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REVIEW

Leveraging geographic information systems (GIS) in water, sanitation, and hygiene (WASH) research: a systematic review of applications and challenges

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Abstract
Safe drinking water, sanitation, and hygiene (WASH) are essential for the health, well-being, and socio-economic development of communities. Despite global efforts, the challenge of providing safe access to WASH service persists, particularly in low- and middle-income countries. Geographic Information Systems (GIS) play a pivotal role in understanding and addressing these challenges by enabling the monitoring, mapping, and analysis of WASH facilities and their impacts. This systematic literature review aims to comprehensively understand how GIS is being used in WASH research. The review reveals that GIS is being used in various aspects of WASH, including mapping and monitoring of WASH facilities, spatial analysis of WASH-related health outcomes, and planning. The review also highlights the challenges of using GIS in WASH, such as data availability and quality, integration of technological advancement and adoption of a comprehensive approach. The review provides valuable insights for researchers, practitioners, and policymakers working in the field of WASH.

Keywords GIS · WASH · Water · Sanitation · Sustainable development goal

1 Introduction

Safe drinking water, sanitation, and hygiene are essential for the health, well-being, and also socio-economic development of a community [1–3]. These interrelated elements are collectively referred to as WASH (Water, Sanitation, and Hygiene). Each year approximately 1.4 million people die as a result of insufficient access to safe drinking water, sanitation, and hygiene [4]. Safe WASH also plays a crucial role in supporting livelihoods, promoting regular schools and dignity, and developing resilient communities. The lack of WASH disproportionately affects women and girls, limiting their work opportunities, community involvement, and education while also causing stress and anxiety [5]. Access to clean, safe drinking water is a fundamental human right. Sanitation, which involves having access to hygienic toilets and the safe disposal of waste, helps prevent water contamination, among other benefits. Contaminated water and untreated waste pose significant health risks, including waterborne diseases such as cholera and diarrhea. Good hygiene practices, such as handwashing with soap at critical times—after using the toilet, before eating or preparing food, and after potential faecal contact—are vital for preventing the transmission of germs. Diarrheal disease, a major cause of illness and death in young children in low-income countries, is significantly linked to poor water, hygiene, and sanitation [1, 6, 7]. Ensuring access to safe, affordable and sustainable access to WASH is critical in preventing waterborne diseases and is integral to international development. The importance of WASH is also emphasised in the first two targets of the UN's Sustainable Development Goal (SDG) 6, which aims to significantly improve water and sanitation globally. The targets are: SDG 6.1 by 2030, achieve universal and equitable access to safe and affordable drinking water for all. And SDG 6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying particular attention to the needs of women and girls and those in vulnerable situations.

Despite significant efforts, the global challenge of safe WASH persists, with 2.2 billion people lacking access to safe drinking water, 3.5 billion lacking access to safe

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sanitation, and 2.2 billion lacking basic handwashing facilities [8]. Further, substantial disparities remain, particularly in rural and low-income regions [9]. These disparities lead to a rise in waterborne diseases, undernutrition, and other negative health outcomes in those regions, especially for young children who are most susceptible. In low- and middle-income countries (LMICs), diarrhea leads to over half a million childhood deaths each year [10].

Geographic information systems (GIS), a powerful tool for modelling geographic phenomena, plays a crucial role in understanding and addressing the WASH challenges [11]. It provides researchers, policymakers, and practitioners with a powerful tool to analyze spatial data, identify service coverage disparities, and plan and execute resource distribution. Almost every event occurs at some location, and understanding where something happens is critically important [12]. GIS is employed to make computer representations of spatial phenomena and derive meaningful information from them. This computer-based system handles georeferenced data, including data capturing, preparation, data management, processing, manipulating, analysing, and presenting [13]. This system essentially constitutes a spatial database management system, data analysis tools and methods, cartographic tools and data sharing tools. The components of a GIS include hardware, software, data, people, methods, and networks. The hardware component can consist of computers, printers, and mobile devices. Software includes analysis and visualisation tools, with examples such as ArcGIS, Geoserver, QGIS, and uDig. The data component comprises geospatial and attribute data. Geospatial data have a location component, either in terms of coordinates or text such as a zip code or place name. Attribute data provide additional information about each spatial feature, such as names, categories, or other descriptive details. These data can be modelled using either a vector data model or a raster data model. In GIS, terms like geographic, geospatial, and spatial are often used interchangeably to describe georeferenced data or data that includes spatial components. **While subtle differences exist between these terms, they are frequently used synonymously in everyday practice.** We have also used them interchangeably in this study. The people component includes users, analysts, and decision-makers who interact with the GIS to interpret and utilise the data effectively. GIS methods encompass procedures and workflows for data collection, analysis, and interpretation. As an information system, GIS also includes a network component for data and information sharing. Together, these components form a comprehensive system for understanding and managing geographic information.

