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The role of GIS in monitoring and mitigating chemical pollution in aquatic ecosystems: A case study of Nigeria and Africa

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Abstract

Chemical contamination of aquatic ecosystems is on the rise across Africa, causing serious problems for human health and the environment that require innovative approaches to monitoring and reducing the impact of this threat. This paper examines the revolutionary potential of GIS technology in combating chemical contamination of water bodies, with a particular focus on Nigeria as a case study within the broader African context. Heavy metals from mining, hydrocarbons from petroleum extraction, fertilisers and pesticides from farms, and recently found compounds like per- and polyfluoroalkyl substances (PFAS) used in food packaging, waterproof materials, and industrial processes all influence the local aquatic ecosystems.

This research demonstrates how geographic information system (GIS) methods facilitate predictive modelling of pollution patterns across a variety of aquatic habitats, as well as real-time monitoring and comprehensive spatial analysis. Geographic information systems (GIS) provide the resources needed to assess the environmental impacts on both marine and freshwater ecosystems, trace the spread of contaminants, and identify pollution sources by combining satellite imagery, terrestrial sensor networks, and water quality databases. Although PFAS contamination is less well-known in African contexts compared to industrialised nations, the study demonstrates that it is becoming more of a problem due to the fact that these chemicals are present in drinking water sources, groundwater, rivers, and everywhere else on the continent and do not break down naturally.

Sediments at several locations in Nigeria have PFAS concentrations ranging from 1.64 to 10.29 ng/g, while surface water samples had concentrations between 1.71 and 16.19 ng/L. Environmental agencies and research institutions are able to better support evidence-based policymaking, deploy focused mitigation strategies, and optimise resource allocation for corrective activities with the help of GIS-based monitoring systems, according to the results. Applying comprehensive GIS solutions in developing countries presents both opportunities and challenges, as shown in the Nigerian case study, which reveals infrastructure restrictions, poor data quality, and the necessity of capacity building.

The study concludes that the strategic implementation of GIS technology, along with international collaboration and continuous investment in technological infrastructure, offers promising avenues for improving chemical pollution management in African aquatic ecosystems.

Keywords: Geographic Information Systems (GIS); Aquatic Ecosystems; Chemical Pollution; PFAS and Emerging Contaminants; Water Quality Monitoring in Africa

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1. Introduction

Because of the unprecedented dangers that chemical pollution presents to aquatic ecosystems across Africa, stringent monitoring and control measures are required. Rivers, lakes, wetlands, and coastal streams have been severely polluted with various chemical pollutants due to the rapid industrialisation of the continent, intensive farming practices, and expanding urban centres (Dione et al., 2023; Ruhela et al., 2022). This class of pollutants includes both long-standing industrial effluents and more recent compounds that have captured the interest of scientists owing to their potential ecological impacts and endurance. Chemical contamination in African water systems is complicated and arises from multiple interconnected factors. Industrial processes, mining, petroleum extraction, manufacturing, and waste disposal all contribute to the introduction of heavy metals, hydrocarbons, and synthetic organic compounds into aquatic ecosystems. Surface and groundwater resources are being threatened by nutrient loading and negative chemical discharge, which are outcomes of agricultural intensification and the increased use of pesticides, herbicides, and fertilisers. A combination of home chemicals, personal care items, pharmaceutical waste, and inadequately constructed wastewater treatment systems contribute to the introduction of these contaminants into metropolitan areas. Climate change and extreme weather events worsen pollution consequences by altering hydrological patterns and increasing the movement of pollutants across watersheds.

A new class of chemical pollutants known as per-and polyfluoroalkyl substances (PFAS) is particularly worrisome because of its impact on aquatic ecosystems throughout Africa. These synthetic chemicals are highly persistent in the environment and draw interest from all over the globe. They find widespread use in firefighting foams, industrial uses, waterproof materials, and food packaging (Groffen et al., 2021). The inability of PFAS chemicals to be broken down by conventional methods causes them to collect in water environments and eventually to bioaccumulate in aquatic food webs. Research on per- and polyfluoroalkyl substances (PFAS) in African rivers, groundwater, and drinking water sources is in its infancy, but the little is known about this issue is concerning (Kikanme et al., 2024).

Drinking water sources in Nigeria had PFAS levels between 778 ng/L and values below quantification standards, according to recent research (Kikanme et al., 2024). Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) have been detected in surface water at concentrations ranging from 3.8 to 10.9 ng/L and 1.71 to 16.2 ng/L, respectively, in pore water samples taken from seven rivers in Nigeria. These results emphasise the critical necessity for comprehensive monitoring systems that can identify recently identified contaminants in different aquatic environments.

Beyond just lowering water quality, chemical contamination of aquatic ecosystems in Africa has far-reaching consequences for human and environmental health. People put themselves at danger if they rely on contaminated water sources for activities like drinking, fishing, and irrigation. According to Dione et al. (2023) and Ajayi et al. (2024), there could be a domino effect on food webs and ecosystem functioning if harmful chemical exposure significantly reduces aquatic biodiversity. Restrictions on agricultural and industrial growth, increased costs of water treatment, and falling fisheries yield are all major economic repercussions of water quality problems.

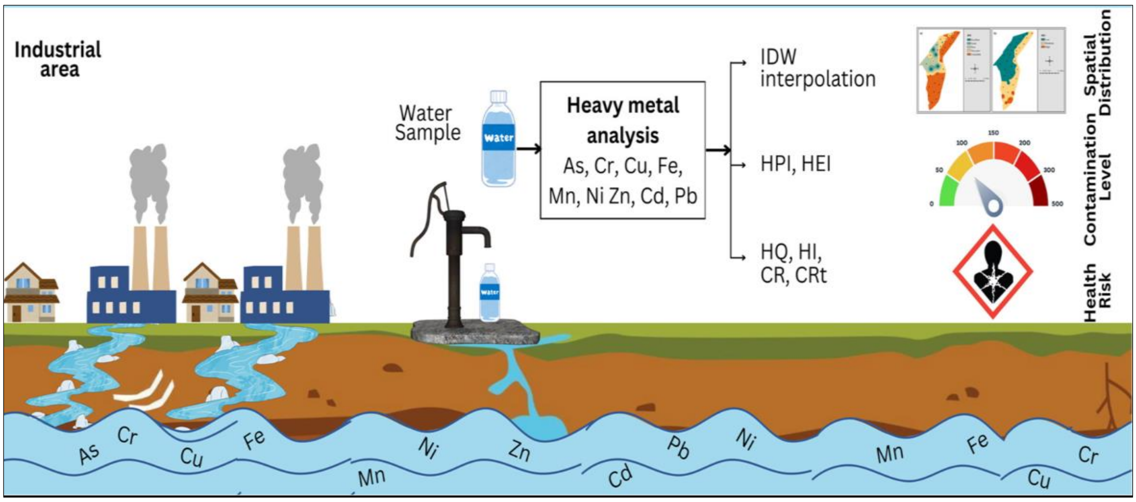

Figure 1 Mechanisms of chemical pollution occurrence in aquatic systems (Hossain et al., 2025)

