

Review

GIS Applications in Monitoring and Managing Heavy Metal Contamination of Water Resources

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Abstract

Heavy metal contamination of aquatic systems represents a critical environmental and public health concern due to the persistence, toxicity, and bioaccumulative potential of these elements. Geographic information systems (GISs) have emerged as indispensable tools for the spatial assessment and management of heavy metals (HMs) in water resources. This review systematically synthesizes current research on GIS applications in detecting, monitoring, and modeling heavy metal pollution in surface and groundwater. A bibliometric analysis highlights five principal research directions: (i) global research trends on GISs and heavy metals in water, (ii) occurrence of HMs in relation to World Health Organization (WHO) permissible limits, (iii) GIS-based modeling frameworks for contamination assessment, (iv) identification of pollution sources, and (v) health risk evaluations through geospatial analyses. Case studies demonstrate the adaptability of GISs across multiple spatial scales, ranging from localized aquifers and river basins to regional hydrological systems, with frequent integration of advanced statistical techniques, remote sensing data, and machine learning approaches. Evidence indicates that concentrations of some HMs often surpass WHO thresholds, posing substantial risks to human health and aquatic ecosystems. Furthermore, GIS-supported analyses increasingly function as decision support systems, providing actionable insights for policymakers, environmental managers, and public health authorities. The synthesis presented herein confirms that the GIS is evolving beyond a descriptive mapping tool into a predictive, integrative framework for environmental governance. Future research directions should focus on coupling GISs with real-time monitoring networks, artificial intelligence, and transdisciplinary collaborations to enhance the precision, accessibility, and policy relevance of heavy metal risk assessments in water resources.

Keywords: geographic information systems; GIS; water quality; groundwater contamination; surface water; spatial analysis



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1. Introduction

The term heavy metals (HMs) is widely used in environmental sciences to describe metals and metalloids associated with contamination, toxicity, and harmful effects on living organisms. However, its definition varies across the literature, being based alternately on density, atomic weight, or atomic number, which has led to debate regarding its nomenclature [1]. To address this ambiguity, Appenroth [2] proposed a more systematic classification grounded in the periodic table. This classification groups HMs into three subcategories: (1) transition metals—all transition elements except lanthanum (La) and actinium (Ac), (2) rare earth metals—comprising lanthanides and actinides, including La and Ac, and (3) lead-group elements—a heterogeneous set of p-block elements (Bi, Al, Ga, In, Tl, Sn, Pb, Sb, and Po) and metalloids (Ge, As, and Te), with Pb as the most representative member in toxicology and environmental sciences. In this review, we adopt Appenroth's classification as a consistent framework for discussing heavy metals.

HMs reach aquatic environments through multiple pathways, including agricultural runoff, industrial effluents, household discharges, and commercial applications [3]. Their persistence and toxicity raise serious concerns, prompting the development of various remediation technologies. Among the most studied approaches are chemical precipitation and coagulation [4,5], ion exchange [6,7], membrane filtration [8,9], bioremediation [10,11], heterogeneous photocatalysis [12,13], and adsorption [14,15].

Monitoring and characterizing heavy metal contamination increasingly rely on advanced tools for the acquisition, storage, analysis, and visualization of environmental data. Geographic information systems (GISs) offer a powerful, integrative framework to assess spatial patterns of pollutants and their dynamics. Through GISs, geospatial data can be managed and analyzed in an interactive manner, providing insights into sources, dispersion, and risks associated with heavy metals in water.

A typical GIS-based environmental assessment involves several stages:

- (a) Data collection—sampling of soil, water, air, or sediments, followed by chemical analyses to quantify heavy metal concentrations. Standards for sampling protocols and analytical instrumentation must be explicitly reported.
- (b) Georeferencing—assigning GPS coordinates to each sample and compiling a spatial database in line with international reporting standards.
- (c) System development and integration—importing data into GIS software, developing analytical models, and, where appropriate, integrating specialized hydrological or hydraulic applications (e.g., EPANET, SWMM, HEC-RAS, and TUFLOW). This step typically produces thematic maps showing pollutant distributions.
- (d) Spatial analysis—identifying high-risk areas, correlating pollutant concentrations with anthropogenic sources, such as industry, traffic, or agriculture, and modeling dispersion across space and time.

The final stage emphasizes visualization and reporting, achieved through interactive maps, charts, and decision support tools, which provide valuable information for environmental managers, policymakers, and the public.

Although numerous review studies have addressed statistical approaches, such as factor analysis [16–19] and environmental issues more broadly [20–23], no comprehensive review has specifically examined the use of GISs in identifying heavy metals in water. To fill this gap, we conducted a systematic review of ISI-indexed articles, combining traditional and bibliometric approaches. Bibliometrics—the quantitative study of scientific communication through the application of mathematical and statistical techniques—was first defined by Pritchard in 1969 as the use of mathematics and statistics to shed light on written communication and the development of a discipline [24,25]. Bibliometric analysis is well established across diverse research domains, including energy [26], geosciences [27],

and engineering [28], where it has been applied to identify research trends, evaluate scientific impact, and map knowledge structures. This article aims to discuss existing knowledge, current research trends, and emerging directions, thereby offering a foundation for future investigations into the intersection of GIS applications and water pollution by HMs.

The goal of this study is to evaluate how geographic information system (GIS) techniques can support the analysis of spatial distribution and concentration of HMs in water resources, in order to identify potential contamination hotspots, assess associated environmental and health risks, and provide a scientific basis for sustainable water resource management.

2. Materials and Methods

This review followed a two-stage approach: a bibliometric analysis and a systematic literature review, both conducted according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines—under Creative Commons Attribution License (CC BY 4.0) [29]. The methodological workflow is illustrated in Figures 1 and 2.

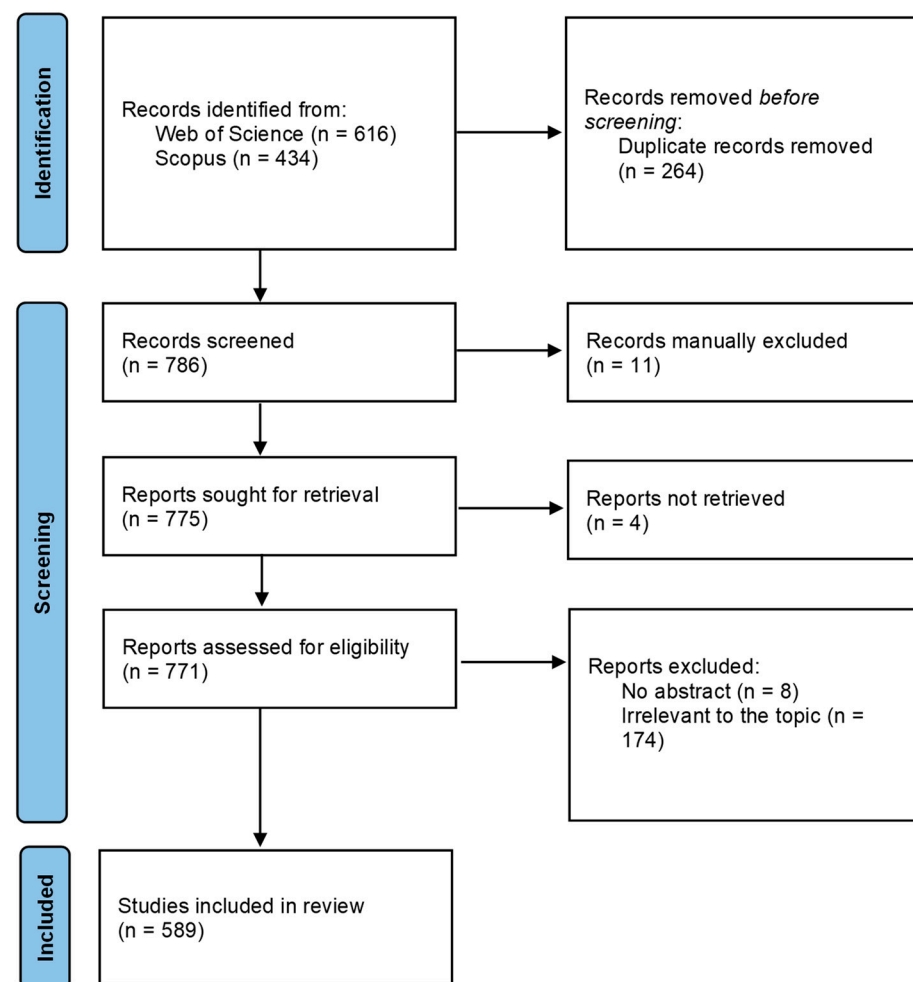


Figure 1. Selection process of the eligible reports based on the PRISMA 2020 flow diagram.

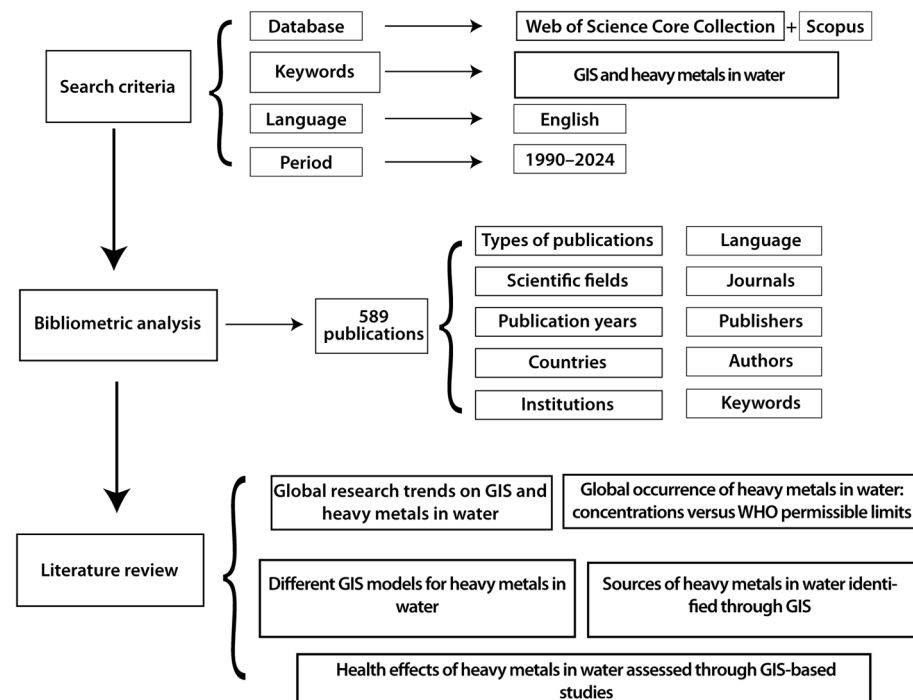


Figure 2. Schematic presentation of the workflow used in our research.