GIS leverages advanced algorithms, spatial analysis, modelling, and geo-visualisation to create a powerful tool for monitoring and mapping the spatial and temporal distributions of WASH facilities and their outcome on socio-economic development. Given the evolving landscape of GIS analysis in WASH, a review of current research is essential to understand how these tools are being utilised and stay informed on best practices.

We conducted a systematic literature review to comprehensively understand how Geospatial technologies are being used in WASH. The review reveals areas where further investigation is needed within the field and provides a foundation for researchers who are conducting new studies on the topic. Further, it highlights best practices that practitioners and researchers can implement. The systematic literature review methodology involves a rigorous search of electronic databases to identify all relevant studies. These studies are then analysed and summarised to address the research questions defined for this review. Ultimately, this systematic literature review provides valuable insights into the current state of geospatial technology applications in WASH.

The structure of this paper is organised as follows. Section 2 details the research methodology used for the systematic review. Section 3 presents the results and discussion, followed by the conclusions in Sect. 4.

2 Methodology

The review follows the established guidelines for systematic literature reviews outlined by Kitchenham, Brereton [14]. This rigorous approach ensures a comprehensive and unbiased analysis of the research. The process began by defining the research questions. With these questions in hand, we searched the Scopus database to identify relevant studies. Scopus provides high-quality, peer-reviewed research across various disciplines. These studies were then filtered and assessed using a set of exclusion and quality criteria. Data from the selected studies were extracted and synthesised to address the research questions.

"This review included studies from a global perspective to capture diverse applications of GIS in WASH across different socio-economic and environmental contexts. However, particular attention was given to studies from low- and middle-income countries (LMICs), where GIS can be instrumental in addressing WASH challenges."

3 Research questions

The following four research questions were defined to guide the study:

- How has GIS been used in different contexts in WASH studies, and what are the study focuses?
- **Which GIS software, tools and data sources have been used for WASH studies?**

- **What is the geographical distribution of the study sites?**
- What are the challenges and **recommendations for future research and practice**?

3.1 Article search and selection

To identify relevant research on geospatial applications in water sanitation and hygiene (WASH), we conducted a systematic search in the Scopus database on April 10, 2024. Scopus is recognised for its inclusion of articles subjected to rigorous peer review and published in indexed journals, ensuring the quality of the included studies. We used Boolean operators to combine relevant keywords and capture a broad range of WASH-related geospatial applications. A search encompassing titles, abstracts, and keywords was conducted within the Scopus database using the query:

("GIS" OR "geospatial" OR "Geographic Information") AND ("Water-Sanitation-Hygiene" OR "Water, sanitation and hygiene" OR "water and hygiene" OR "sanitation and hygiene" OR "water and sanitation" OR "hygiene and water" OR "hygiene and sanitation" OR "sanitation and water").

This initial search resulted in 135 articles. We then implemented following exclusion criteria to refine the results:

- Excluded articles published before 2015
- Excluded review papers, book chapters, and any format besides research articles
- Limited to English-language articles

After applying the exclusion criteria, the number of relevant articles was narrowed down to 67. Titles and abstracts of the 67 articles were reviewed to assess their alignment with the study's focus on geospatial applications in WASH. We further removed 23 articles that were not specifically focused on geospatial applications for WASH, resulting in 44 articles that were considered for full review.

The selected articles underwent a comprehensive full-text review to extract detailed data relevant to the study objectives. Data extraction included key elements such as study location, research focus, geospatial methods and tools utilized, data sources, scale of analysis, software tools employed, and challenges encountered. This structured approach ensured that all critical aspects of the studies were systematically captured and analysed (Fig. 1).