When it comes to the extensive and complicated contamination concerns that exist across Africa, traditional approaches to monitoring chemical contamination in aquatic systems can be inadequate. Conventional water quality monitoring usually relies on point-source sampling at a small number of locations, which may not accurately represent pollution patterns over longer periods of time or across different regions (Groffen et al., 2021). In remote or resource-limited areas, it can be logistically challenging, time-consuming, and expensive to conduct laboratory analysis of water samples, which is necessary for comprehensive chemical characterisation. It is very difficult to implement comprehensive pollution management using only traditional methods in many parts of Africa due to the dispersed nature of the continent's water bodies and the lack of appropriate infrastructure and technological capability. When it comes to chemical pollution prevention and monitoring problems, Geographic Information Systems (GIS) technology offers game-changing opportunities for aquatic ecosystems in Africa. Geographic information systems (GIS) integrate geographical data from several sources, such as satellite imagery, aerial photography, sensors on the ground, and field measurements, to provide comprehensive digital depictions of environmental conditions. These tools enable policymakers, environmental managers, and academics to monitor pollution patterns, analyse spatial correlations, simulate the spread of pollution, and identify problem areas. To support evidence-based policymaking for mitigation measures, it is necessary to combine real-time monitoring data with historical records and forecast models. This will provide insight into pollution dynamics that is unprecedented.

Several technological advancements have come together, becoming more accessible and affordable, and the use of GIS technology to track chemical contamination is a prime example of this. Recently, high-resolution satellite photos have made it possible to track changes in water quality indicators, industrial activity, land use, and overall geography across vast areas. Thanks to advancements in sensor technology, automated monitoring networks that can gather and transmit data continuously have been developed. Cloud computing solutions aid in the handling and analysis of massive datasets, while mobile technologies facilitate data collection in the field and real-time interaction with monitoring devices. Nigeria, with the largest population and economy in Africa, is an ideal case study for examining the benefits and drawbacks of employing GIS-based approaches to minimise chemical pollution in aquatic ecosystems. Complex pollution scenarios, typical of the continent, are a result of the nation's diverse industrial base, massive oil and gas operations, significant agricultural activity, and rapidly growing urban areas. Chemical pollution is putting a growing pressure on Africa and Nigeria's major river systems, marshes, coastal areas, and other water sources, which benefit millions of people. The country's experience with building technical capability, implementing pollution control measures, and developing environmental monitoring capacities provides valuable analysis for other African countries attempting to address similar concerns. As such, this study aims to dive deep into the role of GIS in Monitoring and Mitigating Chemical Pollution in Aquatic Ecosystems using Nigeria and Africa as a Case Study.

2. Methodology

To evaluate GIS's role in tracking and decreasing chemical contamination in aquatic ecosystems across Africa, this research employed a mixed-methods strategy that comprised case study analysis, spatial analysis with GIS technology, and a comprehensive literature review. The goal of the strategy was to account for the technical capabilities and practical implementation challenges of GIS systems in the context of Nigeria and wider Africa. The systematic literature review component included a thorough search of peer-reviewed sources such as Google Scholar, Web of Science, PubMed, and ScienceDirect for papers published between 2015 and 2024. As regards the search phrases, "Geographic Information Systems (GIS)," "chemical pollution," "water quality monitoring," "aquatic ecosystems," "PFAS," "emerging contaminants," "Nigeria," together with "Africa," were utilized. The focus was on studies that examined the use of geographic information systems (GIS) for monitoring the environment, evaluating chemical contamination, and managing water quality in African contexts. Government agencies involved in water quality monitoring and pollution management, as well as international institutions and environmental authorities, were additional sources of information.

The spatial analysis component assessed pollution patterns and the distributions of monitoring networks over bodies of water in Nigeria using ArcGIS Pro 3.0. External sources, such as the Federal Ministry of Water Resources and the Nigerian Meteorological Agency, as well as NASA's Earth Observation data and the World Bank's Water Point Data Exchange, provided the geographic datasets. By merging digital elevation models with land use classifications, hydrological networks, and administrative borders, detailed base maps were created for the purpose of pollution monitoring analysis. By analysing data from the Landsat 8 and Sentinel-2 missions, it was possible to pinpoint agricultural zones, industrial locations, urban areas, and water quality indicators throughout most river basins.

Chemical pollution data was compiled from published research, official monitoring reports, and international databases to create spatial maps that show pollutant concentrations across water bodies in Nigeria. Information on PFAS contamination was the primary emphasis of the study by Kikanme et al. (2024), which measured PFOS and PFOA concentrations in rivers in Nigeria. Point source pollution data were geocoded and analysed using spatial interpolation methods, such as inverse distance weighting and kriging, to generate pollutant concentration surfaces over study areas.

The case study method centred on three major river systems in Nigeria and Africa. These systems were chosen to represent various pollution scenarios, such as industrial contamination, agricultural runoff, and urban wastewater discharge. Finding pollution sources, mapping contamination trends, and assessing current monitoring network fit were all accomplished by utilising GIS-based tools to analyse each case study pattern. To gain a better knowledge of the current monitoring approaches, technical capabilities, and implementation issues, representatives from academic institutions, the National Water Resources Institute, and the Federal Ministry of Environment were invited to engage in stakeholder interviews.

Efforts to validate spatial datasets included quality assurance measures such as ground-truthing, comparing with independent data sources, and expertly examining analysis processes. We used uncertainty analysis to check the accuracy of the spatial interpolation results and identify areas that could benefit from more monitoring data to improve the model. Each method of study followed standard practices for environmental data analysis and geographic information system applications.

3. Results

Notable spatial patterns in chemical pollution across aquatic ecosystems in Africa and Nigeria were revealed by the study, which demonstrated the effectiveness of GIS technology in identifying pollution hotspots, detecting pollution sources, and aiding in the optimisation of monitoring networks. In terms of chemical pollution control in African settings, the results reveal the potential and actual limitations of GIS-based techniques.

