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A Comprehensive Review of the High Iron Concentrations Reported In Groundwater in the Niger Delta Sedimentary Basin

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Review Article

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ABSTRACT

This article is aimed at reviewing the occurrence of high concentrations of iron (Fe) in groundwater within the Niger Delta Sedimentary Basin (NDSB) and suggests remediation techniques with over 90% efficiency. Secondary information (article, textbook, and monograph), citing relevant articles from Google search engine that are related to this article with the basin was retrieved. Articles published within the last ten years on iron concentration in groundwater were used for this investigation. Keywords that were specifically considered in the searches that make up the secondary information were heavy metal content in groundwater; Niger Delta Sedimentary Basin; water quality; remediation techniques for iron-contaminated water, the biological implication of iron-contaminated water, etc. Findings from this study revealed that anthropogenic sources such as crude oil spillage, landfill and effluent discharges and geogenic factors of saline water intrusion into the aquifers are the major factors responsible for the high iron content in the groundwater across the study area. Deductions from the study suggested that oxidation-precipitation-filtration techniques, Point-of-Use Filters techniques, Membrane Filtration (Reverse Osmosis/Nano filtration), Flocculation-Coagulation and Distillation are some of the modern remediation techniques with over 90% efficiency that could be employed for domestic and industrial purpose. Therefore, to maintain sustainability and quality health within the region, it is penitent to prioritize the reduction of human impacts on groundwater, boost community awareness, and employ modern remediation techniques to mitigate contaminated water.

Keywords: Contamination; Remediation techniques; Oil spillage; Groundwater

INTRODUCTION

The Earth's surface does not contain enough freshwater resources for domestic and other uses, according to Akinseye and Eyankware [1,2]. Both geological and anthropogenic sources have the potential to alter the chemistry of surface and groundwater, worsen the pollution of arable soils and sediments, and raise the concentration of heavy metals in water and soils [3-5]. Iron is a silent, often-unnoticed phenomenon that forms the very essence of our groundwater beneath the surface of the Earth in the coastal region of the Niger Delta Sedimentary Basin [6-8]. Although groundwater contains iron, it adds a subtle touch to the complex web of Earth's natural processes. Water is still essential for life as we know it. According to Orians and Merrin, iron (Fe) is the fourth most abundant element in the Earth's crust, making up roughly 5.63% of its weight [9]. It has an atomic number of 26 and the chemical symbol Fe. Iron in groundwater, however, is far more than just a chemical element; it has consequences for human health and environmental health. Anthropogenic or geogenic factors are the main sources of iron fluoride in groundwater [10]. Aquifer recharge from iron-contaminated effluent discharge, dissolution of ferrous boreholes and hand pumps, and other human influence activities that release iron into the environment are examples of the geogenic factors that result from the rapid growth in population and urbanization [11,12]. But iron-bearing minerals like siderite, magnetite, hematite, and goethite may also help dissolve and release iron into groundwater when they are present in an aquifer flow system [13].

Additionally, factors such as dissolved oxygen levels and pH on the solubility of iron contribute to the presence of iron in groundwater [14]. Dissolve oxygen: Iron in groundwater can exist in two main forms: ferrous iron (Fe^{2+}) and ferric iron (Fe^{3+}). The speciation of iron affects its solubility, in low-oxygen conditions, ferrous iron is soluble and relatively harmless [15]. Nevertheless, it oxidizes to ferric iron under high-oxygen conditions, forming insoluble iron oxides, which can easily precipitate as iron compounds in the aquifer. This can result in both aesthetic and operational issues the pH level of groundwater influences the solubility of iron in groundwater. Groundwater with low pH tends to dissolve more iron from rocks and minerals, which increases their concentration within groundwater. Conversely, in alkaline conditions, iron tends to precipitate and become less soluble. This precipitate forms a rusty red and clogs screens, and pumps system. This accounts for the reddish-brown coloration observed within a few minutes of pumping and its prevalence in an overhead water tank in many locations across the study area. In some locations, it gives the water a strong, undesirable metallic taste which further results in both aesthetic and operational issues furthermore, other factors that may influence the concentration of iron in groundwater include seasonal variations in groundwater level and biogenic factors. Increased groundwater level may encourage redox reaction, meanwhile, the presence of microorganisms in the subsurface can play a role in iron cycling. Some iron-oxidizing bacteria (such as *Acidithiobacillus ferrooxidans, Leptospirillum ferrooxidans, Gallionella, Sideroxydans,* etc) and iron-reducing bacteria (such as *Geobacter, Shewanella, Geothrix,* etc), can promote iron redox reactions, and thereby influence the solubility of iron in groundwater [16]. Since, Fe is an important nutrient for the buildup of the body mechanism of some plants and organisms, the organic matter and plant debris in the soil can also release Fe as they decompose. Various methods, such as oxidation, filtration, and physical-chemical processes, are employed to address high iron concentrations in groundwater. These methods aim to raise the water's redox potential, oxidize the ferrous iron, and subsequently remove the resulting iron particles. It is therefore essential to consider the most reliable and efficient treatment methods to ensure water quality and mitigate operational issues. This study aims to review the causes, health implications, and remediation techniques of high Fe concentration in groundwater within the NDSB with 90% efficiency within the past few years. This study was aimed at reviewing the sources and effects of high iron concentration in groundwater within the Niger Delta Sedimentary Basin, its health implications, and remediation techniques that have 90% efficiency.