2.1. Literature Search and Data Sources

The bibliometric analysis was performed using two major databases: Web of Science (Science Citation Index Expanded, SCI-Expanded) and Scopus, ensuring broad coverage of peer-reviewed publications. Data were retrieved on 20 May 2025.

Several keyword combinations were initially tested to identify the most effective search string; however, these yielded fewer or less relevant results, often including studies outside the focus of GIS-based analyses. Ultimately, the phrase “GIS and heavy metals in water” was selected, as it provided the most comprehensive and thematically relevant dataset for the purposes of this review. While the use of alternative terms might capture other domains of research, our chosen string ensured a focused collection of publications directly addressing the integration of GISs with heavy metal contamination in aquatic systems.

2.2. Data Integration and Screening

From the database queries, 434 publications were retrieved from Scopus and 616 from Web of Science, totaling 1050 records. To merge the datasets, all references were exported and compiled into a single Microsoft Excel file. The records were sorted alphabetically by author names, after which duplicates were identified and removed by manually comparing both author names and titles. This step eliminated 264 duplicates, leaving 786 unique records.

Subsequently, titles and abstracts were screened according to the following inclusion criteria: articles published with an abstract, and studies explicitly addressing GIS applications in monitoring or managing HMs in water (title or abstract level). Exclusion criteria included letters and non-scientific materials, unpublished work, or inaccessible full texts. This process excluded 57 references, and 1 full-text paper could not be accessed. The remaining 578 articles were examined in detail. Of these, 148 were excluded as irrelevant and 8 lacked abstracts, leaving 589 studies for bibliometric and systematic review.

2.3. Bibliometric Analysis

The bibliometric analysis was conducted using Web of Science Core Collection tools (version 5.35, Clarivate, Philadelphia, PA, USA), Scopus analytics, Microsoft Excel (2024), Geochart [30–33], and VOSviewer (version 1.6.20) [34]. The analysis focused on nine main aspects: types of publications, research domains, year of publication, country of origin, authors, institutions, journals, publishers, and keywords.

Bibliometric indicators, such as links, total link strength, and node size, were incorporated into the analysis. The links attribute quantifies the number of direct connections between a publication and other documents. The total link strength assesses the overall intensity of these connections, particularly useful in co-authorship and keyword co-occurrence networks. Node size indicates the relative weight or frequency of an item (e.g., author, keyword, and institution).

This combination of indicators allowed us to identify collaborative research clusters and assess the role of scientific networks in advancing knowledge on GISs and heavy metals in aquatic environments.

2.4. Systematic Literature Review

In the second stage, the 589 selected articles underwent a detailed literature review. Findings were structured into five main thematic clusters: global research trends on GISs and HMs in water, global occurrence of HMs in water versus WHO permissible limits, different GIS models applied to HMs in water, sources of HMs in water identified through GISs, and health effects of HMs in water assessed through GIS-based studies.

3. Results and Discussion

3.1. Bibliometric Review—Synthesis of Literature

Out of the total number of 589 publications that we inventoried, the vast majority are articles (540, i.e., 92% of the total), followed by proceedings papers (33, i.e., 6% of the total), review articles (13, i.e., 2% of the total), and 3 book chapters (Figure 3). This distribution of publications is also found in the case of other studied topics [35,36].

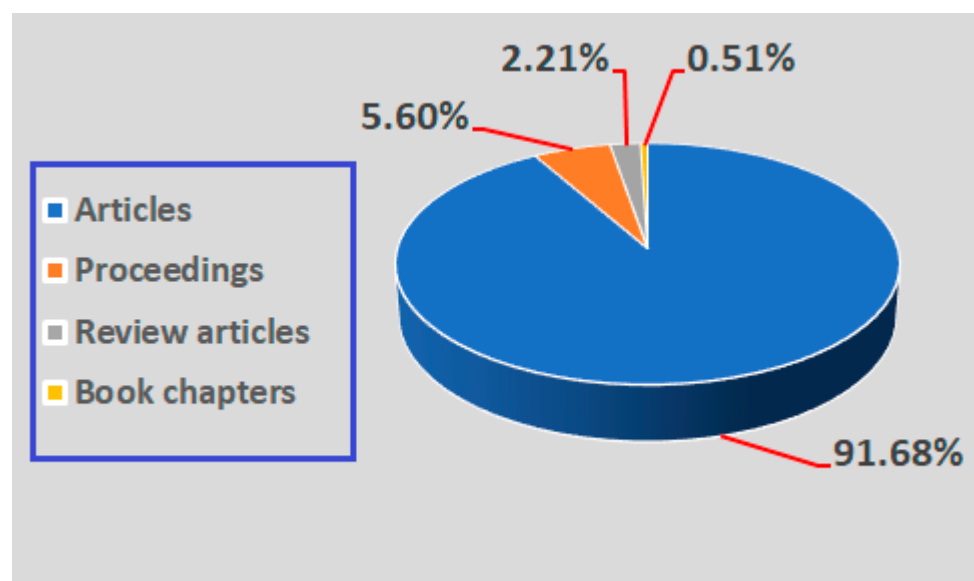


Figure 3. Distribution of the main publication types related to GISs and HMs in water.

The publications can be classified into different categories of research areas. Among the 53 inventoried categories, the most representative are: Environmental Sciences (326 articles),

Water Resources (101 articles), Engineering (41 articles), and Geology (33 articles) (Figure 4). The high share of Environmental Sciences and Water Resources categories confirms that research on GISs and HMs in water is mainly application-driven, while the contributions from Engineering and Geology suggest complementary interests in monitoring technologies and natural background conditions.

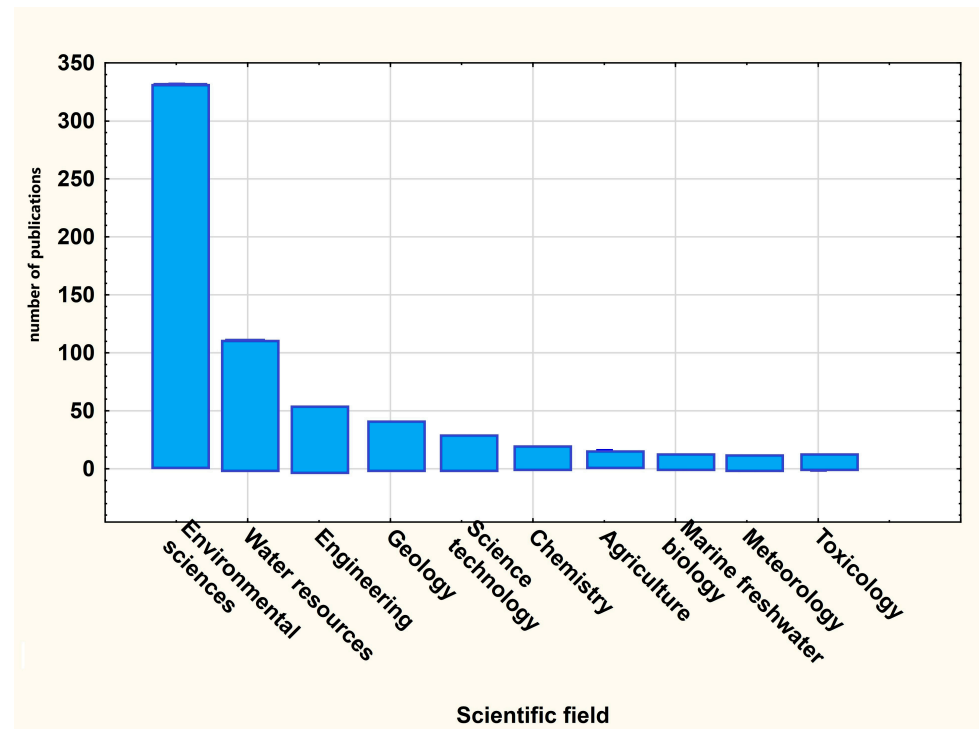


Figure 4. Distribution of the primary research areas in publications on GISs and heavy metals in water.

As in the case of other topics [37–39], the number of published articles on GISs and HMs in water has experienced exponential growth, starting with 1 article per year (1990 and 1995) and reaching 60–70 articles per year (2023 and 2024; Figure 5). The exponential growth in publications after 2015 reflects both the global urgency of heavy metal pollution and the wider availability of open-source GIS platforms and remote sensing datasets, which have lowered methodological barriers [40,41].

Among the 87 countries with authors who have published articles on this topic, China stands out (with 120 articles), as well as India (with 109 articles). They are followed by the USA (with 45 articles), Pakistan (with 42 articles), Egypt (with 40 articles), and Iran (with 39 articles; Figure 5). The strong output from China and India mirrors not only their acute contamination problems but also their rapid industrialization, large population pressures, and substantial governmental investment in environmental research and higher education [42,43]. National research funding schemes and strategic priorities for water security have further boosted publication activity. Meanwhile, contributions from countries such as Pakistan, Egypt, and Iran underline the vulnerability of developing economies to water pollution and the increasing recognition of GIS as a cost-effective tool for environmental monitoring [44,45]. By contrast, the smaller share of articles from industrialized nations may suggest a shift of focus toward remediation technologies, advanced treatment systems, and policy frameworks rather than mapping contamination.

