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Research article

Investigation of groundwater vulnerability to open dumpsites and its potential risk using electrical resistivity and water analysis

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ABSTRACT

Understanding the impacts of open dumpsites and its implication on groundwater systems is a critical component of water security for sound long-term environmental management strategies. However, predicting the impacts of dynamic dumpsites on environmental systems is a difficult task that requires a technical approach. This paper applies electrical resistivity and physico-chemical water analysis techniques to investigate the groundwater vulnerability to open dumpsite leachates and its potential environmental risk. A total of twenty-nine (29) vertical electrical sounding (VES) were acquired within and around the dumpsites. A physicochemical properties analysis of water from seven hand-dug wells (HDWs) within a 200 *m* radius of the dumpsite was performed. The subsoil resistivity values encountered within the dumpsite and off-dumpsite vary from 2.4 Ωm to 17 Ωm and 68 Ωm – 611 Ωm respectively. The study links up the subsurface geo-electrical properties (resistivities) with the physiochemical water analysis, which affirmed the electrical resistivity technique efficiency in dumpsite investigation. The geophysical and water analysis results indicate that the groundwater systems within and around the dumpsite are highly susceptible to dumpsite leachates and require urgent evacuation to avoid the impending risks posed to both human health and the environment. While the geophysical analysis indicates high leachates infiltrating index in the subsoil, which invariably affects the groundwater resources, the physicochemical analysis indicates a high concentration of heavy metals, COD, BOD, TDS and high electrical conductivity (EC), affirming the geophysical results. The leachate plumes of the dumpsite suggest to have masterminded the groundwater pollution, the high heavy metals dominating the 7 HDWs have significantly influenced the chemistry of the groundwater quality within the area. Thus, dumpsite is the major cause of groundwater pollution. Indications show that the impacts of dumpsite leachates decreased with depth and source distance. More also, groundwater systems within a 200 *m* radius of the dumpsite are at risk of a high vulnerability index. Besides the study indications, some influential regional factors such as climatic conditions, hydrology and geology of the dumpsites have further amplified the impending major environmental crisis. Consequently, the study suggests future environmental preservation for the future direction.

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1. Introduction

Open dumpsite is fast becoming one of the major global environmental challenges, especially in developing nations. Understanding the implications of open dumpsites and their impacts on groundwater systems is a critical component of water security for sound long-term environmental management strategies. The open dumpsite is an unfavourable global phenomenon which had mastered the act of polluting the groundwater system. While [1] described open dumpsites as non-engineered landfill sites [2], identified open dumpsites as a necessary evil, and [3] labelled dumpsites as unfriendly environmental phenomena, which often contaminate the groundwater [1], and placed it on a pedestal of water insecurity due to the dumpsite leachate percolation into groundwater. Most developing countries are now struggling with the challenge of managing a large number of solid wastes and their environmental impacts [3–5]. The United Nations Environment Programme (UNEP) and the International Solid Waste Association (ISWA) argued that the rate of municipal solid waste (MSW) generation is fast becoming consistent in developed countries. UNEP's prediction indicates anxiety due to a sudden upsurge in waste generation [6], while national and international economies continue to crawl. This unwanted rise has been largely attributed to population expansion, urbanization, industrialization, and migration as well as bilateral trading [7].

According to Ref. [6], Nigeria maintains the top position among the 50 world's biggest active dumpsites from 30 countries. With Nigeria alone constituting 12% of the 50 world's biggest active dumpsites, the hazards and threats posed by these dumpsites to human health and the environment require urgent attention [6], and this has compelled the current work. The unfavourable dumpsite phenomena have been a difficult task for Nigeria to manage due to the ever-upsurging solid waste generated [8]. These situations predict difficult times for the future of environmental management in Nigeria [9–12], and the rest of the African nations [13–15]. Therefore, the prevailing indiscriminately disposal of solid wastes in open dumpsites in developing nations has reached a critical situation that poses hazardous impacts on human habitations [2,16,17]. Recent studies indicate that unattended solid waste at an open dumpsite can degenerate into serious health and environmental hazards [18–21]. A study indicates that about 2.01 billion tonnes of solid waste are generated all over the world annually, which is expected to grow to 2.2 billion tonnes by 2025 [22]. [2] describes waste management in developing nations, especially Nigeria as a wobbly one due to poor technical capacity and the high financial burden of waste management, supported by Ref. [8].

However, some considerable literature noted that the ground resistivities are usually influenced and controlled by many geological parameters such as the fluid content, mineral and porosity [23–25]. That is; subsoil information regarding the hydro-geological, stratigraphic sequence characteristics, lithology, and subsurface strata can be obtained via resistivity survey techniques. The technique has been widely used in prospecting for groundwater exploration and leachate plumes [26]. Though; the details on the characteristics of dumpsite leachates may sometimes be difficult to evaluate with a geophysical technique alone, especially the level of risk associated with seeping contaminants [27,28], integrated geophysical technique with physiochemical water analysis can provide a total characterization of dumpsite leachate plume contaminants generated by MSW [2,23,24]. Therefore, the combined electrical resistivity technique and physiochemical water analysis appear to be more suitable for such kinds of environmental studies [2]. The top priority of this study is to investigate groundwater vulnerability to open dumpsites leachate plumes and its potential environmental risk using electrical resistivity and water analysis.

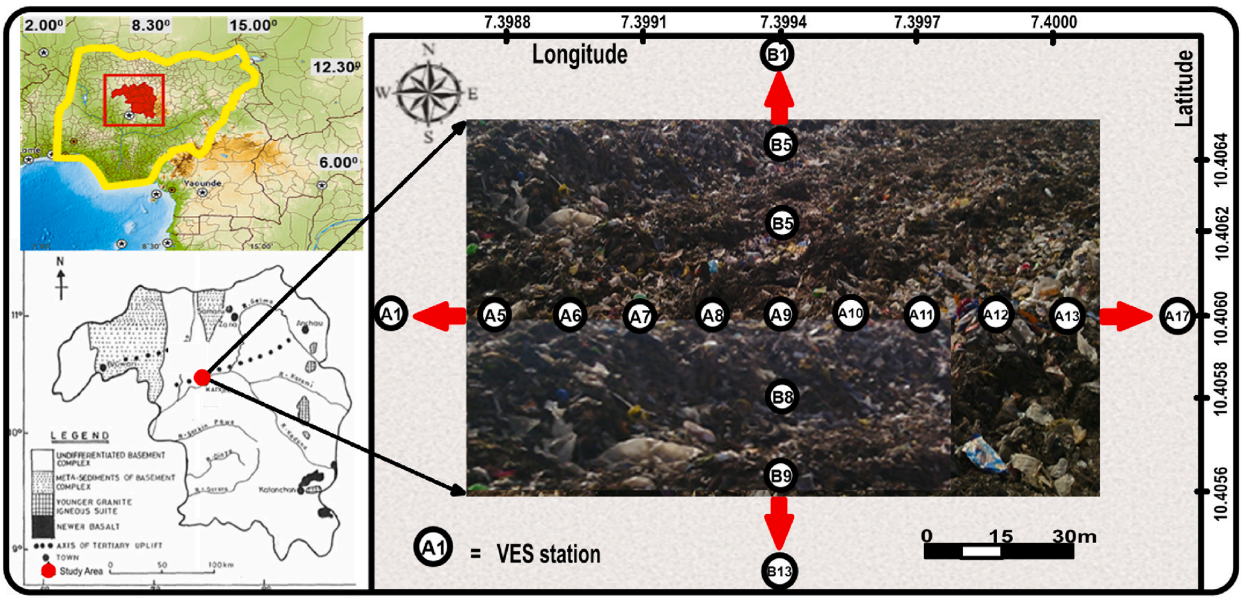

Fig. 1. Image of the case study of the active open dumpsite showing the VES points.

