about the quantity, type, journal, geographical, institutional, and funding patterns of publications. The results indicate that the publications' annual output has increased over the years, and especially after 2000, it presents a remarkable growth rate. The most studied PTEs were As and Pb; nevertheless, the research on the rest of PTEs cannot be neglected as it shows continuously increasing trends over time. The evolution of instrumentation and the dissemination of contamination case studies that affect a large part of the world population contributed significantly to the scientific community and relative stakeholders' interest. According to the analysis, the USA and China are the two principal countries with the most considerable contribution, producing the most research regarding the number of publications, research institutions, and funding sponsors. China owns the most influential research institution (i.e., Chinese Academy of Sciences) and largest funding sponsor (i.e., National Natural Science Foundation of China; ≈5% of global funding) on a worldwide scale due to its investment in research and development (R&D) and is expected to become the greatest force in the future.

Keywords Scientometric analysis · Research trends · Scopus database · Environmental science and pollution research · Groundwater contamination · Potentially toxic elements

Introduction

Environmental science (ES) is an interdisciplinary academic field that integrates physical, chemical, and biological components of nature, examining solutions to environmental issues. It contains many academic disciplines such as ecology, biology, physics, chemistry, plant science, zoology, mineralogy, oceanography, limnology, soil science, geology, physical geography, engineering, and atmospheric science.

Environmental science and pollution research (ESPR) is related to all areas of the ES field and emphasizes on chemical compounds. One of the research topics that have increasingly concerned the scientific community and the ES field in recent years is the occurrence, distribution, and release of chemical elements into the environment. In particular, these elements' fate in natural waters is crucial, as they are linked to public health. These elements are referred to in the international literature under various terms such as "heavy metals," "trace elements," and "metals and metalloids." However, in recent years, the term "potentially toxic elements" (PTEs) has begun to prevail in many publications, replacing terminology of the past, such as "heavy metals," which members of the scientific community consider to be outdated to inappropriate (Pourret and Hursthouse 2019; Pourret et al. 2021). The most common PTEs found in published ESPR studies are arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), antimony (Sb), and zinc (Zn). These elements are usually found in concentrations below the detection limit (DL) in natural waters (most of the time <1 μg/L due to the high sensitivity of modern, powerful

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analytical techniques), while in some extreme cases, they reach up to an amount of mg/L. However, even in very low concentrations, they can be toxic to living organisms. For this reason, the World Health Organization (WHO) and various countries' legal frameworks have set drinking limit values for these PTEs. However, these controversial limits are being questioned by scientists because they are not based on epidemiological studies, and a stricter approach is required (Ahmad and Bhattacharya 2019; Li et al. 2020). All of the PTEs mentioned above, except Co, are in the list of 126 priority pollutants of the US Environmental Protection Agency (USEPA) (USEPA 2014).

Scientometrics belongs to the academic discipline of bibliometrics, and it is the field of study that analyzes and measures the scholarly literature. Quality assessment of published articles' scientific validity requires a successful scientometric analysis (Masic 2016). This approach provides information about the publication (quantity, quality, type, language, etc.), country, journal, author, institution, and funding patterns to investigate the global research trends and productivity in a scientific field. Scientometric databases and statistical tools have been used for data analysis. In the ES field, scientometric studies have been carried out in previous years. The international research on scientometric analysis focuses on modern academic disciplines such as climate change (Haunschild et al. 2016), carbon sequestration (Huang et al. 2020a, b), soil science (Lin et al. 2019; Mokhnacheva and Tsvetkova 2020), coal and fly ash geochemistry (Yang et al. 2018), and various topics of groundwater research that are related to remediation (Zhang et al. 2017), modeling (Zare et al. 2017), and water quality (Fu et al. 2013; Hu et al. 2010; Ouyang et al. 2018; Nishy and Saroja 2018). The majority of the studies mentioned above focus on trends of the last 20 years, neglecting the past's influence and the real reasons that led to today's progress. Nevertheless, the research topic of PTE occurrences in groundwater is still almost uncharted. A thorough, in-depth analysis will provide a valuable reference for future research and a global overview to identify the research trends and opportunities for ES field researchers currently working on this topic.

This study seeks to quantitatively and qualitatively evaluate publications on the ESPR, focusing on the presence of PTEs in groundwater for 50 years (1970–2019). The assessment includes general patterns of annual publication outputs, types of manuscripts and used languages, impact on ES field journals, national and institutional research distribution, and funding sponsors' information in groundwater quality research. This study's findings are valuable for the scientific community to identify scientific trends and research over the last 50 years, focus on research gaps in unexplored landscapes of science, and guide environmental geoscientists in evaluating and orienting their research to provide new insight for future research challenges and opportunities.

Methods

Documents used in this study were compiled from the Scopus database on May 18, 2021. The Scopus database is a large-scale multidisciplinary scientometric database containing enriched data and linked scholarly content and indexes a considerable amount of peer-reviewed literature as well scientific content. It constitutes the most important and most frequently used scientific database in most academic disciplines and research topics, including ESPR. Only a few documents existed before 1970; therefore, this study's time span was limited to 50 years (1970–2019). Before the search process, a series of search terms, including "Groundwater" and "Antimony" or "Arsenic" or "Chromium" or "Nickel" or "Cadmium" or "Cobalt" or "Copper" or "Lead" or "Mercury" or "Zinc," were used to search for all publications that contained these words in the title, abstract, and keywords. All the criteria used to create the database, including all the relative documents, are given in Table 1.

Table 1 Search fields and variable selections are used to form the database for the present work.

