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Geospatial Analysis and Physicochemical Assessment of Groundwater Quality Vulnerability to Municipal Solid Waste from Landfills

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ABSTRACT: This study aims to find a more realistic management approach to Municipal solid waste (MSW), focusing on Ndokwa West LGA, Delta State, Nigeria. It employs a combination of geospatial analyses and laboratory examination of water samples from three borehole locations congruent to landfills in the study area. GPS-measured positions of the five landfill sites were plotted on the topographic plan of the study area and analysed. This landfills' location, which is the southeastern part of the area, is a lowland. By hydraulic gradient and flow pattern of the area deducted from DEM, these landfills are within the pathway of major groundwater resources. Proximity analyses with 5 to 10 km buffer zones show that most of the topographic features are at risk of considerable pollution due to landfill's leachate into the surrounding area. Groundwater vulnerability map shows 21.5% of the studied area at a high risk of contamination, 7.5% at medium, and ~71% at low risk. The Dissolved Oxygen (DO) levels from the three boreholes were significant, suggesting severe pollution, and pointing to the landfill as the main cause. Colour showed an unobjectionable state and signified pollution of the wells. Temperature (0°C) ranged from 20 to 26°C, much higher than the 5°C limit, set by the WHO and NSDWQ. The water pH ranges from 6.05 to 7.02, suggesting traces of heavy metals in water samples. Nitrate and nitrite have values ranging from 5.0 to 6.162 and 0.251 to 0.455 mg/l, suggesting the water samples contain some contaminants. Lead (Pb) (from 0.25 to 0.65 mg/l) is practically beyond the WHO and NSDWQ permissible limits for heavy metals. The accumulation of lead in landfills has substantial effects on groundwater pollution. The Heavy Metal Index Calculation scale rated the result of heavy metals analyses as 'VI,' representing a 'Seriously Affected' water supply system.

KEYWORDS: Waste, municipal solid waste, groundwater, contamination, landfill, leachate, geospatial analysis, physicochemical assessment, developing countries

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Introduction

Waste is regularly generated from diverse human activities, although it is also a major concern for environmental management. Recent data reporting suggests that the global trend in the spatial distribution of waste is expected to grow rapidly (Maalouf & Mavropoulos, 2023). This is not unexpected considering that the chief players in global waste production: the low- and middle-income earners, dominate the fastest-growing regions of the world. Still, the situation highlights a need for appropriate waste management, which supports conservation by reducing overuse of and reliance on natural resources and promotes sustainability by keeping harmful compounds out of the surrounding ecosystem. However, the combination of elevated poverty levels, growing human populations, urbanisation, and insufficiently financed governmental structures, pose a significant challenge in the proper handling and elimination of municipal solid waste (MSW). This is more apparent in developing countries, such as Nigeria, where the landfill approach dominates (Adedara et al., 2023; Nnaji, 2015; Jagun et al., 2023). The landfill method is still by far the simplest, most economical, and highly cost-effective approach to waste disposal in both advanced and emerging societies. However, the by-product of the disposed wastes, which includes a highly concentrated complex effluent containing dissolved organic matter, inorganic compounds (such as NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+}, $SO4^{2+}$, Cl^-) heavy metals such as (Cd, Cr, Cu, Pb, Zn, Ni) and xenobiotic organic substances commonly referred to as leachate presents significant environmental contamination concerns (Hamidi et al., 2023; Saxan et al., 2022; Teng et al., 2021).

When MSW is disposed of in landfills or open dumps, a whole or partial component of the waste usually travels with groundwater overflow, infiltrates with precipitation, and gradually releases its initial interstitial water (Hamidi et al., 2023). During decomposition, certain by-products infiltrate and contaminate the water that moves through the landfills. The leachate builds up in the lower part of the landfill and seeps down into the soil (Teng et al., 2021). The potential pollution source of leachate originating from the nearby site makes groundwater contamination more likely in the vicinity of landfills. This contamination presents a significant threat to the local and regional consumers of groundwater resources, but also to the broader natural ecosystem (Rashid et al., 2023).

Although the effects of landfill leachate on surface and groundwater have received significant attention in recent times, it remains a major research hub because of urbanisation and rapid population growth, which by far tips the extreme need for quality drinking water. Today, there exists a wealth of approaches to evaluate surface and groundwater contamination (refer to a comprehensive review of approaches in Patel et al., 2023). Empirical analyses of impurities or their modelling using rigorous and analytical procedures are among the major approaches in the current literature (Bose et al., 2023; Cheng et al., 2023). Even though there has been a lot of investigation into this all-important environmental issue, scientific solutions for nutrient release, nutrient leaching, metal discharge through macro pores as suspended solids, and degradation because of sorption of sludge organic matter are still not understood by many. Not to mention, these processes are mostly the primary drivers of groundwater contamination in developing countries (Javed et al., 2017; Kaur et al., 2021; Ngene et al., 2021; Rashid et al., 2019).

How to manage waste in developing countries effectively and more dynamically with data-driven approaches and create aesthetically valued urban areas still motivates research. Understanding the location of landfills and their spatial correlation with groundwater resources is crucial for developing a multi-criteria approach to MSW management and safeguarding groundwater resources in a region (Makonyo & Msabi, 2021). The significance of safeguarding groundwater resources for the well-being of humans and other biotic and abiotic components of the environment cannot be underestimated. Within the context of climate change, this is an issue of concern for countries with persistently low Environmental Performance Index (EPI) cited in Wolf et al., 2022, that suffer from severe to acute water shortages, and inexorable hazards such as flooding. While open dumps are widely accepted as a means of disposing of solid wastes in developing countries, although Ferronato and Torretta (2019) have intuited that most of them are being discarded today, more research should focus on the assessment of the groundwater quality, and the outcome should inform policies and plans for aquifer and local water resources protection and management of the wider aquatic ecosystem.

The study's main aim is to examine MSW, and its effects on groundwater resources in the area – Ndokwa West LGA of Delta State, Nigeria – and to reveal MSW management failures and major health risks faced by the local communities on account of leachate's contamination of the groundwater resources. It utilises geospatial analyses to identify, map, and topologically assess the vulnerability of aquatic ecosystems to landfills in the study area, and then, with laboratory investigations, examines the physical, and biochemical properties of water samples collected from groundwater resources that are topologically connected to open dumps in the study locations.

Review of Municipal Solid Waste Management

Extensive research shows a clear link between the disposal of solid waste in landfills and the persistent contamination of groundwater resources on a global scale (Alao, 2023; Javahershenas et al., 2022). Over the years, various waste handling techniques have been adopted, including incineration, source reduction, recycling and composting, but the landfill method, which is widespread and has drawn much attention, often depends on the technologically advanced societal capacity (Vijayalakashmi, 2020). The cavities where solid waste is frequently disposed of comprise burrow pits, valleys, former quarry locations, excavations, or a specific area within urban residential and commercial zones where the ability to gather, manage, discard, or recycle solid waste with considerations of cost-effectiveness and safety is restricted (Mohammed et al., 2021; Seruga, 2021).

Groundwater pollution stems mainly from the effects of industrialisation, urbanisation, and rapid population density (Arshad & Umar, 2022; Das et al., 2019). These factors have been progressively expanding over time, and indeed their environmental impacts have received a lot of research attention. However, the current realities are clear signs that there is still a need for a more targeted approach. Groundwater quality is endogenous to the physical and chemical parameters that are soluble, resulting from both routine weathering of parent rock materials and extant anthropogenic activities. Landfills' leachates cause harmful chemical and biological components to diffuse into the groundwater and other aquatic ecosystems, undermining their natural properties, quality, and usability (Modupe et al., 2020). This condition upsells the need for research to assess the topographic, ecological, and economic consequences of leachate, the health implications and quality assurances of groundwater resources, and the more convenient method of MSW management.

Even now, the management of solid waste is a difficult issue for stakeholders because of the multivariate and ever-dynamic issues that are involved – demography through the rapid growth of the human population, and industrial and technological advances which contribute to more complex wastes that infiltrate the soil – and the limited knowledge that exists currently regarding the complex science involved in leachate's pathway to groundwater resources (Navarro & Vincenzo, 2019). Leachate from landfills enters the groundwater by infiltration. The widely circulated science promotes the idea that leachate is a chemical component formed when excess rainwater filters through landfill waste. So, the groundwater resulting from rainfall carries leachate which settles at the bottom of landfills, reaching the subsoil after decomposition of the solid waste has occurred. The means to mitigate this process is at the core of MSW management, and over the years, various authors have provided epistemological perspectives, especially in less developing countries (Modupe et al., 2020).

Studies that consider solid waste management techniques present a review of the myriads of improper approaches and their consequences, in sharp contrast to the environmentally friendly ones (e.g. Das et al., 2019; Hamidi et al., 2023; S. Nanda & Berruti, 2021). Jouhara et al. (2017) and Aruna et al. (2018) argue that improper waste management is defined by the conventional methods involving burning of wastes, disposal into rivers, seas, and waterways, and dumping on the roadsides. The immediate implication of these practices is the distortion of environmental amenity – pollution of air and water, offensive odour release, and insect breeding, which are the main sources of tropical diseases such as malaria which is pervasive in poor countries. Within the environment, improper waste management has a severe effect on agricultural soils and subsequent reduction in yield and productivity (Alghamdi et al., 2021; Tingayev & Cheprunova, 2022). There are serious concerns for global warming, increased daytime temperature, ozone layer depletion, and climate change because of Carbon II oxide produced when solid wastes are burned in the open air (Ikhlayel, 2018; Reyna-Bensusan et al., 2018). In a study that reviewed the immediate and long-term impacts of improper waste disposal in developing countries, Navarro and Vincenzo (2019) and Lone et al. (2020) underlined the environmental consequences and social *causatums*. A feeling of having lost the image that defines a community, and the essence of power within a community ranks in terms of morals and ethics, prevails. On a more specific note, while the health implications of inappropriate waste management are the main impetus to re-thinking better ways of managing MSW, a piece of up-to-date knowledge regarding the geospatial condition of the environment and the biochemical characteristics of its aquatic ecosystem for places that are still using the landfill waste disposal approach should draw the attention of research.

Research on landfills' pollution of the aquatic ecosystem groundwater quality has existed in the academic literature for a long time. The pre-eminent and consistent episteme in various investigations is that water samples from sources near landfills contained trace to significant amounts of chemicals, heavy metals, and bacteriological compounds (Imri et al., 2020; Keeren et al., 2020). Recently, Owamah et al. (2021), with reference to the Niger Delta University of Nigeria, examined water samples from boreholes and hand-dug wells for biological and physicochemical components. The study identified the presence of total coliform bacteria and *Escherichia-Coli* (*E-coli*) in the samples, and small elevated values of Pb^{2+} and Cd^{+} which were linked to petroleum exploration and heavy industrial activities going on in the surrounding areas. Such an investigation is just one out of many that have revealed alarming situations with the country's aquatic ecosystem, particularly within the context of groundwater resources.

It is a truism and of course, there is ample evidence of microbial action on the groundwater most likely through the country's extensive anthropogenic activities – poor sanitation. So, the leaching of heavy metals: most notably Ca^{2+} and Mg^{2+} into the groundwater table has arguably caused higher levels of water hardness. Since the groundwater resources in the study area serve multiple domestic purposes, there is an inch of certainty that health problems (including the spread of typhoid fever and worm infestation) of MSW management will be severe for both human beings and animals. Many researchers for example Owamah et al. (2021) and Mgbolu et al. (2024) are of the view that industrial waste disposal and the build-up of heavy metals are among the potential threats to groundwater resources in Nigeria. The presence of Fe, Pb, and Cr in significant amounts increased toxicity levels in the groundwater and therefore posed an even more serious environmental risk to humans, animals, and even the soil (Nkwunonwo, Odika, & Onyia, 2020). As these heavy metals diffuse into the soils, they continue in the local food chain through grazing animals and end up in the digestive system of human beings who eventually consume the animals. Within the human system, the effects of heavy metals could be fatal in extreme cases.