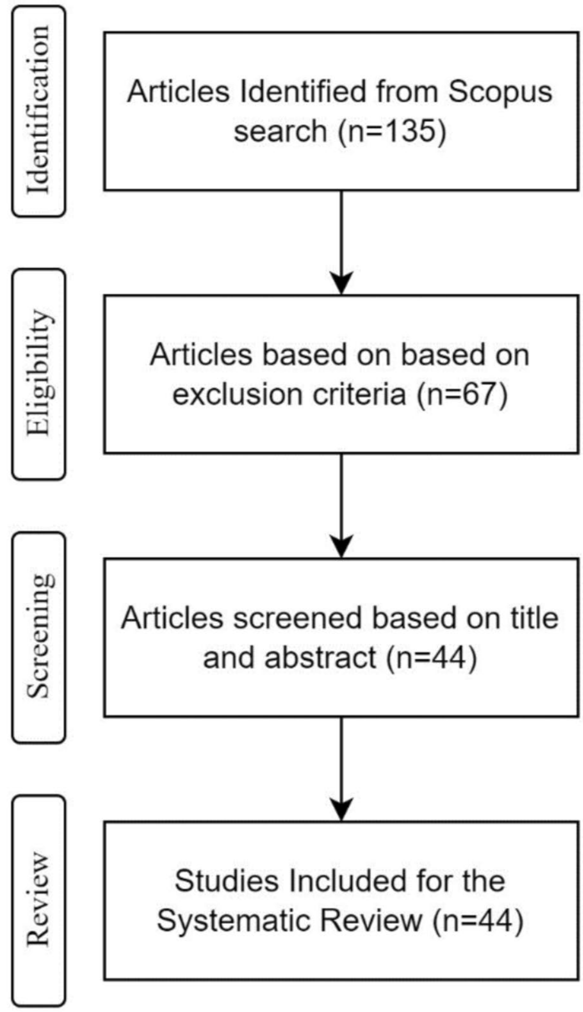


Fig. 1 Selection of publications for the review

4 Result

This section presents the findings from our analysis of the selected articles. To understand trends in publication and gain valuable insights into the evolving research landscape, we examined the distribution of publications by year and analysed the keywords, titles and abstracts from reviewed articles. Figure 2 presents the distribution of the 44 selected articles published over the past decade. The number of articles has increased steadily, reaching a peak in 2022 with ten publications. There is a slight decline in 2023, followed by a moderate increase in 2024 (up to April). There is only one article for the year 2015, and interestingly, the Sustainable Development Goals (SDGs) were adopted by the United Nations in September 2015, with Goal 6 emphasising the importance of ensuring clean water and sanitation for all.

Figure 3 illustrates the most frequently used terms in the titles, keywords, and abstracts of the reviewed studies. The font size indicates the frequency of each term. The tag cloud highlight the most common terms found in titles, keywords, and abstracts, providing a quick and intuitive overview of the key topics and themes in the literature. As we use the terms "Water," "Sanitation," "Hygiene," and "GIS" in our search query, these central themes of the review show high

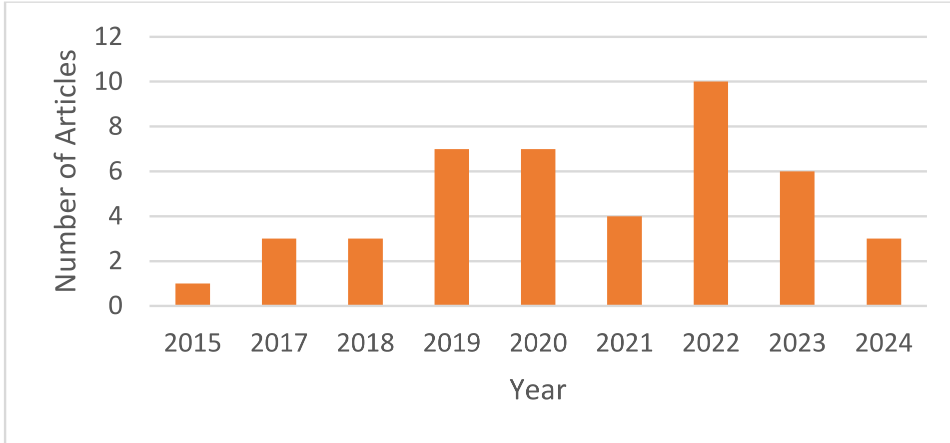


Fig. 2 Distribution of the selected publication each year

Fig. 3 Word cloud visualization of keywords and abstract from reviewed article

frequency. Apart from those terms, the higher frequency of "Environmental," "Groundwater," and "Urban" reflects the varied contexts in which WASH issues arise. The frequent occurrence of "Health" underscores the essential connection between WASH and health outcomes. The inclusion of terms like "Analysis," "Index," "MCA," "Lorenz," "Multimodal," "Openstreetmap," "ArcGIS", and "Neighborhood" suggests the varied techniques used in the reviewed research.