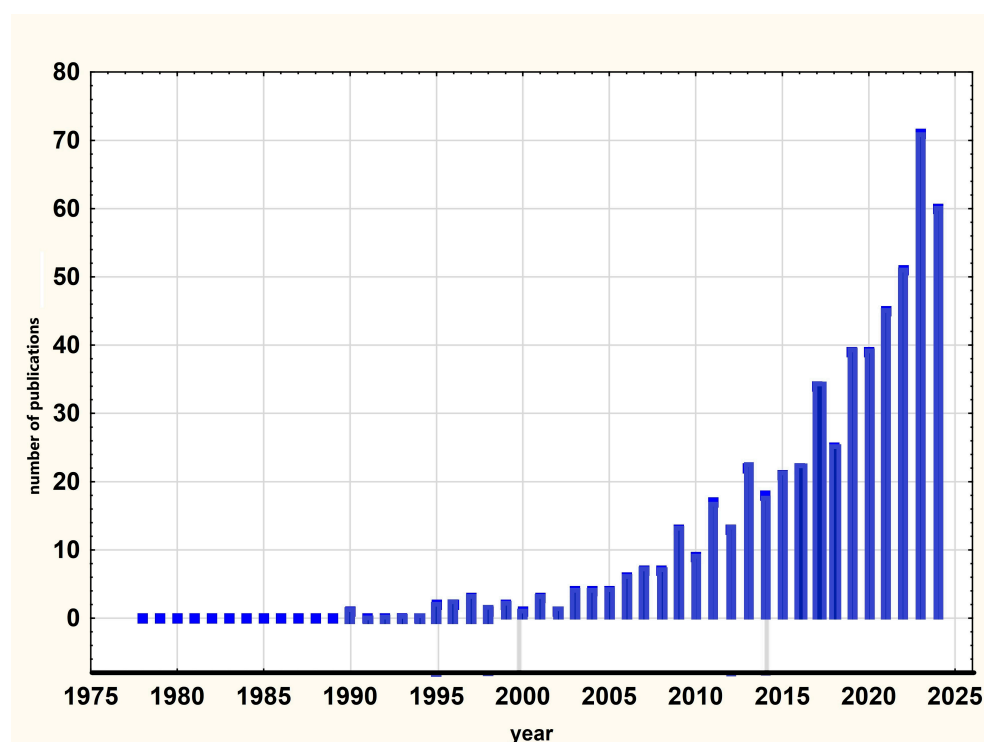


Figure 5. Annual distribution of articles on GISs and HMs in water.

The countries of the authors who published on this topic are grouped into several clusters, three of which are more comprehensive: cluster 1—Australia, Iran, Italy, Pakistan, Spain, Sweden, and the USA; cluster 2—Canada, France, Morocco, Philippines, South Korea, Thailand, and Tunisia; cluster 3—England, Germany, Iraq, Malaysia, Poland, and Turkey (Figure 6). The clustering of countries reveals international collaboration networks, often shaped by shared environmental challenges, such as irrigation, groundwater depletion, or industrial pollution [46,47].

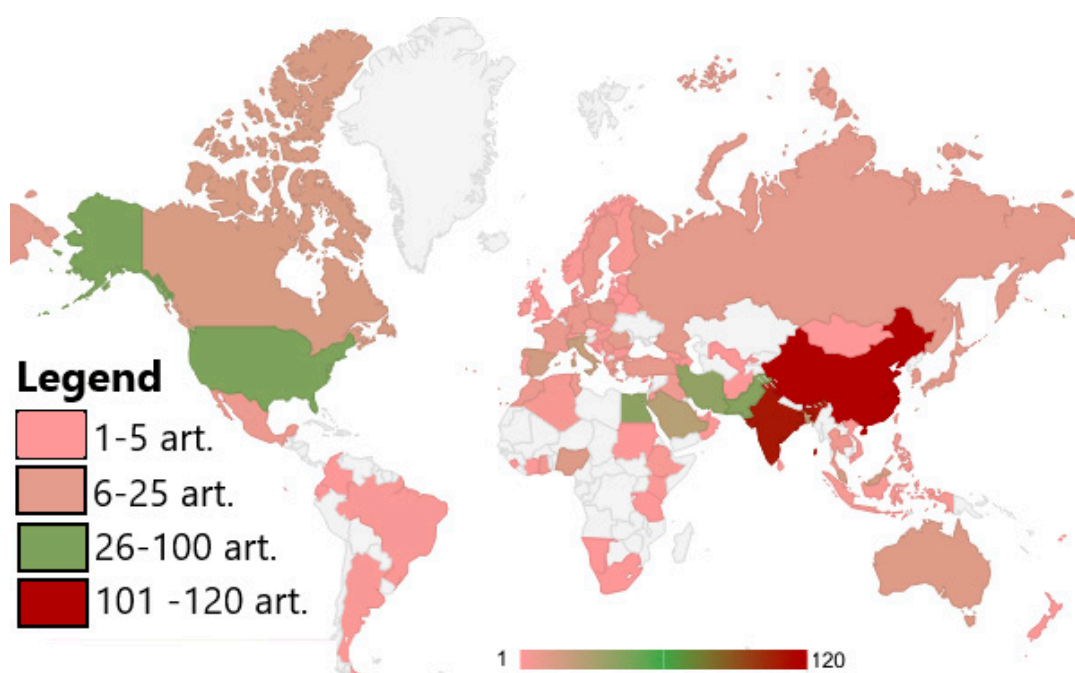


Figure 6. Countries with contributing authors of articles on GISs and HMs in water.

The publications on this topic are found, according to our inventory, in 257 journals. Among these, those with the highest number of published articles are *Environmental Monitoring and Assessment* (34 articles), *Water* (32 articles), and *Environmental Science and Pollution Research* (25 articles; Table 1 and Figure 7). Journals with the largest number of contributions, such as *Environmental Monitoring and Assessment* and *Water*, reflect the applied and interdisciplinary nature of this field, while the concentration of publications in a few major publishers highlights the centralization of dissemination channels.

Table 1. Leading journals publishing on GISs and HMs in water (the journals are ordered by ‘total link strength’).

Crt. No.	Journal	Publisher	Documents	Citations	Total Link Strength
1	<i>Environmental Monitoring and Assessment</i>	Springer/Springer Science and Business Media	34	859	33
2	<i>Water</i>	MDPI (Basel)	32	546	25
3	<i>Chemosphere</i>	Elsevier (Elsevier Ltd.)	13	893	23
4	<i>Applied Water Science</i>	Springer/SpringerOpen, (Springer Science and Business Media)	12	374	21
5	<i>Environmental Science and Pollution Research</i>	Springer (Springer Nature)	25	579	17
6	<i>Environmental Pollution</i>	Elsevier (Elsevier Sci. Ltd.)	9	729	16
7	<i>Groundwater for Sustainable Development</i>	Elsevier B.V.	8	122	12
8	<i>Science of the Total Environment</i>	Elsevier (Elsevier B.V.)	18	1308	11
9	<i>Sustainability</i>	MDPI (Basel)	11	176	11
10	<i>Environmental Earth Sciences</i>	Springer (Springer Science and Business Media Springer-Verlag)	17	342	10
11	<i>Environmental Geochemistry and Health</i>	Springer/Kluwer Academic Publishers (Dordrecht)	10	269	8
12	<i>Water Air and Soil Solution</i>	Springer Science + Business Media	12	133	7

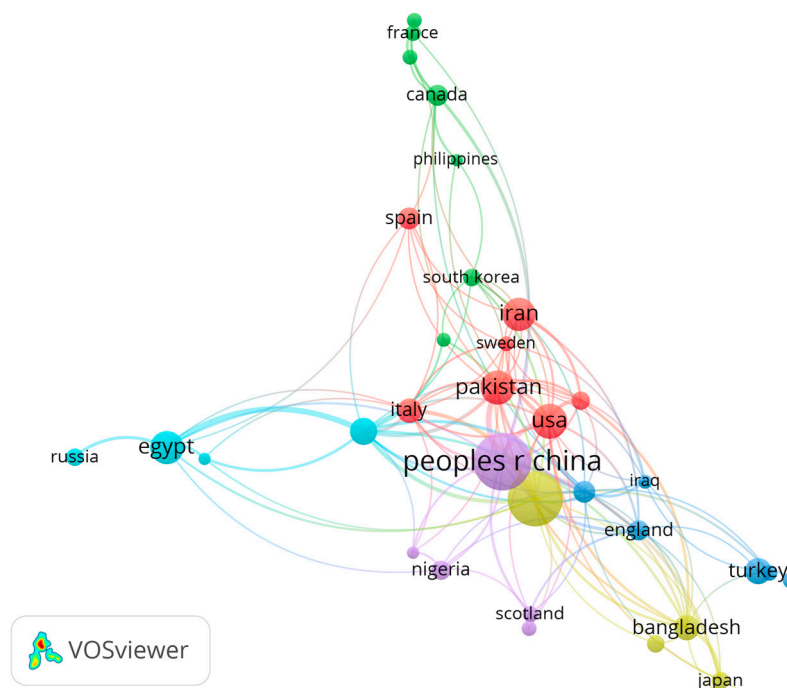


Figure 7. Country clusters of authors publishing on GISs and HMs in water.

Among the 102 publishers who have published articles on this subject, the most representative are Springer Nature (182 articles), Elsevier (137 articles), and MDPI (71 articles) (Figure 8). The institutions to which the authors of these articles belong, ranked by importance, are as follows: Egyptian Knowledge Bank (39 articles), Chinese Academy of Sciences (19 articles), Indian Institute of Technology System (17 articles), and King Saud University (13 articles).