Finding solutions to mitigate these effects is also a crucial topic in the current literature. This is a critical point in ample global case studies (refer to Table 1 for pertinent examples) that have analyzed the concentration of pollutants in runoff and groundwater resulting from open dumping, providing essential policy information. Although responsible governance and strict compliance to actionable waste management policies have been promoted. However, to prevent pollution of nearby groundwater resources, it is important to note that situating the landfills at considerable distances from residential areas – is both inevitable and a major practical approach. This is the responsibility of geospatial analyses which are being conducted in the present study. Other suggestions from various authors include sorting and treatment of waste before disposal, reconfiguration of landfills using clay or plastic liners to hinder leachate infiltration into the water table, implementation of eco-friendly methods to recycle greenhouse gases emitted from the landfill, and establishment of a sustainable land management plan (Imri et al., 2020; Keeren et al., 2020; Sachin & Dhanesh, 2018). These views require extensive laboratory experiments to know the level of contamination emanating from local landfills and then use knowledge-based techniques such as geospatial science for site selection for landfills. Thus, it explains why the present study is significant regarding the MSW in developing countries where these core science-based approaches to waste management have been little addressed in the literature.

Based on the empirical grounds and conclusions from previous studies, this study intends to conduct a thorough physical and bio-chemical analysis of the groundwater samples around the landfill sites in Ndokwa West LGA, while utilising a geospatial (GIS) approach to evaluate the topological relationships between landfills and geographic footprints, and to ultimately model the groundwater quality vulnerability to landfills in the area. This is aimed at ascertaining the current level of

Table 1. Sample Case Studies Revealing the Concentration of Landfills' Contaminants in Groundwater, Compared with the International Benchmarks, and Drinking Water Standards.

STUDY	CITY/REGION	COUNTRY	ENVIRONMENT POLLUTED	POLLUTANT	CONCENTRATIONS	LIMITS
Prechthai et al. (2008)	Nonthaburi	Thailand	Runoff (Mg l^{-1})	Mn	0.49>	0.4
				Cr	0.99>	0.05
				Cd	0.01>	0.003
				Pb	0.1>	0.01
				Ni	0.5>	0.07
				Zn	1.32	4
				Cu	0.63	2
				Hg	0.95>	0.002
Kanmani and Gandhimathi (2012)	Tiruchirappalli	India	Groundwater (Mg l^{-1})	Cd	0.16–1.04>	0.003
				Cu	0.6–2.7	2
				Mn	0.2–1.8>	0.4
				Pb	0.8–5.1>	0.01
Reyes-López (2008)	Mexicali	Mexico	Groundwater (Mg l^{-1})	BOD5	4.3–6.5	20[a]
				COD	23.5–188>	120[b]
				Na	600>	200
				S04-	1,000>	300
Ashraf et al. (2013)	Sepang	Malaysia	Groundwater (Mg l^{-1})	BOD5	128–142>	120
				COD	2,698–2,891>	120
				Cl	123.8–127.7>	5
				Ni	0.44–0.65>	0.07
				As	0.06–0.07>	0.01
				Pb	0.04–0.08>	0.01
Abd El-Salam and Abu-Zuid (2015)	Alexandria (Landfill)	Egypt	Groundwater (Mg l^{-1})	Ni	0.007–0.152	0.07
				Pb	0.002–0.009	0.01
				Cr	0.006–0.058>	0.05
				Mn	0.039–0.673>	0.4
				Cd	0.001–0.051>	0.003
				Zn	0.001–0.343	4
Keeren et al. (2020)	Malaysia	Malaysia	Groundwater (Mg l^{-1})	LPI	15.32	0
Imri et al. (2020)	Hod Hasharon	Israel	Groundwater (Mg l^{-1})	DOC NH4+ Fe2+	27–33 30–35 18–35	0
Sachin and Dhanesh (2018)	Varanasi Ramna	India	Groundwater (Mg l^{-1})	LPI	16.81 12.40	0

Note. Water limits (World Health Organisation [WHO], 2004).
[a]Water release after wastewater treatment.
[b]Leachate Potential Index.

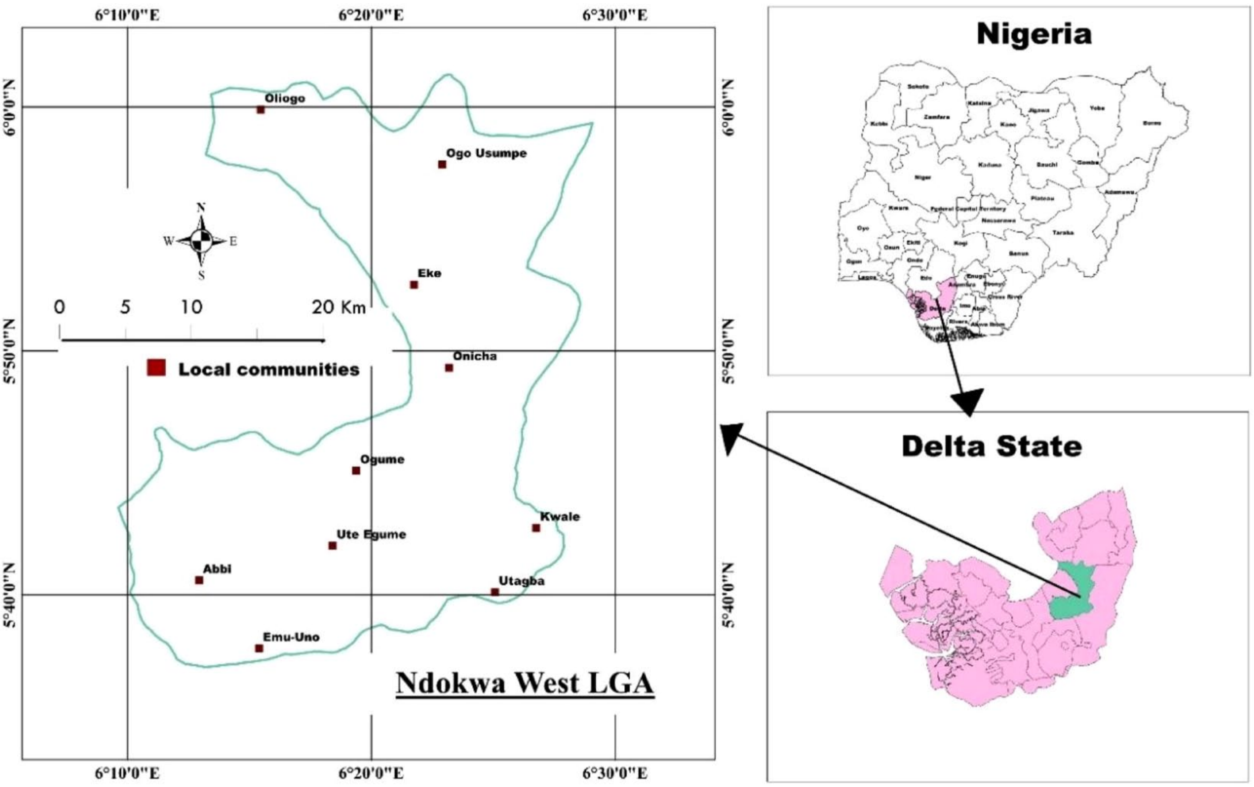

Figure 1. The study area: Ndokwa West LGA, Delta State in Nigeria, a West-African sub-Sahara country.
Source. Figure was drafted by authors.

contamination and to further recommend proper management practices aimed at forestalling imminent health hazards subject to the improper MSW management practice in the study area. This study is of great importance as it connects to the alarming rate at which privately owned boreholes are spreading in the study area, especially within and around the landfill site in Ndokwa West.

Description of the Study Area

This study was based on landfills along Ashaka Road in Kwale, Ndokwa-West LGA of Delta State, Nigeria. The area lies within Latitudes 5° 36′ and 6° 18′ North of the equator and Longitudes 6°10′ and 6° 31′ East of the prime meridian (Figure 1). It is characterised by a tropical climate zone with a hot temperature and a distinct rainy and dry season. The rainy season comes in April and finishes in October, often characterised by occasional flooding in some parts of the study area, which raises a major concern for MSW management. The dry season for the area starts in November and ends in March, with a hazy northeast trade wind bringing harmattan to the area between the months of November and January. The annual temperature ranges from 28°C to 33°C with a mean annual rainfall of about 3000 mm.

The geological formation of the area exhibits the distinct traits of a gently sloping, flat, and unremarkable plain, primarily composed of sandstone. When rain falls, the water intermixes with the decaying components of the waste dump and draws out chemicals or constituents from the waste to produce leachate (Anomohanran, 2014). The leachate seeps through the base of the refuse dump, collecting dissolved materials from the decomposing waste, and may be extremely toxic, depending on the characteristics of the landfill. It finds its way through the pores and spaces of the sedimentary sandstone, which provides a passage for the leachate to pass through to the groundwater underneath, contaminating the groundwater resources.

Given the assessment of Aweto and Akpoborie (2011), the area is highly influenced by the geology and groundwater resources of Delta State which are characterised by the presence of small quantities of calcium and magnesium ions. However, it is important to note that extensive human activities can contribute to an increase in the concentration of these ions, which can impact negatively on microbial processes in the area. In the period of increased precipitation, the groundwater in the saturation zone experiences expansion because of the infiltration rate exceeding evaporation, resulting in seepage into the base of the excavation pit, directly contacting the landfill's leachate. Subsequently, it recedes underground, from a topographically elevated area to a lower region, towards various borehole locations for extraction (Plummer et al., 2001, 2021). This mechanism is a common occurrence in landfills in Kwale, Ndokwa-West LGA, where the perceived pollution of the groundwater is thought to have an unfavourable impact on public health, the larger community, and consumers of water.

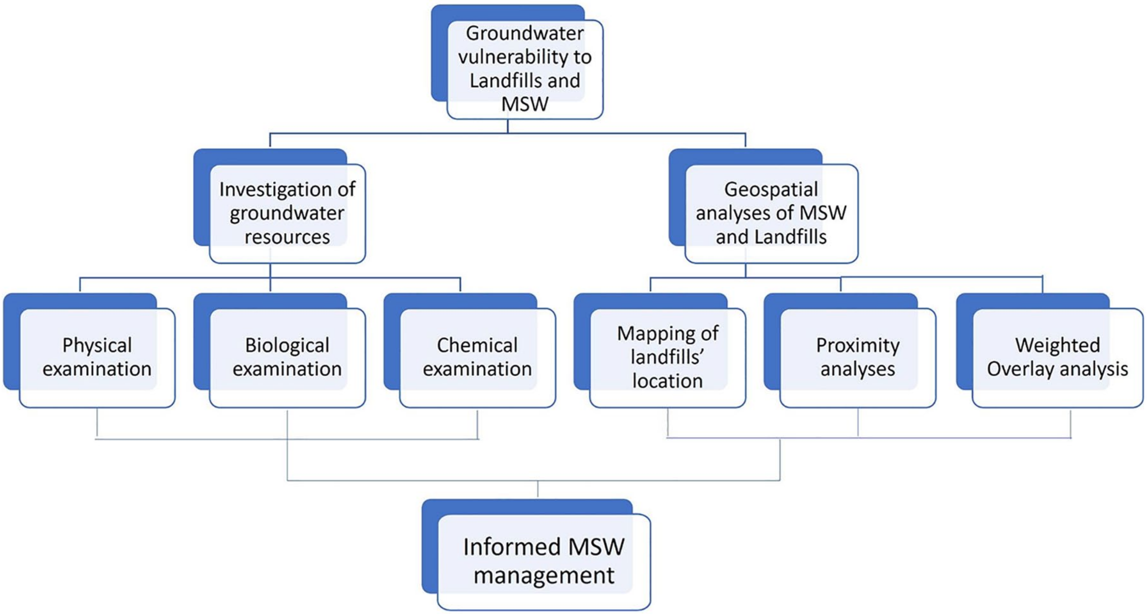

Figure 2. Flow diagram of the study's design and method.