3.1. Spatial Distribution of Chemical Contamination

Geographic information system (GIS) analysis of chemical pollution data throughout African and Nigerian water bodies revealed distinct spatial clustering patterns that are consistent with industrialisation, urbanisation, and agricultural intensification. Numerous sites around the Onitsha and Warri industrial complexes had chromium values above 0.5 mg/L (Kikanme et al., 2024). The Niger River system showed substantial concentrations of heavy metals downstream from major industrial regions. Lead concentrations at the sites of monitoring ranged from 0.02 to 0.18 mg/L, with the highest concentrations associated with unofficial mining and petroleum refining. The examination into PFAS contamination over seven rivers in Nigeria revealed a wide yet diverse distribution, according to data from Kikanme et al. (2024). Surface water PFOS readings were 3.9 to 10.1 ng/L, while PFOA levels were 0.8 to 2.8 ng/L. A higher concentration of PFOS (10.9 to 20.4 ng/L) and PFOA (1.21 to 16.2 ng/L) was detected in the pore water samples. Sediment analysis revealed PFOS levels ranging from 1.64 to 10.29 ng/g across all sampling locations. The spatial distribution of point source contamination from industrial sites and wastewater treatment plants is shown by higher concentrations in urban and industrialised river reaches (Kikanme et al., 2024).

Meanwhile, several African nations have reported heavy metal contamination of water, sediment, and soil (marked 1–14 in Figure 2). Metals such as lead (Pb), mercury (Hg), copper (Cu), cobalt (Co), zinc (Zn), chromium (Cr), nickel (Ni), manganese (Mn), iron (Fe), arsenic (As), and vanadium (V) are among the most notable heavy metals that have been recorded. Nations not depicted in Figure 2 have scant information on heavy metal contamination; most of these nations are relatively less developed ones in Africa.

Research on heavy metal contamination in North Africa has largely focused on coastal areas (Fig. 2). The Mediterranean coast of Egypt is polluted with industrial and municipal waste at El-Mex Bay and Eastern Harbour (in Fig. 2) since numerous neighbouring industries discharge their effluents directly into the bay (Abdallah, 2008). El-Mex Bay is further polluted by the Omoum Drain, which carries phosphate fertilisers and other metals like Cu and Zn from industrial waste directly into the bay (El-Rayis and Abdallah, 2006).

Exploitation of petroleum is one of the primary causes of pollution in West Africa. According to Chindah et al. (2004) and Oloruntegbe et al. (2009), crude oil is released into the environment in the Niger Delta region of Nigeria due to pipeline corrosion, oil industry discharges, and frequent acts of sabotage against oil installations. More than two million barrels of crude oil have leaked into the environment because of more than four thousand leak occurrences that have been recorded in Nigeria's oil spill records since 1960 (Oloruntegbe et al., 2009). instead of The Bonny/New Calabar River Estuary in the Niger Delta has been shown to be contaminated by Pb, Cd, Cu, Zn, V, and Cr because the rivers absorb wastewater from oil refineries and other related operations (Chindah et al., 2004). According to Emoyan et al. (2006), the Ijana River has elevated levels of lead (0.025-0.064), cadmium (0.01 0.11), chromium (0.03-0.09), and nickel

(0.03-0.09). These levels were mostly caused by wastewater from the Warri oil refinery. In contrast to the low concentrations noted before the dredging, a separate study found high concentrations of lead (2.57 mg/l) and cadmium (0.39 mg/l) in the Warri River after the excavation of an access canal for an oil well (Ohimain et al., 2008). In the Qua-Iboe River in other regions of Nigeria, Oze et al. (2006) found concentrations of Pb (0.3 ± 0.1), Cd (0.03 ± 0.01), Cr (0.53 ± 0.01), and Ni (0.21 ± 0.01), which they linked to wastewater from processing and treating crude oil.

As revealed in figure 2, East African Dandora solid waste disposal site, which occupies around 30 acres of land in Nairobi City, Kenya. The dumping facility in Nairobi receives around 2,000 metric tonnes of solid trash every day, which includes materials from many sectors including as agriculture, industry, households, and healthcare (UNEP, 2007). Soil samples taken near the Nairobi Riverbank above the recommended limits for hazardous elements (mg/kg) such as lead (264.0 mg/kg), cadmium (40.0 mg/kg), mercury (18.6), and other heavy metals (Cr, Mn, Fe, Cu, Zn, and Co) (UNEP, 2007). Industry and residential garbage have also contributed to the contamination of Lake Victoria, in addition to small-scale gold mining operations that employ mercury near the lake (JICA, 2002). Sediment contamination with lead (54.6 ± 11.1), cadmium (7.0 ± 2.1), and mercury (2.8 ± 0.8) has been documented on the coast of Tanzania (see Fig. 2). Figure 2 shows that on the Ugandan side of the lake, there was water contamination with 1.4 mg/l of lead, 0.02 mg/l of cadmium, and 0.13 mg/l of nickel, along with 0.03-0.108 mg/kg of mercury in the sediments. Similarly, Pb (0.496 ± 0.159), Cd (0.01 ± 0.002), and Cr (1.935 ± 0.258) contamination was found in the water on the Kenyan shore (mg/l).

South Africa is the world's leading producer of gold, and Zambia has large reserves of copper and iron ore, so it's no surprise that mining is the leading cause of environmental degradation in Southern Africa. According to Ravengai et al. (2005), there have been reports of contaminated transboundary water streams, such as the Mazowe River in Zimbabwe, which flows into the Zambezi River in Mozambique. In South Africa, water contamination with Pb, Cr, Zn, Cu, Mn, Co, As, and Ni is attributed to gold mining. This contamination occurs in areas where tailings dumps are abundant, such as the headwaters of the Natalspruit stream in Johannesburg (Fig. 2). An thorough study conducted in Zimbabwe in 2006 by Meck et al. found that water in streams contaminated with levels of Pb (1.02 ± 0.25), Cd (0.12 ± 0.00), Ni (2.37 ± 0.26) and Cr (2.48 ± 0.10) that above prescribed limits, and the contamination was attributed to gold mining activity in stream/river catchment zones. In a similar vein, extremely high concentrations of Cu (12,855 ± 1459) and Co (1,030 ± 58) were detected in sediments from the Kafue River during the rainy season. This river draws water from significant copper and cobalt mines across Zambia's Copperbelt Province (Pettersson and Ingri, 2003). Contamination of wetland sediments in the Copperbelt mining area has been found to include Pb (9-75), Cd (<0.1-0.8), Ni (3-220), Cr (9-130), and Zn (1-125) in milligrammes per kilogramme. (New and von der Heyden, 2004). According to Tembo et al. (2006), the high concentration of lead (0.36 ± 1.0 mg/l) found in the water of the Kafue River basin could be due to the river's ability to carry metals over long distances and the employment of lead bullets in the basin's yearly commercial hunting operations, which aim to manage the wildlife population. The vast pollution of Cu (up to 10,500 mg/kg), Zn (205 mg/kg), and Ni (1,950 mg/kg) in the sediments of the Gruben River in Namibia was attributed to the Khan copper mines (Fig. 2). Industrial, agricultural, and domestic garbage have received less attention from researchers than mining waste. Okonkwo et al. (2005) found that a sewage treatment plant, trash dumping, and the use of fertilisers and pesticides, which included Pb and Cd, on nearby farms were the sources of lead, cadmium, copper, and zinc pollution in the Thohoyandou rivers in South Africa. Similarly, municipal waste was shown to be a source of Hg (trace -0.013 mg/l) contamination in groundwater in Lusaka City, Zambia (Weele et al., 2004). The use of sewage sludge in agricultural soils causes considerable levels of Pb (6.77 mg/kg), Cd (3.68 mg/kg), Hg (0.05 mg/kg), Zn (221.0 mg/kg), Cr (16.1), and Cu (111.0 mg/kg), according to a recent study in Harare (Zimbabwe) by Muchuweti et al. (2006).