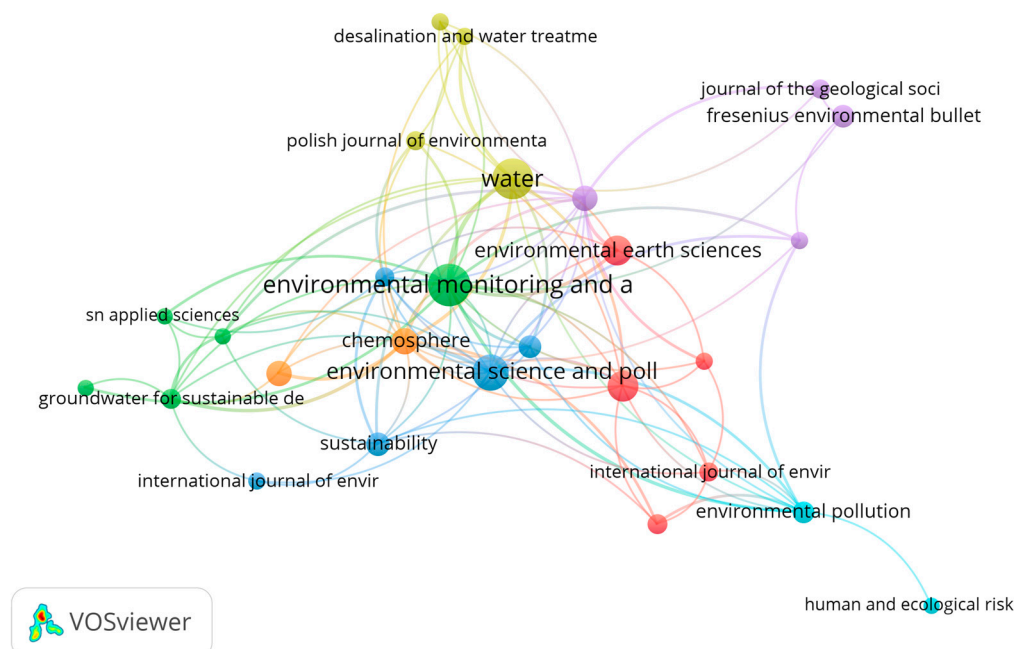


Figure 8. Key journals featuring articles on GISs and HMs in water.

In these articles, the most frequently used keywords are GIS, HMs, contamination, pollution, and water (Table 2). Keyword analysis shows that the field has evolved from general detection and monitoring toward more complex assessments of risks, impacts, and management implications (Figure 9). This shift suggests a maturation of the research domain, with the GIS no longer seen only as a cartographic tool but increasingly integrated into environmental governance and decision-making.

Table 2. Most frequently used keywords in published articles on GISs and HMs in water (the keywords are ordered by ‘total link strength’).

Crt. No.	Keyword	Occurrences	Total Link Strength
1	GIS	265	1160
2	heavy metals	259	1125
3	contamination	152	779
4	pollution	149	686
5	groundwater	103	505
6	river	95	493
7	water	110	487
8	sediments	73	348
9	drinking water	58	338
10	water quality	66	295
11	groundwater quality	49	236
12	basin	42	201
13	water quality	42	195
14	trace elements	37	181

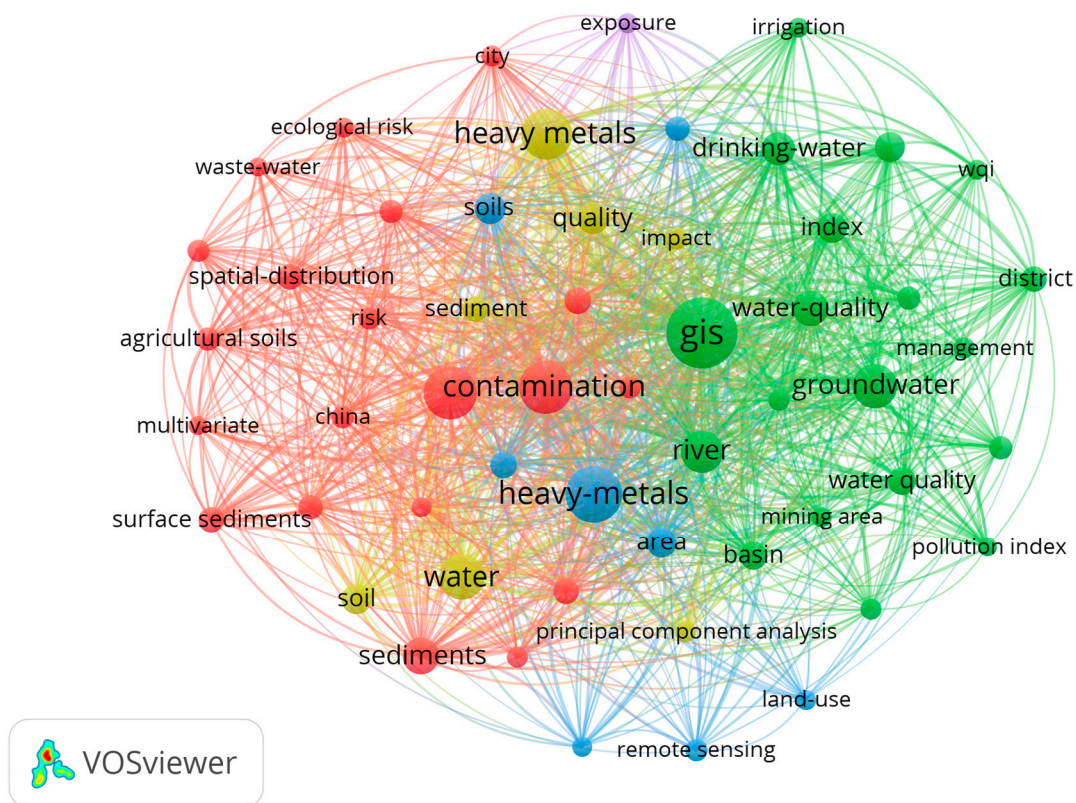


Figure 9. Authors' keywords related to GISs and HMs in water.

Based on their connections, keywords can be grouped into several clusters. Among them, the clusters with 19 words are as follows: the first cluster includes China, city, contamination, ecological risk, heavy metal, heavy metal contamination, heavy metal pollution, lead, pollution, risk, sediments, spatial distribution, and wastewater, while the second cluster includes words related to the origin of HMs, such as basin, drinking water, GIS, groundwater, irrigation, management, mining area, river, and surface water (Figure 9).

An interesting aspect to analyze is the evolution over time of the use of keywords in articles published on this topic. As can be seen in Figure 10, in the period 2017–2019, the keywords used were general ones: HMs, lead, quality, management, and remote sensing. In the period 2019–2020, they became more applied to the consequences of heavy metal pollution: contamination, risk, spatial distribution, and water quality. In the period 2020–2022, they referred mainly to their risk and impact: risk assessment, groundwater quality, and impact.

Table 3. Cont.

Cur. No.	Area of Research	Region	Citing Article
7	GIS-based hydrochemical assessment of groundwater	Bakoya Massif, Morocco	Benaïssa et al., 2024 [54]
8	GIS, multivariate statistics analysis, and health risk assessment of water supply quality for human use	Central Mexico	Hernández-Mena et al., 2021 [55]
9	GIS approach for the evaluation of water resources' quality indicators	Aydar-Arnasay Lakes System, Uzbekistan	Kulmatov et al., 2024 [56]
10	Groundwater risk assessment of shallow aquifers	Atankwidi Basin, Ghana	Anim-Gyampo et al., 2019 [57]
11	Heavy metal and polycyclic aromatic hydrocarbons	Ebrié lagoon, Côte d'Ivoire	Affian et al., 2009 [58]
12	HMs and geo-accumulation index development for groundwater	Mathura city, Uttar Pradesh, India	Ahmed et al., 2019 [59]
13	Heavy metal pollution characteristics and systemic risk assessment of the environment around the tailings site	China	He et al., 2024 [60]
14	Hydrogeochemical study and geospatial analysis of water quality	Kombolcha City, Ethiopia	Adamu et al., 2024 [61]
15	Hydro-transport-oriented Zn, Cu, and Pb behavior assessment and source identification in the river network of a historically mined area	Hokuroku Basin, Japan	Lu et al., 2019 [62]
16	Lead distribution by urban sediment	Porto Alegre, Brazil	Martinez and Poletto, 2010 [63]
17	Metal pollution and health–ecological risk assessment	Saronikos Gulf, Greece	Gkaragkouni et al., 2025 [64]
18	Modeling the vulnerability of groundwater to pollution	SE Nigeria	Aghamelu et al., 2023 [65]
19	MOIRA-PLUS: a decision support system for the management of complex freshwater ecosystems contaminated by radionuclides and HMs	general	Monte et al., 2009 [66]
20	Monitoring of heavy metal pollution of groundwater	Mersin, Turkey	Demirel, 2007 [67]
21	Monitoring HMs and spatial analysis using pollution indices and cartographic visualization	Lake Henci, Kosovo	Jusufi et al., 2024 [68]
22	Natural and anthropogenic contributions to concentration and distribution of HMs in surface water	Formoso river, Brazil	Baggio and Heinrich, 2012 [69]
23	Seasonal assessment of heavy metal contamination of groundwater	Sierra Leone	Sankoh et al., 2023 [70]
24	Spatial diversity of Cr distribution in soil and groundwater sites in relation with land use management	Central Evia and Assopos-Thiva Basins, Greece	Megremi et al., 2019 [71]
25	Spatial variations of As, Fe, Mn, and NO ₃ contaminations of drinking water	Surma basin, Bangladesh	Ahmed et al., 2019 [72]

Table 3. *Cont.*

Cur. No.	Area of Research	Region	Citing Article
26	Synthetic assessment on pollution level and potential ecological risk of HMs	Kaozhou Bay, China	Cai et al., 2005 [73]
27	Transition metals in freshwater and inland water	Marinduque island, Philippines	Agarin et al., 2021 [74]
28	Urbanization and quality of stormwater runoff	Phoenix in Arizona, USA	Kang et al., 2014 [75]
29	Utilizing hydrogeochemical data and GIS tools to assess the groundwater quality in arid regions	Wadi Feiran Basin, Southwestern Sinai, Egypt	Omar et al., 2024 [76]
30	Vulnerabilities of urban drinking water	Bacau, Romania	Banica et al., 2016 [77]
31	Water quality monitoring	Al-Habbaniyah Lake, Iraq	Al-Fahdawi et al., 2015 [78]

The compilation of studies in Table 3 highlights the global scope of research applying GISs to heavy metal contamination in water resources. Case studies span Europe, Asia, Africa, and the Americas, illustrating that water quality issues linked to HMs are of worldwide concern rather than confined to specific regions.