Methodology

This study is framed around the understanding that MSW is poorly managed in Ndokwa-West LGA of Delta State, Nigeria, and that leachate from landfills contaminates nearby groundwater resources. Yet, the composition, extent, and pathway of contamination as well as the level of vulnerability of groundwater are unknown, the implications being that an informed decision is needed to provide solutions to the health, economic, and ecological consequences of improper disposal of MSW in the study area. To this effect, this study utilised data on landfill's location, and groundwater resources with other ancillary datasets and applies two important techniques – geospatial analyses to examine the proximity and vulnerability of groundwater resources with respect to landfills, and groundwater quality assessment in terms of its physical biological and chemical compositions.

Assessment of groundwater vulnerability was accomplished by integrating an assemblage of datasets – soil, slope, rainfall, land use, digital elevation model (DEM), main sources of MSW, and elevation – within a weighted overlay tool in ESRI ArcGIS 10.8 geospatial science software. This section includes descriptions of the research data and their sources, their post-processing, and preparations, as well as the various analyses that have been conducted in this research. Figure 2 is a schematic description of the research methodology.

Description of the research data and their sources

The management of MSW is a significant aim of urban development, and it is even captured by some goals enshrined within the global sustainable development agenda of the United Nations (UN, 2015: SDGs) – good health and wellbeing (SDG-3); clean water and sanitation (SDG-6); and sustainable cities and communities (SDG-11). The high point is to make the environment safe from any danger from air, water, and land and to set forth the science that promotes the sustainability of ecosystem processes. Pujara et al. (2019) revealed how the management of MSW in India promotes mitigating environmental impacts to achieve sustainable development ambitions. With the new global realities in land and water pollution, sustainability science must advance its agenda on exploring spatial and temporal characteristics of MSW, along with its impacts on local ecosystems, and efforts being made to identify contaminants' pathways and leachates and address them.

The present study, which undertakes a location-based investigation of MSW with a triumvirate assessment of its influence on groundwater resources in Ndokwa West LGA, is of significance within the context of actualising SDGs for the study area and the region. It utilises geospatial techniques to coordinate, identify, map, and topologically assess landfills in the study area, and then, with a laboratory investigation, examines the physical, and biochemical quality of water samples collected from groundwater resources that are topologically connected to landfills' location within the study area. Figure 3 delineates the spatial extent of the sampled data. The pictures on Plates 1 to 5 were taken from those dumpsites – which form the scientific realism of the present research – and were geocoded to the sampled areas. This is presented in Figure 4. Table 2 presents a listing of all the datasets used in the study and their sources. Besides this listing, a few other datasets (such as elevation, slope and contour) were derived from the DEM.

Dumpsite 1 had reached the anaerobic, non-methanogenic phase, which occurred approximately 3 weeks after the waste was deposited. Dumpsites 2 and 4 were still in the initial stages of anaerobic degradation, which had only begun a few days

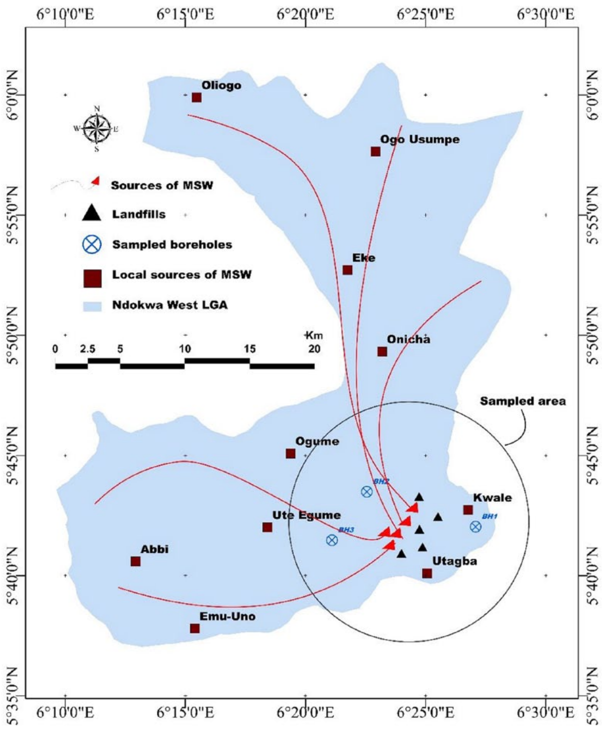

Figure 3. Study area map showing the spatial extent of the sampled data, location of the landfills and the sampled boreholes.
Source. Drafted by authors.

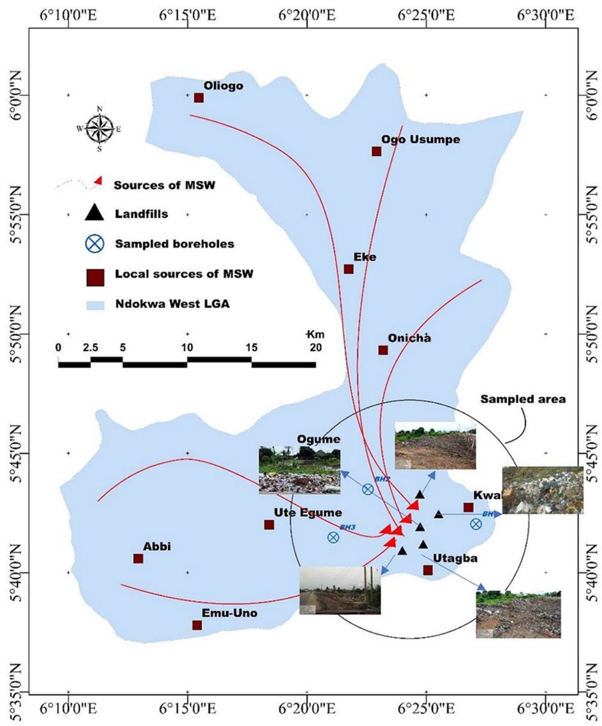

Figure 4. Study area map showing the spatial extent of the sampled data, location of boreholes and landfills and geocoded pictures of dumpsites.
Source. Drafted by authors.

Plates 1-5. Shows waste dumps on the landfill site at different stages of degradation.

prior. Dumpsites 3 and 5, on the other hand, had progressed to the anaerobic, methanogenic phase, which had been 6 months since the waste was initially deposited.

Data preparations and post-processing. The main datasets that needed to be prepared were data representing the local sources of solid waste in the area, digital soil data, elevation and slope.

Table 2. Study's Data Requirements and Their Sources.

S/NO.	DATA	FORMAT	SOURCE
1	Landfill sites	GPS coordinates, images	Field data collection (August 2023–September 2023)
2	Digital Elevation Model: 1-arc second (30 m) SRTM	Raster image (Geotiff)	NASA's USGS earth explorer https://earthexplorer.usgs.gov/
3	Political Boundary of the study area	Vector (shape file)	Online: GIS data MAPOG https://gisdata.mapog.com/nigeria
4	Topographic features of the study area	Vector (shape files)	Digitized from google earth
5	Boreholes	4″ Existing boreholes (water samples)	Field data collection (August 2023–September 2023)
6	Land use data	Geotiff	Sentinel-2 10 m land use/land cover from ESRI hub: https://livingatlas.arcgis.com/landcover/
7	Rainfall data	High resolution gridded data v4.07	University of East Anglia Climatic Research Unit (CRU) https://crudata.uea.ac.uk/cru/data/hrg/
8	Digital soil data	Shapefiles	Nkwunonwo, Okeke, et al. (2020): https://doi.org/10.1016/j.dib.2020.105941
9	Literature	Summaries, Quantitative	Scholarly databases

We included a contour map to validate the elevation data. The rainfall and land use data representing the study area of interest were meticulously cropped from their base maps using data management tools in ESRI ArcGIS. Sentinel-2 10 m land use/land cover dataset which is available under a creative commons by attribution (cc by 4.0) license is the base map source of the land use data, while the University of Anglia's CRU (Climatic Research Unit) 0.5° high-resolution gridded precipitation (time series) dataset is the source of the rainfall data. Detailed information about this dataset, including its limitations and merits, has been documented in Harris et al. (2020).

Ten random points covering the Ndokwa West extent were created in GIS and used to prepare the point source data for local sources of solid waste. Of these points that represent the various communities in the area, six of them fall within the medium population density areas while four were in the high population density areas. These are representatives of the various houses from where the solid waste emerged. From various studies, we extrapolated the values of point-source solid waste from households, although this was a bit hard because of the inconsistencies and overgeneralisation in previous studies related to the amount of point-source solid waste generated by households per capita per day. The current values related to various studies are given in Table 3, which showed values for the sub-Saharan regions, Nigeria, Abuja, and Lagos as the benchmark. We chose the values presented by Kaza et al. (2018) since it is the most recent and most related to other studies.

Using two values of Kaza et al. (2018) we computed the average solid waste generated: about the 25.8 kg collected in two months (by using 0.43 kg/capita/day) and 30.6 kg for the high population density areas (by factoring 0.51 kg/capita/day). We computed these values using 2 months since that is how long the field data collection and sampling lasted. Table 4 shows the values, which were eventually used to create a raster layer of MSW point sources by IDW interpolation. The resulting image is shown as MSW spatial distribution in Figure 5.

Soil data was extracted from Nigeria's GIS-based digital soil map and soil database project of Nkwunonwo, Okeke, et al. (2020) which is freely available in Mendeley's repository. This dataset records 58 soil mapping units of Nigeria's soil distribution with extensive metadata including soil slope, soil drainage system, soil pH scale and soil topography. In this study, the Ndokwa-West area of interest was clipped off using the extraction tool of ESRI ArcGIS 10.8. The resulting data which is shown in Figure 6 encloses four soil mapping units (2a, 5a, 5c and 9a) and their metadata.

The elevation and slope data were extracted from the 1-arc second (that is 30-m horizontal resolution) Shuttle Radar Topography Mission (SRTM) DEM (Figure 7) freely available from NASA's USGS Earth Explorer repository. The Spatial Analyst tool available in the ArcGIS was used to convert the DEM to slope. Elevation was created from the z-values. Contour values were also extracted to have a better appreciation of the topographic profile of the area. These datasets are shown in Figures 8 to 10.

Also, gridded global rainfall data from the University of Anglia's CRU and first added as a raster to the ArcGIS software using a multidimensional tool. Land use data from Sentinel's data hub was equally added. This dataset is accompanied by metadata (an Excel sheet) which describes the land use and land cover classes and how to assemble them in an analysis. Ndokwa west area of interest was then clipped off from these datasets using the raster processing data management tools. Figures 11 and 12 are the data output.

Table 3. Documented Point Source Amounts of Municipal Solid Waste Across Various Geographies.

LOCATION	AMOUNT OF MSW GENERATED	EVIDENCE (STUDY)
Sub-Saharan Africa	0.5 to 0.8 kg/capita/day	Salami et al. (2019); Adedara et al. (2023)
Nigeria (Summarised)	0.51 kg/capita/day	Kaza et al. (2018)
	0.49 kg/capita/day	Nnaji (2015)
	0.43 kg/capita/day	Oyebode (2018)
Abuja	0.634 kg/capita/day	Ogwueleka (2013).
	of 0.67 kg/capita/day	Anyaegbunam (2013)
	0.57 kg/capita/day	Nnaji (2015)
	0.5 to 1.5 kg/capita/day	Kadafa (2017)
Lagos	0.95 kg/day; 22.75 kg/week in Medium density areas; 30.39 kg/week in High density areas	Aliu et al. (2014)
	0.5 kg/capita/day	Anestina et al. (2014); Ezeah and Roberts (2014)
	0.72 kg/capita/day	LAWMA (2012) – cited in Olukanni and Oresanya (2018)

Table 4. Computed Amounts of MSW From Point Source Locations Within Ndokwa West LGA.