Figure 2 Map of Africa showing sites where heavy metal pollution exceeding maximum limits in aquatic systems (Yabe et al., 2010)

Previous research from Nigeria has shown that surface freshwaters contain more cadmium, chromium, manganese, and lead than is recommended for human consumption (Izah et al., 2016). Heavy metal contamination indices calculated using drinking water quality indicators by the US Environmental Protection Agency (1890.65) and the World Health Organisation (13,656.74) were similarly significantly higher than the 100-point threshold. These results prove that surface waters are not safe to consume. The cadmium enrichment factor, contamination factor, and ecological risk factor indexes were all greater than the maximum threshold, with values of 684.62, 41.73, and 1251.90, respectively. According to other studies, cadmium significantly increases the environmental risk associated with surface water contamination in Nigeria (Ubuoh et al., 2023). There is a non-carcinogenic and a carcinogenic risk to the public's health from the current levels of heavy metal contamination in Nigerian surface waters, which are reaching alarming levels (Oni et al., 2022). Nigeria is fortunate to have an abundance of surface freshwater resources, and many indigenous peoples along the coast rely on this water for domestic purposes, including drinking (Omokaro et al., 2024). A large number of them also make a living from fish farming and other aquatic resources. It is imperative that levels of heavy metal contamination be kept below what is necessary to protect aquatic life and end users from the harmful consequences of pollution.

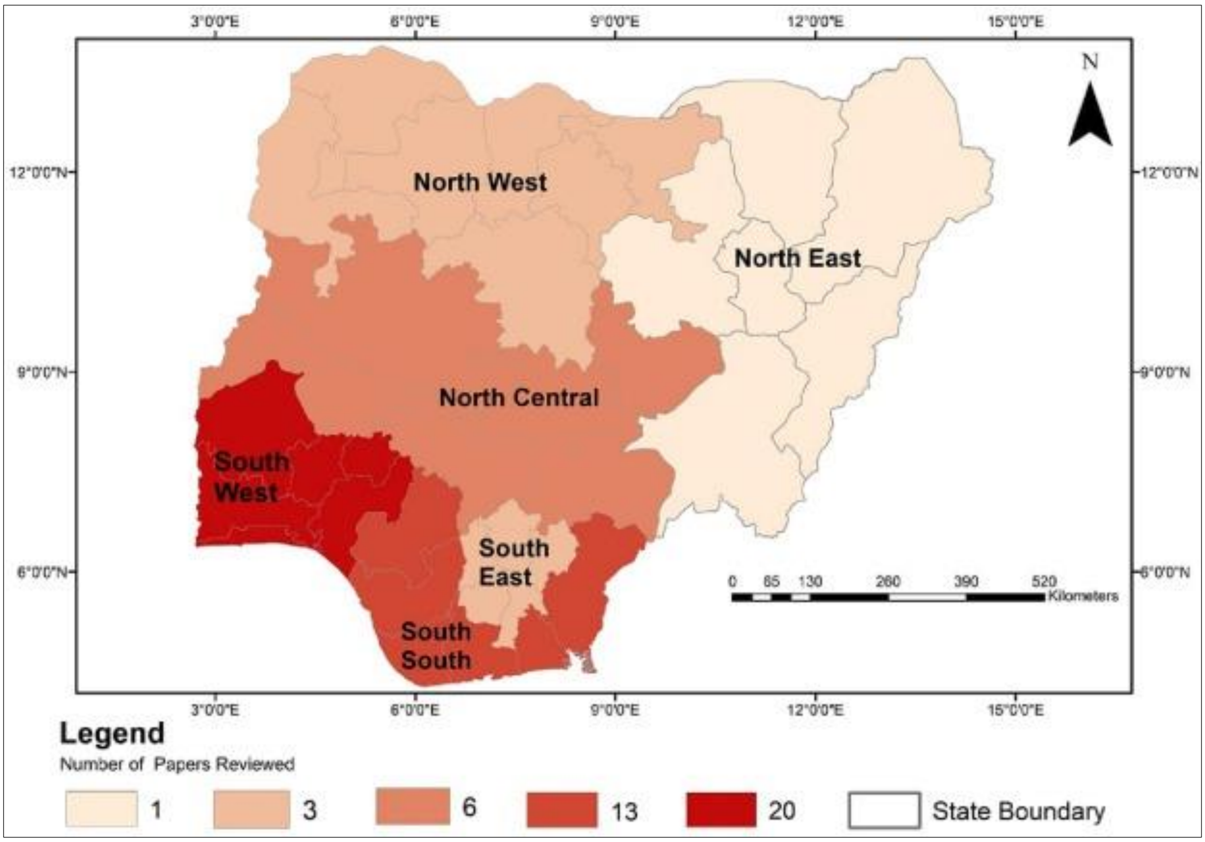

Figure 3 Spatial distribution of heavy metal contamination across Nigerian river systems (Bawa-Allah, 2023)

Pollutants known as per- and polyfluoroalkyl compounds (PFAS) are present in water and sediment all over the world. There is a lack of research on their occurrence in aquatic ecosystems in Africa, despite the growing concerns about their ecological and health dangers. Prior studies have shown that PFAS contamination varies significantly between regions; sites further upstream usually have higher levels than those further downstream (Briggs et al., 2020). The graphic below further illustrates this point, showing that there were statistically significant changes ($p < 0.05$) in the in-surface water samples L_PFBS, 4:2 FTS, 6:2 FTS, and L_PFHpS. Perfluoro carboxylic acids made up 50.47–57.15 percent of the PFAS class in surface water, but perfluoro sulfonic acids made up more of the class in sediments. At upstream, there is a higher concentration of L_PFHxS (23.91 ng/g), L_PFDS (38.89 ng/g), and L_PFHpS (43.00 ng/g) compared to downstream (31.96, 27.84, and 18.02 ng/g, respectively). Water quality management and pollution reduction approaches are supported by the results, which reveal sources of contamination and the partitioning between surface water and sediments (Okwuosa et al., 2025).