Search fields	Variable selection
Search within	Article title, Abstract, Keywords
Search documents	Groundwater AND Antimony OR Arsenic OR Cadmium OR Copper OR Chromium OR Lead OR Mercury OR Cobalt OR Nickel OR Zinc
Time span	1970–2019
Added to Scopus	Anytime
Subject area	Environmental Science
Document type	Articles, Conference Paper, Review, Conference Review, Book Chapter
Open access	Without choice*/All Open access**

*All the available results (Open access + pay-per view)

**Limit the dataset to open access journal publications only

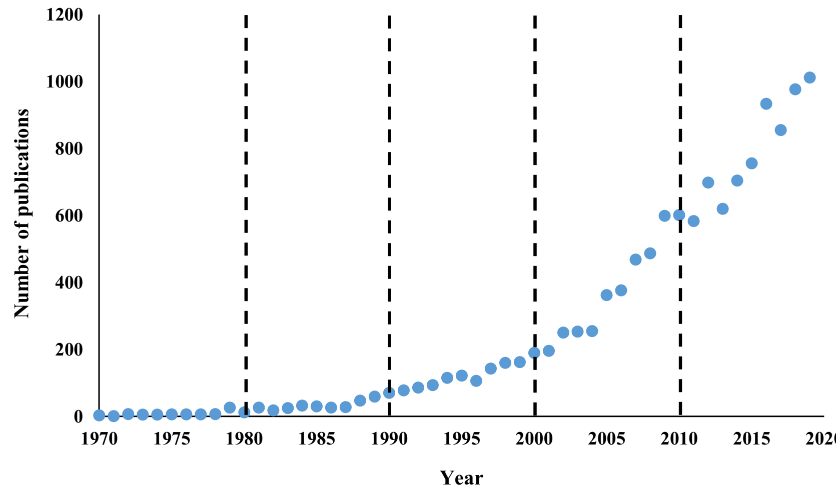

Fig. 1 Annual distribution of publications identified by the Scopus database on the research topic of PTEs in groundwater during 1970–2019. The vertical black dashed line shows the decades.

The final examination was based on parameters including the number of publications, document types, language, open access, countries, journals, research institutions, and funding sponsors. The evaluation of different countries and research institutions was performed through author affiliations. In the case of synergistic work in a publication, the affiliation of the first author was considered. Raw data are available as electronic Supplementary Information in the Zenodo repository (https://zenodo.org/record/4772278).

Results and discussion

Research trends and scientific "hotspots"

The number of publications on a research topic, overtime, is an essential indicator of its growth. A total of 93468 documents in the ES field, from the Scopus database, during 1970–2019 contain the word "groundwater" during 1970–2019. A total of 12683 (13.6% of the total amount of 93468) documents include at least one PTE at a focal point of the publication (title or abstract or keyword) combined with the word "Groundwater" in the aforementioned 50-year period. The annual number of publications containing the word "groundwater" and at least one PTE in title, abstract, and keywords are presented in Fig. 1. The black dashed lines represent the decades' change (i.e., the 1970s, 1980s, 1990s, 2000s, and 2010s). The number of publications related to PTE in groundwater consistently increased over the defined study period, and after 2000, it is evident that the number of publications increased significantly. Specifically, from only three publications in 1970 to 1700 in 2000, with 12683 publications having been identified in the database. Notably, after 2000, the percentage of total groundwater publication that mentions at least one PTE exceeds 10% systematically (Fig. 2), suggesting that authors were focusing on the occurrence, distribution, transport, and fate of PTEs in the environment than they formerly did. From 1970 to 1980, the production of publications was insufficient (Fig. 1), with a percentage of total publications that mention at least one PTE that fluctuates (<10%; Fig. 2) due to the relatively small number of total publications. It should be noted that even if the total number

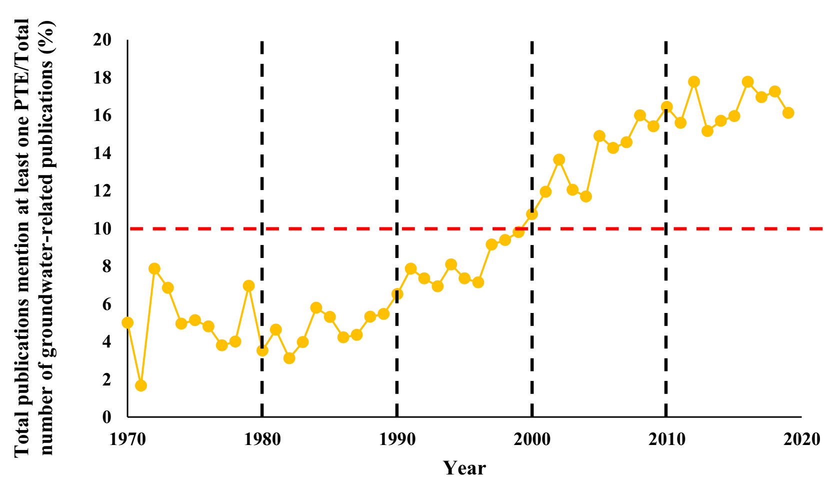

Fig. 2 Annual percentage of total publications mention at least one PTE in the ES field over the total groundwater-related publications during 1970–2019. The vertical black dashed line shows the decades, and the defined red line corresponds to a growth rate of 10%.