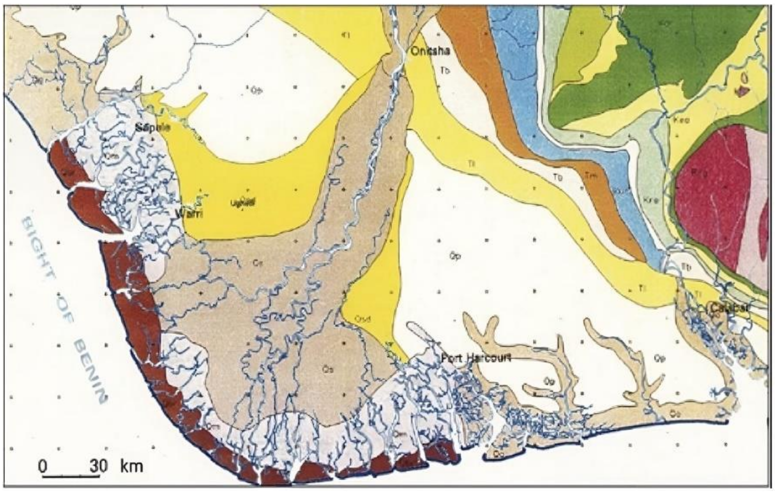
LITERATURE REVIEW

Location and accessibility

The Niger Delta region of Nigeria is an ecologically rich and culturally diverse area located in the southern part of Nigeria. It is characterized by a vast network of rivers, creeks, and swamps, making it a unique and challenging environment in terms of accessibility. Poor infrastructure, such as inadequate water transportation systems, weak road networks, and a dearth of essential services like power and medical facilities, limits the accessibility of the area.

Structural evolution, stratigraphic, and aquiferous unit of the Niger Delta Sedimentary Basin: The structural evolution of the Niger Delta began in the early Cretaceous as a failed arm of the triple rift junction connected with the opening of the South Atlantic during the separation of the South American plate and the African plate [17]. Short and Stauble, noted that the epirogenic process of crustal divergence, translation, and its subsequent rifting produced several faults within the late Jurassic to mid-Cretaceous [18]. At the beginning of the Paleocene, the Akata Formation was deposited which is predominantly made up of turbidite sands, thick shales, and tiny quantities of silt and clay. The Agbada formation was formed in the Eocene. It is a marine facies with freshwater and deep sea characteristics. This is the principal oil and natural gas-bearing faces in the basin. The Benin Formation started its deposition from the Miocene to date.

Figure 1. Niger delta sedimentary basin.



Hydrogeology of the area

The Benin Formation is the basic aquiferous unit within the NDSB [19]. It is made up of mainly coastal and continental floodplain sands, deltaic plains, and alluvial deposits of about 2,000 meters thick the basin extends outward from the Gulf of Guinea [17,18]. The geomorphology and lithology of the basin are summarized in Table 1.

Table 1. Geomorphology of the Niger Delta basin.

Age	Geological unit	Lithology
Quaternary-Recent	Alluvium (general) freshwater back swamp meander belt. North-East of the coastal belt and dips at a low angle toward the southwest [20]	Gravel, sand, clay, silt, pebble [21]
	Mangrove and salt water	clay, some silt, sand, gravel
	Back swamps	Medium-fine grain

	Active-abandoned Beach ridges-Somebreiro Warri Deltaic plain which stretches along the western part of the Basin	Coarse and medium grain sands, Clay, and some silt
Miocene	Coastal plain sand of the Benin Formation	Intercalations of peaty materials, medium grain to Coarse sand with silt and clay lenses; fluviatile marine [22].
Eocene	Agbada Formation	Mixture of clay silt and sand, (fluviatile marine).

The Google search engine was used in the current study to obtain information relevant to the investigation. Published papers on iron and pH, as well as analytical instrument documentation, on Fe in water resources in the Niger Delta region of Nigeria from 2011 to 2023, were downloaded and reviewed. These relevant papers were thoroughly studied and findings from the paper were carefully presented in tabular form with details of publication particulars, study location, period, approach, and methodology as shown in Table 2. The evaluation of the quality of water resources is predicated on the following:

1) The concentration of iron and
2) The concentration of pH and analytical instruments were well documented.

Table 2. The concentration of iron in published articles across the Niger Delta basin within the past few years.