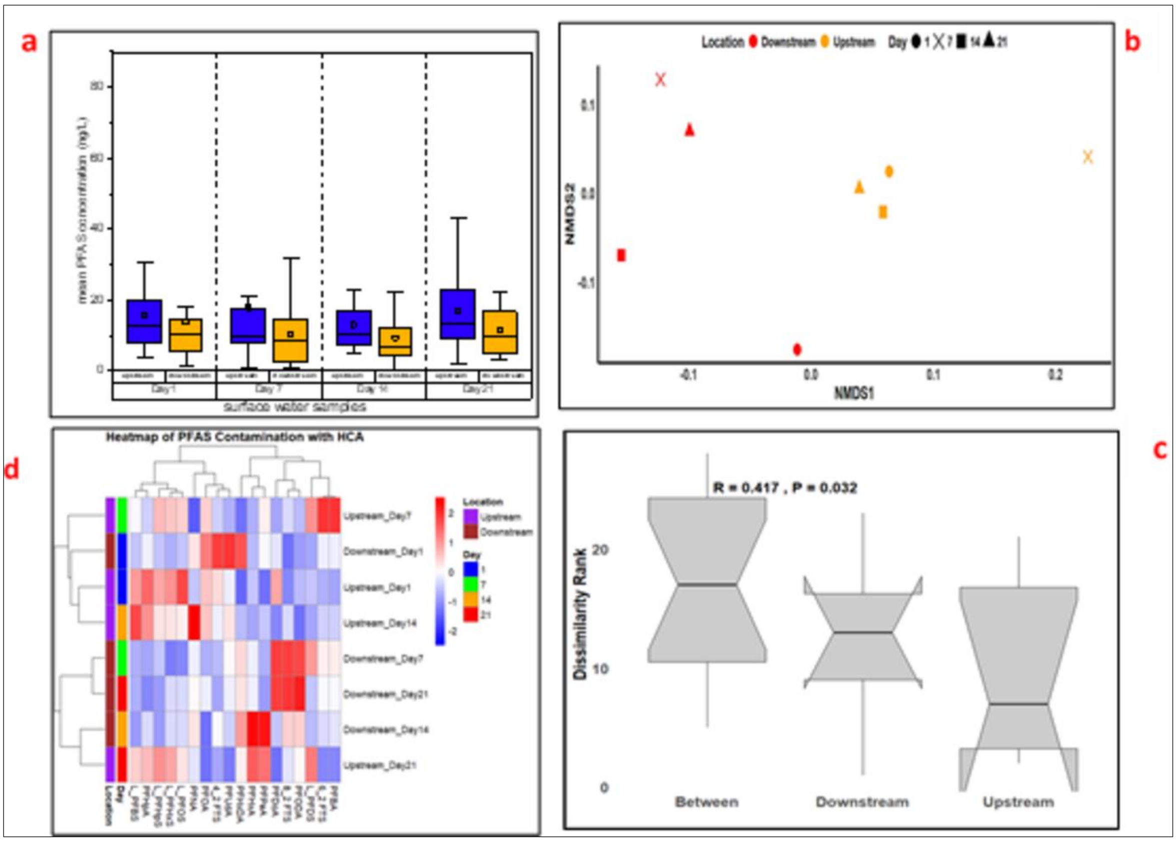

Figure 4a Spatial and temporal distribution of PFAS in surface water a case study of Apies River in South Africa. Mean PFAS concentrations (a), NMDS plot of PFAS composition (b), ANOSIM analysis (c), and hierarchical cluster analysis (d) (Okwuosa et al., 2025)

Most notoriously perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), per- and polyfluoroalkyl substances (PFAS) have become pervasive environmental contaminants due of their permanent chemical structures and wide use in consumer and commercial items. Even although they are being phased out in some wealthier countries, these compounds continue to create severe ecological and human health risks especially in Sub-Saharan Africa (SSA), where monitoring and regulatory systems are still poor (Apelberg et al., 2007; Fenton et al., 2021). In this first-of-kind regional analysis, Kasambala et al. (2024) painstakingly compile and assess data from research conducted between 2005 and 2021 to analyse PFAS incidence throughout surface water, groundwater, wastewater, soil, air, food, aquatic life, and human tissues in SSA.

Depending on location and medium, PFOS and PFOA have been identified in rivers, lakes, and wastewater systems throughout East Africa including Tanzania, Uganda, and Kenya (Dalahmeh et al., 2018; Hope, 2020). Amounts range between 0.037 ng/L and 2.5 ng/L. For example, the damage of the adjacent wetland habitat linked to PFAS contamination in Lake Victoria underlined the impact of industrialisation and poor waste management on PFAS spread (Orata et al., 2009). Comparably, the area of Southern Africa—especially South Africa—showcases higher degrees of PFAS. One study looked at river water near industrial sites and found PFOA levels ranging from 314 ng/L and PFOS levels from 182 ng/L (Mudumbi, 2012). Bioaccumulation was particularly obvious in marine fish and shellfish with PFOS levels in fish muscle (Abafe et al., 2021) at 289 ng/g. PFAS were also present in human serum and baby formula, which poses problems about food exposure (Hanssen et al., 2010; Macheka et al., 2021). Whereas PFOS was found at 1.39 ng/L in surface water in Nigeria, PFOA levels in sludge from wastewater treatment plants varied from 424 ng/g (Sindiku et al., 2013; Kurwadkar et al., 2022). In River Pra, Ghana found PFAS levels ranging from 398 ng/L, significantly beyond recommended worldwide safety limits (Essumang et al., 2017). Roasted fish from Mali and Cameroon revealed detectable amounts of PFAS, therefore confirming food chain contamination as the primary exposure source (Vaccher et al., 2020; Adewusi et al., 2020). While Central Africa lags in PFAS research, only Democratic Republic of Congo has limited data showing low PFAS prevalence in human samples most likely a consequence of underreporting due of insufficient infrastructure rather than real absence (Bayebila et al., 2021; Kurwadkar et al., 2022).

Long-chain PFAS are more bio-accumulative and persistent; half-lives in human serum range from 2.7 to 5.3 years (Nicole, 2020; Olsen et al., 2005). Previous studies have covered PFAS transport mechanisms, stressing the need of their chemical properties such strong carbon-fluorine bonds and water solubility in enabling long-distance movement across water, air, and sediment. Currently only Kenya and South Africa have the capabilities required to investigate PFAS using modern technology (Ssebugere et al., 2020). This difference greatly hinders evidence-based policymaking and effective environmental preservation. Sadly, especially in Sub Saharan Africa (SSA), removal methods offer only somewhat restricted options. Though already in use, granular activated carbon (GAC) and biochar have potential but suffer with short-chain PFAS. More advanced but costly and typically impracticable for general usage in low-resource contexts are UV photolysis, reverse osmosis, and electrochemical oxidation (Leung et al., 2022; Ekesiöö, 2023).