We conducted a full-text analysis of the 44 identified articles. This analysis explored their key aspects to answer our research questions. Based on the findings following research question are addressed.

RQ1: Study Focus and Thematic Area.

While water, sanitation, and hygiene (WASH) are inherently interconnected, our analysis revealed that many of the reviewed studies focused primarily on one or two of these themes. So, we have categorised the studies based on their major highlights (Fig. 4). The highest number of studies (13) concentrated solely on water. These studies explored various aspects, including identifying suitable locations for groundwater exploration, assessing water quality, pinpointing pollution sources, and analysing the impact of historical practices on water access. The largest number, 16 studies, cover all aspects of WASH (water, sanitation, and hygiene). This

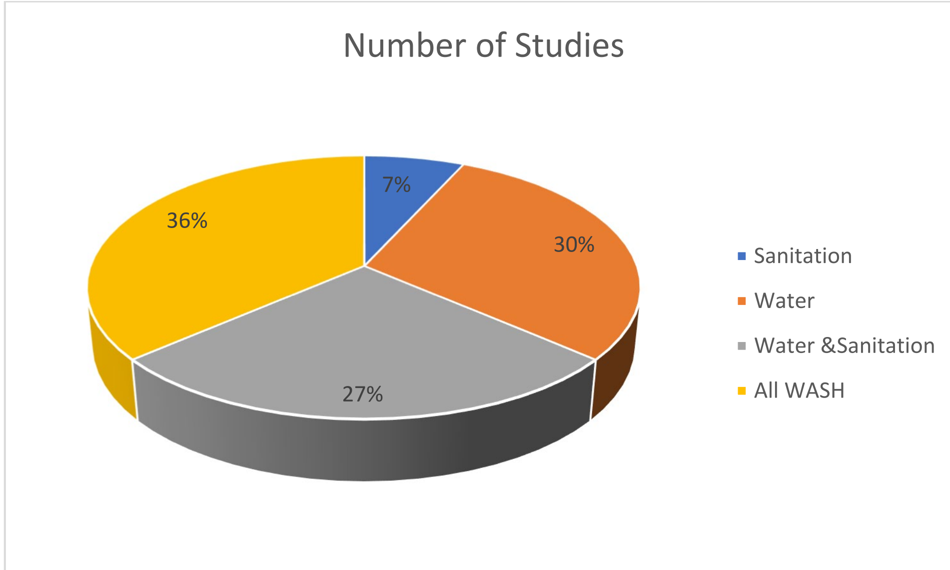


Fig. 4 Study focus

focus on a comprehensive approach underscores the interconnectedness of these strategies for effectively addressing WASH-related public health issues. Furthermore, 12 studies address both water and sanitation together. This suggests an understanding that water and sanitation are often interlinked and that improvements in one area can influence the other. Only three studies focus exclusively on sanitation and none solely on hygiene. Hygiene and sanitation-related aspects were more frequently examined in conjunction with water-related problems or within broader WASH initiatives. This gap in research focused specifically to sanitation and hygiene suggests a potential area for increased attention in the future.

Regarding the study theme, GIS technology has demonstrated its efficacy in enhancing WASH services through various applications. One key area of impact is highlighting disparities in WASH access and quality. By identifying regions most in need, GIS empowers targeted interventions. For instance, [15] identified significant disparities in the accessibility of WASH services among various informal settlements. Similarly, mapping efforts have revealed critical residential and environmental deprivations in slum communities in Lagos, Nigeria, underscoring the necessity for targeted planning and management interventions [16]. In rural India, integrating multiple WASH parameters into a composite WASH Quality Index (WaSHQI) within a geospatial framework has aided in assessing and addressing spatial inequalities in WASH facilities [17].