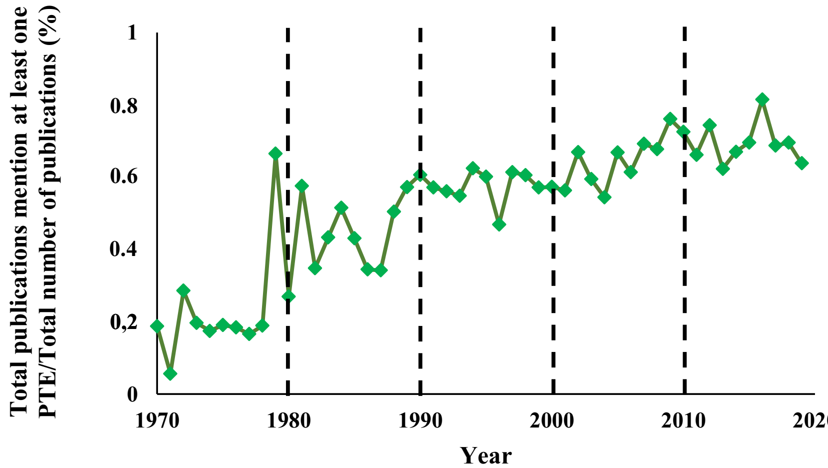

Fig. 3 Annual evolution of publications on the research topic of PTEs in groundwater over the overall publications during 1970–2019 (percentage of the number of articles using at least one PTE divided by the total number of all articles published that year). The vertical black dashed line shows the decades.

of publications has also simultaneously increased, the percentage of publications using at least one PTE in the title and/or abstract and/or keywords presents a higher increase than the overall increase of the number of journal articles (Fig. 3). The articles on this topic show a systematic upward trend which since 2010 exceeds 0.7% of global publication production.

The annual percentage of total publication for As and Pb is illustrated in Fig. 4. Generally, all PTEs present an increasing trend over the years (Fig. 4, Supplementary material, Fig. S1). Nevertheless, the scientific community has focused on the study of As and Pb, which according to Fig. 4 are the most interesting PTEs and are considered scientific "hotspots"—from a research point of view—of the defined 50-year period. The WHO has been established the guideline value of 10 μg/L in drinking water for As and Pb (World Health Organization (WHO) 2017) due to their toxicity in living organisms even at very low concentrations. Arsenic is mobilized in the typical pH range of groundwater (6.5–8.5) under both oxidizing and reducing conditions (Smedley and Kinniburgh 2002), while Pb is mobilized in groundwater under acidic geochemical conditions (Hem 1985), and its presence has been associated with the sulfide ore mineralization and acid drainage. According to recently published literature, As and Pb, even today, are a significant public health concern in many parts of the world due to their occurrence in drinking water (Hu et al. 2010; Ahmad and Bhattacharya 2019; Uppal et al. 2019; Jarvis and Fawell 2021), provoking us to seek access to water of better quality, with safer drinking limits and better management and decision-making strategies. On the other hand, the rest of the PTEs (Cr, Cd, Co, Ni, Sb, Cu, Zn, and Hg), while also presenting increasing trends (Supplementary material, Fig. S1), they are uncharted compared with As and Pb, and further research is required in the future to understand their occurrence in the environment.

Concerning the research of PTEs in groundwater, many geoscientists around the world are focusing their study on (a) natural and/or anthropogenic influences using multivariate statistics and stable isotopes, (b) spatial distribution and vulnerability assessments through modern geographical information system (GIS) tools, (c) PTE removal from the aqueous

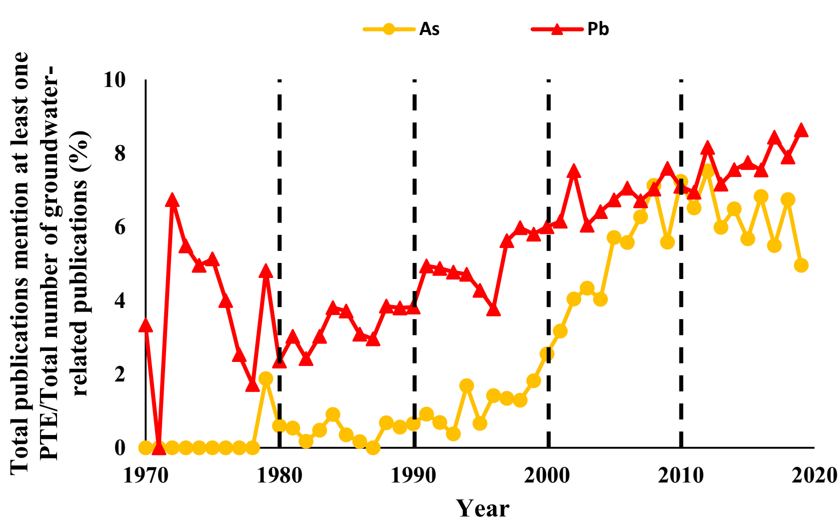

Fig. 4 Annual percentage of total publications that are related to As and Pb in groundwater over the total groundwater-related publications during 1970–2019. The vertical black dashed line shows the decades.

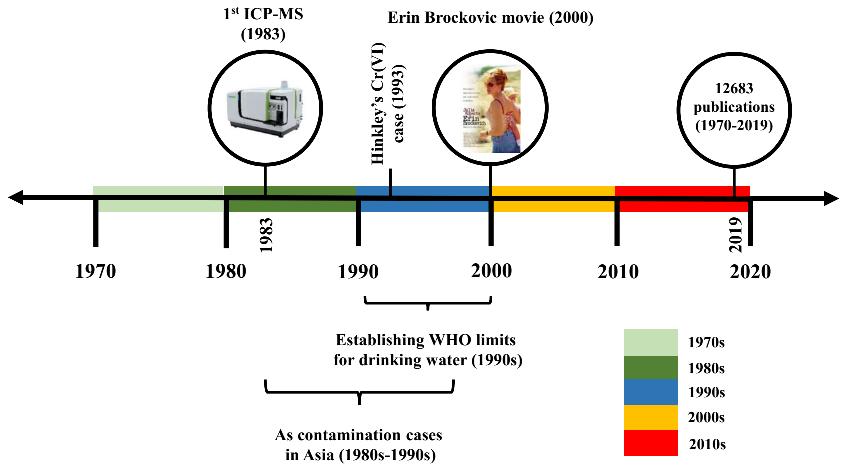

Fig. 5 Major events for the research topic of PTEs in groundwater in the timescale of 1970–2019.