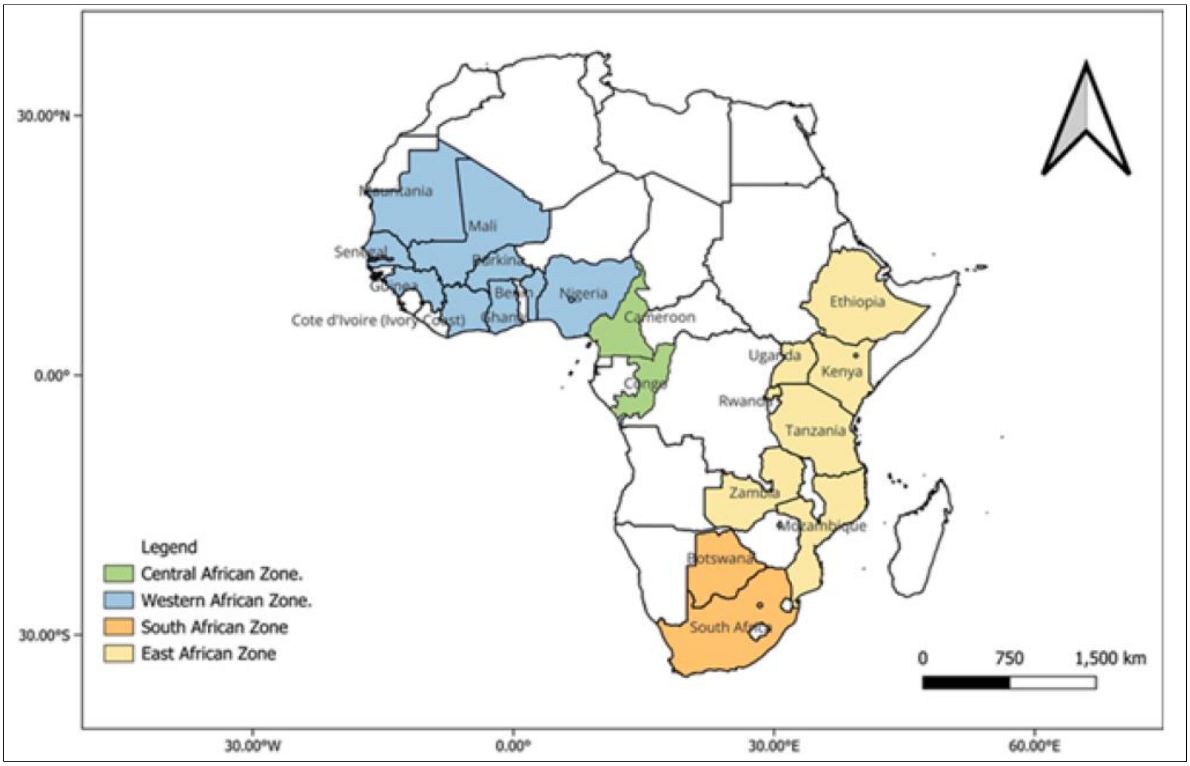

Figure 4b Map of Africa showing countries of sub-Saharan in which PFAS were reported (Drawn by Hildegard R. Kasambala)

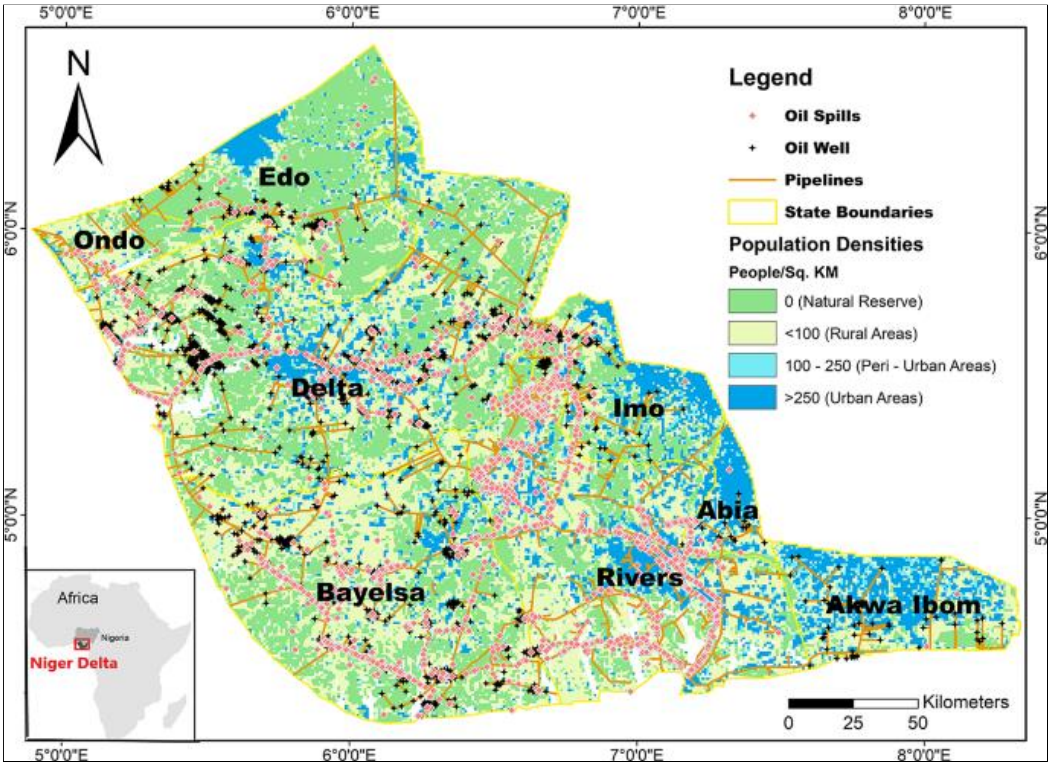

Figure 5 Integrated view of the Niger Delta region, highlighting the spatial relationship between population density and oil-related infrastructure (Oyebamiji et al., 2024)

3.2. GIS-Based Monitoring Network Assessment

According to a study by Omokaro et al. (2024), there are significant gaps in pollution surveillance coverage over aquatic systems in Nigeria. These gaps were found while looking at current techniques of water quality monitoring. Upstream regions and rural watersheds are underserved by current monitoring stations, while major urban centres have a concentrated distribution. To improve the spatial representation and early warning capacity for chemical contamination incidents, 47 priority sites for additional monitoring stations were identified using GIS-based network optimisation analysis (Jiang et al., 2012).

According to spatial interpolation research that used kriging techniques, the current monitoring density only provides enough coverage for around 35% of the significant river reaches in Nigeria (Nkeki et al., 2013). According to Omokaro et al. (2024), there are notable variations in surveillance capacities across various areas, as evidenced by the coefficient of variation for monitoring station spacing, which ranges from 0.42 in the Lagos coastal zone to 1.78 in the upper Niger River basin. Inadequate upstream and downstream monitoring coverage is present in 62% of industrial facilities and 74% of large urban areas, according to assessments of buffer zones around existing monitoring sites (Sekharan et al., 2022).