Another theme explored the link between WASH practices and disease burden. Studies have shown that good sanitation and hygiene practices are crucial for controlling waterborne diseases like cholera, typhoid, and enteric fever. For example, a GIS-based analysis of cholera outbreaks in Harare, Zimbabwe, demonstrated that prompt and intense community action significantly reduced outbreak duration and case numbers [18]. Similarly, a large-scale geospatial analysis revealed drivers of subnational mortality reductions and highlighted potential intervention strategies for vulnerable populations [19]. Additionally, in southern Ghana, integrating remote sensing (RS) environmental data with WASH variables improved the spatial prediction of schistosomiasis risk aiding in targeted control strategies [19].

Further, GIS applications have extended to explore the sustainable management of water and sanitation infrastructure. Many studies have focused on the availability and suitability of water and sanitation sources [20, 21]. Martínez-Santos, Martín-Loeches [22] have shown that uncontrolled on-site sanitation poses risks to domestic water supplies in low-income countries, necessitating improved water treatment practices. Their findings underscore the need for improved sanitation practices, including better placement and construction of latrines to minimise groundwater contamination. Further research by Hui and Wescoat [23] identified water and sanitation deficiencies in peri-urban areas, suggesting the use of annual datasets and GIS mapping for improved governance. In addition, hydrogeochemical analysis has highlighted fluoride contamination in groundwater, emphasising the need for better groundwater management to meet SDG 6 [22]. Additionally, in Ghana, the integration of GIS techniques with hydrochemistry has proven effective in evaluating groundwater quality, analysing its spatial variations, and identifying the factors influencing overall water quality [24].

RQ2: Data, GIS Tools and GIS Analysis.

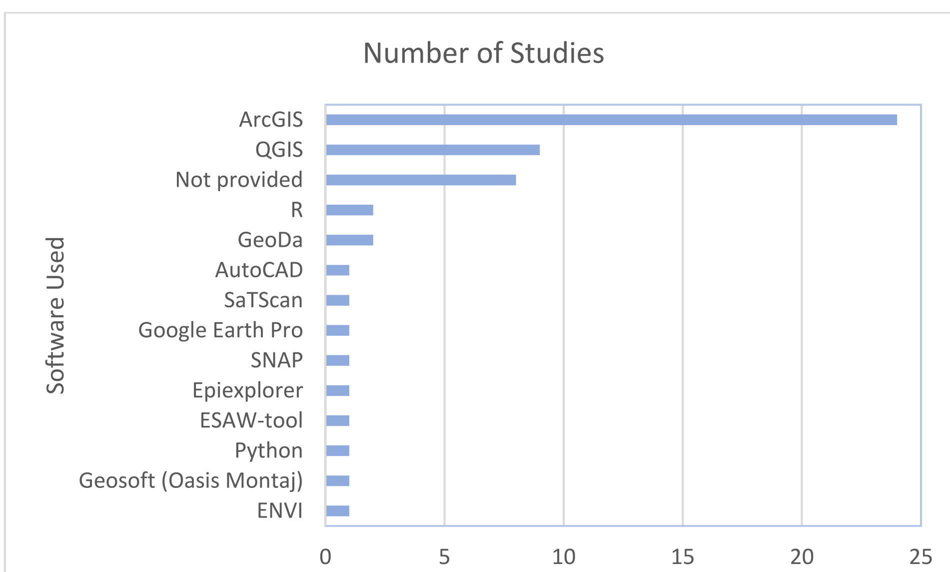
This section effectively summarises the data, GIS tools, and analysis methods used in the reviewed WASH studies, which concerns the second research question. The reviewed studies utilised various data types, including primary data collected directly, secondary data from existing sources, and a combination of both. Approximately 40% of the reviewed studies used existing (secondary) data such as government reports, census data, historical records, and previously published studies. Data from international organisations such as the United Nations and the World Bank were also used. These sources provide comprehensive and standardised data across various topics, facilitating robust and large-scale studies. For regional or global scale studies, data from Demographic and Health Surveys (DHS) were frequently used [25–27]. Large-scale surveys like DHS and national censuses, which provide data on sanitation, hygiene, and water access, could be important and easily accessible sources for future studies as they are available across different countries. Existing geospatial data like satellite imagery, elevation data, and OpenStreetMap (OSM) were also categorised as secondary data. Many of these data are globally available at regular intervals enabling broad and detailed spatial analyses. They could also serve as data sources in future studies.