S/NO.	LOCAL COMMUNITY	MSW AMOUNT (KG/CAPITA/DAY) *2 MONTHS	POPULATION DENSITY
1	Ogo-Usumpe	25.8	Medium
2	Eke	25.8	Medium
3	Oliogo	30.6	High
4	Abbi	30.6	High
5	Onicha	30.6	High
6	Ute-Egume	25.8	Medium
7	Ogume	30.6	High
8	Kwale	25.8	Medium
9	Utagba	30.6	High
10	Emu-Uno	30.6	High

Data analyses

This study conducts a geospatial analysis of landfills, assessment of groundwater quality, and vulnerability to the MSW. This addresses a major lacuna in knowledge of groundwater quality, and in stakeholders' decisions towards establishing potential landfill sites within the study area. Descriptions of these analyses are the focus of the next subsections.

Geospatial analysis of MSW and groundwater vulnerability modelling. The goals of much of what has been in MSW management revolve around enhancing the efficiency of MSW management. In the current literature, Lu et al. (2015) explored a smart routing for municipal solid waste collection. The authors employed Dijkstra's ODC network analyst to devise a novel routing approach for MSM management in Sfax, the second most densely inhabited city in Tunisia. Amal et al. (2020) used GIS and multi-criteria decisions to analyse municipal solid waste collection. Whilst environmental and socio-economic constraints to landfills are the primary focus of the geospatial analyses in these studies, findings showed the important spatial relationships that existed between the MSW and sensitive ecosystem variables, such as the groundwater resources, houses, road networks, residential and commercial areas, and the pathway to leachates pollution. Integrating spatial analyses and evaluation of water samples contiguous to landfill sites is crucial to comprehending the effects of landfills on the ecosystem and devising strategies for sustainable conservation of the local ecosystem resources.

Against the foregoing background, the present study aimed to identify proximate sensitive environmental and socio-economic features and footprints to the landfills and examine how they are being impacted by landfills through an assessment of water samples from nearby groundwater resources. For this to be achieved, this study utilised land use and land cover data, geopolitical limits data, and topographic information of the study area showing built-up areas and settlements, water bodies, roads, vegetation and soil. The DEM used in this study with a 30-m horizontal resolution was required to create the area's elevation and drainage outlines. Then, maps showing the spatial distribution of the landfill sites, and point sources of MSW were produced. Proximate geographic features were identified through a buffer analysis of these landfill sites. Multiple buffer rings (1, 2, 5 and 10 km) were created around the five landfills and dissolved into a single raster feature for

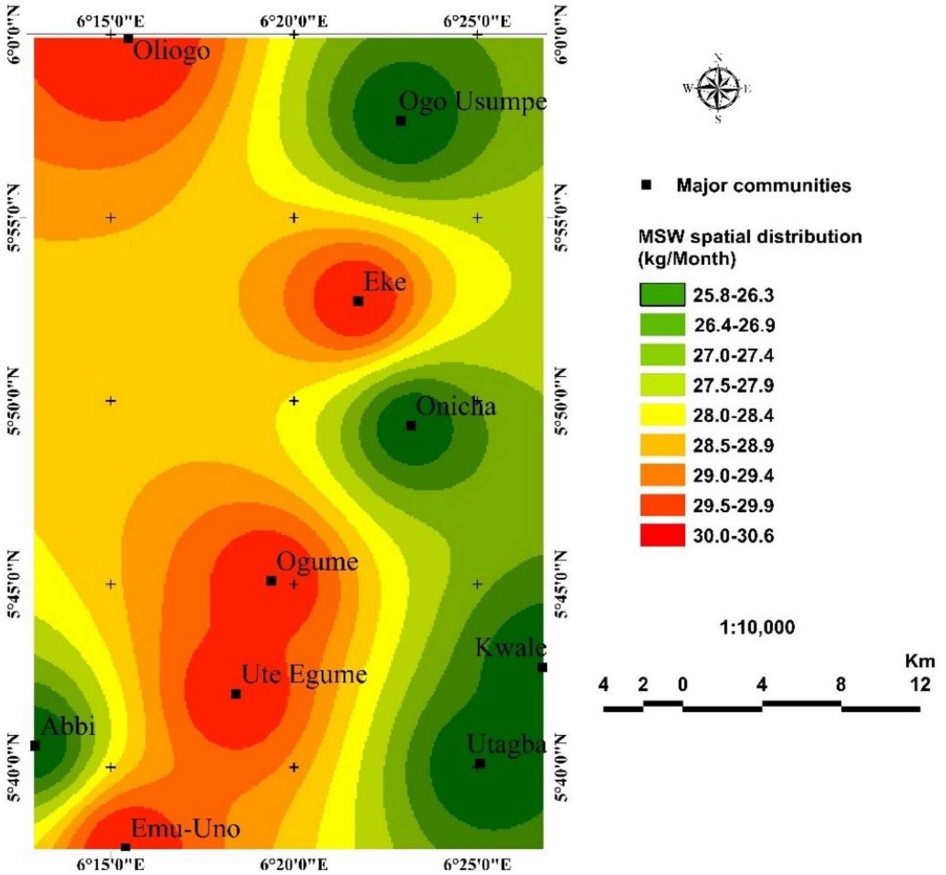

Figure 5. Spatial distribution of Municipal solid waste in Ndokwa West.

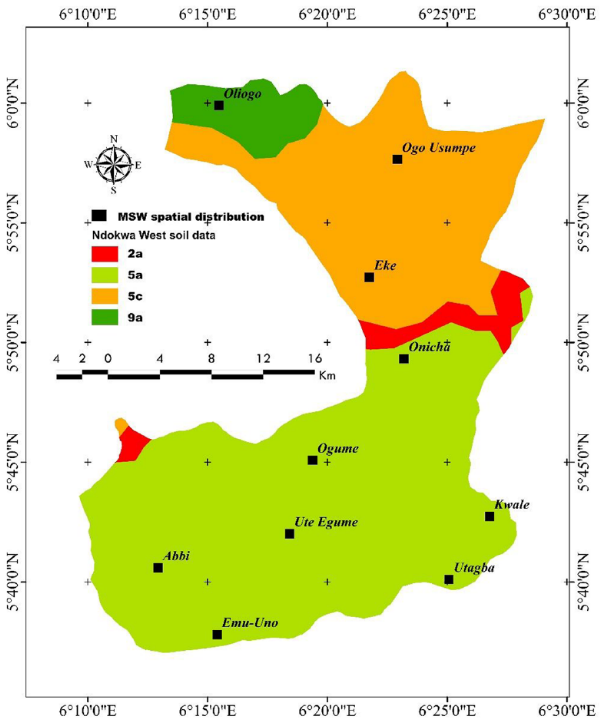

Figure 6. Soil data of Ndokwa West LGA showing four soil mapping units: 2a, 5a, 5c and 9a.

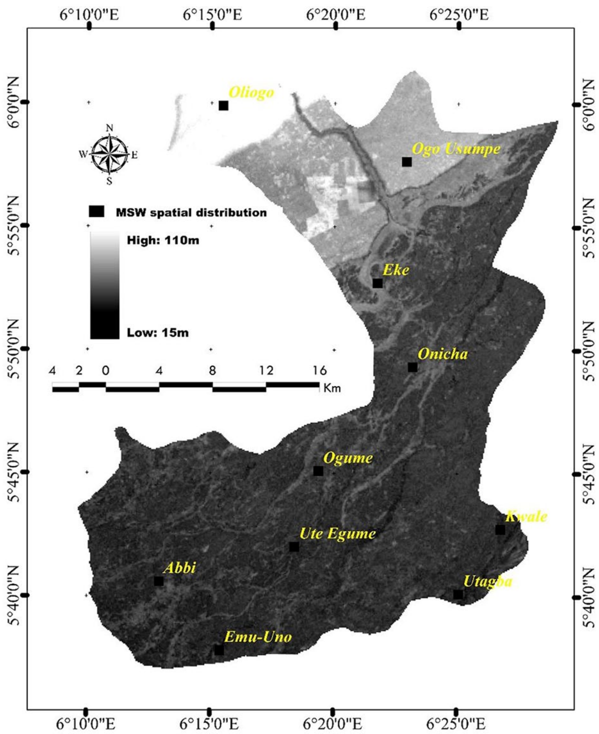

Figure 7. 30-m horizontal resolution shuttle radar topography mission (SRTM) DEM from USGS. This represents Ndokwa West LGA.

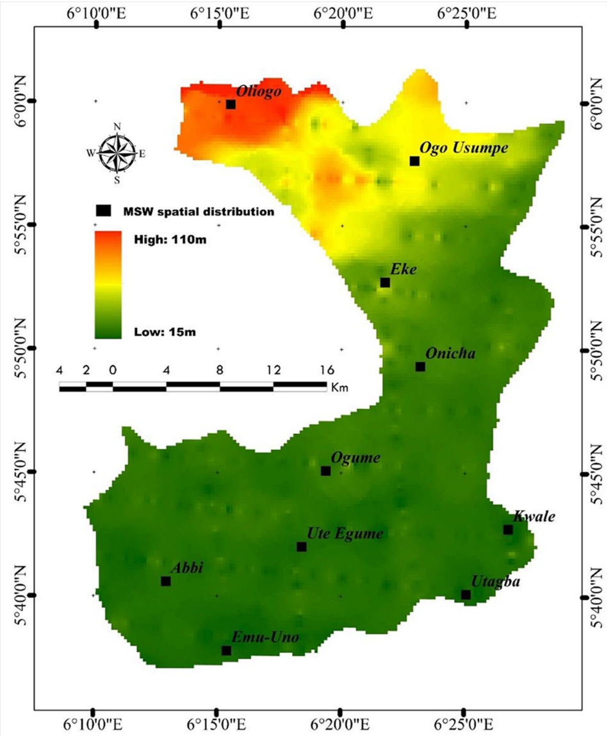

Figure 8. Elevation data of Ndokwa West LGA created from the USGS 30-m horizontal resolution SRTM.

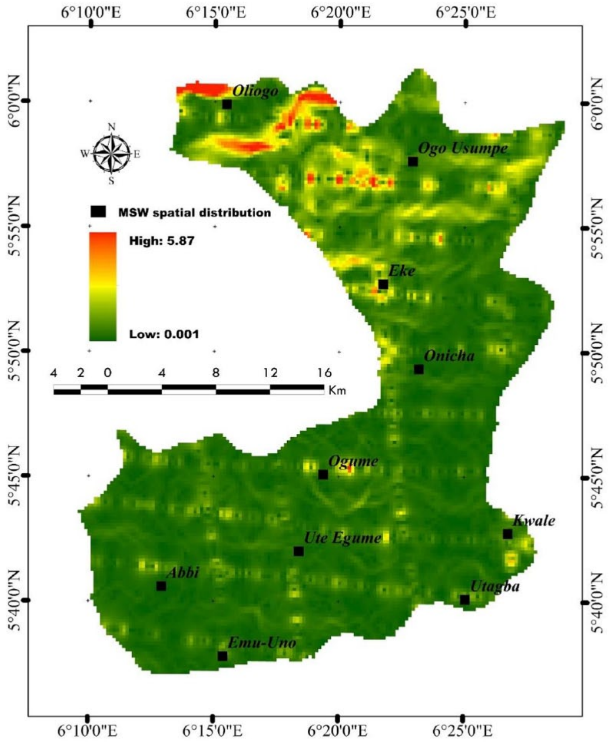

Figure 9. Slope data of Ndokwa West LGA created from the USGS 30-m horizontal resolution SRTM.