2. Materials and methods

2.1. Regional geology and hydrogeology

The regional geology of Kaduna, Northern Nigeria consists of the Precambrian migmatite-gneiss complex, meta-sediments/meta-volcanic, which mostly quartzites, schists, amphibolites, and Iron formations (Fig. 1). Others include the calc-alkaline granites, the African granitoid, and volcanic of the Jurassic age towards the south-eastern border of the States [29]. The uppermost soil sometimes is capped by laterites and sandstones. The laterites are usually consolidated, especially at the topsoil and weathered into lateritic nodules mixed with sandy and silty clays [30]. Laterite soils are widespread in African nations including Nigeria, which is sometimes served as landfill liners [3]. The average overburden and weathered layer thickness of Kaduna Millennium City are usually encountered at about 28 m and 20 m respectively [31]. While the water-bearing unit is usually encountered in silty/sand/clay and fractured zones with the depth to water table found within 5 m on average [31,32]. On the other hand, the hydrogeology of every terrain is unique and largely influenced by climatic factors. The drainage systems of an area also plays an important role in shaping and reshaping the region [2]. However, a study noted that the quality of water improved by siting dumpsites away from downstream [33].

2.2. Regional climate condition and characteristics of dumpsite leachate

Recent studies show that the characteristics of landfill leachates are not unconnected with the nature of the regional climate [34–36]. Though, geological and climatic factors such as soil EC, heat and rain can increase the rate at which a dumpsite MSW decomposes and leaches down the soil to contaminate groundwater [37,38]. The temporal and spatial patterns of soil temperatures in Nigeria were investigated, and it was observed that the effect of latitudinal position on soil temperatures, and air temperatures increase with increasing distance from the coast [39]. However, there is an exception to this pattern on the Jos plateau due to the elevation factor, soil temperatures increase from the plateau outwards. Consequently, it was noted that the monthly variations of soil temperatures in Nigeria have bi-modal peaks, which reflect the pattern of air temperature peaks. In a tropical country like Nigeria, there may be a slight change in some other studies across the world [40]; because the waste characteristics, most times depend on the nature of the countries concerned [41].

Most African countries are usually hot, especially Northern Nigeria, where the daytime temperatures alternate between 24 °C and 38 °C annually, as it is related to the meteorological conditions, and this can influence the character of dumpsite leachate [2,42]. Therefore, the characteristics of the landfills located in such difficult terrain are mainly affected by the meteorological conditions of the terrain, and the environmental impact may be difficult to predict. The temperature of the waste layer in the dumpsites increases generally due to the high pressure created, which invariably catalysed the degradation of the newly filled MSW because heat is a major factor that spread gas and leachate plumes [43–46]. That is, a region may be controlled and influenced by the characteristics of a dynamic dumpsite leachate plume contaminants by the conditions of climatic. Consequently, the rate of decomposition, gas emission rate, temperature around a dumpsite and pollution rate may be triggered.

Municipal Solid waste dumped in dumpsites usually undergoes a series of chemical reactions and physical and complex biochemical processes that result in the generation of both leachate plume contaminants and odorous gas emissions [47]. These leachate plumes usually developed when water dissolves the solid waste into a dynamic liquid which in turn is transported in form of contaminants. These leachates are generally characterized by high chemical oxygen demand (COD) and biological oxygen demand (BOD) with unwanted substances such as inorganic and organic contaminants [48,49]. This is because, recent studies have also shown that climatic data such as wind, pressure and temperature, can influence and control the degree of heat and gas emission emerging from landfills [17,25,42]. The major four major categories of contaminants found in municipal dumpsite leachate are; inorganic compounds, organic contaminants and substrates, heavy metals, colour and total dissolved solids (TDS) [34], and they can be classified into three main groups as shown in Table 1.

2.3. Geophysical technique

The electrical Resistivity Technique was adopted for acquiring geophysical field data using the Schlumberger array (Fig. 2). A total of twenty-nine (29) VES points were investigated within the dumpsite with (AB/2) = 70 m maximum spread. Minimum of four

Table 1
Characteristics of Leachate and treatability according to the age of landfill [41,49,50].

Age	Young [0–5]	Intermediate [5–10]	Old [> 10]
PH	<6.5	6.5–7.5	>7.5
COD (Mg/L)	>10,000	5000–10,000	<5000
BOD_5/COD	0.5–10	0.1–0.5	>0.1
NH_3–N(Mg/L)	<400	–	>400
H.M	Medium-low	Low	Low
VFA/HFA	VFA (80%)	VFA (5–30%)	HFA (80%)
Biodegradability	High	Medium	Low

Note: VFA is volatile fatty acids; HFA is humic and fluvic acids; BOD is biological oxygen demand; COD is chemical oxygen demand; and HM is heavy metals.

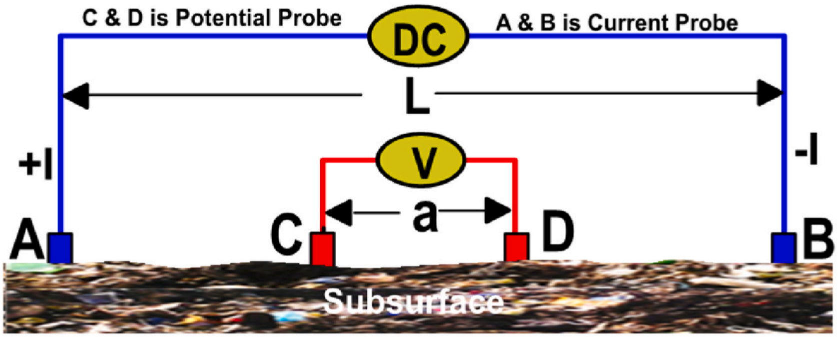

Fig. 2. Schlumberger Configuration.

electrodes was used for Schlumberger configuration during the field data acquisition. Schlumberger array has been used to acquire VES data and the operational principle of Schlumberger array is Ohm's law in Eq. (1) [51]:

$$V = IR \tag{1}$$

The subsoil's reaction to the flow of current in the ground can be expressed by (2) [52]:

$$\Rightarrow \rho_a = RK \tag{2}$$

K is a geometrical factor (K-factor) that depends on the configuration of the four electrodes shown in Fig. 2 [52]. The K-factor can be expressed from Fig. 2 as in Eq. (3) [52]:

$$K = 2\pi\left[\left(\frac{1}{AC} - \frac{1}{CB}\right) - \left(\frac{1}{AD} - \frac{1}{BD}\right)\right]^{-1} \tag{3}$$

Considering Fig. 2, we write Eq. (4) [54].

$$\begin{cases} AC = BD = \left(\dfrac{L-a}{2}\right) \\ CB = AD = \left(\dfrac{L+a}{2}\right) \end{cases} \tag{4}$$

Substituting (4) into (3), the geometry factor for the Conventional Schlumberger array, becomes:

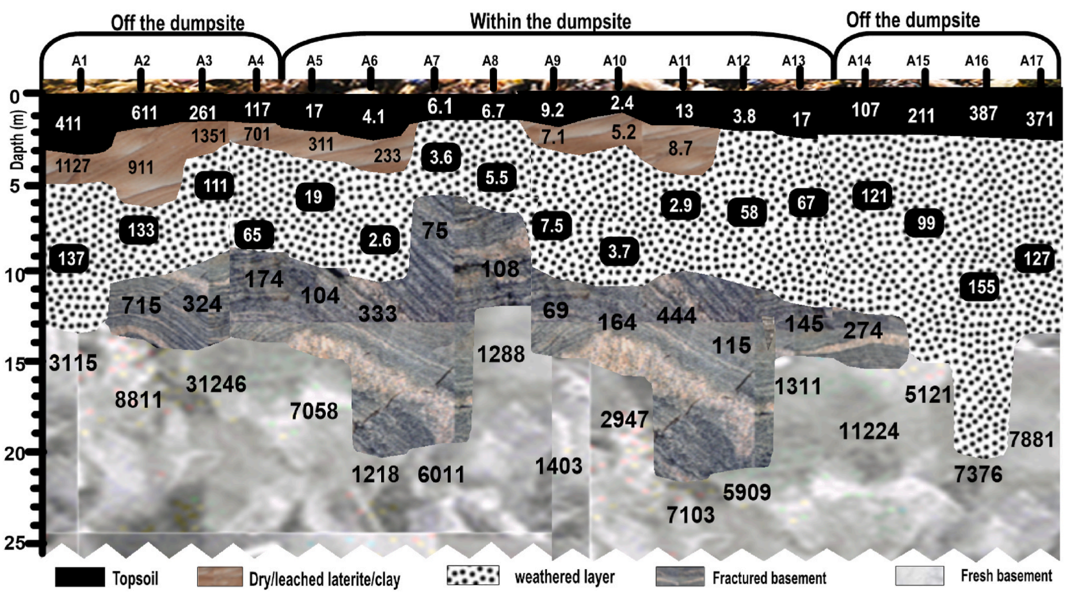

Fig. 3. Geoelectric/geologic profiles of the dumpsite showing the resistivity values along West – East azimuth. The resistivity values is a reflection of the dumpsite leachate infiltration of the subsoil.