Author(s)	Topic	Analytical Method	Sources of pollution	pH	Fe conc.
Amadi, et al., [8]	Geostatistical Assessment of Groundwater Quality from Coastal Aquifers of Eastern Niger Delta, Nigeria	Spectrophotometric method	Geogenic		0.05-6.87 (0.62) mg/l
Emumejaye, et al., [23]	Effects of Gas Flaring On Surface and Ground Water in Irri Town and Environs, Niger Delta, Nigeria	Unicam AA (Atomic Absorption) Spectrometer, AAS (Atomic Absorption Spectroscopy)	Gas flaring		0.02–1.42 mg/l
Raimi et al., [6]	Health Risk Assessment on Heavy Metals Ingestion through Groundwater Drinking Pathway for Residents in an Oil and Gas Producing Area of Rivers State, Nigeria		Oil and Gas Producing	5.81	5.3/6.9 mg/l

Okezie, and Ehika [24]	Evaluation of some geophysical and physicochemical characteristics of soil and Groundwater Resources in Sapele, South-South Nigeria		hydrocarbon	4.6-5.1.	(0.772-0.915 mg/L
Aweto [7]	Geoelectrical and geochemical evaluation of groundwater resources in Sapele metropolis, Western Niger Delta.	The Atomic Absorption Spectrophotometer		5.7-6.8(6.2)	0.25-1.8 (0.87) mg/L
Choker [25]	Metals' content and physicochemical characteristics of Well Waters in	Atomic Absorption Spectrophotometer		6.22 - 7.43.	0.12–1.00 (0.48) mg/L
	Sapele Metropolis, South-Southern Nigeria	Atomic Absorption Spectrophotometer			
Nwankwoala, and Omemu [26]	Quality Implications of Physico-Chemical Properties	Atomic Absorption Spectrophotometer		6.4 – 6.56	0.35–12.14 mg/L
	and Heavy Metal Concentration Levels in Groundwater Sources in Elebele Community, Bayelsa State, Nigeria				
Nwankwoalet al., [21]	Hydrochemical Factors and Correlation Analysis in Groundwater Quality in Yenagoa, Bayelsa State, Nigeria	Atomic Absorption Spectrophotometer	Geogenic	6.50 - 6.86 (6.66)	0.01-0.98 (0.32) mg/L
Agbalagba et al. [27]	Investigation into the physicochemical properties and		Geogenic and anthropogenic	5.20-7.6	0.40-1.40 mg/L
	hydrochemical processes of groundwater from				
	commercial boreholes In Yenagoa, Bayelsa State,				

	Nigeria				
Ihayere, and Igben. [28]	Water Quality Assessment Using Heavy Metal Indicators in Aghoro Community, Bayelsa State, Nigeria	Atomic Absorption Spectrophotometer.	oil spills		1.17–3.37 mg/L
Aweto, et al., [7]	Hydro-geochemical characterization and Groundwater modeling of the subsurface around Ughelli West Engineered Dumpsite in the Western Niger Delta, Nigeria		Leachate		0.02–0.315 mg/L
Meindinyo and Agbalagba, [29]	Radioactivity concentration and heavy metal assessment of soil and water, in and around Imirigin oil field, Bayelsa state, Nigeria	Atomic absorption Spectrophotometer (AAS)	Anthropogenic	6.4	1.3 mg/L
Agbaire and Tubotu. [30]	Distribution of total petroleum hydrocarbon (TPH) and some heavy metals in the waters of two Niger Delta communities, Delta State, Nigeria	Atomic Absorption Spectrophotometric)method.	petroleum	6.31-7.12 (6.73)	78.3-213 mg/L
Agbaire, and Tubotu. [30]	Distribution of total petroleum hydrocarbon (TPH) and some heavy metals in the waters of two Niger Delta communities, Delta State, Nigeria	Atomic Absorption Spectrophotometric method.	petroleum	6.31-7.12 (6.73)	234-412 mg/L
Amangabara and, Enyinaya. [31]	Groundwater Quality Assessment of Yenagoa and Environs Bayelsa State, Nigeria between 2010 and 2011		industrial activities	8.3 - 10.52 (9.373)	0.565-1.41 (0.286) mg/L
Egbo, et al [32]	Hydrochemical Assessment and Characterization	Atomic Absorption spectrophotometer.	Geogenic	6.0 - 7.94,	0.196-0.390 mg/L