Thematically, the studies can be grouped into several research directions, as follows.

Groundwater Quality and Drinking Water Safety

Research in Sudan, Nigeria, India, Bangladesh, Sierra Leone, the UAE, and Egypt emphasizes groundwater, reflecting its role as the primary drinking water source in many regions. The GIS supports the detection of spatial heterogeneity in pollutants, such as arsenic, lead, manganese, and nitrates, as well as the identification of vulnerable aquifers.

Surface Water Monitoring and Ecosystem Impacts

Investigations in Turkey, Côte d'Ivoire, Brazil, Iraq, and the Philippines demonstrate GIS applications for lakes, rivers, lagoons, and coastal waters, where HMs accumulate due to both natural processes and human activities (urbanization, industry, and agriculture).

A representative case study was carried out in the pre-deltaic Danube area, a highly sensitive transboundary region shared by Romania, Ukraine, and the Republic of Moldova. This zone is particularly important, as the Danube Delta is part of the UNESCO World Heritage and requires continuous monitoring to protect its ecosystems from pollution [79]. Two measurement campaigns were conducted across ten monitoring points along a 57.8 km section of the Danube. The study integrated GIS tools with hydrodynamic modeling to better understand pollutant behavior. A digital terrain model was generated using the OpenTopography service, and a non-stationary hydraulic model was developed in HEC-RAS, incorporating river flow data and cross-sectional profiles. By coupling measured concentrations with hydraulic transport equations, spatial and seasonal distributions of HMs were simulated. Results revealed seasonal variations, with systematically higher concentrations observed in summer. The model successfully reproduced measured values ($R^2 = 0.8715$) and enabled prediction of downstream contamination trends. Importantly, this case illustrates how GIS-based hydrodynamic modeling can provide both reliable monitoring and predictive insights for managing heavy metal pollution in vulnerable aquatic systems [79].

Mining and Industrial Legacy Contamination

Studies from Spain, Japan, Kazakhstan, Greece, and Morocco reveal the persistent influence of historical mining and metallurgical operations. GIS methods are valuable for tracking metal dispersion, hydro-transport, and bioavailability, offering insights into long-term environmental risks.

Risk Assessment and Decision Support Frameworks

Several works [55,66,73] go beyond descriptive mapping by integrating GISs with pollution indices, multivariate statistics, and ecological risk assessments. These studies demonstrate the potential of GIS to function as a decision support system for environmental management and public health protection. In this regard, the Quantum GIS free software (QGIS)-3.34.0-Prizren v10.094 (2023-08-08) is used in forest genetics research to map the natural distribution of species, the origin of provenances, and the field test's locations [80–84].

Also, the table illustrates a variation in spatial scales, ranging from localized sites (individual lakes, tailings dams, or river basins) to larger regional aquifers and coastal systems. This adaptability confirms GIS as a versatile tool for addressing contamination challenges across different hydrological and environmental settings.

While global datasets provide valuable insights into the widespread problem of heavy metal contamination, it is important to emphasize that such findings cannot be overgeneralized. Regional differences in geology, industrial development, agricultural practices, hydrological regimes, and regulatory enforcement strongly influence both the sources and impacts of HMs. For instance, cadmium contamination in South Asia is often linked to fertilizer use, whereas in Eastern Europe legacy mining operations are the dominant source. Similarly, natural geogenic contamination in parts of Bangladesh differs fundamentally from industrial pollution in North Africa or East Asia. Consequently, GIS-based analyses must always be contextualized to local conditions, with recognition that spatial patterns and health risks vary considerably across regions. This highlights the need for region-specific monitoring frameworks and policies, rather than a one-size-fits-all approach.

Policy Implications and Practical Applications

The insights generated by GIS-based assessments have direct relevance for policy development and environmental governance. First, spatially explicit maps of contamination hotspots can guide regulatory authorities in prioritizing monitoring and remediation efforts, ensuring that limited resources are allocated efficiently. Second, integration of GISs with health risk models provides a scientific foundation for establishing or revising water quality standards in line with international guidelines, such as those of the WHO. Third, GIS-supported decision support systems can strengthen land use planning and zoning policies by identifying areas unsuitable for drinking water abstraction or agricultural irrigation due to contamination risks. Moreover, real-time GIS monitoring networks can be incorporated into early warning systems, enabling rapid response to accidental pollution events and reducing risks to public health. Importantly, the GIS facilitates transboundary water governance by providing a common spatial framework for negotiation and cooperation among neighboring countries sharing aquifers or river basins. Finally, findings from GIS-based analyses should be translated into public communication strategies, increasing transparency and enabling communities to participate in decision-making regarding water safety and environmental protection. Collectively, these applications demonstrate that the GIS is not only a technical tool but also a bridge between scientific evidence and practical policy actions.

3.2.2. Global Occurrence of Heavy Metals in Water: Concentrations Versus WHO Permissible Limits

Beyond spatial analyses, the reviewed studies also provide measured concentrations of HMs in water across different regions. To facilitate global comparison, these reported values were compiled and contrasted with the World Health Organization (WHO) maximum permissible limits (2008; Table 4). While the WHO guidelines offer a useful global benchmark, it is important to note their limitations. National standards often vary, with some countries adopting stricter thresholds for drinking water. Furthermore, permissible limits may differ between groundwater and surface water, as well as between intended uses (e.g., drinking, irrigation, and ecological protection). Therefore, the comparisons presented here should be interpreted cautiously and considered indicative rather than absolute assessments of compliance.

Table 4. Concentrations of heavy metals in water across different regions of the world compared with WHO permissible limits (2008).

Cur. No.	Element	Value (mg/L)	World Health Organization (WHO) Maximum Permissible Limit 2008 (mg/L)	Region	Citing Article
1	Aluminum (Al)	0.18–0.58	0.2	Makkah Al-Mukarramah Province, Saudi Arabia	Alqarawi et al., 2022 [85]
2		0–6.411		Elazig, Turkey	Baran et al., 2023 [86]
3		0.058–0.195		Lumbardhi river, Kosova	Faiku and Hazizi, 2016 [87]
4		0.0478		Chandrapur district, India	Satapathy et al., 2009 [43]
5	Arsenic (As)	0.00581	0.01	Abu-Qir, Egypt	El-Alfy et al., 2023 [88]
6		0.00043–0.0285		Lumbardhi river, Kosova	Faiku and Hazizi, 2016 [87]
7		0.00013–0.001		Divandarreh, Iran	Ghahramani et al., 2020 [89]
8		0.00174–0.00385		Lower Dir, Pakistan	Rashid et al., 2019 [44]
9		0.00189–0.00269		Pearl River Estuary, China	Zhao et al., 2020 [90]
10		0.00–0.0038		Spring water, Jordan	Al-Ameer et al., 2020 [91]
11		0.03		Skardu, Pakistan	Ahsan et al., 2021 [92]
12		0.001026		Lahore, Pakistan	Anwar et al., 2024 [93]
13		0.01837		Mediterranean Sea coast, Egypt	Darwish et al., 2022 [45]
14	Cadmium (Cd)	0.006	Cd = 0.005	Krzna River, Poland	Kluska and Jabłońska, 2024 [94]
15		0.0089		Bahia Blanca Estuary, Argentina	Severini et al., 2018 [95]
16		0.00097		Mediterranean Sea coast, Egypt	Darwish et al., 2022 [45]
17	Cobalt (Co)	0.0035	0.07	Abu-Qir, Egypt	El-Alfy et al., 2023 [88]

Table 4. Cont.

Cur. No.	Element	Value (mg/L)	World Health Organization (WHO) Maximum Permissible Limit 2008 (mg/L)	Region	Citing Article
18	Chromium (Cr)	0.0039–0.638	Cr = 0.05	Kamber-Shahdadkot, Sindh, Pakistan	Lanjwani et al., 2022 [96]
19		0.10		Lower Dir, Pakistan	Rashid et al., 2019 [44]
20		0.001724–0.004948		Spring water, Jordan	Al-Ameer et al., 2020 [91]
21		0.001–18.3		Aligarh, India	Badar et al., 2024 [97]
22		0.006–0.235		Elazig, Turkey	Baran et al., 2023 [86]
23	Copper (Cu)	0–0.134	Cu = 0.05	Kamber-Shahdadkot, Sindh, Pakistan	Lanjwani et al., 2022 [96]
24		0.09		Lower Dir, Pakistan	Rashid et al., 2019 [44]
25		0.0016		Chandrapur district, India	Satapathy et al., 2009 [43]
26		0.0256		Bahia Blanca Estuary, Argentina	Severini et al., 2018 [95]
27		0.165–1.57		Baia Mare, Romania	Sur et al., 2022 [98]
28		0.867–2.353		Skardu, Pakistan	Ahsan et al., 2021 [92]
29		0.02–0.18		Makkah Al-Mu-karramah Province, Saudi Arabia	Alqarawy et al., 2022 [85]
30		0.0014–0.0044		Lumbardhi river, Kosova	Faiku and Hazizi, 2016 [87]
31		0.0016		Chandrapur district, India	Satapathy et al., 2009 [43]
32		0.10–1.60		Lake Tana, Ethiopia	Sishu et al., 2024 [99]
33	Lead (Pb)	0.036–0.195	Pb = 0.05	Baia Mare, Romania	Sur et al., 2022 [98]
34		0.00–0.0183		Spring water, Jordan	Al-Ameer et al., 2020 [91]
35		0.012–0.035		Makkah Al-Mu-karramah Province, Saudi Arabia	Alqarawy et al., 2022 [85]
36		0–0.065		Elazig, Turkey	Baran et al., 2023 [86]
37		0.00286		Abu-Qir, Egypt	El-Alfy et al., 2023 [88]
38	Manganese (Mn)	0.00002–0.00149	Mn = 0.1	Shallow Lakes in Jiangsu Province, China	Li et al., 2016 [42]
39		0.2464–1.1628		Spring water, Jordan	Al-Ameer et al., 2020 [91]
40		0.54–1.43		Makkah Al-Mu-karramah Province, Saudi Arabia	Alqarawy et al., 2022 [85]
41		0–0.316		Elazig, Turkey	Baran et al., 2023 [86]
42		0–0.14		Kamber-Shahdadkot, Sindh, Pakistan	Lanjwani et al., 2022 [96]
43	Mercury (Hg)	0.00379	Hg = 0.01	Abu-Qir, Egypt	El-Alfy et al., 2023 [88]
44		0.0007–0.0037		Northern Quebec large boreal lakes, Canada	Moingt et al., 2013 [100]

Table 4. Cont.