3.3. Pollution Source Identification and Tracking

Ahuchaogu et al. (2020) discovered that GIS overlay analysis successfully linked chemical pollution levels over study areas to land use patterns. Industrial zones showed a strong positive correlation ($r = 0.73$, $p = 0.001$) with heavy metal concentrations in neighbouring bodies of water, according to Ahuchaogu et al. (2020). There was a strong association between urban regions and PFAS exposure and pharmaceutical residues, while agricultural areas were associated with greater levels of nutrients and pesticides. More research by Ade (2022) utilising GIS-based flow accumulation and watershed delineation techniques identified 23 major industrial discharge sources polluting the Niger-Benue rivers. Within 5 kilometres upstream of detection sites, specific point sources were associated with 68% of the reported pollution episodes, according to spatial analysis. According to Hussain et al. (2025), there were dispersed patterns in agricultural runoff that are consistent with contamination mechanisms that occur on a watershed scale.

3.4. Predictive Modelling Results

Topographic, hydrological, and land use factors-based spatial regression models achieved moderate to high projected accuracy for chemical contamination patterns. Heavy metal concentration models explained 64-78% of the spatial variance across several river systems, with elevation, distance to industrial facilities, and upstream land use as the key predictors (Zhou et al., 2023). Due to complex source-receptor interactions and a lack of readily available training data, PFAS concentration models exhibited worse prediction performance (R^2 = 0.42-0.56) (Fenton et al., 2021). Temporal analysis of pollution patterns using current monitoring data revealed an increase in contamination in 73% of the river reaches monitored from 2015 to 2023 (Furdek Turk et al., 2024). Nearly 2,340 metric tonnes of heavy metals enter Nigerian river systems per year, with 67% of those metals coming from industrial sources, according to GIS-based watershed modelling (Fashae and Obateru, 2023).

3.5. Technology Implementation Assessment

According to a study by Mohammed et al. (2024), the effectiveness of Nigeria's pollution monitoring systems is hindered by significant institutional and technical capacity limits. Current GIS infrastructure only allows for simple data visualisation and basic spatial analysis; it does not integrate with automated data processing systems or real-time monitoring sensors (Li et al., 2020), even though human capacity assessment showed that less than 40% of environmental monitoring staff have advanced GIS abilities needed for thorough pollution analysis. So, according to the training needs analysis, the most important areas to focus on are database management, remote sensing integration, and spatial statistics (Sheffield et al., 2018). In addition, research on the availability of equipment has shown that the majority of environmental agencies are using outdated GIS software and hardware configurations, which severely limit their ability to conduct analyses (Zhu, 2016).

According to Olateju (2021), GIS-based monitoring systems have the potential to save 35-45% in efficiency compared to traditional monitoring methods. This is because they allow for better spatial targeting of sample operations and have reduced expenses associated with collecting field data. Worrall (1994) and Adelusi et al. (2025) estimate that initial expenditures ranging from $2.3 million to $4.1 million per major river basin are necessary for comprehensive GIS deployment. This amounts to a significant financial barrier for organisations with low resources.

3.6. Public Health Implications of Chemical Pollution in Aquatic Ecosystems

The widespread contamination of water bodies across Africa and Nigeria has profound public health implications, particularly in terms of water quality, disease transmission, and overall community health. Heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg), which have been detected in water, sediment, and soil, are known to pose significant health risks. Exposure to these contaminants through drinking water, recreational water activities, and consumption of contaminated fish and shellfish can lead to severe health conditions, including neurological damage, kidney failure, and cancer (Chindah et al., 2004; Emoyan et al., 2006; Okonkwo et al., 2005). Additionally, the contamination of aquatic ecosystems due to industrial discharges and mining activities, particularly in regions such as the Niger Delta, poses long-term health risks to local populations who depend on these water sources for drinking and agriculture (Oloruntegbe et al., 2009).

Increased concentrations of persistent chemicals, such as PFOS and PFOA, have also been linked to various health concerns, including endocrine disruption and developmental harm (Kikanme et al., 2024). The findings from this study, which showed elevated levels of these pollutants in Nigerian water bodies, suggest an urgent need for effective monitoring and mitigation measures to protect public health.

Furthermore, the impact of pollution on aquatic food sources cannot be understated. As indicated by the contamination of Lake Victoria and other rivers, the presence of heavy metals in aquatic organisms may lead to bioaccumulation, affecting food security and human health (JICA, 2002). Therefore, the need for effective GIS-based monitoring systems is critical in mitigating these risks and ensuring the health and safety of the affected populations.

4. Discussion

The results of this study show that Geographic Information Systems technology has great potential to improve chemical pollution monitoring and mitigating in aquatic ecosystems of Africa and Nigeria (Fashae et al., 2021), but it also shows that major implementation challenges must be addressed. GIS-based approaches are found to be useful in the spatial analysis results to maximise monitoring networks, spot contamination patterns, and support evidence-based decision-making for pollution control strategies (Chatrabhuj et al., 2024). With values in pore water samples ranging from above 20 ng/L to below detection thresholds, Aborode et al. (2025) showed that PFAS contamination in African water systems has been recorded. This emphasises how urgently systematic observation of emerging contaminants across Africa is needed. These findings show how vulnerable African aquatic systems are due of regulatory frameworks and little monitoring capacity, even if they accord with global trends indicating great PFAS contamination (Groffen et al., 2021). Levels of contamination are probably only the start of a long-term accumulation process involving PFAS compounds, which are resistant to natural breakdown mechanisms (Dickman and Aga, 2022). Efforts to reduce this will call for ongoing surveillance. The complex interactions among pollution sources, hydrological processes, and environmental variables define aquatic systems in Africa, as noted by Carafa et al. (2011). Consistent with past studies from other African countries dealing with comparable demands from industrial development, the high correlation between heavy metal concentrations and industrial activities (r = 0.73) shows that pollution from point sources is still the main cause of water quality deterioration (Ruhela et al., 2022). Still, it is now abundantly evident that diffuse pollution from urban and agricultural sectors is growing more significant; so, future monitoring systems will have to consider both routes of contamination.

The ability of GIS technology to trace contamination patterns and locate pollution sources makes it clearly better than conventional monitoring methods based on fixed-point sampling (Dias and Tchepel, 2014). The capacity to track 68% of pollution events to specific upstream sources within 5km represent a notable increase in investigative capacity. This enables targeted remedial activities and supports enforcement actions (Khanam et al., 2023). This ability is especially important since limited resources call for effective allocation of monitoring and enforcement actions in the African setting.

The study did uncover some major shortcomings in the way GIS is now applied, which compromises its effectiveness in pollution monitoring. Dube et al. (2023) noted that as presently, monitoring systems hardly cover 35% of significant river reaches sufficiently, emphasizing the desperate need for strategic expansion of surveillance infrastructure in Nigeria and across Africa. This implies that during pollution crises understudied areas could go undetected.