	Selected Boreholes Water in Onopa, Azikoro, and Agbura Axis of Atissa in Yenagoa Metropolis of Bayelsa State, Nigeria.				
Nwankwoala et al., [33]	Heavy metal concentration levels in groundwater and wastewater sources in parts of Trans-Amadi, Port Harcourt, Nigeria.	Flame Spectrophotometer and Atomic Absorption Spectrophotometer	Industrial and municipal waste		<0.010-26.741 mg/L
Raimi et al., [6]	Health Risk Assessment on Heavy Metals Ingestion through Groundwater Drinking Pathway for Residents in an Oil and Gas Producing Area of Rivers State, Nigeria		oil and gas	5.4	5.3 mg/L
Owamah, et al., [34]	Spatial distribution of heavy metals in groundwater around automobile workshops in a popular Niger-Delta University town, Nigeria.	Atomic Absorption Spectrometry	Automobile workshop		0.3118–0.4171 mg/l
Ubong, et al., [35]	Physicochemical and heavy metal contents of groundwater in Okrika mainland, Rivers State.		Geogenic	5.27-5.30	<0.001-1.593 mg/l
Rawlings and Seghosime. [36]	Effect of Open Dumping of Municipal Solid Waste on Groundwater Quality in Ekuredeltsekiri, Warri South LGA, Delta State, Nigeria.	Atomic Absorption Spectrometry	Leachate		0.32-0.425 mg/l

	Assessment of Groundwater Quality	Atomic Absorption Spectrometry	Leachate		0.021 - 0.482 mg/l
Ogbaran, and Uguru. [37]	Around an Active Dumpsite using	Atomic Absorption Spectrometry			
	Pollution Index				
Uzobo, et al., [38]	Distribution and Impact of Organic-Leachates Linked to Water and Sediment in Otuasega, Niger Delta Region, Nigeria.		Organic-Leachates		0.89 to 2.52 Mg/l

Health implication of iron on man

Iron is an essential nutrient required by the body. It facilitates the delivery of oxygen to every part of the body. The occurrence of iron in natural water bodies is usually in the form of either a soluble ferrous (Fe^{2+}) ion or an insoluble ferric (Fe^{3+}) ion [39]. It is impossible to talk about the health implications of iron on men without mentioning the genetic polymorphism of proteins involved in the metabolism of iron in humans. In humans, genome-wide association studies found a linkage between various gene polymorphisms Single Nucleotide Polymorphism (SNP)) and iron status, notably, polymorphism of the gene coding for *Mt2* [40]. Iron deficiency can produce anemia, which manifests as weariness and weakness, and a chronic deficit can result in organ failure. An P, presented evidence that genetic polymorphism of the *Mt2* gene is associated with the risk of developing iron deficiency anemia [41]. Other investigators showed an association between *Mt2* polymorphism and the risk of developing type 2 diabetes [42]. The impacts of high iron intake in humans include hemochromatosis, a disorder leading to frequent transfusions of blood, which can cause impotence, sterility, thyroid disorders, heart ailments, and chronic tiredness. In an analysis of genes modulating iron status, Pelucchi, showed that *CYBRD1* modulates the phenotype of homozygous *C282Y* hemochromatosis, indicating a role of *CYBRD1* in the regulation of iron metabolism [43]. As reported by Berego, the prolonged consumption of drinking water with a high concentration of iron may lead to liver disease called hemosiderosis [44]. Kociuba and Pruss, reported that excessive iron intake has negative health effects, including Kashin-Beck disease and an increased risk of heart disease [45]. On the other hand, the deposits of iron can result in promoting the growth of iron bacteria. However, in places with high groundwater iron concentrations, cases of cancer, miscarriage, and digestive, respiratory, and neurological system diseases have also been documented. Ayenuddin reported that Hazard Quotient *via* ingestion (HQ ingestion), hazard quotient *via* dermal absorption (HQ dermal), and Carcinogenic Risk Index (CR) can be used for the carcinogenic risk involved in the intake of iron [46]. Reported high iron buildup has also been linked to Parkinson's disease, rheumatoid arthritis, birth abnormalities, and liver illnesses.

Sources of Fe in groundwater of the NDSB

The occurrence of iron within the groundwater can be categorized into two sources *viz*: Geogenic and anthropogenic sources.

Geogenic source: Some geogenic factors that introduce iron into a groundwater flow system include the incursion of saline water, dissolution of iron-bearing compounds, volcanic activities, etc. The influence of saline water: The migration and transformation of heavy metals like iron in dynamic coastal regions can be influenced by the interaction of freshwater and saltwater. This transformation influences the concentration of those elements in the groundwater aquifer. Zhang, noted that the mixing processes of fresh-salt water in estuarine and coastal regions of the Pearl River Estuary (PRE), in South China have a substantial impact on the characteristics of heavy metals partitioning. The study found that hydrodynamic force—caused by the salt wedge's landward incursion—was the primary factor responsible for the buildup of heavy metals in the northern and western PRE. The study also observed that some of the metals partitioned towards particle phases in offshore waters due to the re-suspension of sediment and the mixing of freshwater and seawater offshore, which were produced by seawater intrusion. Elsewhere, in South-Eastern Sardinia of Italy, Sodde, and Barrocu observed that Seawater intrusion has a significant effect on the heavy metal pollution of the alluvial plain sediment of the Quirra and FluminiPisale Rivers [47]. Sources of Iron in saline water have been attributed to various sources such as the deposition of atmospheric dust and sediment dissolution; Iron can originate from the dissolution of sediment along continental margins carried into the ocean [48]. Hydrothermal activity; Seafloor hot springs, known as hydrothermal vents, are a significant source of iron in the oceans. It was observed that Iron from vent systems within the Southern Ocean helps sustain major oceanic ecosystems and supports phytoplankton growth, River Waters, and Glacial outwash; Since the NDSB adjoins the Gulf of Guinea, its deposits reflect the progradation of marine environment [49]. Metals such as Iron can accumulate in the coastal sediments over time as a result of the deposition and precipitation of iron-rich deposits from rivers, erosion of coastal rocks, and biogeochemical reactions. Groundwater interacting with these deposits can acquire high iron content. The dissolution of these metals can be largely influenced by acidified groundwater conditions. The acidic nature of the groundwater as reflected by the low pH reading across the study area suggests the dissolution of coastal sediment as a major factor responsible for the high iron content. River waters, melting glaciers, icebergs, and sea ice can contribute to the iron content in the ocean [50].