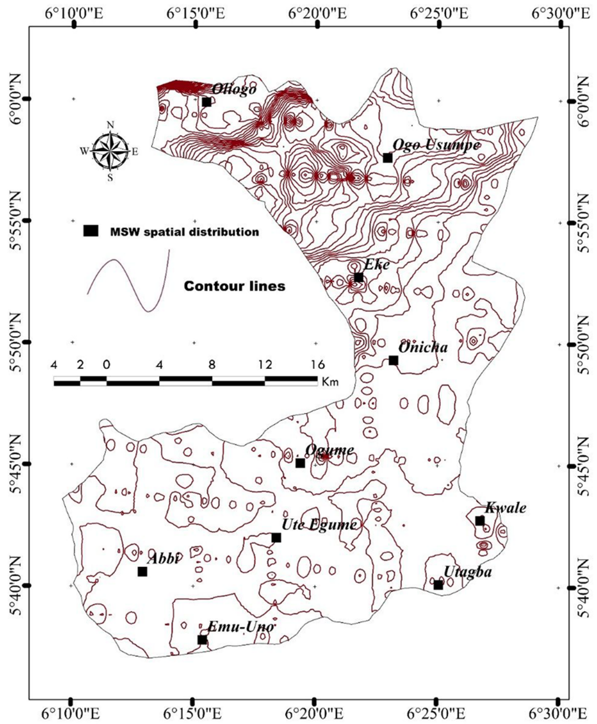

Figure 10. Contour map of Ndokwa West LGA based on the USGS 30-m horizontal resolution SRTM.

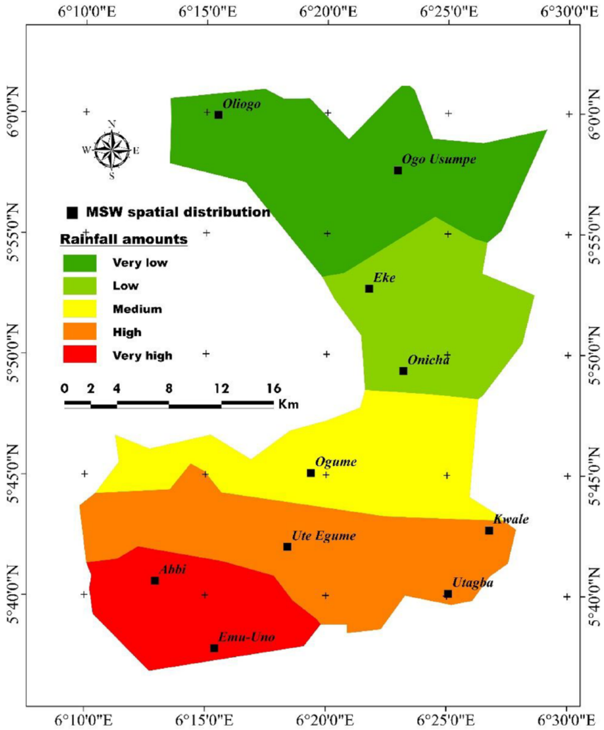

Figure 11. Time series rainfall data of Ndokwa West LGA, based on University of Anglia's Climatic Research Unit (CRU) data. It is gridded at 0.5 resolution.

use in estimating the vulnerability profiles of the study area's groundwater.

The most significant aspect of this study's geospatial analyses, and of course its culmination is the production of a groundwater quality vulnerability map of the study area. This was achieved using the weighted overlay technique in the GIS spatial analyst tool to merge various datasets that were created.

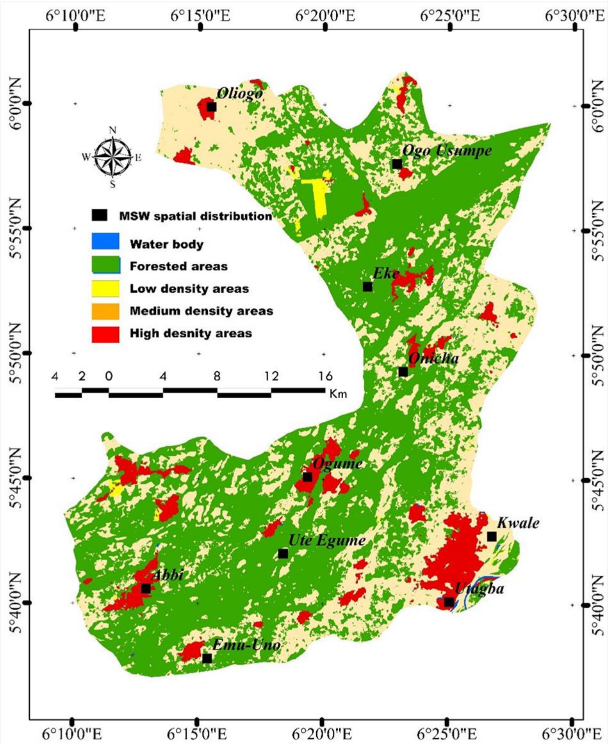

Figure 12. Land use and land cover data of Ndokwa West LGA, based on Sentinel's 10-m land use and land cover data hub.

Seven datasets representing key attribution and causative variables of groundwater vulnerability to MSW were merged, specifying their weights based on the varied acknowledged importance of variables and evidence drawn from previous studies for example Bera et al. (2021). Table 5 shows the overlay variables and the assumed weights. Three groundwater vulnerability profiles emerged – low, medium and high. To relate these profiles to the land use and land cover characteristics of the area, estimates of the spatial extent for each of the vulnerability profiles were assessed along with the dominant communities within each of the areas. Figure 13 is the flow diagram of this operation.

Assessment of groundwater quality and characteristics. Sampling points for groundwater quality analysis consist of three existing boreholes, measuring 4 to 6 inches in diameter, with an average depth of 40 m in the basement formation. Although the selection of the boreholes was also by randomising using the GIS, authors ensured that the selected boreholes were easily accessible, shallow, were in constant use and that their radial distances from the median point of the five landfills were 50, 80 and 100 m. The water samples from the boreholes were stored in clearly labelled 2-l polyethylene bottles, and then preserved at 4°C for subsequent analysis, to preserve their inherent properties. These analyses, undertaken at Spring Laboratories in Awka, Anambra State,

Table 5. Weighted Overlay Analysis Table Showing the Seven Variables That Entered the Analysis Their New Reclassified Classes and the Assumed Weights.

S/NO.	VARIABLE	CLASSES		WEIGHT (%)
1	Local sources of MSW	Very low	1	40
		Low	2	
		Medium	3	
		High	4	
		Very high	5	
2	Elevation	Very low	5	5
		Low	4	
		Medium	3	
		High	2	
		Very high	1	
3	Slope	Very low	5	5
		Low	4	
		Medium	3	
		High	2	
		Very high	1	
4	Rainfall	Very low	1	5
		Low	2	
		Medium	3	
		High	4	
		Very high	5	
5	Landfills (buffer rings: proximity to groundwater resources)	1 km	1	20
		2 km	3	
		5 km	4	
		10 km	5	
6	Soil data	2a	1	10
		9a	3	
		5c	4	
		5a	5	
7	Land use	Water body	1	15
		Forested	3	
		Low density	1	
		Medium density	3	
		High density	5	
Total				100

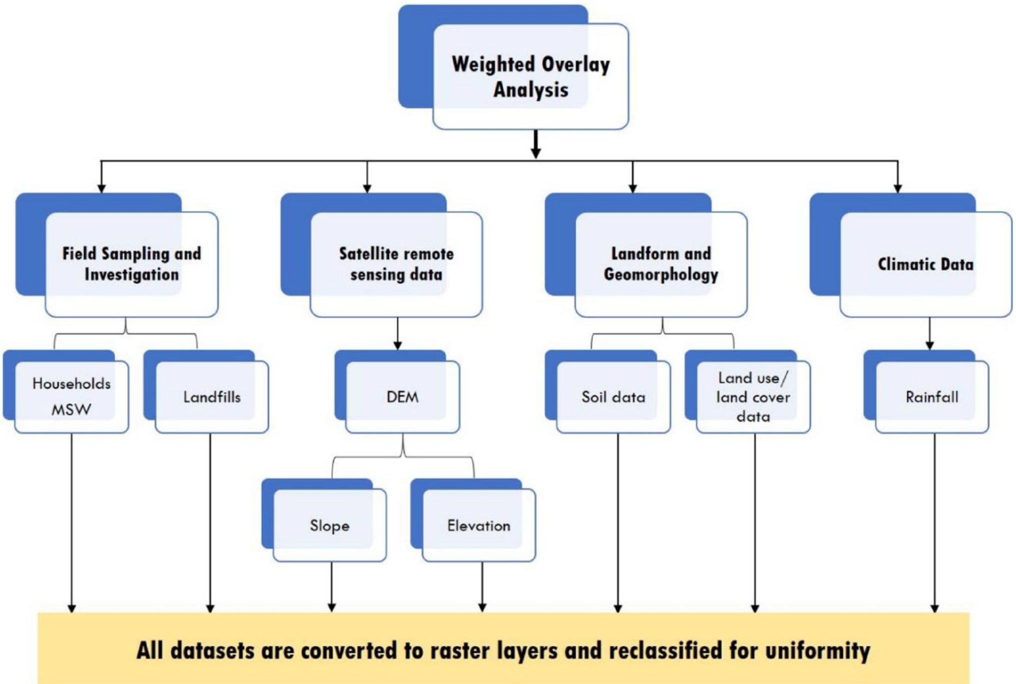

Figure 13. Weighted overlay process that we applied to estimate the groundwater vulnerability profiles of part of Ndokwa West LGA.

Nigeria, involved testing the water samples from each borehole for physical, chemical, and bacteriological parameters, along with heavy metals content. The laboratory was chosen because of its modern collection of laboratory tools used for various water sample analysis. The designs of previous studies for example Christopher and Mohd (2011) and Amal et al. (2020) largely inform the choice of what is being analysed in this study for each of the parameters. This includes smell, taste, colour, turbidity, and temperature for the physical parameters; pH, dissolved oxygen (DO), total dissolved solids (TDS), total hardness, Nitrate (NO_3) and nitrite (NO_2), Cl, Ca, for the chemical parameters; and total Fe, Cu, Zn, K, Mg, Na and Pb for the heavy metals. The bacteriological analyses investigated the presence of bacteria and other microbial activities.

Direct measurement using a Mettler Toledo Digital pH meter was used to measure the pH values of the water samples, while temperature measurements were taken using a mercury thermometer and turbidity was determined using a Hach 2100A turbidimeter. The DO levels, total hardness, and TDS in the samples were assessed using a spectrophotometer through classical laboratory analysis. Standard titration techniques were used for laboratory analysis of chloride in water samples (American Public Health Association, 2005). The concentration of heavy metals – Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Fe^{2+}, Cu^{2+}, Zn^{2+} and Pb^{2+} – in the samples was assessed using the atomic absorption spectrophotometer (AAS). The bacteriological parameter was determined through the employment of the membrane filter and autoclave technique for thermotolerant coliform bacteria and *E-coli* analysis. The World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) values were used as control variables.

Results

Map of the location of landfills

The present study considered five landfills, all of which are in the study area's southeastern part (as already depicted in Figure 3). These landfills are also the service locations for all MSW generated across the LGA. A geospatial analysis of the study area's DEM, delineating relief, direction of groundwater flow, and hydraulic gradient of the location, suggests that groundwater flows in the direction towards the landfill's locations. This increases the health concerns since the water is also consumed by dozens of the residents in the LGA. Figure 14 is a detailed map of the overlaid with topographic features and the locations of the landfills.

Buffer layers of landfills' location

A proximity analysis of the landfill's location was conducted in a GIS. In this analysis, four distinct buffer zones (1, 2, 5 and 10 km) were created around the landfills. Then a vector layer of the topographic features – road networks, houses, street layers, health centres, schools, churches, and recreational centres – of the study area was overlaid on the resulting buffer zones. The aim was to identify the geographical features at various risk levels of leachate pollution from landfills. Figures 15 and 16 show the resulting buffer zones and the geographic features within each buffered zone.