About 35% of the studies collected their own (primary) data through field surveys, while the remaining studies used a combined approach. Direct data collection methods include obtaining detailed and context-specific information through face-to-face interviews, blood cultures, groundwater sampling, structured survey questionnaires, GPS-based spatial data collection, and multi-level cluster-random surveys.

Researchers leverage a wide range of GIS software to address WASH issues. Among these tools, ArcGIS stands out as the most frequently used software in the studies reviewed. Developed by ESRI, ArcGIS is a proprietary GIS software known for its stable functioning and comprehensive range of functionalities. It was utilised in 24 of the studies, with various versions, including ArcGIS Desktop and ArcGIS Pro being mentioned. QGIS is the second most frequently cited GIS software, appearing in 9 studies. As a free and open-source alternative to ArcGIS, QGIS provides significant flexibility and accessibility. Some studies employed a combination of GIS software to complement their GIS analyses. For instance, visualisation and statistical modelling platforms like R were used for geostatistical analysis [26, 27]. Some studies utilised both QGIS for data access and ArcGIS for analysis, while others combined ArcGIS with geostatistical tools such as GeoDa, which is specialised in spatial statistics. Several reviewed studies developed their own software for specific needs. Examples include the Ecological Sustainability Assessment of Water Distribution (ESAW-tool) and Epiexplorer. These tools highlight the innovative approaches taken to address particular WASH challenges. Programming languages like R and Python and deep learning libraries such as TensorFlow were also mentioned, indicating a trend towards integrating programming and automation in GIS workflows. Other specialised GIS software mentioned includes remote sensing (RS) software such as ENVI, IDRISI, and SNAP (Sentinel Application Platform). Geosoft (Oasis Montaj), known for its specialisation in geophysical and geospatial data, was also noted.

A diverse set of GIS analysis methods was used in the reviewed studies (Fig. 5). The most frequent use of GIS was for the visualisation of spatial data, often referred to in the literature as mapping, thematic mapping, or geovisualization. These techniques were used to display the spatial distribution of WASH facilities, water quality, and other relevant factors, helping to identify patterns and trends and effectively communicating information to stakeholders. The study demonstrated that Simple visualisations created with GIS could prove to be a powerful tool for understanding WASH phenomena. In addition to visualisation, various spatial analyses, including geostatistical modelling, were also conducted in the studies. These analyses

Fig. 5 GIS software utilized in reviewed studies



included Euclidean distance, zonal statistics, multicriteria analysis, buffer analysis, interpolation (kriging), spatial autocorrelation, cluster analysis, watershed analysis, WASH index estimation, and water quality index estimation. Advanced statistical analyses included Poisson point process modelling, Cox regression models, univariate and multivariate regression, and principal component analysis (PCA). Some studies also integrated machine learning techniques, including bi-logistic regression and support vector machines (SVM). Additionally, remote sensing analysis was performed, including Land Use Land Cover (LULC) classification and index computation such as the Modified Normalized Difference Water Index (MNDWI) and object detection.

RQ3: Geographic Distribution of Studies.

The reviewed articles reveal a geographical concentration of research in South Asia and Sub-Saharan Africa, with India receiving the most attention (9 studies) (Fig. 6). India, in fact, has the highest density of open defecation, which is twice the global average [28]. Other notable countries with multiple studies include Ghana (3 studies) and South Africa (3 studies). Despite the pressing issues of WASH services in many other South Asian and African regions like Nepal, Bangladesh, Niger, and South Sudan, the reviewed studies do not include these countries. This exclusion suggests a critical research gap. Targeted research in these neglected regions is crucial for understanding their specific WASH issues and informing effective interventions. Such efforts would contribute to improved public health outcomes and progress towards sustainable development goals in these vulnerable areas.

Interestingly, one of the studies is also from the USA. While water and sanitation access challenges are typically associated with developing countries, a surprising reality is that over 400,000 U.S. homes lack basic indoor plumbing [29]. The study suggests that communities with high minority populations are significantly more likely to have inadequate plumbing access, emphasising the need to address historical injustices for modern-day equity.

Apart from the data mentioned in the map, some studies focused on regional and global scales. Specifically, two studies concentrated on Africa, one on a part of Europe, one on a part of South Asia, and two adopted a global perspective.