The incursion of seawater on the shallow groundwater aquifer within the NDSB has been widely recorded, this have been revealed by the dominance of Na-Cl facies within the study area [19,51,52]. Olobaniyi, and Owoyemi, evaluated the hydrogeochemical characteristics of the groundwater in Warri's deltaic plain sands aquifer in the western region NDSB and discovered that the area is mainly dominated by Na-Cl facies. They also observed that groundwater faces change with distance away from the sea, from NaCl to $NaHCO_3$ which indicates a reverse ionic exchange reaction. In like manner, Akpoborie and Efobo, further assessed the Shallow Aquifer's Major Ion Geochemistry in Warri Metropolis, in the western portion of the Basin, and discovered that the groundwater in some parts of Warri has been intruded by salt water [52]. Studies on groundwater within NDSB have revealed varying iron concentrations in different geomorphologic zones, with some areas exhibiting high iron content exceeding the WHO (World Health Organization) recommendation for domestic uses as revealed in Table 2. Nwankwoala and Ngah, who had also reported the influence of saline water invasion and groundwater mixing on coastal aquifers within the eastern part of the NDSB. Therefore, this study opined that the effect of the mixing of saline water and fresh water is a major factor responsible for the high level of iron in groundwater within the basin [19].

Anthropogenic factors: Anthropogenic activities have also been fingered as a major contributor to the high concentrations of iron in groundwater within the Basin. These include activities associated with crude oil exploration and exploitation, leachate migration, and industrial effluent discharge: crude oil is a complex of organic and inorganic compounds including heavy metals. The NDSB is well known across Nigeria as one of the basin housing the largest crude oil reservoir in the country. Its exploration and exploitation have its reported attendant effects on air, soil, and water pollution. Cases of high iron concentration attributed to groundwater pollution from crude oil have been well documented across the basin. In the central part of the basin, Raimi, assessed the heavy metal concentration in the groundwater of the Ebocha-Obrikom community, an oil producing area within the central region of the study area, the study observed that the mean concentration of iron and pH within the studied area were 6.9 mg/l and 5.81 [6]. This is also synonymous with the findings of Okezie, and Ehika, assessed the physicochemical and geophysical properties of the groundwater resources within Sapele, Delta State (Western part of the basin) [24]. The study observed that the Fe concentration is within the range of 0.772-0.915 mg/l with a pH of 4.6-5.1. The study attributed the high concentration of iron to the pollution from petroleum spillages within the area. In consonance with the above observation, Agbaire and Tubotu, also reported high Iron concentrations of 78.3-213 mg/l and 234-412 mg/l in Obuguru and Burutu communities, Delta State, Nigeria (Western part of the basin) respectively, as a result of petroleum activities within the area [30].

Landfill and effluent discharge: The lack of a properly controlled landfill system within the Niger Delta basin had encouraged the practice of open dumping of waste in trenches and burrow pits. This is widely practiced without due consideration to the Geology of the area. In some of the dumpsite locations, the high porosity and permeability which characterized many parts of the basin encourage leachate percolation. This further introduces toxic chemicals and heavy metals to groundwater. The effects of leachate percolation on groundwater quality and their impacts have been widely reported across the basin [34,53-55]. However, the impact of leachate percolation leading to the increase in Fe concentration in groundwater has also been widely reported across the Niger Delta Sedimentary Basin. Rawlings and Seghosime, studied the effect of open dumping of municipal solid waste on groundwater quality in Ekurede Itsekiri, Warri South LGA, Delta State, Nigeria [36]. The study observed that iron concentration in groundwater obtained from boreholes at distances between the ranges of 60-230 m from an open dumpsite across the area ranges from 0.32-0.425 mg/L. In the same thought, Ogbaran and Uguru, also assessed the groundwater quality around an active dumpsite In the Ozoro Community of Delta State using Pollution Index [37]. The study observed that the concentration of Fe ranged from 0.021-0.482 mg/L. in the same line of thought, Uzobo, examined the distribution and impact of Organic-Leachates linked to water and sediment in Otuasega, Niger Delta Region, Nigeria [38]. The study also observed that the average concentration of iron in groundwater within the study area ranges from 0.89 to 2.52 mg/L.