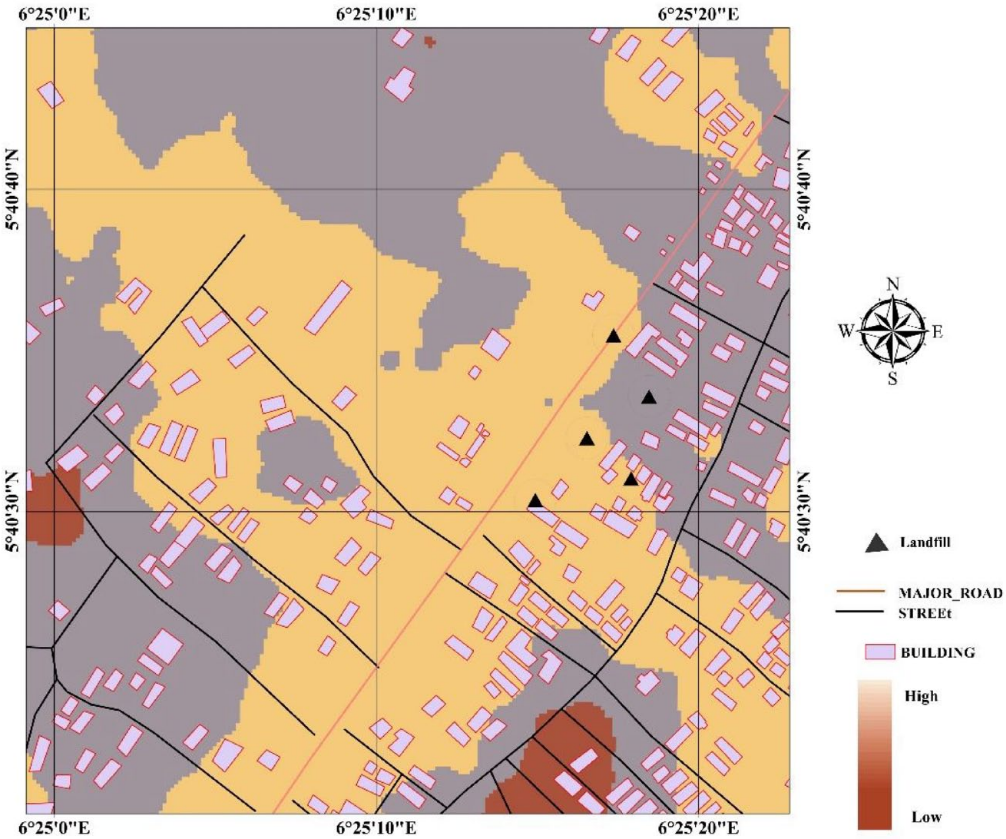

Figure 14. Geospatial map of the study area, showing the vectorised details and overlay.

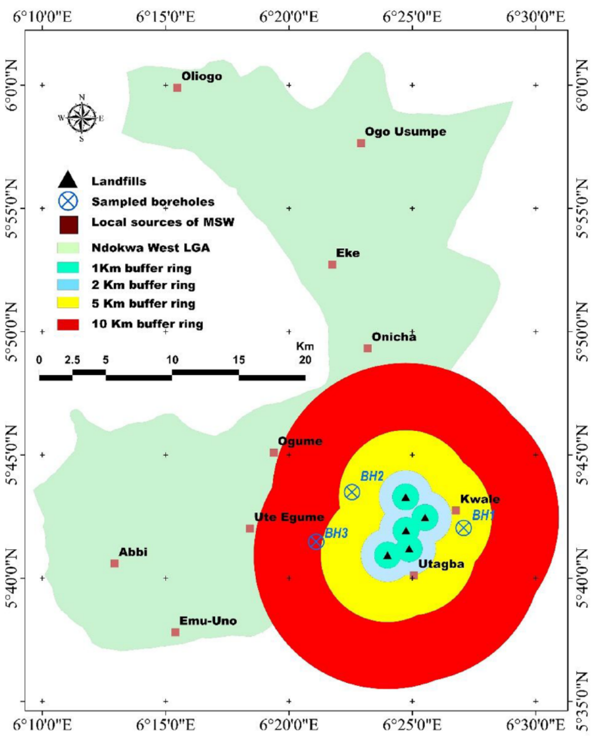

Figure 15. Buffer zones created around the landfills enclosing topographic footprints in the southern part of Ndokwa West LGA.

Groundwater quality vulnerability model

The groundwater quality vulnerability map in Figure 17 showed that most of the areas are of low vulnerability to groundwater contamination. These are mostly the areas closest to the landfills, and areas that have high-density populations. In all 21.53% of the areas are highly vulnerable to groundwater pollution, as low as 7.5% of the areas exhibit a medium vulnerability while as large as 70.9% are of low vulnerability to groundwater contamination (see Table 6).

Physical characteristics of sampled water

Tables 5 and 7 to 9 present the outcomes of these analyses and how they compared with the WHO and the NSDWQ benchmarks. Data presented in Table 7 (and Figure 18) are the physical properties of water samples from the boreholes (BH_i), which involve odour, taste, colour, turbidity, temperature and conductivity.

The samples exhibited lower turbidity readings, which fall within the 5 NTU (nephelometric turbidity unit) range stipulated by the WHO (2004). Any values greater than this maximum means that contamination is impossible. The turbidity values of the present samples are 2.8 NTU, 1.4 NTU and 2.40 NTU, respectively, for BH1, BH2 and BH3 (Figure 19).

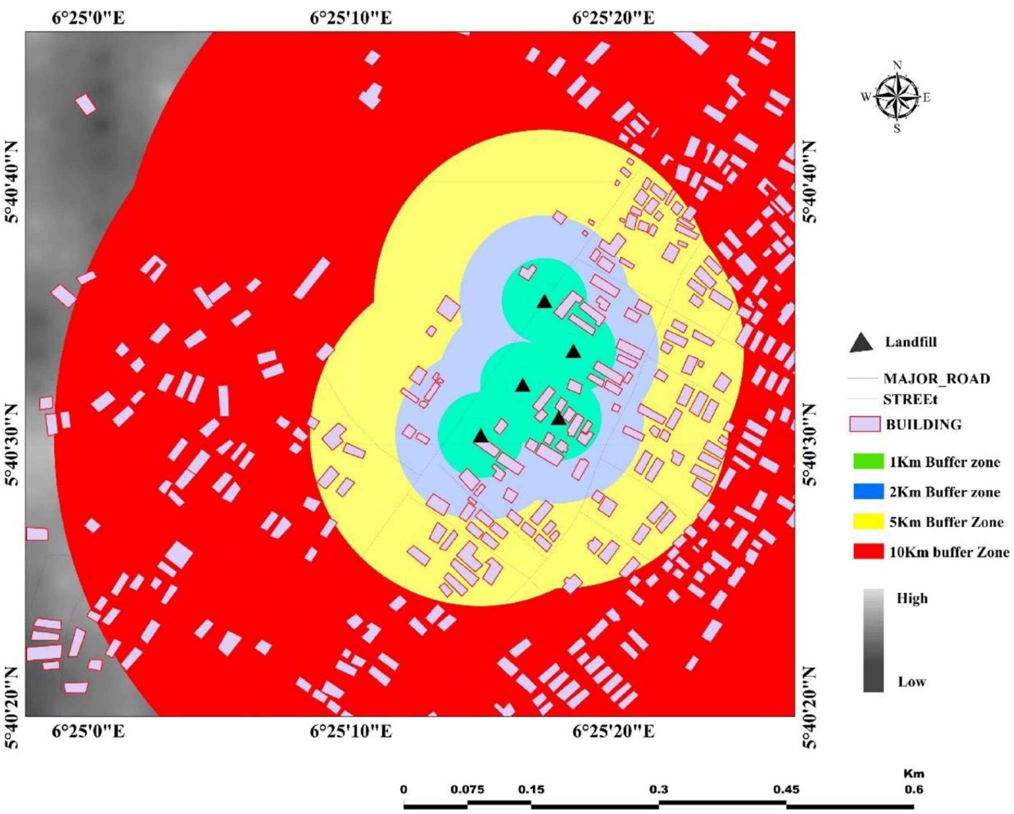

Figure 16. The study area: showing landfill with topographic features overlaid by various buffer zone.

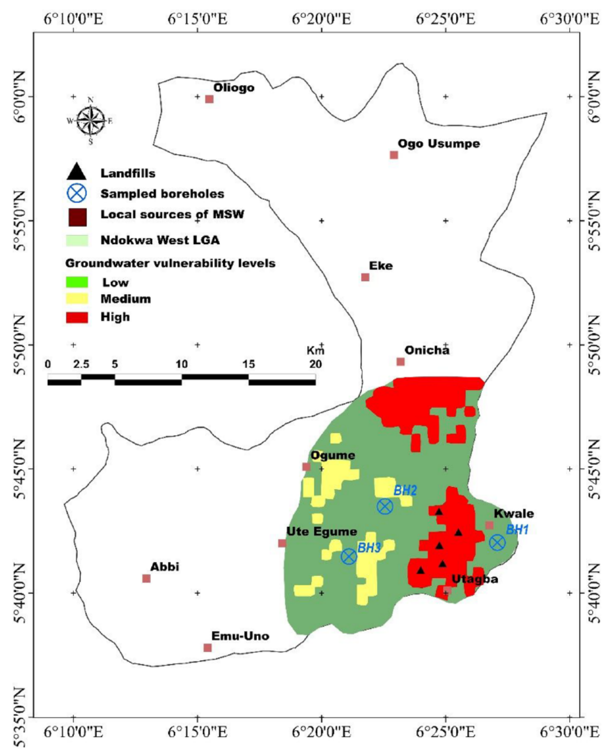

Figure 17. Groundwater quality vulnerability map showing three levels: low, medium and high vulnerability areas.

Chemical characteristics of sampled water

The chemical properties of the samples analyzed are represented in Table 8 (and Figure 19). The pH varies from 6.05 to 7.02, with BH1 (50 m) having 7.02, BH2 (80 m) having a reading of 6.34, and BH3 (100 m) having a figure of 6.05, which is more to the acidic side. The value for DO in BH1 and BH3 stood at 55.0 and 88.0 mg l^{-1}. Total hardness (TH) is not known to have adverse health effects on human beings, except when the investigation reveals significant occurrences (say >200 mg/l).

The amount of TDS in the tested samples indicates pollution, although the determined values which practically ranged from 1.37 to 2.14 mg l^{-1}, are relatively lower than the WHO and NSDWQ standards. The titration values for Chloride ranged from 17.5 to 30 mg l^{-1} which is far below the WHO and NSDWQ benchmark of 250 mg l^{-1}. In the present investigation, the values found for Nitrates and nitrites range from 5.0 to 6.162 mg l^{-1} and from 0.251 to 0.455 mg l^{-1} respectively.

Heavy metals characteristics of the sampled water

Except for Pb, the concentrations of all the metals in the tested samples were below the WHO and NSDWQ benchmarks (Table 9 and Figure 20). The concentrations of Pb, which are higher than the WHO and NSDWQ benchmarks, range from 0.25 to 0.65 mg/l in BH_1, BH_2 and BH_3, respectively. Zinc's concentration ranged from 0.046 to 0.141 mg l^{-1}. The

Table 6. Spatial Characteristics of the Groundwater Vulnerability Model of Ndokwa West LGA.

VULNERABILITY PROFILE	SPATIAL EXTENT (KM^2)	% COVERAGE	ENCLOSED COMMUNITIES
Low	12.205	70.93	Kwale, Uta-Eguma
Medium	1.297	7.54	Ogume
High	3.705	21.53	Utagba

Table 7. Results of Physical Analyses of the Sample from Three Boreholes.

SAMPLES	ODOUR	TASTE	COLOUR	TURBIDITY (NTU)	TEMP (°C)	CONDUCTIVITY (US/CM)
BH1	Unobjectionable	Tasteless	Colourless	2.8	26	34
BH2	Unobjectionable	Tasteless	Colourless	1.4	22	26
BH3	Unobjectionable	Tasteless	Colourless	2.4	20	48

Table 8. Results of Chemical Analyses of the Sample from Three Boreholes.