Cur. No.	Element	Value (mg/L)	World Health Organization (WHO) Maximum Permissible Limit 2008 (mg/L)	Region	Citing Article
45	Nickel (Ni)	0.0455–0.0927	Ni = 0.07	Pearl River Estuary, China	Zhao et al., 2020 [90]
46		0.001481–0.002811		Spring water, Jordan	Al-Ameer et al., 2020 [91]
47		0.41–0.56		Makkah Al-Mukarramah Province, Saudi Arabia	Alqarawy et al., 2022 [85]
48		0.002445		Lahore, Pakistan	Anwar et al., 2024 [93]
49	Zinc (Zn)	0–0.007	Zn = 5.0	Delhi, India	Kaur and Rani, 2006 [101]
50		0.0046–0.0061		Krzna River, Poland	Kluska and Jabłońska, 2024 [94]
51		0.0027		Bahia Blanca Estuary, Argentina	Severini et al., 2018 [95]
52		0.01–0.718		Baia Mare, Romania	Sur et al., 2022 [98]
53		0.02–0.12		Makkah Al-Mukarramah Province, Saudi Arabia	Alqarawy et al., 2022 [85]
54		0.06–0.51		Aligarh, India	Badar et al., 2024 [97]
55		0.02477		Mediterranean Sea coast, Egypt	Darwish et al., 2022 [45]
56		0.0198–0.0314		Divandarreh, Iran	Ghahramani et al., 2020 [89]
57		0.05–0.18		Delhi, India	Kaur and Rani, 2006 [101]

Element-Specific Exceedances Relative to WHO Standards

The data presented in Table 3 illustrate the worldwide variability of heavy metal concentrations in different water bodies, highlighting both natural geochemical variations and anthropogenic influences. When compared against the WHO maximum permissible limits (2008), several important observations emerge.

Aluminum (Al): Concentrations exceeded the WHO limit (0.2 mg/L) in Turkey (up to 6.411 mg/L), indicating potential risks of neurological effects and water quality issues. In contrast, values reported from Kosovo, India, and Saudi Arabia were generally within or close to permissible thresholds.

Arsenic (As): Most reported concentrations were below the 0.01 mg/L limit, although certain sites (e.g., Kosovo, Pakistan, and China) showed levels approaching or slightly exceeding the guideline. Chronic exposure to arsenic remains a major public health concern, particularly in regions with geogenic contamination.

Cadmium (Cd): While many studies reported safe levels, notable exceedances were observed in Pakistan (0.03 mg/L) and Egypt (0.01837 mg/L), both surpassing the WHO limit (0.005 mg/L). These hotspots suggest localized contamination from industrial or mining activities.

Cobalt (Co): Although the WHO does not provide a strict guideline for Co, values varied widely, with some extremely high levels (up to 0.638 mg/L in Sindh, Pakistan), raising concerns about emerging health risks associated with long-term exposure.

Chromium (Cr): Concentrations in several regions, such as Aligarh, India (up to 18.3 mg/L), and Baia Mare, Romania (up to 1.57 mg/L), greatly exceeded the WHO threshold (0.05 mg/L). Such levels point to severe contamination likely linked to tannery, electroplating, or mining activities.

Copper (Cu): Strikingly high concentrations were recorded in Skardu, Pakistan (up to 2.353 mg/L), far above the WHO guideline of 0.05 mg/L. Although copper is an essential trace element, these elevated levels pose risks of gastrointestinal irritation and liver/kidney damage.

Lead (Pb): Most reported concentrations were below the permissible limit (0.05 mg/L), but sites in Turkey and Saudi Arabia showed concerning values (up to 0.065 mg/L). Lead contamination, even at low levels, is a critical concern due to its cumulative toxicity.

Manganese (Mn): Considerable exceedances were found in Jordan and Saudi Arabia (up to 1.43 mg/L), well above the 0.1 mg/L limit. Elevated Mn may impair neurological development in children, making this a pressing public health issue.

Mercury (Hg): While most regions reported values below the 0.01 mg/L limit, the Pearl River Estuary in China showed extreme levels (0.0455–0.0927 mg/L). This is alarming given mercury's potent neurotoxicity and biomagnification in aquatic food webs.

Nickel (Ni): Values exceeded the 0.07 mg/L guideline in several regions, notably Saudi Arabia (0.56 mg/L) and Romania (0.718 mg/L). Nickel pollution often reflects industrial effluents and poses risks of carcinogenicity and skin disorders.

Zinc (Zn): All reported concentrations were within the WHO safe limit (5 mg/L). Although not a major health risk, elevated Zn can impart an undesirable taste and reduce water quality.

Critical Synthesis: Geogenic Versus Anthropogenic Drivers

Taken together, these findings reveal that exceedances of permissible limits arise from both geogenic and anthropogenic processes. In South Asia, for example, high cadmium, chromium, and copper concentrations in Pakistan and India can largely be traced to mining, tannery effluents, and industrial discharges. By contrast, naturally occurring geochemical conditions explain elevated arsenic in Bangladesh and Iran, or manganese in Jordan, where the geological setting contributes to persistent groundwater contamination. In Eastern Europe, hotspots such as Baia Mare (Romania) and Aligarh (India) are strongly linked to mining and metallurgical legacies, while in coastal and estuarine regions like the Pearl River Estuary (China) and Abu-Qir (Egypt), industrial emissions and urban wastewater play dominant roles.

This contrast between geogenic and anthropogenic sources highlights the need for tailored monitoring and mitigation strategies. Regions with natural enrichment require long-term groundwater management and alternative water supply planning, whereas areas impacted by industrial activity demand stricter effluent controls and remediation efforts. GIS-based approaches are particularly valuable in this context, as they help distinguish spatial patterns linked to geological formations from those driven by human activity, supporting more precise risk mapping and management interventions.

Overall, the global dataset reveals regional disparities in heavy metal contamination, with hotspots in South Asia, North Africa, and Eastern Europe showing particularly high levels of cadmium, chromium, copper, manganese, mercury, and nickel. These exceedances highlight the urgent need for region-specific water monitoring, remediation strategies, and stricter enforcement of environmental regulations. Moreover, the integration of GIS-based approaches can provide valuable spatial insights, allowing identification of contamination clusters, source attribution, and risk mapping to protect public health.

3.2.3. Different GIS Models for Heavy Metals in Water

The application of geographic information system (GIS) models has become an essential tool in assessing heavy metal contamination and overall water quality in both surface and groundwater systems. Various modeling approaches demonstrate how GISs can integrate spatial, hydrological, and chemical datasets to provide effective visualizations and decision support tools for environmental management, including forestry [102–110].

For example, in the middle Nile Delta, Egypt, irrigation water quality (IWQ) was assessed using GIS-based indicators that addressed salinity, permeability, ion toxicity, and related risks to sensitive crops. A total of 27 canal water samples were analyzed, and spatial variability in heavy metal concentrations was mapped using the inverse distance weighting (IDW) method in ArcGIS 10.7, providing a clear representation of water quality conditions across the region [111]. Similarly, in the Sarno River Basin, Italy, contamination maps were produced for As, Cd, Cr, Cu, Hg, Pb, and Zn by combining measured values with regional background concentrations. This GIS-aided method also integrated factor analysis, which helped to identify the extent and nature of contamination sources within river sediments [112].

Large-scale applications have also been demonstrated. In Germany, heavy metal inputs (Cd, Cr, Cu, Hg, Ni, Pb, and Zn) into major river basins between 1985 and 2000 were quantified through the MONERIS model. This GIS-integrated approach accounted for both point-source emissions (wastewater treatment plants and industrial discharges) and diffuse sources, providing a long-term assessment of heavy metal fluxes at the basin scale [113]. Likewise, in Iraq, the GIS was combined with a weighted arithmetic water quality index (WQI) and IDW interpolation to map spatial variations in water quality, demonstrating the effectiveness of integrating water indices with geospatial analysis [114].

Advanced hydrological modeling has also been coupled with GIS for predicting contaminant transport. In the Marmara Region, Turkey, GIS data were integrated with the storm water management model (SWMM) to simulate catchment hydrology and contaminant loads. By incorporating kinetic equations for nutrient losses and heavy metal transport, the model successfully predicted runoff loads of Cu, Ni, Zn, total nitrogen (TN), and total phosphorus (TP), showing how land use and precipitation influence contaminant distribution [115]. Complementary to these hydrological models, a GIS-based software—3.34.0-Prizren v10.094 (2023-08-08), tool was developed for the Nile River in Egypt to facilitate water quality assessment. This tool included a graphical user interface (GUI), enabling decision-makers to visualize and interpret spatial patterns of water quality with greater ease [116].