solution and remediation techniques, (d) health risk assessments, (e) drinking and irrigation suitability, (f) geochemical modeling conceptualization, and (g) calculation of PTE-based indices to quantify their impact in groundwater quality. However, one of the most significant issues that the scientific community face, even today, is the misused of the chemical element's speciation, which is very often confused with other terms (i.e., chemical element's fractionation), leading to misunderstandings, inaccurate results, and incorrect conclusions among the scientific community (Pourret et al. 2020a). The chemical form of an element provides information about mobility, effect, and toxicity to living organisms and the environment, and the determination of chemical element's speciation is of great importance for ES field and, in particular, in the ESPR studies that are usually neglected due to its difficulty to measure it, and it is expensive (Pourret and Husthouse, 2019). Special attention is suggested to the environmental studies that will be written in the future to avoid the mistakes of the past; such a series of suggestions to avoid pitfalls are given by Pourret et al. (2020a).

Figure 5 illustrates a timescale with major events of the 50 years of 1970–2019 that had an essential role in the evolution of the number of publications related to PTEs in groundwater. In the 1970s, the production of publications is limited, and the only clear conclusion that can be drawn is that the research was not focused on the study of PTEs in groundwater. Although some publications seem to refer to Pb, the total number of publications related to groundwater is insufficient, and as a result, it would be wrong to make any conclusions. The limited number of publications until 1980 is the combined result of a lack of prior research and know-how for measuring the concentrations of PTEs. The first inductively coupled plasma-mass spectrometer (ICP-MS) was introduced in 1983 by MDS Sciex (Potter 2008). Before ICP-MS, other techniques used to perform elemental analysis included atomic absorption spectroscopy (AAS) and inductively coupled plasma-optical emission spectroscopy (ICP-OES). The use of ICP-MS marked the beginning of a new era where this analytical instrument could determine a large set of trace elements, including detecting the isotopic composition of various elements in a wide concentration range, having extremely low DLs. However, despite the potential, ICP-MS instruments were big, expensive, difficult to use, unreliable (Potter 2008), and multi-element identification was a problematic, inaccurate, costly, and time-consuming process, leaving the scientific community unable to study these issues in-depth. The 1980s and 1990s showcase a constant increase in the percentage of total publications that mention at least one PTE, suggesting the scientific community's growing interest in addressing new challenges in the ES field. During this period, famous cases of elevated concentrations of PTEs in groundwater were discovered. Especially, As raised global concerns since the 1990s (Li et al. 2020) due to the known examples of As contamination in large part of Asia, including highly populated countries (China, India, Bangladesh, Pakistan, Vietnam, Cambodia, Myanmar, Thailand, etc.) (Smedley and Kinniburgh 2002; Mukherjee et al. 2006; Uppal et al. 2019), and the case of Hinckley's Cr (VI) contamination, an issue that became widely known around the world with the famous 2000 Oscar film "Erin Brockovich." These cases enhanced the awareness of groundwater contamination and PTE occurrences in water resources, in the scientific community, and relative stakeholders (i.e., government, consumers, and geological surveys); therefore, the 1990s are characterized by increased concern about PTEs-induced health problems rise (Li et al. 2020). Furthermore, during this period, the WHO significantly tightened the previous water drinking limits for PTEs by revising them, establishing new limits, and publishing guidelines for each PTE. Subsequently, after 2000, scientific research focused on extensive water sampling campaigns involving PTE measurements, followed by large-scale production of publications containing the studies mentioned above results. In many cases, different research teams worked on the same case study and issue, having different interpretations of their results. This fact suggests that there are still many open questions unanswered, and the ES is

Table 2 Publication classification by document type of the research topic of PTEs in groundwater in the ES field during 1970–2019.

Document type	Number	Percentage
Journal article	11101	87.5
Conference proceedings	1261	9.94
Book chapter	321	2.53
Total	**12683**	**100**

an attractive field for seeking new challenges. Today, ICP-MS is the premier technique for trace metal analysis. It allows the relatively easy multi-element determination of PTEs, which can unlock hidden geochemical features of various cases on a worldwide scale, leading to the understanding of the release mechanism, transport, and fate of PTEs in natural waters.

The distribution of document types identified by the Scopus database was analyzed. The final database contains three different document types: (a) journal articles, including original research articles and review articles, (b) conference proceedings, and (c) book chapters. The classification of the document types is summarized in Table 2. Approximately 87.5% are "journal articles," 9.94% are "conference papers," and the remainder is "book chapters." However, journal articles are expected to be the dominant document type because the Scopus database includes limited and specific conference proceedings and book chapters. Generally, journal articles are the most representative peer-review type, and the analysis of these will provide interesting information about this research field. The following discussion aimed to determine the pattern of scientific production and research activity trends, which consisted of countries, journals, institutes, and funding the research subjects addressed. The English language has the absolute advantage as it is the most frequently used language with almost 96% of all documents (12209), followed by Chinese, German, French, Spanish, and Russian. The use of English in scientific manuscripts is widely used in all scientific fields and is generally accepted by the scientific community because it allows access and dissemination of knowledge.