PARAMETERS	BH1 (50 M)	BH2 (80 M)	BH3 (100 M)	WHO	NSDWQ
pH	7.02	.34	6.05	6.5 to 8.5	6.5 to 8.5
Dissolved oxygen (mg/l)	55	72	88	2.5	5.0
Total hardness (mg/l)	294.4	232.5	278.6	100	150
Nitrate (mg/l)	5.0	4.03	6.162	10	10
Nitrite (mg/l)	0.41	0.455	0.251	0.20	0.20
Chloride (mg/l)	17.5	25.5	30	100	100
TDS (mg/l)	2.14	1.52	1.37	250	250

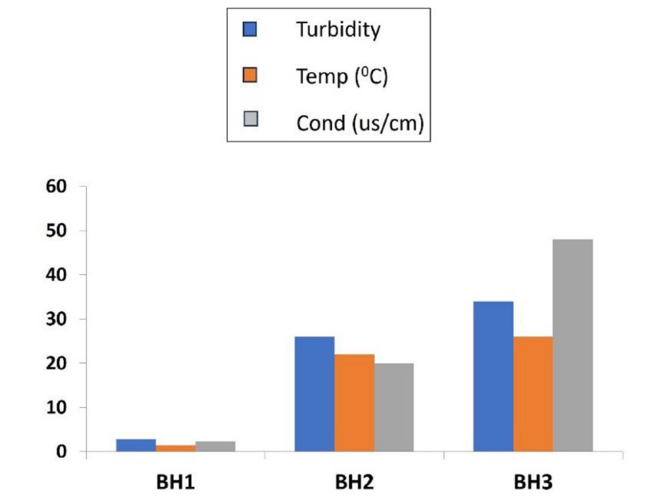

Figure 18. Shows graphical representation of parameters in the physical sample test conducted.

concentration of iron (Fe) in the samples is 0.060, 0.029 and 0.025 mg/l respectively for the boreholes BH_1, BH_2, and BH_3. The concentration of Calcium, though low (with a value range from 0.146 to 0.344 mg l^{-1}).

Biological characteristics

Table 10 shows the result of samples analysed for bacteriological characteristics. The *E-coli* and thermotolerant coliform bacteria as well as the total heterotrophic bacteria and the total heterotrophic fungi were all Nil.

Heavy metal indexing approach

To validate these physicochemical analyses results obtained for Ndokwa west, the indexing approach for assessing the pollution of groundwater resources by heavy metal was applied. First, the mean concentration values (C_i) were computed for the sampled metals across the three boreholes (refer to values in Table 11). Values for the mean concentration of heavy metals (in ppb) for the sampled location were got by multiplying the values obtained for metals by 1000. From these values, the concentrations of Pb, K and Ca are more for borehole BH1, while BH2 shows more Cu, Zn and Na. For BH3, there is a higher concentration of Na, K and Ca. Then, the WHO standards for the maximum allowable concentration (MAC) for the tested metals was used (see Table 12), and

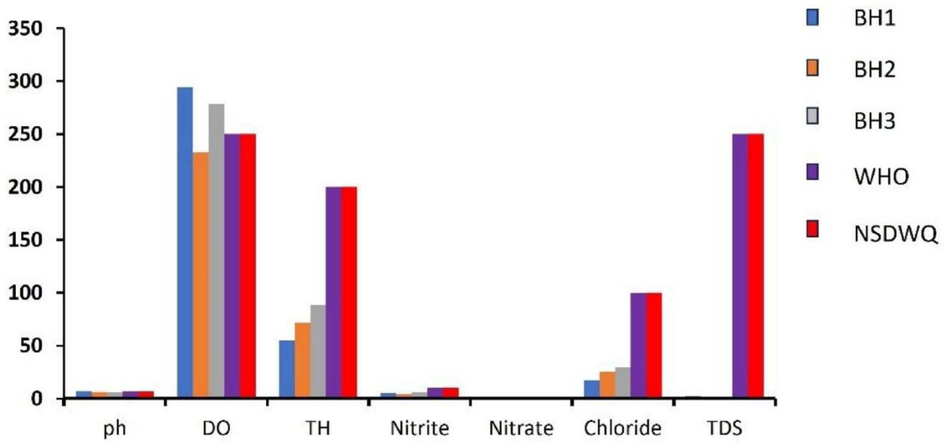

Figure 19. Shows graphical representation of parameters in the chemical sample test conducted.

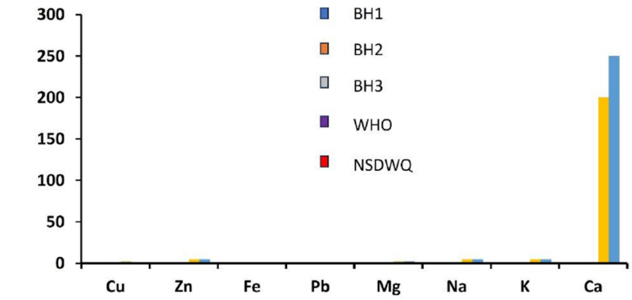

Figure 20. Shows graphical representation of parameters in the heavy metals sample test conducted.

the Heavy Metal Index (MI) was calculated using the formula below:

$$MI = \frac{\sum C_i}{MAC}$$

Where C is the mean concentration, MAC is the Maximum Allowable Concentration

The metal index values were computed for each of the boreholes. Tables 13 to 15 present the values, with the indication that BH1 has the highest Metal index of the three boreholes. The metal index for borehole BH3 is the lowest of the three sampled boreholes, and this is at proximate locations to most of the areas with lower vulnerability to groundwater pollution according to Figure 17. Finally, drawing from Caerio et al. (2005) and Bakan et al. (2010), the indexing evaluation for pollution of groundwater resources by heavy metal from the study area revealed a class **'VI'** result (see Table 16), indicating a '**Seriously Affected'** result for the intrusion of heavy metal for all the tested boreholes' water samples.

Discussions

This study has examined important parameters and developed empirical findings related to MSW, landfills, and how it affects groundwater resources in major areas within the Ndokwa West LGA. What these findings mean to stakeholders and how they should inform positive action towards mediating the effects of landfills and MSW in the groundwater resources and, of course,

Table 9. Heavy Metal Test Results from Borehole Water Samples.

PARAMETERS	BH1 (50 M)	BH2 (80 M)	BH3 (100 M)	WHO STAND.	NSDWQ
Cu (mg/l)	0.141	0.911	0.093	2	1.0
Zn (mg/l)	0.141	0.636	0.046	5.0	5.0
Fe (mg/l)	0.060	0.029	0.025	0.3 to 1.0	0.3 to 1.0
Pb (mg/l)	0.65	0.25	0.061	0.01	0.01
Mg (mg/l)	0.167	0.156	0.168	2.0	2.0
Na (mg/l)	0.167	0.721	0.867	5.0	5.0
K (mg/l)	0.432	0.255	0.492	5.0	5.0
Ca (mg/l)	0.344	0.146	0.341	200	250

Table 10. Represents the Values for Microbiological Parameters' Intrusion in the Groundwater Samples.

SAMPLE ID	CFU/	ML × 10^2	(MPN / 100 ML)	CFU / ML × 10^2
	THB	THF	*T.COLI*	*E.COLI*
BH1 (50 m)	Nil	Nil	Nil	Nil
BH2 (80 m)	Nil	Nil	Nil	Nil
BH3 (100 m)	Nil	Nil	Nil	Nil
WHO STD	100 to 500	<500	0	0

Table 11. Values Computed for the Mean Concentration of Heavy Metals for BH1, BH2 and BH3.

S/NO.	HEAVY METALS	MEAN CONCENTRATION AT SAMPLE LOCATIONS		
		BH1	BH2	BH3
1	Cu	141	911	93
2	Zn	141	636	46
3	Fe	60	29	25
4	Pb	650	250	61
5	Mg	167	156	68
6	Na	167	721	867
7	K	432	255	492
8	Ca	344	146	341

its effect on social, biological, and environmental systems is being discussed here.

Groundwater vulnerability to MSW

By assessing the spatial extents of both the high- and medium-vulnerability areas in the groundwater map of Figure 17, a significant size of geographic features is at risk of leachate and pollution of groundwater resources by the landfills within the study area. The buffer rings, suggesting the sizes of geographic footprints enclosed in each buffer zone, suggest that the groundwater vulnerability also increases as one moves away from the hotspot of landfills. At buffer zones 5 and 10 km, respectively, ~11.3 and ~35.3 km^2 in discrete sizes of the study area were locations where groundwater resources were high and moderately vulnerable. This is a substantial topographic footprint, suggesting that even beyond the present realities, as the population increases with more houses being put in place, more and more people are likely to face health problems because of access to groundwater resources at risk of contamination, and heavy metals' presence in effluents of the landfills.

Similar findings occurred in a recent study to assess the MSW disposal sites in Ethiopia's Wolkite town, in which

Table 12. Values Converted from mg/l to ppb for Maximum Allowable Concentration of Heavy Metals.

S/NO.	HEAVY METALS	MAXIMUM ALLOWABLE CONCENTRATION (MAC)	
		MG/L	PPB
1	Cu	2	2,000
2	Zn	5.0	10,000
3	Fe	1.0	1,000
4	Pb	0.01	10
5	Mg	2.0	2,000
6	Na	5.0	5,000
7	K	5	5,000
8	Ca	200	200,000

Weldeyohanis et al. (2022) discovered a significant socio-economic footprint at discrete buffer zones from the landfill's core location. These include households, businesses, agricultural activities, and wildlife. These are concerns within the geospatial and environmental sciences research and although much research has focused on it, the need to both quantitatively and qualitatively assess the local proximity of topography and landfills, as well as its socio-economic and demographic impacts, still motivates research. The intricate nexus between human disease transmission escalates this need and how landfills create a favourable condition, which Siddiqua et al. (2022) attempted to examine. However, the exact form of the landfill contamination and its characteristics are examined in the triad analyses of groundwater discussed in subsequent sections.

Mgbolu et al. (2019) identified a similar scenario when they examined aquifer vulnerability in some areas of Ndokwa using the DRASTIC model. This study did not apply a proximity analysis to examine the major contributions to the vulnerability scenario, which is what the present study has added to the body of knowledge of groundwater pollution in the study area. Of course, a critical view of the outcome of the groundwater vulnerability model reveals that the major contribution to this vulnerability profile is proximity to the landfills, although high population density and variations in the elevation profile of the areas are also important factors. Lower areas are the collection points of sediment transport and surface water runoff. However, this needs to be empirically determined in sensitivity and validation analyses.

Physical properties of groundwater in the study area

The barely perceptible colour in the water samples signifies contamination and verifies leachate infiltration into the wells (Aharoni et al., 2020; Nigerian Standard for Drinking Water Quality, 2007). Jaji et al. (2007) reported similar findings. The WHO (2004) has set the desirable limit of five Hazen units,

Table 13. Metal Index Value (C_i /MAC) for BH1.

BH1		MEAN CONCENTRATION (C_i) PPB	MAXIMUM AVAILABLE CONCENTRATION (MAC) PPB	METAL INDEX [C_i / MAC]
S/NO.	HEAVY METALS			
1	Cu	141	2,000	0.0705
2	Zn	141	10,000	0.0141
3	Fe	60	1,000	0.06
4	Pb	650	10	65
5	Mg	167	2,000	0.0835
6	Na	167	5,000	0.0334
7	K	432	5,000	0.0864
8	Ca	344	200,000	0.00172
				65.34962

Table 14. Metal Index Value (C_i /MAC) for BH2.

BH2		MEAN CONCENTRATION (C_i) PPB	MAXIMUM AVAILABLE CONCENTRATION (MAC) PPB	METAL INDEX [C_i / MAC]
S/NO.	HEAVY METALS			
1	Cu	911	2,000	0.4555
2	Zn	636	10,000	0.0636
3	Fe	29	1,000	0.029
4	Pb	250	10	25
5	Mg	156	2,000	0.078
6	Na	721	5,000	0.1442
7	K	255	5,000	0.051
8	Ca	146	200,000	0.00073
				25.82203

Table 15. Metal Index Value (C_i /MAC) for BH3.