Groundwater assessments also benefit significantly from GIS applications. In India, groundwater vulnerability mapping was conducted using a modified DRASTIC model that incorporated land use/land cover data. The results showed increased susceptibility of shallow aquifers to pollution, with validation provided by water quality parameters, such as F^- , SO_4^{2-} , and NO_3^- , exceeding permissible limits [117]. Similarly, in Pakistan, the GIS was used to map regional heavy metal concentrations in urban groundwater, enabling the identification and delineation of risk-prone zones [118]. In China, an innovative framework integrating the GIS, multi-criteria decision analysis (MCDA), and remote-sensing-derived land use/land cover (LULC) was applied to develop a groundwater quality index using a geostatistical analytical hierarchy process (AHP). This approach allowed for both spatial evaluation of contamination and scenario-based management of water resources [119].

Urbanized and industrial regions pose specific challenges that GIS-based models can address. In Glasgow, UK, the GRASP (groundwater and soil pollutants) tool was developed to evaluate the threat of leaching metals from soil to shallow groundwater. By integrating soil chemistry data with the GIS, the tool produced risk maps highlighting vulnerable areas

to contamination from surface pollutants. Metals such as Cr, Pb, and Ni were mapped using more than 1600 soil samples, providing actionable information for urban planning [120].

Beyond conventional GIS models, machine learning techniques have been incorporated into water quality assessments [121]. In Bangladesh, arsenic contamination in groundwater was predicted by combining GIS-derived spatial grids with artificial neural networks (ANNs). A back-propagation neural network (BPNN) architecture (6-20-1) was able to capture the highly non-linear relationships among input parameters, improving prediction accuracy for groundwater arsenic levels [90]. Similarly, fuzzy multi-criteria decision-making approaches have been applied. A novel ontology-based WQI was developed within a fuzzy environment and integrated into GIS, enabling spatiotemporal modeling of drinking water quality in groundwater resources [122].

These case studies demonstrate the flexibility and robustness of the GIS as a platform for integrating diverse datasets—ranging from hydrological models and soil chemistry to remote sensing and artificial intelligence—to assess heavy metal contamination in water resources. Interpolation methods, such as IDW [111,114], hydrochemical modeling [115], vulnerability mapping [117], and decision support tools [116,120], highlight the spatial variability and complex drivers of contamination. Meanwhile, advanced hybrid models that integrate GIS with statistical techniques [112], catchment transport simulations [115], or machine learning [122] provide powerful predictive and management-oriented frameworks.

We can say that GIS-based models not only enhance understanding of heavy metal pollution dynamics but also support policymaking by generating accessible, spatially explicit maps. These models allow authorities to identify hotspots, evaluate risks, and prioritize mitigation strategies, making the GIS a critical technology in modern water quality management.

Table 5 summarizes the different GIS models used for analysis of HMs in water.

Table 5. Different GIS models for heavy metals in water.

Cur. No.	Region/Study	GIS Approach Model	Heavy Metals Assessment	Key Methods/Tools	Main Findings/Applications
1	Middle Nile Delta, Egypt	GIS-based indicators	Not specified	IDW interpolation, ArcGIS 10.7	Spatial variability of irrigation water quality; salinity, ion toxicity, risks to crops
2	Sarno River Basin, Italy	GIS + Factor Analysis	As, Cd, Cr, Cu, Hg, Pb, Zn	Contamination mapping using GIS, factor analysis	Identification of contamination extent and sources in river sediments
3	Germany	MONERIS model	Cd, Cr, Cu, Hg, Ni, Pb, Zn	GIS-integrated modeling	Quantified heavy metal inputs into river basins (1985–2000), point and diffuse sources
4	Iraq	GIS + WQI	Not specified	Weighted arithmetic WQI, IDW	Spatial mapping of water quality variations
5	Marmara Region, Turkey	GIS + SWMM	Cu, Ni, Zn, TN, TP	Hydrological modeling, kinetic equations	Predicted contaminant transport from land use and precipitation
6	Nile River, Egypt	GIS-based software tool	Not specified	GUI for visualization	Facilitates water quality assessment and spatial interpretation
7	India	Modified DRASTIC	F^- , SO_4^{2-} , NO_3^-	Groundwater vulnerability mapping	Shallow aquifers highly susceptible to pollution

Table 5. Cont.

Cur. No.	Region/Study	GIS Approach Model	Heavy Metals Assessment	Key Methods/Tools	Main Findings/Applications
8	Pakistan	GIS mapping	Various heavy metals	Spatial mapping	Identification of risk-prone zones in urban groundwater
9	China	GIS + MCDA + Remote Sensing	Not specified	Geostatistical AHP, LULC integration	Scenario-based groundwater quality management
10	Glasgow, UK	GRASP tool	Cr, Pb, Ni	GIS + soil chemistry	Risk maps for urban groundwater contamination
11	Bangladesh	GIS + ANN	Arsenic	Backpropagation neural network (6-20-1)	Predicted non-linear relationships and arsenic levels
12	Various locations	GIS + Fuzzy WQI	Various	Fuzzy multi-criteria decision-making	Spatiotemporal modeling of groundwater quality

3.2.4. Sources of HMs in Water Identified Through GIS

Water resources are highly vulnerable to contamination from a variety of anthropogenic and natural activities, with HMs being a major concern due to their persistence and toxicity. GIS-based studies have enabled the identification and spatial visualization of these contamination sources across diverse environments.

One of the most common pathways of heavy metal input into water bodies is through emissions from rapidly expanding industrial areas, mine tailings, disposal of high-metal wastes, leaded gasoline and paints, fertilizers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion, and electronic waste [123]. Natural sources, such as direct atmospheric deposition and geological weathering, also contribute significantly. In addition, agricultural practices and the discharge of domestic, municipal, and industrial waste products further exacerbate heavy metal contamination [124].

Urbanization and industrialization are key drivers of elevated heavy metal concentrations in water and soils. Rapid urban expansion, coupled with high energy consumption and population migration into large cities, results in the accumulation of pollutants in the urban environment. Potentially toxic elements (PTEs) are released into soils and surrounding ecosystems due to traffic emissions, fuel combustion, tire and brake wear, weathering of street dust and building materials, as well as industrial discharges and waste disposal systems [125,126]. In urban children's parks (UCPs), GIS-based assessments have revealed that PTE contamination is strongly associated with traffic activities, urban infrastructure development, and solid waste dumping [127,128].

Plants indicate water, air, and soil pollution, a phenomenon detectable through remote sensing techniques [129–131]. Water pollution is a stress factor for natural environment (habitats, plants, and animals). At the same time, many organisms (bacteria and plants) and technics are used for natural decontamination of polluted water and riparian ecosystem rehabilitation [132–136].

Local-scale studies also demonstrate the impacts of urban industrial development. For example, the Canal do Cunha watershed in Rio de Janeiro has undergone severe environmental degradation since the 1950s. Deforestation, landfills, drainage works, and valley occupation altered the fluvial dynamics, causing the watershed to act as a conduit for wastewater and contaminated sediments into Guanabara Bay. These inputs directly affect water quality and heavy metal contamination in the western bay area [137].

Accidental pollution events also play a significant role in introducing HMs into aquatic systems. Recent decades have recorded numerous water pollution accidents in countries,

such as China [138,139], the United States [140], and Japan [141]. Historical cases provide further evidence, such as at Los Alamos, New Mexico, where World War II-era nuclear research and weapons testing released radionuclides and HMs into the environment. GIS and image processing have proven effective in reconstructing past contamination pathways, with studies showing that surface water served as the primary transport mechanism for depleted uranium and associated metals, such as copper [142].

In South Asia, GIS-supported studies have highlighted the impacts of local industries and water management on contamination levels. In Nagarparker, Thar (Pakistan), groundwater quality around small dams was found to be unsuitable for drinking due to contamination, especially during post-monsoon periods. The spread of waterborne diseases further indicated poor groundwater quality [143]. Similarly, tannery industries are well-documented as a major source of metal pollution. Effluents from tanneries in India (Palar River, Tamil Nadu), Egypt (Nile River, Cairo), and Mexico (Gomez River, Leon) have severely degraded local water bodies. In Bangladesh, the unregulated establishment of ~250 tanneries along the Buriganga River before 2013 led to the daily discharge of approximately 20,000 m³ of untreated effluent, significantly polluting the river and surrounding lagoon systems [144,145].

Municipal solid waste (MSW) disposal sites also contribute to heavy metal leaching into groundwater. In Sangamner city, India, GIS-based groundwater assessments showed that leachate from MSW dumping yards caused deterioration of water quality, rendering it unsuitable for drinking and domestic use, though marginally acceptable for irrigation [146]. Mining activities further intensify groundwater vulnerability. Open-pit coal mining alters groundwater levels due to dewatering operations and precipitation accumulation in pits [147]. Acid mine drainage (AMD), a by-product of mining, has emerged as a global concern. It introduces HMs, such as arsenic, cadmium, copper, silver, and zinc, into aquatic systems, originating from tailings wastewater and mill processes [148].

We may assess that GIS-based evaluations demonstrate that heavy metal contamination in water stems from a wide spectrum of sources: industrial effluents, urbanization, agriculture, mining, accidental releases, and inadequate waste management. The ability of GIS to integrate spatial and temporal datasets allows for more effective identification, monitoring, and visualization of contamination pathways, supporting environmental management and public health protection.

3.2.5. Health Effects of HMs in Water Assessed Through GIS-Based Studies

Metals such as copper (Cu), zinc (Zn), manganese (Mn), and iron (Fe) are recognized as essential micronutrients; however, at elevated concentrations they become toxic [149]. In contrast, HMs like chromium (Cr), lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), nickel (Ni), fluorine (F), and cobalt (Co) have no biological benefit and are associated with severe disruptions in physiological processes when exposure is prolonged [150,151]. Chronic exposure to these elements has been linked to cancers, neurological and cardiovascular disorders, kidney damage, developmental delays, poisoning, skin abnormalities, and bone diseases [152–154].

Particularly, long-term exposure to even low concentrations of Pb, Cd, and Cr may result in brain and kidney damage, contributing to chronic kidney disease (CKD). Several studies have identified Cd, Pb, Cu, Ni, U, As, and Fe as nephrotoxic heavy metals, capable of causing tubular damage and glomerulopathies [155–157].