Furthermore, the contamination of groundwater from effluent discharge had also been widely reported within the Niger Delta Sedimentary Basin. In the Slaughter Area of the Trans-Amadi Industrial Layout, Port Harcourt, Akhigbe, investigated the effects of domestic and industrial waste on the quality of the surface and groundwater [56]. The study observed that Fe has a mean value of 1.6 mg/L, with 80% of the samples having a concentration above the WHO (World Health Organization) recommended value.

Modern remediation techniques for iron-contaminated water with over 90% efficiency

Oxidation-precipitation-filtration process: This is one of the most widely used techniques for the removal of iron from water. It involves the oxidation of soluble, ferrous (Fe^{2+}) to insoluble, ferric Fe^{3+} which precipitate as an insoluble complex of iron hydroxide $Fe(OH)_3$ from the water. The precipitated iron gets removed from the water through a simple process of filtration. Oxidants such as potassium permanganate ($KMnO_4$), hydrogen peroxide, chlorine, and ozone have been widely used. The selection of an oxidant for the treatment depends on the cost of the oxidant and the amount of water to be treated. The efficiency of this technique has been widely reported among researchers. The removal of iron Fe^{2+} from groundwater was experimented with by Elsheikh, utilizing oxidation techniques such as aeration, dosage of potassium permanganate or chlorine, and/or ozone followed by filtration [57]. The study observed that only the aeration method can remove up to 90% of iron from the water however, aeration with chlorine dosage can remove up to 100% of iron at a pH greater than 9.0. Meanwhile, by using a potassium permanganate dose of 2.0 ppm, the experiment showed that up to 100% of iron can be removed at pH=7.0. Ozone was considered a very effective oxidant, as it removes about 93% of iron when used at pH=7.0. The study thus opined that aeration with chlorine enhances the metal removal process. The simulations of groundwater conditions by the addition of salts of different concentrations to groundwater by Elsheikh, also reveal that potassium permanganate gives good results in iron removal and also observed that up to 100% of iron at pH=7.0 can be removed by using half of the theoretically required potassium permanganate dosage [58].

Point-of-use filters: This involves the removal of particulate matter from water by forcing the water through a porous media (filter). Some of these media such as sand, gravel, and clay can be natural, while some others can be a membrane wall of different materials. The filtration method can be classified into two based on the speed of operation. (1) Slow media filtration; (2) Rapid/rough media filtration. Slow media filters typically operate at about 0.1 to 0.2 m/hr with 1 to 2m media depth, the filter has a runtime of several months when compared to rapid sand filters which is about 24-48 hr. The speed of a rapid filter is about 2-10 m/hr. Some typical media filtration for iron removal from groundwater includes carbonate materials, sand, Granular Activated Carbon (GAC), greensand, anthracite, ceramic, or their combinations. The use of these media has been proven to be highly efficient in the removal of iron from groundwater. Calcium Carbonate-Based Mineral (CCBM): CCBM has shown to be an effective technique in the remediation of Fe-contaminated groundwater. It is a commonly used material in drinking water treatment [59]. The working principle involves the dissolution of Calcium carbonate in water and the release of calcium and carbonate ions as shown in Equations 1-3.

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-} \text{..} \text{(Equation 1)}$$

Fe (II) can react with carbonate to form carbonate siderite or calcium siderite as shown in equations 2 and 3: Siderite has a low solubility product ($K_{sp}=3.2 \times 10^{-11}$) and easily forms precipitates (YU, 2011)

$$Fe^{2+} + CO_3^{2-} \leftrightarrow FeCO_3 \text{ ....} \text{(Equation 2)}$$

$$Fe^{2+} + Ca^{2+} + 2CO_3^{2-} \leftrightarrow CaFe\,(CO_3)^{2-} \text{...} \text{(Equation 3)}$$