$$K = 2\pi\left[\left(\frac{2}{L-a} - \frac{2}{L+a}\right) - \left(\frac{2}{L+a} - \frac{2}{L-a}\right)\right]^{-1} \tag{5}$$

Equation (5), can be expressed further to obtain (6), so that [54];

$$K = \frac{\pi}{4}\left[\frac{L^2 - a^2}{a}\right] \tag{6}$$

2.4. Data acquisition and processing

An Ohmega Ω resistivity Meter was used to acquire geophysical field data within the dumpsite. A pphysiochemical data of water from a total of seven (7) hand-dug wells (HDW) was within a radius of 200 *m* from the dumpsites. A clean bottled plastic rubbers were used to obtain water sample from seven HDWs for physiochemical water analysis. After electrical resistivity data acquisition via Schlumberger array, the geophysical field data was reduced and computed using Microsoft Excel software and consequently feed into computer software (Res ID version 1) for interpretation. The model block of the computer software and the accuracy fit are evaluated in terms of a root mean square (RMS) error [53].

3. Results and discussion

The qualitative data obtained from the computer software was used to model the geo-electric subsoil depth profile within and around the dumpsite to reveal subsurface information such as subsoil layers, layer resistivity and thickness (Figs. 3 and 4). Table 2 is a typical resistivity value compiled in different basement areas from recent studies within the 20 km radius of the dumpsite, which was used compared with the current study.

3.1. Geo-electrical results and its implications on groundwater

Fig. 3 is a subsoil depth profile of three to five geological layers. A total of seventeen (17) VES points taken along West–East azimuth were examined. The first layer (topsoil) resistivity is highly variable ranging from 4.8 Ωm to 611 Ωm. The VES points (A5 – A13) located within the dumpsite were marred with poor resistivity values, which indicate high EC, while the VES points (A1 - A5 and A14 – A17) located off the dumpsite were characterized by high subsurface resistivity values relatively closed to the resistivity values in Table 2. That is; the dumpsite subsurface is highly conductive (low tolerance), while the off-dumpsite is highly resistive (Fig. 3), which implies that the groundwater systems and the subsoil are heavily impacted by the dumpsite leachates [2]. [42] noted that the dumpsite leachates released into the environment hardly remain at the surface, but seeped down the soil to the water-bearing unit. The weathered unit resistivity values were found within the range of 2.9 Ωm – 19 Ωm, while fractured unit resistivity varies between 67 Ωm

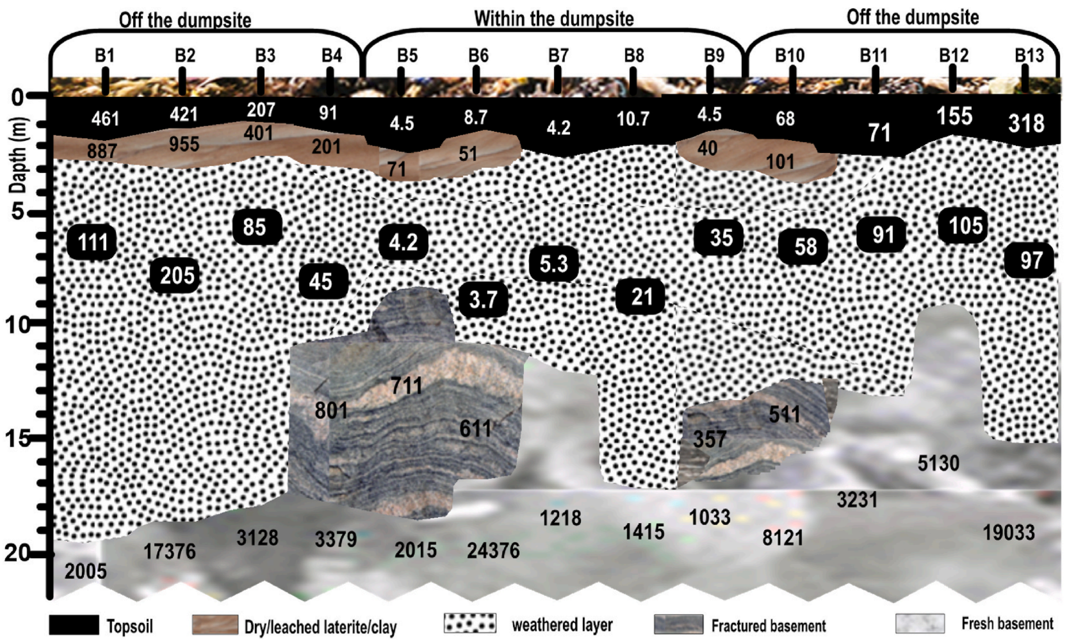

Fig. 4. Geoelectric/geologic profiles of the dumpsite showing the resistivity values along North – South azimuth. The resistivity values is a reflection of the dumpsite leachate infiltration of the subsoil.

Table 2
Typical subsoil resistivity values compiled from different locations within a 20 km radius of the study area [31,32,51,54]

Soil and Rock Types	Resistivity (Ωm)
Consolidated Lateritic/clay topsoil	300–5000
Weathered lateritic/clay	250–450
Wet sand, fine, silty	30–150
Weathered basement	50–100
Slightly weathered basement	200–500
Dry sand	500–1000
Fractured basement	400–1300
Fresh crystalline basement rock	>1500

and 444 Ωm, which grossly contradicted the ambient resistivity values compiled in Table 2. This implies that underground resources including groundwater have been greatly affected by the dumpsite leachate plumes. The subsurface resistivity values indicate the trend of dumpsite leachate plumes infiltration within the depth of 0 m–10 *m*. However, the last and infinite layer is characterized by high resistivity values ranging from 1288 Ωm to 31,246, which invariably show no significant difference between the dumpsite and off-dumpsite. This layer suggests fresh bedrock, and the seeping dumpsite leachates have little or no impact on the basement rock.

Fig. 4 show no significant deviation from Fig. 3, in both subsoil's electrical resistivity values and the stratiform. The off-dumpsite VES investigated (B1 – B4 & B10 – B10) affirmed the horizontal impact of the dumpsite leachates. The off-dumpsite investigation was extended to 60 *m* away from the dumpsite. It was observed that as the survey moved toward the dumpsite, the subsoil resistivity significantly decreased. This implies that the leachate plumes have not only leached the soil vertically but have also impacted the ground horizontally beyond 50 *m*.

Table 3 shows the typical resistivity values of different lithologies encountered in the study. In comparison, Tables 2 and 3 indicate the wide variation between the dumpsite and its ambient subsurface resistivity values. This confirms the impacts of the dumpsite leachates on the ground soil, which invariably has a significant impact on the chemical components of the groundwater systems and places human health on the high-risk radar as well. To minimize the environmental and human health risks, adequate techniques and treatment involving chemical, biological and physical processes are needed. However, total evacuation of the dumpsites is most likely the best way forward considering the location of the dumping ground.