A study conducted in Tehran, Iran, revealed that exposure to Pb, Hg, and As significantly contributed to overall non-carcinogenic health risks in potential consumers of urban runoff. Moreover, carcinogenic risk values for As, Cd, and Pb were projected to increase by 2030, particularly in areas of high development and traffic activity. This high-

lights the influence of land use and climate change scenarios on heavy-metal-related health risks [158].

Similarly, GIS-based spatial analyses have demonstrated correlations between heavy metal concentrations in drinking water and cancer incidence. For example, an investigation found that beryllium (Be), nickel (Ni), antimony (Sb), and molybdenum (Mo) exhibited significant associations with cancer densities across residential areas [159]. Such findings underscore the critical role of geospatial methods in identifying and predicting vulnerable populations at risk from environmental exposure to toxic elements.

Potentially toxic elements (PTEs) are especially concerning due to their bioaccumulation potential and disproportionate impact on vulnerable groups, including children and the elderly. Recreational exposure in public parks can also increase health risks, with elevated PTE levels linked to developmental delays, behavioral abnormalities, and cancer when present in high concentrations [160]. More broadly, prolonged exposure to PTEs has been associated with immune system disruption, neurological and cardiovascular impairments, as well as kidney and bone malfunctions [161].

In a recent work, the results obtained for the dynamics of the concentrations of the metals Al, As, Cd, Cr, and Fe and the evaluation of the specific absorption coefficients for the explanation and correlation with the results of the measurements in the pre-deltaic Danube area were presented. This paper was able to expose the self-purification capacity of the Danube and highlight the existence of a concentration reduction gradient along the course of the river, even in a seasonal variation of heavy metal concentration [79].

Clinical observations further support these findings. Patients with renal failure have been linked to contaminated drinking water containing Pb and Cd. High Pb levels are particularly dangerous, with potential outcomes including irreversible damage to the central nervous system, kidneys, and brain. Clinical manifestations of Pb exposure include hyperactivity, cognitive impairment, hypertension, hearing loss, headaches, slowed growth, reproductive dysfunction, and musculoskeletal pain. Nickel contamination has been associated with dermatotoxicity in hypersensitive individuals, while chronic exposure to Cr (especially chromic acid) can cause dermatitis and skin ulceration. Arsenic exposure is also particularly hazardous, as it coagulates proteins, forms complexes with coenzymes, and inhibits adenosine triphosphate (ATP) production during cellular respiration [123].

Integration of GIS with health risk assessment models

A key advancement in this field lies in coupling GIS with quantitative health risk assessment (HRA) frameworks. By incorporating exposure pathways (ingestion, dermal contact, and inhalation), dose–response functions, and population vulnerability indices into GIS platforms, researchers can move beyond descriptive mapping toward actionable risk predictions. For instance, spatial health risk maps allow calculation of hazard quotient (HQ) and cancer risk (CR) values at neighborhood scales, pinpointing critical zones where risk exceeds the WHO or USEPA thresholds. This approach enables local authorities to prioritize interventions (e.g., groundwater treatment, restriction of polluted agricultural irrigation, or targeted health monitoring). Furthermore, scenario modeling within GIS—such as projecting changes under urban expansion or climate variability—strengthens the predictive dimension of public health planning.

In summary, we may admit that GIS-supported assessments have demonstrated that heavy metal contamination in water sources poses a wide array of acute and chronic health risks. The integration of geospatial tools enhances the capacity to map exposure pathways, quantify risks, and forecast the impacts of environmental changes, thereby strengthening the scientific foundation for public health interventions.

Table 6 summarizes the sources of heavy metals identified through the GIS.

Table 6. Sources of heavy metals identified through the GIS.

Cur. Nr.	Source Type	Specific Examples/Regions	Heavy Metals	GIS Applications/Findings
1	Industrial emissions	Factories, tanneries (India, Egypt, Mexico, Bangladesh)	Cr, Pb, Cd, Cu, As, Zn	Mapping contamination from effluents; identifying hotspots
2	Urbanization/traffic	Urban areas, children's parks (UK, global)	Pb, Cr, Ni	GIS-based risk maps showing relation with traffic, solid waste
3	Agriculture	Fertilizers, pesticides, animal manure	Cd, Cu, Zn, Pb	Spatial visualization of contamination from agricultural runoff
4	Mining	Coal mines, tailings, AMD (global)	As, Cd, Cu, Zn, Ag	The GIS identifies vulnerable groundwater zones and AMD-affected sites
5	Waste disposal	MSW landfills (India)	Various metals	GIS-based groundwater assessments show leachate impact
6	Accidental pollution	Water pollution accidents (China, USA, Japan)	Various metals, radionuclides	GIS + remote sensing reconstructs contamination pathways
7	Natural sources	Geological weathering, atmospheric deposition	Various metals	Baseline contribution mapped in GISs
8	Water management issues	Dams, drainage canals (Pakistan, Brazil)	Various metals	The GIS shows temporal and local-scale contamination patterns

Climate change is a persistent global phenomenon that can, under certain circumstances, lead to droughts, significantly impacting the availability and quality of drinking water. In addition, it may trigger secondary effects, including seawater intrusion, water quality degradation, and shortages of potable water. While surface water resources are directly influenced by long-term changes in key climatic variables, such as rainfall, evapotranspiration, and air temperature, the response of groundwater to climate variability is often more complex [162]. To date, only a limited number of studies have examined the influence of meteorological factors on heavy metal contamination using either simulation models or short-term water quality datasets [163–167]. For instance, Visser et al. [164] found that decreased precipitation and rising temperatures under projected climate change scenarios could reduce the leaching of HMs, such as cadmium (Cd) and zinc (Zn), during summer in the Keersop catchment (Netherlands) between 2071 and 2100.

Importantly, fluctuations in climate variables can also influence the accuracy and relevance of GIS-based environmental assessments [166,167]. Therefore, it is essential for researchers to account for temporal variations and climate-induced changes when interpreting GIS data in studies of heavy metal contamination (Figure 11).

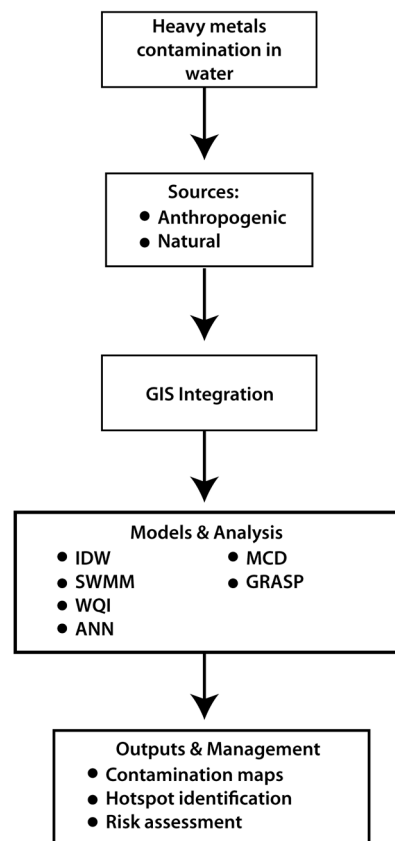


Figure 11. Summarized research content.

4. Conclusions

This review synthesized bibliometric and case study evidence on the application of geographic information systems (GISs) in monitoring and managing heavy metal contamination in aquatic systems. The following key conclusions can be drawn:

1. Research trends and distribution
 - Scientific output on GISs and heavy metal contamination has grown exponentially in the past decade, reflecting both the urgency of pollution issues and the accessibility of open-source GIS platforms.
 - Research is unevenly distributed, with South Asia, North Africa, and Eastern Europe dominating the literature, while regions such as sub-Saharan Africa and Latin America remain underrepresented.
2. GIS applications and strengths
 - The GIS is a versatile tool for integrating spatial, hydrological, and chemical datasets, enabling identification of pollution hotspots, dispersion pathways, and contamination sources.
 - Coupling the GIS with advanced methods (multivariate statistics, machine learning, and decision support models) extends its role from descriptive mapping to predictive risk assessment and environmental management.
3. Heavy metal occurrence and risks
 - Concentrations of Cd, Cr, Cu, Mn, Hg, and Ni frequently exceed the WHO limits worldwide, posing serious ecological and health threats.
 - GIS-based analyses help attribute exceedances to anthropogenic (e.g., urban runoff and industrial discharge) or geogenic sources, supporting the design of targeted remediation strategies.

4. Limitations and challenges

- Bibliometric analyses face biases related to database coverage, keyword selection, and bibliometric tool limitations.
- GIS-based studies are constrained by:
- Gaps in monitoring networks and data quality, especially in developing countries.
- Lack of standardized sampling and analytical protocols.
- Mismatches between GIS spatial resolution and contamination hotspots.
- These limitations reduce comparability across studies and restrict broader generalization.

5. Weaknesses in the international research landscape

- Research is fragmented, with limited integration of geospatial contamination data and clinical/epidemiological outcomes.
- Underrepresented regions lack adequate monitoring capacity, limiting global assessments of heavy metal risks.
- Addressing these weaknesses requires greater international collaboration, open-access data platforms, and harmonized methodologies.

6. Future research directions

To strengthen GIS applications in heavy metal pollution studies, future work should prioritize:

- Integration with health risk assessment: develop GIS-based models linking pollutant distribution, exposure pathways, and population vulnerability.
- Real-time monitoring: incorporate remote sensing, IoT water sensors, and AI-driven analytics into GIS platforms for early warning systems.
- Data standardization: establish international standards for sampling, laboratory methods, and GIS resolution to enable comparability.
- Decision support integration: embed the GIS in multi-criteria decision analysis (MCDA) frameworks for remediation, land use, and water resource management.

In conclusion, the GIS should be viewed not merely as a cartographic tool, but as a comprehensive framework for environmental monitoring, risk assessment, and policy support. By addressing current methodological and data limitations, and by fostering global collaboration, the GIS can play a pivotal role in protecting aquatic systems and safeguarding public health against heavy metal contamination.

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