In recent years, there has been a strong effort for wider and easier access to scientific data, reflected in open access publishing. The percentage of manuscripts published as open access was calculated 18.1% (a total of 2009 documents from 11001) of the overall publications on this topic (Fig. 6a), considering only journal articles. In general, after 1990, there has been a continuous increase, particularly rapid in the last decade (Fig. 6b). Similar results regarding the increase of open access documents were reached by Pourret et al. (2020b) in geochemistry, a field related to the topic of the present study.

The long-standing questions on this field that researchers are asked to provide answers are as follows: (a) Which PTEs present unusually high concentrations in groundwater? (b) What are the possible natural and anthropogenic sources of PTEs in the groundwater of a study area? (c) What are the particular geochemical conditions that favor the mobility of PTEs in soils and groundwater? (d) Do threshold values of PTEs exceed their background values in groundwater? (e) Which is the most effective way to remove PTEs from an aqueous solution? It is certain that as science evolves, new questions will emerge, but in general, these questions cover a very large part of what most papers are seeking. The answers to the questions mentioned above are sought in the published journal articles of recent years (2019–2021) related to the occurrence, mobility, transport, and fate of PTEs in groundwater, highlighting the future research trends and challenges on ESPR. Various techniques have been developed for decoding the complex record of natural and anthropogenic impacts of PTEs and other trace elements in groundwater. The most important methods that have been used and will continue to dominate in these studies are multivariate statistics (i.e., principal component analysis, hierarchical cluster analysis, non-metric multidimensional scaling) (Papazotos et al. 2019; Vasileiou et al. 2019), spatial statistics (bivariate and local Moran's I indices, local indicator of spatial

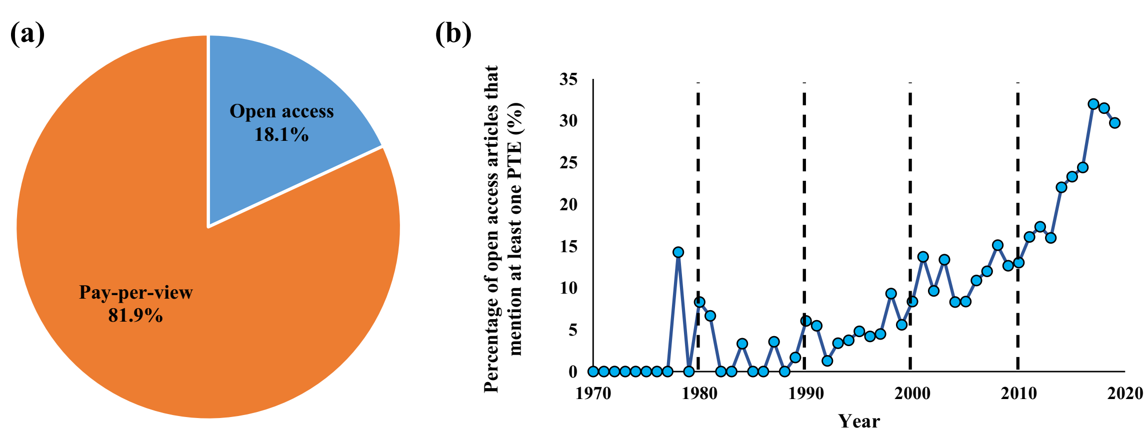

Fig. 6 **a** Percentage of open access journal articles vs. pay-per-view journal articles over the total journal article publications during 1970–2019. **b** Diachronically evolution of the percentage of open access journal articles during 1970–2019. The vertical black dashed line shows the decades.

association cluster maps) (Vasileiou et al. 2019; Quino-Lima et al. 2020), and machine learning algorithms (Singha et al. 2020; Yaseen 2021), which allow the advanced analysis of large databases that include many parameters, as it is happening in hydrogeochemical studies. In addition, an alternative approach, that has been increasingly used in recent years, is the combined use of suitable stable isotopic signatures (e.g., $\delta^{53}Cr$, $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ $\delta^{11}B$, $\delta^{15}N$, and $\delta^{18}O$) that can help to distinguish the origin of PTEs in water resources (Puig et al. 2017; Kruk et al. 2020; Perraki et al. 2021). In recent years, emphasis has been placed on the investigation and co-occurrence of pollutants in an aquifer. Typical examples of new issues that need further investigation are the co-existence of As with fluoride (F^-) (Kumar et al. 2020; Alarcón-Herrera et al. 2020) and Cr(VI) with nitrate (NO_3^-) (Papazotos et al. 2019; Vasileiou et al. 2019), which are increasingly mentioned in the updated literature. Taking into account the last relationship and especially the impact of NO_3^- in groundwater, the relatively neglected role of agricultural activities in the elevated groundwater concentrations of Cr(VI) and other PTEs highlights the role of nitrogen (N)- or/and phosphorous (P)-bearing fertilizers (Kubier et al. 2019; Papazotos et al. 2019; Vasileiou et al. 2019; Papazotos et al. 2020; Perraki et al. 2021), providing to the researchers a "hot" topic with many open questions to study in the coming years about the multifold role of fertilizers in the occurrence and mobilization of PTEs in groundwater. The systematic monitoring of PTEs is not the only ESPR of interest that the scientific community is focused on. Another one, which concerns geoscientists and engineers, is the research on removal technologies (such as biochar, activated carbon, carbon film, biopolymers, and clay materials). However, future research is expected to focus on the application of nanomaterials (materials between 1 and 100 nm) as an adsorbent in removing pollutants (PTEs, organic compounds, and pathogens) from groundwater (Yu et al. 2021). In addition, another aspect that has not been adequately studied and related to groundwater monitoring and removal technologies is the occurrence of microplastics in water resources (Selvam et al. 2021). The previously mentioned issue is a rising "hot" topic that researchers have already begun to study by researchers of various disciplines. Last but not least, another huge chapter of the ESPR is geochemical modeling, on which researchers need to focus on the generation of new thermodynamic and kinetic data (in addition to surface complexation models, among other mechanistic models) (Khalidy and Santos 2021) to optimize the modeling procedure.