3.2. Physicochemical analysis of water around the dumpsites

Table 4 shows the result of the physiochemical analysis of water obtained from the investigated seven HDWs. The measured parameters include Chromium (Cr), Chloride, chemical oxygen demand (COD); the potential of hydrogen (pH); cadmium (Cd^{2+}); biological oxygen demand (BOD); total dissolved solids (TDS); lead (Pb^{2+}); the electrical conductivity (EC), (Cl) and iron (Fe) in April 2022. The analysis was done at the Water Resources Department, Ahmadu Bello University and National Research Institute for Chemical Technology, both in Zaria, Nigeria. The bar charts were used to analyze the results obtained from the physiochemical analysis in the laboratory.

Fig. 5 shows the amount of pH contains in each of the seven HDWs investigated. The HDW1 indicates acidic water higher than WHO guideline limits, while HDW4, HDW5, HDW6 and HDW7 show higher alkaline values beyond 6.8 WHO permissible limits. That is, HDW1, HDW4, HDW5, HDW6 and HDW7 can cause detrimental plumbing damage to human health, while the rest of the wells (HDW 2 & HDW3), show moderate values within the WHO permissible limits.

Fig. 6 shows the EC of water obtained from the seven HDWs investigated. The HDWs water EC is high compared to healthy water drinking guidelines [55], this implies that the water contains a high concentration of the dissolved substance. High EC could indicate the heavy presence of salt, high temperature, heavy metals, and higher impurities (dissolved substances, chemicals, and minerals) in the water, which are harmful to human health when taken in excess. High concentrations of heavy metals reflect the high subsoil EC, which was affirmed by the geophysical technique applied at the dumpsite. This is because the presence of heavy metal in water and dissolved salts usually result in high EC readings [4].

Fig. 7 presents the level of heavy metal elements present in the seven investigated HDWs. The concentrations of Pb, Cd, Fe and Cr were high in all the HDWs located within the range 27 m–199 *m* from the dumpsite. However, there was a decrease in concentration as the wells increased in distance. The laboratory results of HDWs show four heavy metals (Cd, Fe, Pb and Cr) have a high content in the

Table 3
Typical subsoil resistivity values obtained from this study for comparative analysis.

Soil and Rock Types	Resistivity values (Ωm) within the dumpsite	Resistivity values (Ωm) off the dumpsite
Topsoil (lateritic/clay)	2.4–17	68–611
Weathered lateritic/clay, silty	5.2–311	101–1351
Weathered basement	2.6–67	45–205
Fractured basement	69–711	274–801
Fresh crystalline basement rock	>1000	>1000

Table 4
Physio-chemical analysis of the sample water obtained from seven hand-dug wells (HDW) within a 200 *m* radius of the dumpsite for groundwater vulnerability risk analysis.

Parameter	Unit	HDW 1	HDW 2	HDW 3	HDW 4	HDW 5	HDW 6	HDW 7	Average Value	[55]
Depth	m	8.9	6.9	5.6	7.9	4.7	5.7	5.5	6.5	–
Distance	m	27	32	33	42	147	75	199	79	–
Direction	–	NNW	WWS	SW	SS	NNE	NEE	NN	–	–
EC	ms/cm	1.221	0.971	0.873	1.001	1.024	0.699	0.578	0.910	0.100
pH	–	6.7	6.9	6.8	7.3	7.1	7.1	7.8	7.100	6.5–6.8
TDS	mg/l	1301	918	1212	871	617	597	400	845	500–1000
COD	mg/l	1017	955	871	1011	912	897	902	938	80
BOD	mg/l	561	472	509	471	461	387	459	474	<40
Lead	mg/l	1.992	1.555	1.098	0.911	0.974	0.871	0.768	1.167	0.01
Cadmium	mg/l	0.042	0.033	0.040	0.031	0.029	0.021	0.024	0.031	0.003
Iron	mg/l	1.918	1.767	1.479	0.971	1.075	0.782	0.775	1.253	0.30–1.00
Chromium	mg/l	0.512	0.497	0.511	0.397	0.4913	0.333	0.398	0.449	0.050
Chloride	mg/l	611	619	579	411	319	401	297	462	200–300

Note: chemical oxygen demand (COD); biological oxygen demand (BOD); total dissolved solids (TDS); the potential of hydrogen (pH); electrical conductivity (EC).

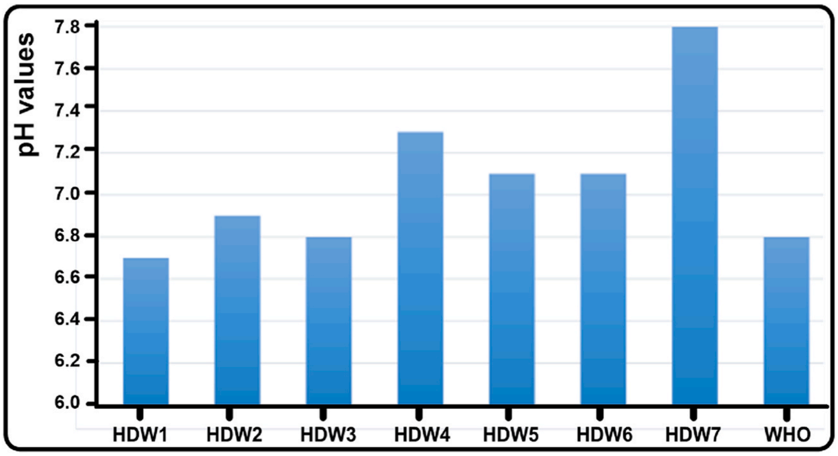

Fig. 5. Level of pH Present in the seven hand-dug wells within a 200 *m* radius of the dumpsite.

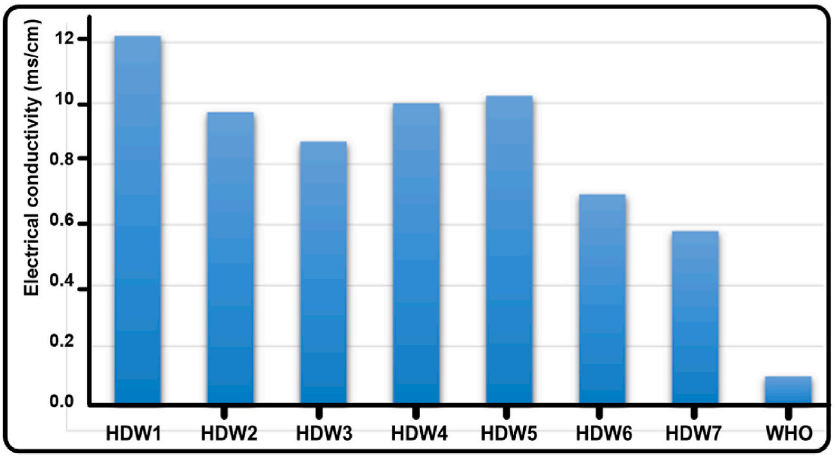

Fig. 6. Electrical conductivity of water in the seven hand-dug wells within a 200 *m* radius of the dumpsite.

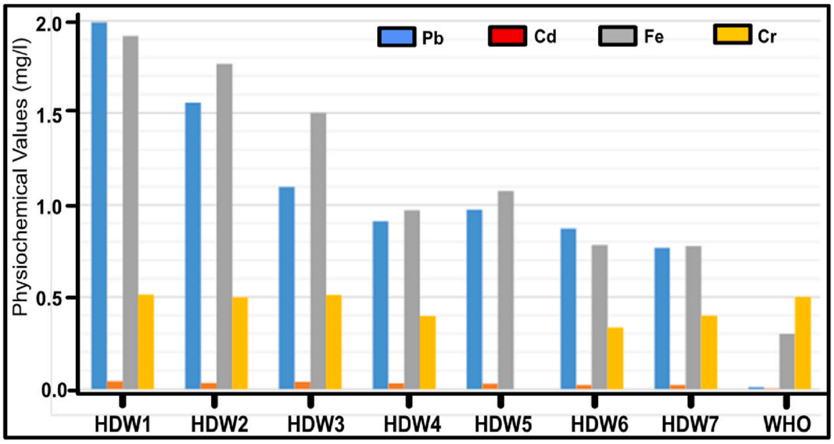

Fig. 7. Level of heavy metal elements present in the seven hand-dug wells within a 200 *m* radius of the dumpsite.

well-water; therefore, the subsoil and groundwater resources have been impacted by the dumpsite leachate contaminant. High concentrations of these heavy metals (Pb, Cd, Fe and Cr) largely account for the high EC (low resistivity values) experienced with the electrical resistivity technique applied at the dumpsite. This may have paved way for the easy flow of dumpsite leachate plumes and consequently communicated to subsoil and groundwater resources beyond the radius of 50 *m* of the dumpsite. The high concentration of metals is toxic in excess to human health, especially when the presence is more or less from its original limits in drinking water as permitted by Ref. [55]. However, the presence of high heavy metals in drinking water is more dangerous because they are not visible to the naked eye. Therefore, they are slow poison to human health because they do not have an immediate impact on the human body.