BH3		MEAN CONCENTRATION (C_i) PPB	MAXIMUM AVAILABLE CONCENTRATION (MAC) PPB	METAL INDEX [C_i / MAC]
S/NO.	HEAVY METALS			
1	Cu	93	2,000	0.0465
2	Zn	46	10,000	0.0046
3	Fe	25	1,000	0.025
4	Pb	61	10	6.1
5	Mg	68	2,000	0.034
6	Na	867	5,000	0.1734
7	K	492	5,000	0.0984
8	Ca	341	200,000	0.001705
				6.483605

Table 16. Summary of Heavy Metals' Index Values BH1, BH2 and BH3.

S/NO.	HEAVY METAL INDEX (MI) CALCULATION			
	SAMPLE LOCATIONS	ΣC_i / MAC	CLASS	PROPERTIES
1	BH1	65.34962	VI	Seriously affected
2	BH2	25.82203	VI	Seriously affected
3	Bh3	6.483605	Vi	Seriously affected

however, the leachate in the samples does not meet the criteria for potability of water, which requires it to be free from colour, odour, taste, pathogenic organisms, and safe for drinking. The temperature range of 20°C to 26°C falls significantly beyond the WHO and NSDWQ's domestic water standard of 5°C, implying the existence of external substances. High temperature is linked to the existence of active microorganisms (specifically in sample 1, owing to its proximity to the landfill). Particles and other materials suspended in the water samples are usually responsible for high turbidity values (Aharoni et al., 2020; Sangodoyin, 1991) suggesting that the wells may be unlined. However, with the samples from the study area, the boreholes seemed properly screened, preventing particles of soil from having their way into the boreholes, which would have increased the turbidity of the water.

Biological and chemical properties of groundwater in the study area

Biological analyses of the samples in the present study considered the coliform group, which has a wide-ranging significance and application in water quality calibration and protection of public health (A. R. ; Onyango et al., 2019; Pal, 2014). Theoretically, the total coliforms collectively define a cluster of bacteria normally found in the environment. Most of these bacteria live in plants, soils, and in the intestines of mammals, including human beings as in the case of *E-coli*. Although the coliform group of bacteria is not usually pathogenic, their presence creates a normal food chain that attracts more harmful microorganisms and therefore increases the vulnerability of water to contamination (Pal, 2014).

The values particularly of *E-coli* and total coliform bacteria count could be attributed to the fact the landfill is relatively new and still growing in terms of leachate production, it has not accumulated enough bacterial leachate to find its way into the borehole through the groundwater. In addition, the soil type underground effectively filters whatever content of bacteria there is from the landfill before it gets to the borehole, unlike the heavy metal parameters that can become soluble in state and infiltrate through any soil type, this finding agrees with that of (Aharoni et al., 2020; A. R. Nanda et al., 2023; Onyango et al., 2019).

The range of pH values confirms that there are especially toxic metals in the samples. These slightly fall below the WHO benchmark (6.5–8.5) and confirm the water from the boreholes is acidic. The likely source of this acidity is Metals such as Zn, dead battery cells (Pb, Hg, and alkaline), cans of aerosol and other disinfectants improperly disposed of in the landfill as waste, all of which after exposure to air and water found their way to the boreholes as leachate. Although the present samples' microbiological monitoring showed the water samples are mostly neutral at 7.02, up to 9.2 may be allowed, so long as no there is no deterioration in bacteriological quality (WHO, 2004), which is the present situation with the study samples, based on all indicators (as shown in Table 8).

The value for DO in BH1 and BH3 stood at 55.0 and 88.0 mg l^{-1}, which indicates oxygen reduction and the presence of pollutants that exhaust the oxygen in the water in the borehole's samples, especially the one contiguous to the landfill (BH1). These observations share similar findings with previous investigations by Akinbile (2006), Jaji et al. (2007), Igbinosa and Okoh (2009) and Aharoni et al. (2020). The depletion of DO by the pollutants is significant from the analyses and highlights how the boreholes are being severely affected by the landfill. While DO remains a major factor in assessing the quality of water, these findings generally suggest that water in the boreholes is unfit for consumption.

Total hardness (TH) is not known to have adverse health effects on human beings, except when the investigation reveals significant occurrences (say >200 mg/l). However, its regular appearance indicates the discharge of Ca and/or Mg ions in the groundwater, which is the reason water is hard and often prevents it from creating lather with soap (Aharoni et al., 2020; Srinivasamoorthy et al., 2009). The hardness of water is not a threat to human health, although there are views that suggest economic implications in water management since it tends to raise the normal boiling point of water (see Aharoni et al., 2020) and impedes water's formation of leather with soap. However, boiling at a certain temperature range can remove temporary hardness while adding carbonates and sulfates to water are solutions to permanent hardness.

Ground and surface waters regularly carry Nitrate, known to be the most highly oxidised form of nitrogen compounds, in addition to being the end-product of the aerobic decomposition of organic nitrogenous matter. Only a trace amount of nitrate is found in clean drinking waters (seldom exceeds 0.1 mg l^{-1}). Water with nitrite levels exceeding 1.0 mg l^{-1} is unfit for human consumption. In the present investigation, the values found for Nitrates and nitrites range from 5.0 to 6.162 mg l^{-1} and from 0.251 to 0.455 mg l^{-1} respectively. This shows a substantial presence of pollutants in all the tested water samples. Nitrites have a relatively short existence being quickly transformed into nitrates by air-borne bacteria. Within their existence, Nitrites react non-reversibly with haemoglobin in human blood cells to produce methemoglobin, which affects the oxygen-carrying ability of red blood cells. This results in a health condition known as methemoglobinemia or 'blue baby' disease, and babies especially those under 3 months of age are at a greater risk of the disease.

Srinivasamoorthy et al. (2009) discussed the routes by which nitrates, which are a key ingredient in farm fertiliser and necessary for crop production, enter the groundwater resources. The quickest route is through rainfall which carries varying amounts of nitrate from farmland and enables them to infiltrate nearby waterways and groundwater table. Leakages from septic tanks, livestock manure, animal wastes, discharges from car exhausts, and leachate from landfills are other routes by which Nitrates also get into waterways. In the present study, nitrate concentration levels for BH_1 and BH_2 samples are higher than the BH_3. This is because of the proximity of the boreholes to the landfill sites and being close to the road, some Nitrates are released from car exhausts, and this adds to the high level of Nitrates in the boreholes.

The amount of TDS in the tested samples indicates pollution, although the determined values which practically ranged from 1.37 to 2.14 mg l^{-1}, are relatively lower than the WHO and NSDWQ standards. The titration values for Chloride ranged from 17.5 to 30 mg l^{-1} which is far below the WHO and NSDWQ benchmark of 250 mg l^{-1}. Although the minutest presence of Chloride indicates pollution; a greater concern lies with the weathered-silicate-rich rocks underlying the landfill. How this is related to anthropogenic activities in urban areas such as the present study location, and its health implications are presented in Igbinosa and Okoh (2009), Srinivasamoorthy et al. (2009) and Ekenta et al. (2015).

Presence of heavy metals in groundwater resources within the study area

It is unlikely that Pb can be detected by sight, smell, or odour, which means lead poisoning can be hard to detect. Its concentration suggests the presence of toxic wastes, perhaps from dead battery cells, aerosol cans, and other toxic materials improperly disposed of in landfills. There are serious health concerns with excessive consumption of water containing Pb. Brain damage and kidney failure are major effects as well as inhibition of the production of red blood cells that transport oxygen to all parts of the body system. Symptoms are often delayed until the concentration in the body has reached a lethal amount. Due to the higher rates at which they absorb Pb^{2+} and produce reactions, infants and younger children are at higher risks of health conditions related to Pb^{2+} accumulation in the body. Abdominal pain, weight loss, fatigue, diarrhoea, vomiting, and hearing loss are among the other health effects that have been identified in studies conducted by Dissanayake et al. (2010), Holecy and Mousavi (2012), Podchashinskiy et al. (2017), Hartono and Pretiwi (2021), Madushika et al. (2023), and WHO (2006) due to excessive ingestion of Pb^{2+}.

Drawing from Igbinosa and Okoh (2009), Dissanayake et al. (2010), Longe and Balogun (2010), and Aharoni et al. (2020), the high concentration of Zinc in the samples implicates two things: (1) gradual leaching of metals from a scrap yard within intolerable proximity to the landfill, and (2) decomposed landfill's solid wastes containing zinc metals which infiltrated the water table. The concentration of iron (Fe) in the samples is 0.060, 0.029 and 0.025 mg/l respectively for the boreholes BH_1, BH_2 and BH_3, indicating that iron is still within the WHO and NSDWQ standards. According to the WHO (2004), the maximum permissible concentration of iron in drinking water is from 1.0 to 3.0 mg l^{-1}, so anything greater than this value signifies that water is unfit for consumption because it produces an offensive and sour taste in the mouth. Goiter in adults is also related to the consumption of water with iron concentration exceeding the specified benchmarks. Chukwujekwu's (2023) recent study on the health effects of specific dietary compositions among adults in Ugheli, near Ndokwa West in Delta State, supports earlier conclusions regarding iron consumption.

The concentration of Calcium, though low (with values ranging from 0.146 to 0.344 mg l^{-1}), still presents concerns for hardness in water. This is with regards to total hardness and forming a lather with soap which is a major challenge for domestic users (Akinbile, 2006; Chukwujekwu, 2023). Magnesium, Potassium, and Sodium were also tested, but not detected, suggesting that in the meantime, the water sample is free of such contaminants. These concentrations explain the type of solid waste that are present in the study area, and the types of anthropogenic activities that thrive in these locations. For example, these values signal the presence of traffic emissions, domestic cooking soaking and washing, and combustion from warehouses, and factories. Whilst this suggests the presence greater concentration of heavy metals, it also validates the groundwater vulnerability model (Figure 18) which showed areas around the borehole, BH1, with higher vulnerability.

Conclusion and Recommendation

Municipal solid waste (MSW) poses significant health and environmental threats to cities and rural areas globally, while its management spurs diverse interests in research and policy. One debate in the current literature concerns the appropriate siting of landfalls and how to manage its leachate contamination of groundwater resources and other topographic features. With the help of geospatial analysis and a triumvirate assessment of the quality of groundwater resources, this study has examined critical issues surrounding MSW and groundwater contamination from nearby landfills in Ndokwa West areas of Delta State, Nigeria. The major aim is to determine the vulnerability model of groundwater subject to landfills and improper management of MSW in the area. This study made use of samples of water from three boreholes in Ndokwa West and other datasets, detailing the spatial characteristics of the landfills and the nearby topographical features. The study produced maps of the geospatial locations of the five landfills within the study area, which shows that the studied landfills are in the southeastern region where they serve as the main gathering house for all the MSW in the region. The elevation outline of the area shows that groundwater flows downwards with its main path contiguous to the sites of the landfills. Proximity analyses with buffer zones of varying sizes revealed topographic features within the neighbourhood of the landfills' geospatial location. This includes road networks, buildings, and other relevant features. The vulnerability model of the area, developed with a GIS-based weighted overlay, reveals 21.5% of the area in a highly vulnerable state, 7.5% in a moderate and ~71% at low vulnerability. Physicochemical examination of the water samples from nearby boreholes revealed dissolved oxygen, and heavy metals, particularly Pb^{2+} in the landfills' leachate. With significant amounts of heavy metals, particularly Pb^{2+}, all three boreholes have a '**VI**' rating on the Heavy Metal Index calculation scale, representing a '**Seriously Affected**' water supply system. These findings underline the health and socio-economic challenges that the local population and households, who rely on groundwater for drinking and other domestic purposes, will face due to leachate from landfills and contamination of the aquifer ecosystem by heavy metals. Serious MSW management weakness by the local government and waste management agencies within the region is also highlighted. A major limitation of this study is the quality of geospatial data that were used for the analyses, and the limitation in groundwater sampling locations. The individual sensitivities of the variables that formed the vulnerability model should be assessed in a later study.

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Data Availability Statement

The geospatial information and boreholes' water samples are all included in the manuscript. Datasets generated from the various analyses conducted in this study are also included in the manuscript.

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