Key journal analysis

Many scientific journals engage in research in the ES field and publish articles related to the occurrence, mobilization, transport, and fate of PTEs in groundwater. The top twenty most productive journals, which account for approximately 41.9% of the total publications, are listed in descending frequency order in Table 3. The most productive journals for PTEs in groundwater in the ES field are the Science of the Total Environment (rank 1), Environmental Science and Technology (rank 2), and Environmental Earth Sciences (rank 3), with 556, 550, and 412 articles, respectively. In general, these journals cover related publications in the scientific fields of geoscience, biological science, environmental science, agriculture, forestry, geochemistry, water resources, and climate change. This fact suggests that the research on PTEs in groundwater is an issue that demands systematic monitoring and a holistic approach for geoscientists and engineers. However, since journals have a different starting year, the average number of publications per active year was calculated to identify each journal's real contribution to the ES field. According to the previously mentioned indicator, the journal with the highest publication rate by far, compared to the rest of this academic discipline, is Environmental Earth Sciences (37.5%) (Fig. 7). The Environmental Science and Pollution Research journal is ranked in the 16th place according to the number of publications (a total of 151 publications), providing a significant contribution (5.81%) on this topic (Table 3). High-impact journals are increasingly dealing with the issue of PTEs in groundwater. This research topic interests many renowned scientists in the global scientific community stemming and from different academic disciplines. The occurrence, distribution, mobilization, transport, and fate of PTEs in groundwater are a widely recognized global severe threat. The rapid growth of ESPR subjects reflects the awareness about the significance of this issue.

Global distribution of research on PTEs in groundwater

Some countries are more productive in the research on PTEs in groundwater than others, providing important information about the research direction worldwide. The top ten most productive countries for total publications are presented in Table 4 and their annual productivity on publications in Fig. 8. The USA has the absolute advantage in the total number of published research with 3366 publications and 26.5% of the world's production. Other countries are the following: China (1449 publications), India (1340 publications), Germany (933 publications), Australia (645 publications), UK (638 publications), Canada (632 publications), France (491 publications), The Netherlands (377 publications), and Italy (376 publications). The countries mentioned above cover over 80% of world production. Among the top ten countries were two Asian countries, two American countries, one Oceanian country, and five European countries. The analysis demonstrates that most scientific research is concentrated in developed countries due to their adequacy in technological equipment and research funds, greater experience, and long history in environmental issues. However, developing countries such as China and India published large amounts of studies related

Table 3 The top twenty most productive journals on the research topic of PTEs in groundwater in the ES field.

Journal	*N*	% of all	Rank	Active years	Starting year	*N*/ Active years
Science of the Total Environment	556	4.38	1	48	1972	11.6
Environmental Science and Technology	550	4.34	2	53	1967	10.4
Environmental Earth Sciences	412	3.25	3	11	2009	37.5
Journal of Hydrology	401	3.16	4	57	1963	7.04
Applied Geochemistry	387	3.05	5	34	1986	11.4
Water Resources Research	362	2.85	6	55	1965	6.58
Journal of Hazardous Materials	295	2.33	7	45	1975	6.56
Chemosphere	278	2.19	8	48	1972	5.79
Environmental Monitoring and Assessment	257	2.03	9	39	1981	6.59
Water Research	245	1.93	10	53	1967	4.62
Water Air and Soil Pollution	227	1.79	11	49	1971	4.63
Journal of Contaminant Hydrology	217	1.71	12	34	1986	6.38
Environmental Geology	171	1.35	13	35	1975*	4.89
Environmental Pollution	161	1.27	14	40	1980	4.03
Hydrogeology Journal	160	1.26	15	28	1992	5.71
Environmental Science and Pollution Research	151	1.19	16	26	1994	5.81
Water Science and Technology	136	1.07	17	51	1969	2.67
Environmental Geochemistry and Health	118	0.93	18	37	1983	3.19
Journal of Environmental Science and Health Part A Toxic Hazardous Substances and Environmental Engineering	117	0.92	19	28	1978**	4.18
Water Switzerland	116	0.91	20	11	2009	10.5
Total	**5317**	**41.9**				

*Archived from 2009

**Coverage 1978–1979, 1987, 1996–today

to the ES during 1970–2019; they are still located at the edge of the collaborative network (Li and Zhao 2015). The USA ranks first in publication productivity and other-related studies associated with water resources research (Hu et al. 2010; Wang et al. 2011; Niu et al. 2014; Zhange et al., 2017), reflecting the many research centers, the quality of research, and the multiple funding sources. The USA is a worldwide research center and an immigration science center that provides high-quality ESPR publications. Also, many of the

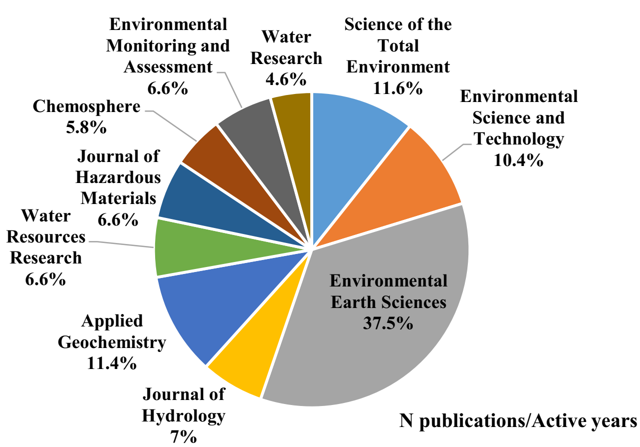

Fig. 7 The contribution of the top ten most productive journals on the research topic of PTEs in groundwater in the ES field according to the average number of publications per active year.