RQ4: Challenges and Recommendations.

This section provides challenges in GIS-based WASH and recommends points to address such issues. One of the major challenges in conducting any geospatial research is the availability of data suitable for analysing the problem at hand. The accuracy and reliability of any GIS analysis heavily depend on the quality of the underlying data [13]. Data preparation in GIS is the most resource-intensive component. The review shows that many WASH studies have used demographic and health survey data, census data, and governmental reports to conduct their analyses. Such data can be important sources for future research as well. However, these sources may not always provide comprehensive or up-to-date location-specific information needed for accurate GIS analysis. This lack of precise, timely and detailed spatial data can compromise the validity of the results and hinder effective decision-making on WASH issues. To overcome the challenges related to data availability researchers should supplement existing datasets with other sources where possible.

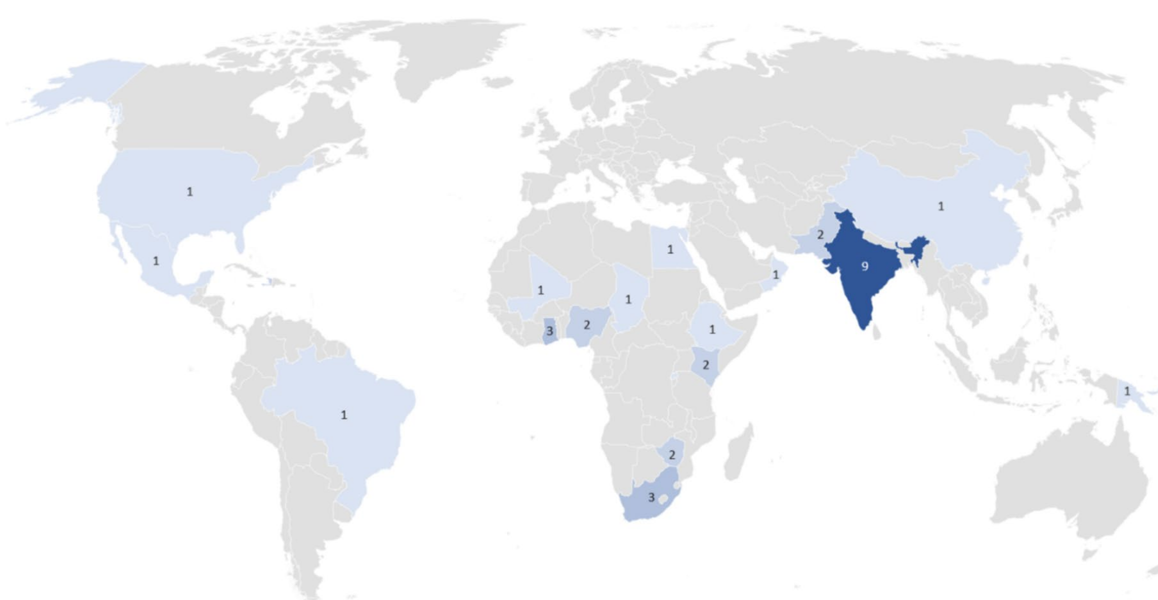


Fig. 6 Study area in the reviewed studies

Researchers could explore the technique of crowdsourcing to collect data [30]. Crowdsourcing can leverage the power of community involvement to gather real-time, localised data, which can significantly enhance the quality and scope of geospatial research. Further focus should also be on data sharing. Many organisations collect these data in isolation and do not share them. Governments and organizations should prioritize developing standardized data and sharing frameworks to ensure seamless data utilization across multiple organizations. Developing and strengthening national spatial data infrastructure and incorporating WASH data in it should also be the priority. Similarly, existing data like remote sensing data and open street maps should also be explored to tackle this challenge.