The complex environmental behaviour of PFAS and the limited availability of training data for developing contaminants help to explain why spatial models for PFAS contamination predict performance somewhat poorly than those for heavy metals (Olawade et al., 2025). Because their transport and fate mechanisms are different from those of conventional pollutants, specific modelling approaches and more comprehensive monitoring datasets for PFAS compounds are essential for reliable forecasts (Groffen et al., 2021). This constraint emphasises the need of continuous financing for research on novel approaches of monitoring and modelling pollutants. The technological and institutional capacity constraints identified in this study (Wehn and Almomani, 2019) impede GIS pollution monitoring in African settings. Less than 40% of environmental monitoring experts in Africa have advanced GIS capabilities, hence capacity building initiatives are much needed to close the notable training gap among them (Taylor, 2004). The preponderance of old software and hardware configurations limits analytical skills as well as the possible advantages of GIS technology acceptance (Musa et al., 2024). GIS-based monitoring systems (Chen et al., 2022) can raise efficiency by 35–45% even if the initial expenses projected at $2.3–4.1 million per major river basin are high. More effective pollution management methods resulting from better spatial targeting of sample operations, less expensive field data collecting, and more analytical capacity help to drive efficiency benefits. Nevertheless, given the high initial investment requirements, long-term financial commitments and perhaps even foreign aid are required to enable significant GIS adoption. across the more major issues affecting environmental monitoring systems in developing nations are poor infrastructure, insufficient technical competency, and poor coordination across organisations and institutions. The integration challenges this study underlined mirror more general issues (Bahauddin et al., 2014). Albahri et al. (2018) claim that solving the fundamental infrastructure constraints is essential to enable real-time monitoring possibilities. One such restriction is the effect on data flow from remote monitoring stations of internet connectivity problems. Given these challenges, it seems that for GIS implementation to be successful, coordination of investments in technological systems and supporting infrastructure is necessary.

These findings have consequences not only for Nigeria but also for other African nations experiencing comparable pollution monitoring issues. Resource planning and investment objectives can be informed by capacity building and infrastructure needs; the research and review of spatial analytic techniques and GIS applications of the study can be applied to many national settings. Ali et al. (2024) claim that GIS technologies have been effective in identifying pollution sources and strengthening monitoring systems. Appropriate initiatives for technology transfer and capacity building will help to reap similar benefits elsewhere throughout the continent. Environmental managers and legislators must act fast to address the recent revelation of PFAS contamination as a known threat to aquatic systems in Africa since it marks a major shift in the way pollution is under control. Due to their persistence and bio accumulative characteristics, and their extensive use in consumer goods and industrial applications, contamination levels would keep rising in the lack of proactive intervention efforts (Kikanme et al., 2024). Given the low analytical capacity for PFAS detection in most

African nations, there is an immediate need for investments in specialized laboratory facilities and technical training programs.

5. Conclusion

This thorough study shows that Geographic Information Systems technology offers significant advantages over conventional surveillance methods and serves as a transformative tool for monitoring and reducing chemical pollution in African aquatic ecosystems, thereby exposing important implementation challenges that have to be methodically addressed. The results of the study offer convincing proof for the efficiency of GIS-based monitoring systems in spotting contamination trends, streamlining surveillance networks, and supporting evidence-based pollution management measures for many aquatic ecosystems. Therefore, the development of PFAS and other new pollutants as observed hazards to African aquatic systems points to a basic change in pollution monitoring needs that calls for quick policy attention and financial commitment. The inadequate analytical capacity for identifying these compounds over most of the continent generates immediate need for specialised laboratory facilities, technical training programs, and regulatory systems able of handling persistent organic pollutants with complicated environmental behaviour. But the way GIS systems combine ground-based sensors, satellite images, and spatial modelling tools offers hitherto unheard-of chances for thorough pollution monitoring across large distances. More complex knowledge of pollution dynamics and proactive management responses to developing contamination hazards is made possible by the capacity to integrate real-time monitoring data, historical records, and prediction models within unified analytical frameworks.

Recommendations

Based on the comprehensive analysis of GIS applications for chemical pollution monitoring in African aquatic ecosystems, this study presents the following strategic recommendations for enhancing monitoring capabilities, addressing implementation challenges, and supporting sustainable pollution management across the continent.

5.1. Immediate Priority Actions

- Comprehensive PFAS monitoring programs should be prioritised by environmental agencies and government institutions across major river systems and groundwater sources, as these contaminants are present in Nigerian waters and likely across Africa. These programmes should use specialised analytical capabilities to detect PFAS chemicals at ecologically appropriate quantities, supported by trained staff and standardised sampling techniques. The monitoring networks should start downstream of industrial facilities, airports, military locations, and wastewater treatment plants, where PFAS contamination is most likely.
- Immediate investment in technical capacity building is crucial, with a priority on training environmental monitoring staff in advanced GIS tools, spatial statistics, and integrated data analysis. Training should emphasise practical skills through hands-on workshops, mentorship from experienced practitioners, and technological support. To enable knowledge transfer and collaborative research, universities and research institutes with superior GIS capabilities should form international alliances. Immediate attention is needed to expand and optimise existing monitoring networks, with GIS-based analysis identifying 47 priority areas for future stations in Nigerian river systems. Standards-based network optimisation exercises should be done for other African countries to ensure comparable results and coordinated regional monitoring. New monitoring stations should have automated data collection, real-time transmission, and quality assurance methods to maximise data utility and reliability.

5.2. Policy and Regulatory Development

- African nations should create and apply comprehensive regulatory systems covering new pollutants, including PFAS chemicals, to enable efficient pollution management and remedial action programs. While keeping consistency with international best practices, these frameworks should set environmental quality criteria, monitoring requirements, and enforcement mechanisms fit for local conditions. Procedures for stakeholder participation should guarantee that regulatory development includes comments from civil society, business, and impacted populations.
- For all significant development projects influencing aquatic ecosystems, environmental impact assessment processes should be revised to demand thorough study of chemical pollution hazards including new pollutants. These processes should demand the application of GIS-based analysis techniques for analysing cumulative impact scenarios, locating sensitive receptors, and determining pollutant dispersion patterns. Establishing monitoring and reporting criteria will help to promote adaptive management strategies and track long-term patterns of pollution.

- Negotiated international cooperation agreements should provide financial help for GIS-based pollution monitoring system installation, capacity building, and technology transfer support. These agreements ought to cover intellectual property issues, technological adaption needs, and sustainable financial sources for continuous system running and maintenance. Establishing partnerships with development banks, international organisations, and donor agencies can help to mobilise required technical knowledge and resources

Compliance with ethical standards

Disclosure of conflict of interest

The author declares no conflicts of interest related to this publication.

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