Table 4 The top ten most productive countries on the research topic of PTEs in groundwater in the ES field during 1970–2019.

Country	*N*	% of all	Rank
USA	3366	26.5	1
China	1449	11.4	2
India	1340	10.6	3
Germany	933	7.36	4
Australia	645	5.09	5
UK	638	5.03	6
Canada	632	4.98	7
France	491	3.87	8
The Netherlands	377	2.97	9
Italy	376	2.96	10
Total	**10247**	**80.8**	

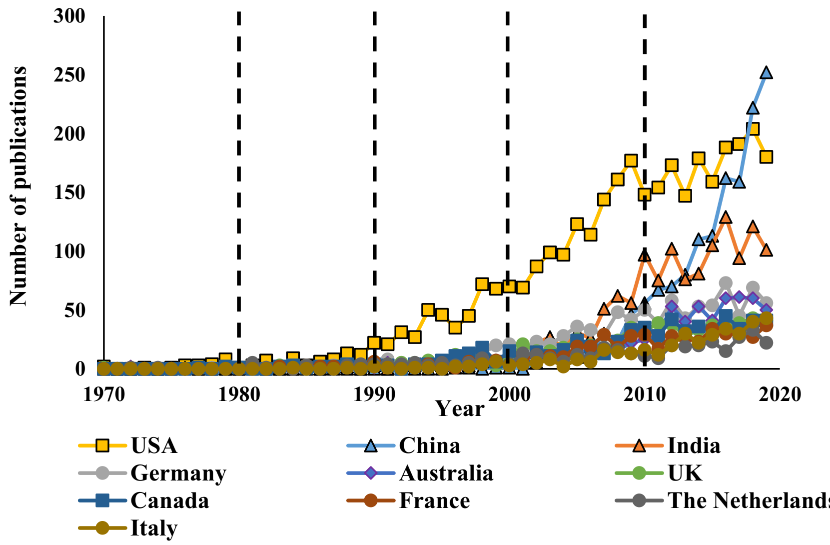

Figure 8 Annual distribution of publications *per top ten productive countries* identified by the Scopus database on the research topic of PTEs in groundwater in the ES field during 1970–2019. The vertical black dashed line shows the decades (square, America; triangle, Asia; circle, Europe; rhombus, Oceania)

countries, leading the way in the ES field, report elevated concentrations of PTEs in groundwater, some of which are among the largest populations (such as China, India, and the USA). The dominance in science of the USA and China is reflected in many ES fields (Nishy and Saroja 2018; Chen et al. 2019; Lin et al. 2019; Ouyang et al., 2019). It is noteworthy that until 2000, only four documents belonged to China, while today, China's annual number of publications presents remarkable growth that makes them world leaders from 2018 (Fig. 8). Henceforth, identifying the problem and addressing it shed light on new scientific achievements and knowledge. When research is unhooked by socio-economic factors that affect it, other fascinating research topics will undoubtedly emerge.

Research institutions and funding sponsors' analysis

The top forty most productive research institutions for total publications are demonstrated in Table 5. The Chinese Academy of Sciences is at the top of this list with 271 publications (2.14% of all publications), while other research institutions with a large number of publications are the China University of Geosciences (255), the US Geological Survey (234), Ministry of Education China (159), and the Royal Institute of Technology KTH (158). China has the most research institutions active in PTEs in groundwater research during 1970–2019, with four research institutions in the top ten (ranked 1, 2, 4, and 10). The second-largest contributor to this scientific field is the USA, with two research institutions in the top ten contributors (ranked 3 and 6). The other four research institutions that complete the top ten list are located in Sweden (ranked 5), Bangladesh (ranked 7), Switzerland (ranked 8), and France (ranked 9). These large research institutions have the scientific and technological background and impact on supporting research into the study of PTEs in groundwater through funding, equipment, and specialized researchers.

Funding sponsors decisively influence the research direction and have a beneficial character towards fostering science and technology to enhance existing knowledge and innovation. National science foundations and governments provide most of the funding, participating decisively in knowledge-transfer strategies and decision-making (Lavis et al. 2003). From 1970 to 2019, the top ten funding sponsors with the most records, which account for 17.8% of publications, were from China, the USA, Canada, and Europe, presented in Table 6 with correspondence to their rank. The National Natural Science Foundation of China is at the top of this list with 633 records (4.99% of all records), while other research institutions with a high number of records are the National Science Foundation (262 records), the European Commission (223 records), Ministry of Education of the People's Republic of China (186 records), National Institutes of Health (175 records), and US Department of Health and Human Services (174 records). It is clear that China is directed at funding research, but the USA and Europe also provide specific funding opportunities to other institutes and private companies (Chai and Shih 2016; Zhang et al. 2017). China has a 5-year plan that focuses on scientific self-reliance, intending to increase spending on research and development (R&D) by more than 7% annually. China is already a scientific powerhouse and has invested heavily in expanding its research over recent decades (Ouyang et al. 2018). China has increased steadily spending on R&D, as a proportion of gross domestic product, since 1995 (OECD 2021). Global tensions, limits on international collaboration, and an emphasis on real-world applications drive China's vision for research (Nature 2021). Research related to the determination of PTE concentrations in groundwater requires experienced interdisciplinary research teams,

Table 5 Top ten most productive research institutions on the research topic of PTEs in groundwater in the ES field during 1970–2019.