Fig. 8 presents the level of TDS, COD, BOD and Cl present in the Seven HDWs. A high TDS value means excess salts in the water. Excess salts in water can cause mineral deposits and scale formation. It also gives rise to corrosion of metal parts made of iron, zinc, etc [5,37,56]. Drinking water, with TDS levels higher than 1000 mg/L, is generally considered unfit for human consumption. A high level of TDS is also a direct indicator of potential concerns and calls for a thorough analysis. Mostly high levels of TDS in drinking water are a result of the high concentration of minerals like calcium and magnesium. According to Ref. [55], TDS levels higher than 1000 mg/L in drinking water, is generally unfit for human consumption. High levels of TDS in drinking water are the consequence of the high concentration of heavy metals such as magnesium and calcium. However, most of these minerals have little or no harm to human health; but may be toxic and harmful to human health. According to Ref. [55], water with a TDS level of less than about 600 mg/L is palatable for drinking and is generally considered to be good. However, when drinking water has TDS beyond 1000 mg/L, it becomes significantly and increasingly unpalatable and is discouraged from drinking. Based on this information, the results presented in Table 4 and Fig. 8, show that HDW1 and DHW3 are unfit for drinking water. Though, while HDW2 and HDW4 are not encouraging or perfectly okay, HDW5, HDW6 and DHW7 are relatively okay for drinking water. High TDS may signify bitter or salty water, but currently, no health-based guideline value for TDS has been proposed yet whether high or low TDS in drinking water because minerals like magnesium and calcium are often the reason behind high TDS levels, which are beneficial to human health.

On the same Fig. 8, the high amount of BOD and COD were encountered across all the seven HDWs. While the COD values vary

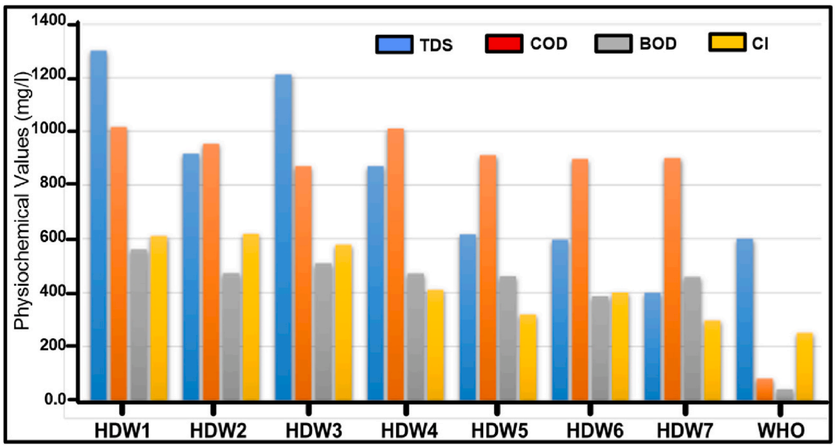

Fig. 8. Level of chemical oxygen demand; biological oxygen demand; total dissolved solids and Chloride present in the seven hand-dug wells within a 200 *m* radius of the dumpsite.

between 902 mg/L – 1017 mg/L, the BOD values vary between 459 mg/L – 561 mg/L (which is on the high side) reveals high organic potency resident in the dumpsite leachate plumes. In comparison, the high content of COD and BOD are far beyond the WHO permissible limits, and it may be attributed to the breaking down of the biodegradable mass overtime at the dumpsite, while the decomposition of the organic components of the solid wastes at the dumpsite by the action of microorganisms may also increase the level of organic matter, especially during the wet season.

The amount of detrimental substances like chloride (Cl) encountered in the seven HDWs were on the high side, which may demand urgent attention. Though, observation from Table 4 indicates that the pH values are relatively poor for drinking water. Note that the HDWs within the radius of 200 *m* of the dumpsite is of shallow depth ranging from 4.7 m–8.9 *m* and have been impacted. High chloride levels can, therefore, lead to increased metal concentrations in water as a result of corrosion. Studies have shown that high chloride content in water can affect the taste of drinking water. Though, Chlorine in its raw form; is a toxic, poisonous and irritant greenish-yellow gas that naturally occurred at room temperature and remains the most popular water disinfectant across the world. Hence, chlorine has no significant health hazards [55]. However, excess chlorine beyond 1000 mg/L is generally considered undrinkable. Based on this information, the seven HDWs show moderate content of chlorine and the water obtained from the wells is considered averagely okay in terms of chloride.

3.3. *Environmental implications*

a. With the increased rate of dumpsites across the world, a critical situation may occur in waste management and treatment, especially those landfills situated in a valley, fractured and shallow aquifers regions
b. With the rapid population expansion and indiscriminate waste disposal, the world may experience a serious scarcity of quality water due rapid increase in open dumpsites.
c. Tropically located dumpsites may experience a critical high rate of degradation and decomposition, which may result in a high rate of leachate plumes infiltrating the ground as well as the emission of dangerous, hazardous and odorous gas into the dumpsite ambient environment due to high temperatures

4. Impacts of open dumpsites and future direction

Fig. 9 illustrates the current situation of open dumpsites in developing nations and the impacts on both soil and groundwater, which is a typical reflection of the results obtained from the geo-electrical resistivity investigation and physiochemical water analysis of the case study. The common three major impacts of open dumpsites in developing nations are all detrimental to human health. Burning of waste materials heap at dumpsites is also popular among the developing nation, especially in Nigeria, where waste materials are disposed carelessly into dumpsites, oceans, rivers, gutters, or burned, and this has generated more environmental problems because the smoke from the burning wastes is hazardous, especially when excessively inhaled. On the other hand, groundwater around dumpsites has been polluted, which has led to a serious scarcity of quality water.