Secondly, the review highlights the underutilised potential of advanced technologies. Technological advancements are transforming information systems in general, and their impact is increasingly visible in geographical information systems (GIS) as well. Transformative technologies like Big Data, cloud computing, the Internet of Things (IoT), and Artificial Intelligence (AI), including recent advances like Large Language Models (LLM), have the potential to revolutionise every sector and research. However, the systematic review of GIS in environmental monitoring suggests that these advanced technologies are not evident in the reviewed research, indicating an untapped potential. For example, while one study [31] demonstrated the use of deep learning and OpenStreetMap data for wastewater treatment plant detection using multimodal remote sensing, broader adoption and exploration of these technologies within the WASH sector is needed. The integration of Machine Learning (ML) can significantly improve the understanding of complex environmental issues by enabling more sophisticated data analysis and predictive modelling. The low-cost IoT sensors could be used to continuously monitor water quality and sanitation infrastructure in developing countries as well. By integrating real-time IoT sensors with machine learning algorithms, we can achieve real-time predictive analytics and automated decision-making for WASH (Water, Sanitation, and Hygiene) management. Further LLMs has the potential to enhance GIS accessibility by lowering technical barriers and enabling innovative applications in WASH management. Additionally, web-based GIS, which provides an efficient way to access GIS services and disseminate geospatial information, is not utilised in any of the studies reviewed. Web-based GIS offers an effective tool for disseminating information to both experts and the general public. With the development of mobile devices and the widespread penetration of the internet in both developed and developing countries, mobile GIS can enhance data collection and help organisations communicate critical information, thereby raising public awareness and sensitivity. Therefore, future research should focus on incorporating these advanced technologies to fully harness their potential, improve the accuracy and efficiency of GIS analyses, and enhance the dissemination and accessibility of geospatial information.

Another issue to consider is enhancing the scope of the research. The review identified critical gaps in WASH research. Current studies do not adequately represent some underdeveloped regions with significant WASH issues. This highlights the need to target these underrepresented regions. Additionally, hygiene practices, a critical component of ensuring safe WASH, are not sufficiently explored; no research is identified using our search criteria, focusing exclusively on hygiene. This underscores the importance of a balanced research focus, encouraging studies that concentrate specifically on hygiene. Maintaining good hygiene is crucial for stopping the spread of diseases and creating a healthier environment for everyone. Furthermore, there is a need for more longitudinal studies to monitor changes in WASH conditions over time. Such studies can provide valuable insights into the long-term impacts of interventions and help in planning future strategies. Finally, effective use of GIS in WASH requires collaboration across disciplines, including hydrology, environmental science, public health, and social sciences. Integrating GIS with public health, sociology, and environmental science can address WASH challenges from multiple perspectives. Fostering interdisciplinary research and cooperation is essential for developing integrated solutions. By addressing these gaps and focusing on these recommendations, future research can develop more effective, comprehensive, and sustainable solutions to global WASH challenges, ultimately improving health and environmental outcomes for underserved populations.

5 Conclusion

This systematic review has evaluated the current studies on the application of GIS in the context of tackling WASH challenges. The review demonstrates that GIS technology plays a vital role in improving WASH services by highlighting disparities, aiding in disease control, and supporting sustainable management of water and sanitation infrastructure. GIS is crucial for addressing spatial inequalities and achieving Sustainable Development Goals (SDGs) related to WASH by empowering targeted interventions and informed decision-making. The review identified various data sources employed in WASH research, including existing data (government reports, surveys) and primary data collected through field studies. ArcGIS emerged as the most frequently used GIS software, followed by the free and open-source QGIS. Spatial visualisation techniques and various spatial analyses, like distance calculations and cluster analysis, were commonly utilised. The review also identified key challenges and gaps in

GIS-based WASH research, particularly related to data availability, the incorporation of technological advancements, and the limited research focus. To address these issues requires using additional data sources and promoting standardized data collection and sharing frameworks. There is a need to integrate cutting-edge technologies like AI (machine learning, deep learning, LLMs), IoT, and web-based GIS to improve analytical capabilities and informed decision making. Future research should expand its scope to include currently neglected areas. Targeted research focusing on these areas is essential to address their specific WASH challenges and achieve the Sustainable Development Goals. Finally, longitudinal studies and interdisciplinary collaboration are essential for creating comprehensive and sustainable solutions. Despite its strengths, this systematic review has a few limitations that should be acknowledged and addressed in future research. First, the review focused on peer-reviewed publications. Important reports published by international organisations like the United Nations or other Governmental and non-government bodies, which might be relevant but did not undergo peer review, were excluded from this review, potentially missing additional insights. Additionally, some studies may use different terminology to represent WASH issues, leading to their exclusion from this review. By integrating cutting-edge technologies, fostering collaboration across disciplines, and addressing the research gaps, future research can leverage the full potential of GIS to create a more equitable and sustainable future for WASH services around the world.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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