Research institution	*N*	% of all	Rank
Chinese Academy of Sciences	271	2.14	1
China University of Geosciences	255	2.01	2
US Geological Survey	234	1.84	3
Ministry of Education China	159	1.25	4
The Royal Institute of Technology KTH	158	1.25	5
US Environmental Protection Agency	136	1.07	6
University of Dhaka	133	1.05	7
Eawag—Swiss Federal Institute of Aquatic Science and Technology	129	1.02	8
CNRS Centre National de la Recherche Scientifique	122	0.96	9
China University of Geosciences, Beijing	119	0.94	10
University of Waterloo	119	0.94	11
School of Water Resources and Environment	110	0.87	12
Wageningen University & Research	107	0.84	13
Lamont-Doherty Earth Observatory	102	0.80	14
National Taiwan University	98	0.77	15
Columbia University	96	0.76	16
University of Chinese Academy of Sciences	91	0.72	17
Jadavpur University	89	0.70	18
CSIRO Land and Water	81	0.64	19
Stanford University	80	0.63	20
National Cheng Kung University	80	0.63	21
Helmholtz Zentrum für Umweltforschung	80	0.63	22
Consejo Nacional de Investigaciones Científicas y Técnicas	79	0.62	23
Lawrence Berkeley National Laboratory	78	0.61	24
ETH Zürich	78	0.61	25
The University of Arizona	77	0.61	26
Indian Institute of Technology Kharagpur	76	0.60	27
BRGM	74	0.58	28
University of Kalyani	74	0.58	29
Pacific Northwest National Laboratory	73	0.58	30
Danmarks Tekniske Universitet	72	0.57	31
Delft University of Technology	71	0.56	32
British Geological Survey	69	0.54	33
Utrecht University	67	0.53	34
Research Center for Eco-Environmental Sciences Chinese Academy of Sciences	67	0.53	35
University of Florida	66	0.52	36
Universidad Nacional Autónoma de México	65	0.51	37
Universität Tübingen	61	0.48	38
Universitat Politècnica de Catalunya	58	0.46	39
National Centre for Groundwater Research and Training	58	0.46	40
Total	**4112**	**32.4**	

resources (facilities, laboratories, technology, etc.), and money. So, research in the ES field is considered impossible to insufficient without the required funding; a significant privilege of reputable research institutions can effectively attract funding sponsors obtaining the absolute advantage, establishing themselves as leading players in this research field.

Conclusions

An overview of the ES field related to PTEs in groundwater was presented, and information about annual publications, countries, journals, research institutions, and funding sponsors was considered. This research topic has increased sharply

Table 6 The top ten funding sponsors with the most records on the research topic of PTEs in groundwater in the ES field during 1970–2019.

Funding sponsor	Records	% of all	Rank
National Natural Science Foundation of China	633	4.99	1
National Science Foundation	262	2.07	2
European Commission	223	1.76	3
Ministry of Education of the People's Republic of China	186	1.47	4
National Institutes of Health	175	1.38	5
US Department of Health and Human Services	174	1.37	6
US Department of Energy	167	1.32	7
National Institute of Environmental Health Sciences	150	1.18	8
Natural Sciences and Engineering Research Council of Canada	147	1.16	9
Government of Canada	141	1.11	10
Total	**2258**	**17.8**	

during 1970–2019. Although PTEs in groundwater are evolving into the ES field's widespread issue, a thorough bibliometric analysis revealing and visualizing the intellectual base, research topic evolution, scientific "hotspots," key journals, dominant countries, and research institutions has not been conducted until today. This work is an initial effort to quantitatively evaluate the ES field's publications focusing on the PTE occurrence in groundwater, summarize information from 50 years, identify future research challenges, and provide insight to researchers so that they attend to the proper direction in the future.

Publication data indicate substantial increases in researcher output during 1970–2019, especially sharply after 2000. The most studied PTEs were As and Pb, which are scientific "hotspots" in this topic; nevertheless, the rest of the PTEs cannot be neglected, as shown by the continuously increasing research trends over time. The development of ICP-MS after 1983 and the case studies of PTE contamination that affects the public health of a considerable part of the world's population in the 1980s–1990s have significantly contributed to enhancing the awareness of the scientific community about this research topic. As indicated from this research, high-impact journals are increasingly dealing with the issue of PTEs in groundwater. The top ten most productive journals contributed almost 30% of all publications in this research topic. The Science of the Total Environment journal has published the largest number of publications. In contrast, the Environmental Earth Sciences journal presents the highest average number of publications per active year, suggesting that it is the most respectful contributor. As PTE occurrences in groundwater are a worldwide concern, the USA is in the leading position of the number of publications by country; China and India include other high-publishing countries in the ES field. However, it seems that China is a rising force in this field. It owns two of the three most productive research institutions; the Chinese Academy of Sciences took the research institutions' leading position in total publications, followed by the China University of Geosciences and the United States Geological Survey. The National Natural Science Foundation of China is the largest funding sponsor, with a percentage that reaches almost 5% of the global funding for this research topic. Furthermore, it seems that China's growth rate in science is very high due to the emphasis placed on R&D, having excellent research institutes and prosperous funding sponsors, and it will soon be the dominant player in the global scientific community. The current understanding of PTEs in groundwater is still limited. Further research focusing on interdisciplinary collaboration is required, and more publications are expected in the future.

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Data availability Data will be made available on request.

Declarations

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