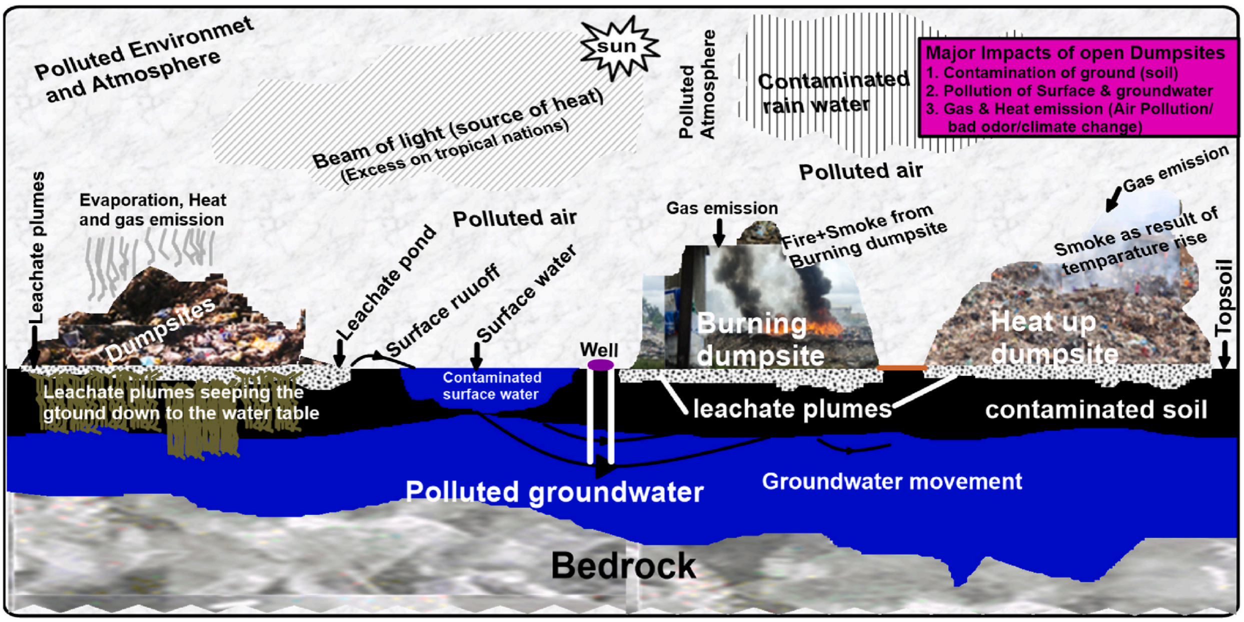

Fig. 9. Illustration of the open dumpsite impacts on groundwater and the environment (current situation of waste management in developing nations).

The landfill gas contributes to major environmental hazards (air pollution/odor), which in turn affect human health. All dumpsites including sanitary landfills emit unwanted and unavoidable odorous gas. Power production is an attractive option for tropical sanitary landfills where the climate nature and waste composition are highly favourable to waste depletion [57]. Therefore, a modern sanitary landfill illustrated in Fig. 10 is proposed for the future direction. The modern sanitary landfill has three major parts that distinguish it from open dumpsites and two major parts different from current sanitary landfills across the globe.

a. **Sanitary Landfill Pad/liner**: this part is already incorporated into the existing sanitary landfills. The sanitary landfill liner is a major gap filled by the existing sanitary landfills. The major function of a sanitary landfill liner is to prevent the leachate plumes from seeping the ground down to the aquifer systems. This part (pad/liner) resolved the challenge of ground and water pollution caused by open dumpsite leachate plumes.
b. **Emission Trapping Systems**: this part is one of the major parts of the proposed modern landfill suggested to sanitary landfill engineers for further action. It can resolve the challenge of bad odor, air pollution, climate change and inhaling of dumpsite gas emissions. The emission trapping systems can be designed to trap landfill gas and heat, which in turn can be used for power generation.
c. **Energy Generation Mechanism**: this part is another major part of a modern sanitary landfill that the sanitary landfill engineers could work toward achieving. The energy generation mechanism should be designed and constructed such that the system can convert waste materials into forms of energy such as electrical, mechanical or thermal energy.

A well-designed and constructed landfill is a good approach and a key factor for Groundwater protection, which in turn guarantee water security and sustainability. Studies show that the challenge of water scarcity does not mean a lack of abundance of water but it is more of water quality available for human consumption [58,59]. Groundwater has been described as the major reliable source of water distribution in the main African cities and it is less vulnerable to contamination and climate change [60]. Therefore, the quality of groundwater can be assessed from aquifer vulnerability to surface contaminants such as dumpsite leachates.

5. Conclusion and recommendations

An electrical resistivity survey was conducted on a dynamic Millennium City open dumpsite, in Kaduna Nigeria as a case study. A total of twenty-nine (29) VES points were acquired to investigate the activities of the dumpsite leachate plumes. While twelve (12) VES points were investigated within the dumpsite, seventeen (17) VES points were investigated around the dumpsite within a radius of 60 *m* to serve as the controlled station with a maximum spread (AB/2) of 70 *m*. The controlled station was extended from the dumpsite at a 15 *m* interval to enhance the comparative analysis of the dumpsite impacts on the soil and groundwater resources. Water samples were collected from seven (7) HDWs for physiochemical water analysis within a radius of 200 *m*. Based on the results of the physiochemical properties of the water obtained from the seven HDWs within a radius of 200 *m* of the dumpsites and the subsurface parameters (resistivity) obtained from the geophysical technique applied within and around the dumpsite. The off-dumpsite VES points (B1 – B4; B10 – B10; A1 – A4 and A14 – A17) investigated affirmed the trends of the horizontal impact of the dumpsite leachates on the ambient environment, which implies that the leachate plumes have not only leached the soil vertically but have also impacted the ground horizontally beyond 50 *m*. The shallow HDWs (vary from 4.7 *m* to 8.9 *m*) within the region of a 200 *m* radius with an average depth of 6.5 *m* have been polluted as revealed by the physiochemical analysis of the seven HDWs. From all indications, all the HDWs within the radius of 200 *m* have been affected by the dumpsite leachates, which may require boreholes to be sunk beyond 15 *m*. From the research findings, the following conclusions were drawn.

a. DC electrical resistivity technique has been successfully used to evaluate the degree of dumpsite leachate contamination within and ambient environments.
b. Having taken the geo-electrical resistivity data beyond the dumpsites to a distance of 60 *m*, and physiochemical data of water from 7 HDWs within the radius of 200 *m* of the dumpsite, it was noted that the leachate plumes of the dumpsite mush have masterminded the sharp alteration of the groundwater chemistry obtained from the 7 HDWs.
c. The results of the geophysical method and the physiochemical analysis of the well water indicate the similar treads. The high heavy metals present in the sample water may have reflected the spread of the dumpsite leachate plumes, which invariably influence and control the groundwater resistivity of the ambient environment.
d. The dumpsite resistivity values were very low, while that of the ambient ground increased with distance. These resistivity values reflect the subsurface tolerance of a dumpsite and the ambient subsoil, which in turn defines the vulnerability and protective capacity of the aquifer systems.
e. The corrosive and toxic nature of the dumpsite leachate plumes as revealed by the surrounding HDW physiochemical analysis may have been responsible for the low resistivity values obtained at the dumpsite by the electrical resistivity technique. That is, leachate plumes can annihilate the highly resistive subsoil of any terrain.
f. The HDWs close to the dumpsite indicate a higher content of heavy metal (Pb, Cd, Fe and Cr), TDS, COD and BOD, while there was a gradual decrease in the concentration with an increase HDWs distance and depth. Thus, to obtain quality drinking water around the dumpsite, boreholes should be sited beyond the depth of 15 *m*, probably into the second aquiferous system, since the leachates impacts decreased with depth and source distance.
g. The alteration in the water chemistry noted in the 7 HDWs is not unconnected to leachate plume encroachment since there were no noticeable contaminant sources within the region. Thus, the pollutants must have taken their bearing from the dumpsites.