Fe^{2+} adsorps and/or co-precipitates on the siderite thereby aiding their removal from the water. This technique has been widely utilized. In Florida, Wang, used CCBMs *in situ* to reduce elevated iron concentrations observed in the groundwater underneath several landfill sites [60]. Two pilot studies involving Permeable Reactive Barriers (PRBs) were utilized. The PRBs are constructed and operated at a landfill site with elevated iron concentration. More than 95% of the Fe^{2+} was removed by limestone PRB, and more than 97% of Fe^{2+} by crushed concrete PRB Scan. It was observed that neither PRB showed any indication of deteriorating performance over the 12-month monitoring period. Groundwater pH after passing through the limestone PRB stayed in the neutral range, while pH from the crushed concrete PRB was above 9. The study reveals that CCBMs are effective materials for Permeable Reactive Barriers (PRB) in removing dissolved iron from the groundwater. Hamidi also observed 90% of Fe^{2+} is removed at an optimum dosage of 40 g from pre-ozonized groundwater samples using a limestone filter. The study noted that the percentage removal for Iron also depends on contact time. The experiment showed that the optimum iron removal was observed at 90% at pH 8 and a shaking speed of 350 rpm. According to the study, an integrated ozone-limestone adsorption technique improved Fe removal by up to 99.5%. Abdul Aziz also reported on the effectiveness of removing Fe from pre-ozonized groundwater using a limestone filter. The experiment found that at an ideal dose of 40 g, limestone has good capability to remove more than 90% of Fe. Concurrently, a combined ozone-limestone adsorption method greatly improved Fe removal, reaching 99.5%. Other material-based filters with high efficiency aside from carbonate have also been widely reported across the globe. Pacini, reported the removal efficiencies between 85% and 95% of Fe and Mn from groundwater with the use of rough gravel and sand media filter. Elsewhere in Saskatchewan Canada, Pokhrel, tested for the efficiency of coagulation, Biological Activated Carbon (BAC) filter, and slow and rapid sand filter in the removal of iron from groundwater. The study observed that the biologically active system removed 99.8% of Fe^{2+} with the ozone pretreatment, the average removal increased to 99.9% for Fe^{2+}. The authors further noted that the slow sand filter system was also highly effective in the removal of iron, as it removes 99.8% of iron. However, with ozone pre-treatment, there were no observed significant changes. While, with a rapid sand treatment system, 99% of iron was removed.

Membrane-Based Filtration (MBF): one of the modern techniques of remediation of iron from groundwater is the MBF technique. The MBF includes a myriad of techniques, these include Reverse Osmosis (RO), Microfiltration (MF), Nanofiltration (NF), and Ultrafiltration (UF). MBF operates on the principle of selective permeation, where the membranes act as selective barriers to separate contaminants from the water [61]. These membranes have specific pore sizes that allow the passage of water molecules while blocking the passage of dissolved contaminants, including iron and other impurities.

The filter's pore size determines what sizes of materials can be eliminated throughout the filtration process. The pore size of an ultrafiltration filter is approximately 0.01 microns, while the pore size of a microfiltration filter is approximately 0.1 microns. Nevertheless, dissolved materials must first be adsorbed (with activated carbon) or coagulated (with alum or iron salts) before they can be removed by microfiltration or ultrafiltration [62]. The pores of a nanofiltration filters are around 0.001 microns in size. According to Labban, nano filtration may also be used to soften hard water since it eliminates divalent ions, which are the source of hardness in water [63]. The pores of reverse osmosis filters are around 0.0001 microns in size. Since RO eliminates monovalent ions, it is likely capable of desalinating water. After going through a reverse osmosis filter, water is practically clean. The efficiency of Membrane-Based Filtration techniques (MBF) for the removal of Fe from water has attracted the attention of various researchers around the globe. Norherdawati, investigated the removal of Fe from water with a high organic carbon loading using nanofiltration membranes [64]. The findings reveal that nanofiltration membranes have up to 99% efficiency for the removal of Fe. The efficiency of the ultrafiltration technique for the treatment of iron in groundwater was also investigated by Tang and reported over 95% efficiency [65]. Recently, Chen, investigated the ability of nano-filtration and ultrafiltration membranes as a filtration unit for iron removal. The study observed that nano-filtration membranes have a removal efficiency of about 99% [66].

Flocculation-coagulation: This Involves the use of coagulant to aggregate and settle colloidal particles, metal ions, and suspended solids in water into larger flocs, with the use of oxidants such as Chlorine, Ozone, Potassium Permanganate, Hydrogen Peroxide or Aeration. These oxidants enable the oxidation of Fe^{2+} to Fe^{3+} and subsequent precipitation of iron which can be coagulated into larger flocs, with the aid of flocculants and coagulants thereby allowing it to be easily removed from the water during filtration. Recently Electrocoagulation/flotation has been developed, its working principle involves the destabilization of dissolved or suspended pollutants present in water by the application of electric current in the contaminated water. The pollutant gets removed from water due to the neutralization of its electric charge. The efficiency of Flocculation-coagulation in the removal of groundwater has been documented by researchers across the globe. Zogo, attempted the deferrization of iron by coagulation-flocculation preceded by chlorination [67]. The study observed that under the least favorable conditions (coagulation at free pH), the removal yields varied from 10 to 73% for Fe. Meanwhile, under ideal circumstances (pre-chlorination and coagulation at pH 6.5), the experiments revealed about 95% removal for Fe. Recently in Rumonge (Burundi), Ntakiyiruta, also displayed the efficiency of the removal of Fe from groundwater by aeration and coagulation-flocculation borehole water [68]. According to the study, Fe and Mn were removed by 55.9% and 47.66%, respectively, during deferrization by air blowing; however, Fe and Mn were removed by substantially greater percentages (91.7% and 90.34%) during the coagulation-flocculation method followed by filtration. Elsewhere in Egypt, El-Sayed, compared the filtration of aerated raw water through a filter of sand bed with and without Alum as a coagulant before the filter [69]. The author observed that Fe removal effectiveness ranges from 89% to 97% without coagulation and 78% to 97% with coagulation. The study also observed that coagulation and flocculation can be used for influent iron concentrations up to 3 mg/l and filtration rates up to 240 m^3/m^2/day.