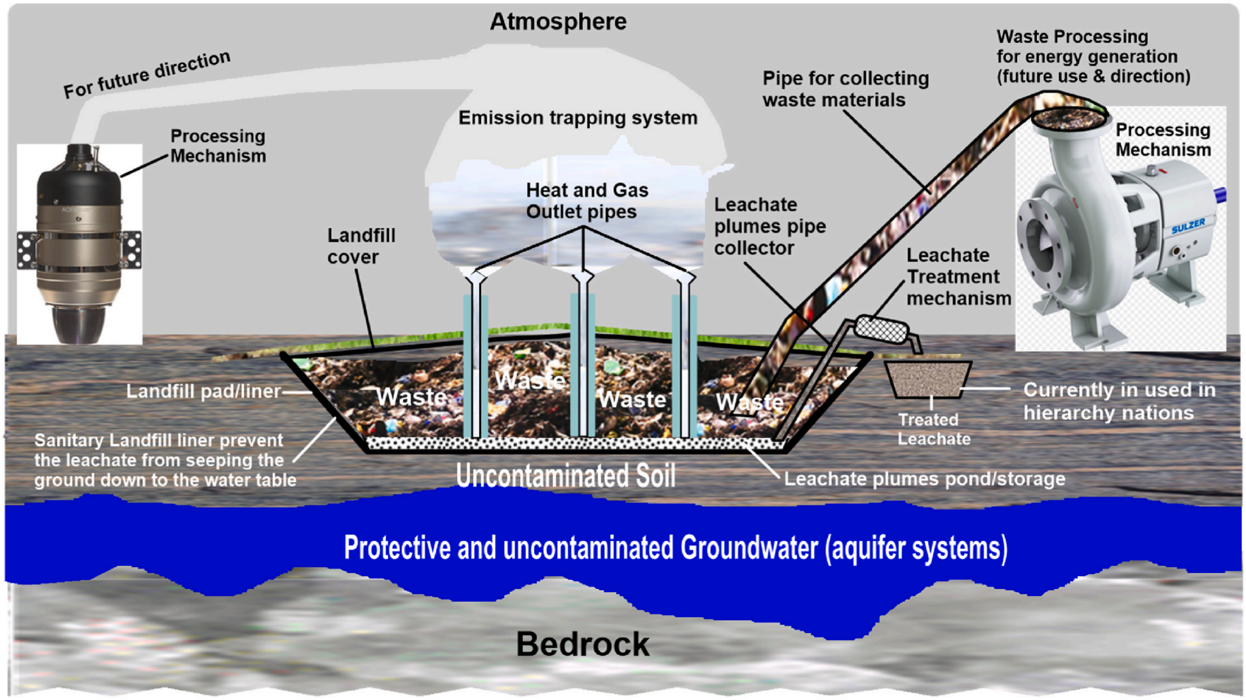

Fig. 10. Proposed modern sanitary landfills for future direction with modern technologies for total environmental security and sustainability.

Based on the research findings and data available data to this work, further physiochemical analysis of the dumpsite leachates should be carried out, followed by the distribution of questionnaires to the people living within a 200 *m* radius of the dumpsite for further risk index analysis are recommendations.

Declarations

Author contribution statement

Joseph Omeiza Alao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Lawal H.A: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Mohammed Shettima Nur: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials.

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Declaration of conflict interest

No conflicting interest.

Data availability statement

All the materials and data used for this research are available for further information.

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References

[1] R. Rana, R. Ganguly, A.K. Gupta, Indexing method for assessment of pollution potential of leachate from non-engineered landfill sites and its effect on ground water quality, Environ. Monit. Assess. 190 (2018) 46, https://doi.org/10.1007/s10661-017-6417-1.
[2] J.O. Alao, Impacts of open dumpsite leachates on soil and groundwater quality, Groundwater for Sustainable Devel. 20 (2023) 100877, https://doi.org/10.1016/j.gsd.2022.100877.
[3] O.O. Ojuri, I.I. Akinwumi, O.E. Oluwatuyi, Nigerian lateritic clay soils as hydraulic barriers to adsorb metals. Geotechnical characterization and chemical compatibility, Environ. Protect. Eng. 43 (2017) 4, https://doi.org/10.37190/epe170416.
[4] A.T. Ahmed, A.E. Alluqmani, M. Shafiquzzaman, Impacts of landfill leachate on groundwater quality in desert climate region, Int. J. Environ. Sci. Technol. (2018), https://doi.org/10.1007/s13762-018-2124-x.
[5] M.G.O. Ohanu, N.F. Ekeh, B.I. Ohanu, M.C. Ohanu, N. Aguzie, N. Ivoke, Evaluation of some heavy metals and physicochemical properties of public refuse dumpsites in Nsukka metropolis, Nigeria, Environ. Monit. Assess. 192 (2020) 477, https://doi.org/10.1007/s10661-020-08450-8.
[6] UNEP, "Global Waste Management Outlook (GWMO), International Solid Waste Association General Secretariat, 2015, ISBN 978-92-807-3479-9, p. 16.
[7] M. Vaccari, G. Vinti, T. Tudor, An analysis of the risk posed by leachate from dumpsites in developing countries, Environments 5 (2018) 99, https://doi.org/10.3390/environments5090099.
[8] O.O. Ojuri, F.O. Ayodele, O.E. Oluwatuyi, Risk assessment and rehabilitation potential of a millennium city dumpsite in Sub-Saharan Africa, Waste Manag. 76 (2018) 621–662, https://doi.org/10.1016/j.wasman.2018.03.002.
[9] M.A. Yusuf, T.A. Abiye, M.J. Butler, K.O. Ibrahim, Origin and residence time of shallow groundwater resources in Lagos coastal basin, southwest Nigeria: an isotopic approach, Heliyon 4 (2018), e00932, https://doi.org/10.1016/j.heliyon.2018.e00932.
[10] K. Adiat, A.A. Adegoroye, A.D. Adebiyi, B.E. Akeredolu, A.A. Akinlalu, Comparative assessment of aquifer susceptibilities to contaminant from dumpsites in different geological locations, Heliyon 5 (2019), e01499, https://doi.org/10.1016/j.heliyon.2019.e01499.
[11] M.Y. Yusuf, T.A. Abiye, K.O. Ibrahim, H.O. Abubakar, Hydrogeochemical and salinity appraisal of surficial lens of freshwater aquifer along Lagos coastal belt, South West, Nigeria, Heliyon 7 (2021), e08231, https://doi.org/10.1016/j.heliyon.2021.e08231.
[12] O.A. Ojo, C.A. Oyelami, M.A. Fakunle, A.K. Ogundana, O.E. Ajayi, T.E. Uche, Integrated approach to unsaturated zone characterization as it relates to burial practices and its impact on the immediate environment, Heliyon 8 (2022), e09831, https://doi.org/10.1016/j.heliyon.2022.e09831.
[13] M.K. Ayaim, B. Fei-Baffoe, A. Sulemana, K. Miezah, F. Adams, Potential sites for landfill development in a developing country: a case study of Ga South Municipality, Ghana, Heliyon 5 (2019), e02537, https://doi.org/10.1016/j.heliyon.2019.e02537.
[14] I.K. Kouame, A. DaoKonan, D. Noufe, J.T. Koffi, B. Kamagate, Analysis of the qualitative evolution of groundwater in the Abouabou area in the Port-Bou€et municipality (Abidjan, Cˆote d'Ivoire), Heliyon 6 (2020), e05268, https://doi.org/10.1016/j.heliyon.2020.e05268.
[15] M.E. El-Mathana, N.G. Mostafa, M. Galal, A. Elawwad, M.E. El-Mathana, N.G. Mostafa, M.M. Galal, A. Elawwad, Assessment and simulation of a solid waste dumpsite impact on the surrounding water resources: a case study in Abu Zaabal, Egypt, Heliyon 7 (2021), e08421, https://doi.org/10.1016/j.heliyon.2021.e08421.
[16] S.S. Mavimbela, O.O. Ololade, J.J. van Tol b, M.P. Aghoghovwia, Characterizing landfill leachate migration potential of a semi-arid duplex soil, Heliyon 5 (2019), e02603, https://doi.org/10.1016/j.heliyon.2019.e02603.
[17] F. Parvin, S.M. Tareq, Impact of landfill leachate contamination on surface and groundwater of Bangladesh: a systematic review and possible public health risks assessment, Appl. Water Sci. 11 (2021) 100, https://doi.org/10.1007/s13201-021-01431-3.
[18] F.P. Sankoh, X. Yan, Q. Tran, Environmental and health impact of solid waste disposal in developing cities: a case study of granville brook dumpsite, freetown, Sierra Leone, J. Environ. Protect. 4 (2013) 665–670, https://doi.org/10.4236/jep.2013.47076.
[19] P. Alam, K. Ahmade, Impact of solid waste on health and the environment, International J. Sustainable Devel. Green Econ. (IJSDGE) 2 (2013). V-2, I-1.
[20] M.D. Vaverková, Landfill impacts on the environment— review, Geosciences 9 (10) (2019), https://doi.org/10.3390/geosciences9100431.
[21] R. Altarez, N.A. Sedigo, Existing land use and extent of lead (Pb) contamination in the grazing food chain of the closed Carmona sanitary landfill in the Philippines, Heliyon 5 (2019), e01680, https://doi.org/10.1016/j.heliyon.2019.e01680.
[22] J.N. Jebaranjitham, J.D. Christy, A. Prasannan, K. Rajagopalan, K.S. Chelladurai, J. Gnanaraja, Current scenario of solid waste management techniques and challenges in Covid-19 – a review, Heliyon 8 (2022), e09855, https://doi.org/10.1016/j.heliyon.2022.e09855.
[23] I.D. Okereke, P. Harcourt, Electrical resistivity investigation of solid waste dumpsite at rumuekpolu in obio akpor L . G . A, Rivers State, Nigeria 1 (11) (2012) 631–637.
[24] C.C. Okpoli, Application of 2D electrical resistivity tomography in landfill site: a case study of iku, ikare akoko, southwestern Nigeria, Hindawi–J. Geolog. Res. Volume (2013) 8, https://doi.org/10.1155/2013/895160.
[25] J.O. Alao, M.S. Ahmad, T.T. Danjumo, A. Ango, J. Emmanuel, Assessment of aquifer protective capacity, against the surface contamination. A case study of Kaduna industrial village, Nigeria, Physical Science Int. J. 26 (1) (2022) 43–51, https://doi.org/10.9734/PSIJ/2022/v26i130306. Article no.PSIJ.85191.
[26] P. Veronica, M. Stefano, F. Riccardo, A review of the advantages and limitations of geophysical investigations in landslide studie, Hindawi @ Int. J. Geophysics 27 (2019), https://doi.org/10.1155/2019/2983087.
[27] A. Green, E. Lanz, H. Maurer, D. Boerner, Template for geophysical investigations of small landfills, Lead. Edge 18 (2) (1999) 248–254.
[28] L. Orlando, E. Marchesi, Georadar as a tool to identify and characterise solid waste dump deposits, J. Appl. Geophys. 48 (3) (2001) 163–174.
[29] M.O. Oyawoye, The basement complex of Nigeria, in: T.F.J. Dessauvagie, A.J. Whiteman (Eds.), African Geology, Ibadan: University Press, Ibadan Nigeria, 1970, pp. 91–97.
[30] O.O. Isaac, C.A. Jonah, A.O. Joel, Assessment of aquifer characteristics in relation to rural water supply in part of northern Nigeria, Researcher 2 (3) (2010) 22–27.
[31] J.A. Omeiza, M.D. Dogara, Aquifer vulnerability to surface contamination: a case of the new millennium city, Kaduna, Kaduna State Nigeria, World J. Applied Physics 3 (1) (2018) 1–12, https://doi.org/10.11648/j.wjap.20180301.11.
[32] H.O. Aboh, M.D. Dogara, J.O. Alao, Evaluation of the geotechnical parameters in part of Kaduna, Kaduna state Nigeria, World J. Appl. Sci. Technol. 8 (2) (2016) 108–117. ISSN: 2141 – 3290, www.wojast.com.
[33] A. Sharma, R. Ganguly, A.K. Gupta, Impact assessment of leachate pollution potential on groundwater: an indexing method, J. Environ. Eng. 146 (3) (2020), https://doi.org/10.1061/(ASCE)EE.1943-7870.0001647.
[34] A. Mojiri, H.A. Aziz, N.Q. Zaman, S.Q. Aziz, M.A. Zahed, Metals removal from municipal landfill leachate and wastewater using adsorbents combined with biological method. Desalin, Water Treat. 57 (2016) 2819–2833, https://doi.org/10.1080/19443994.2014.983180.
[35] M. Vahabian, Y. Hassanzadeh, S. Marofi, Assessment of landfill leachate in semi-arid climate and its impact on the groundwater quality case study: hamedan, Iran, Environ. Monit. Assess. 191 (2019) 109, https://doi.org/10.1007/s10661-019-7215-8.
[36] G. Przydatek, W. Kanownik, Impact of small municipal solid waste landfill on groundwater Quality, Environ. Monit. Assess. 191 (2019) 169, https://doi.org/10.1007/s10661-019-7279-5.
[37] J.O. Oseji, J.C. Egbai, E.C. Okolie, E.C. Ese, Investigation of the aquifer protective capacity and groundwater quality around some open dumpsites in sapele delta state , Nigeria, Applied and Environ. Soil Sci. (2018), https://doi.org/10.1155/2018/3653021.
[38] Q. Bian, Waste heat: the dominating root cause of current global warming, Bian Environ Syst Res 9 (2020) 8, https://doi.org/10.1186/s40068-020-00169-2.
[39] O. Ameyan, O. Alabi, Soil temperatures in Nigeria, Phys. Geogr. 8 (3) (1987) 275–286, https://doi.org/10.1080/02723646.1987.10642328.
[40] M.J. Mortimore, Settlement evolution and land, in: M.J. Mortimore (Ed.), Zaria and its Region) Occasional Paper 4, Department of Geography A. B. U. Zaria, 1970, pp. 102–122.
[41] A. Mojir, L.Z. John, H. Ratnaweera, A. Ohashi, O. Noriatsu, Tomonori Kindaichi, Hiroshi Asakura, Treatment of landfill leachate with different techniques: an overview, J. Water Reuse and Desalination 11 (1) (2021) 66–96, https://doi.org/10.2166/wrd.2020.079.