Distillation: Distillation has proven to be an efficient method of water treatment. It involves the heating of contaminated water to evaporation, leaving the impurities behind. After cooling and condensing, the steam turns into pure water [70]. But other organic substances (like toluene and benzene) evaporate with the water because their boiling temperatures are lower than that of water. If these dangerous substances are not eliminated before condensation, they will re-contaminate the purified product. The efficiency of this method holds for the removal of microbes, and organic and inorganic compounds including heavy metals such as Iron [71]. This technique has about 98% efficiency [72]. The choice of distillation as a remediation method for iron-contaminated water depends on the cost-effect evaluation of the analysis (Table 3).

Table 3. Summary of remediation techniques and their implications.

Methods	Operation	Advantages	Disadvantages
Oxidation-precipitation-filtration process	Adding chemical oxidants like chlorine, potassium permanganate, or hydrogen peroxide to facilitate the oxidation, precipitation, and subsequent removal of iron through simple filtration	1. Effective for high iron concentrations. 2. Relatively quick treatment process.	1. Requires chemical addition. 2. Ongoing chemical costs and handling. 3. By-products and waste disposal issues.
Point-of-Use Filters	Various point-of-use filters such as cartridge filters, ceramic filters, and activated carbon filters. This can be used for the treatment of water at the household level to reduce iron concentrations.	1. Simple and cost-effective for small-scale use. 2. No chemicals or complex equipment is required. 3. Easy installation and maintenance.	1. Limited capacity and flow rate. 2. May need frequent replacement of filter cartridges. 3. Not suitable for large-scale or whole-house treatment.
Membrane Filtration (Reverse Osmosis/Nanofiltration)	Reverse osmosis and nanofiltration are membrane-based processes that can effectively remove iron and other impurities by separating water molecules from contaminants.	1. High removal efficiency for iron and other contaminants. 2. Compact and modular design. 3. Suitable for small-scale applications.	1. High initial cost. 2. Requires periodic maintenance and replacement of membranes. 3. Wastewater disposal may be needed.
Flocculation-Coagulation	This involves the use of Chemical coagulants, such as aluminum sulfate (alum) or ferric chloride, to promote the formation of flocs that encapsulate iron particles for removal through sedimentation and filtration.	1. Effective for high iron concentrations. 2. Can also remove other impurities like turbidity and hardness. 3. pH adjustment can enhance treatment.	1. Chemical addition may be required. 2. Sludge disposal and management may be needed. 3. Maintenance and operational costs can be relatively high.
Distillation	Distillation involves boiling water to vaporize it and then condensing the vapor. It effectively removes iron	1. High-purity water with minimal impurities.	1. High energy consumption. 2. Slow water production rate. 3. High initial cost.

	and other impurities, but it is typically used on a smaller scale or for specific applications.	2. Effective for removing iron and other contaminants.	4. Maintenance and operational costs.

Recommendations

It is recommended that considering that the majority of the pollutants come from oil spillage, open landfills, likely fuel station leaks, and industrial effluents and that the research region is mostly made up of soil types that allow infiltration of leachate, to address this pressing issue,

1. It is imperative to implement measures to reduce excess anthropogenic activities that contribute to elevated iron levels in groundwater. Initiatives such as the proper disposal of industrial waste, and the regulation of activities that release iron into the environment are crucial steps toward mitigating the problem at its source.
2. Community awareness and education programs should be implemented to inform the public about the consequences of high iron concentrations in groundwater and promote responsible water usage. Engaging local communities in water conservation efforts and sustainable practices can play an important role in reducing the anthropogenic impact on groundwater quality.

CONCLUSION

Considering the results of the investigation that was conducted

i. The study finds out that the elevated levels of iron result from excess anthropogenic activities such as crude oil spillage, landfill and effluent discharges. Geogenic activities such as saline water intrusion into the aquifers. These factors do not only affect the quality of the groundwater but also have far-reaching consequences on ecosystems and human well-being.

ii. The consequences of high iron concentration in groundwater were determined to be manifold. From a public health perspective, ingesting water with elevated iron levels may lead to adverse health effects, including gastrointestinal issues and potential long-term complications. Additionally, the aesthetic quality of water is compromised, impacting its taste, odor, and appearance, which has further diminished public confidence in the safety of drinking water in some parts of the study area.

iii. Modern remediation techniques with over 90% efficiency in the removal of iron groundwater include oxidation-precipitation-filtration techniques, point-of-Use filters techniques, membrane filtration (Reverse Osmosis/Nanofiltration), flocculation-coagulation and distillation.

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