[42] J.A. Omeiza, O.O. Abdulwahab, M.S. Nur, T.T. Danjuma, J. Emmanuel, A. Diya'ulhaq, O.O. Adekanye, T.M. Ekwu, Effect of an active open dumpsite on the earth's subsurface and groundwater resource, Asian J. Physical and Chem. Sci. 10 (2) (2022) 15–24, https://doi.org/10.9734/AJOPACS/2022/v10i230152. Article no.AJOPACS.87738.

[43] J.L. Hanson, N. Yesiller, Incorporating thermal effects in modeling of MSW landfills, in: L. Zhan, Y. Chen, A. Bouazza (Eds.), Proceedings of the 8th International Congress on Environmental Geotechnics Volume 2. ICEG 2018. Environmental Science and Engineering, Springer, Singapore, 2019, https://doi.org/10.1007/978-981-13-2224-2_2. Kumar, G., Kopp, K., Reddy, K.R.

[44] G. Kumar, K.R. Reddy, Temperature effects on stability and integrity of geomembrane–geotextile interface in municipal solid waste landfill, Int. J. of Geosynth. and Ground Eng. 7 (2021) 19, https://doi.org/10.1007/s40891-021-00262-1.

[45] M. Thomas, P. Drzewicz, A. Wieckol-Ryk, Influence of elevated temperature and pressure on treatment of landfill leachate by potassium ferrate(VI), Water Air Soil Pollut. 232 (2021) 450, https://doi.org/10.1007/s11270-021-05401-y.

[46] T. Zhang, J. Shi, X. Wu, S. Shu, H. Lin, Simulation of heat transfer in a landfill with layered new and old municipal solid waste, Scientifc Reports 12 (2022) 2970, https://doi.org/10.1038/s41598-022-06722-6.

[47] M. Aljaradin, K.M. Persson, Environmental impact of municipal solid waste landfills in semi-arid climates - case study – Jordan, Open Waste Manag. J. 5 (2012) 28–39.

[48] R.P. Chavez, E.C.c. Pizarro, Y. Galiano, Landfill leachate treatment using activated carbon obtained from coffee waste, Eng. Sanitária Ambient. 24 (2019) 8330842, https://doi.org/10.1590/S1413-41522019178655.

[49] M. Vaccari, T. Tudor, G. Vinti, Characteristics of leachate from landfills and dumpsites in Asia, Africa and Latin America: an overview, Waste Manage. (Tucson, Ariz.) 95 (2019) 419–431, https://doi.org/10.1016/j.wasman.2019.06.032.

[50] J. Tejera, R. Miranda, D. Hermosilla, I. Urra, C. Negro, A. Blanco, Reatment of mature landfill leachate: comparison between homogeneous and heterogeneous photo-Fenton with different pretreatments, Water 11 (2019) 1849, https://doi.org/10.3390/w11091849.

[51] J.O. Alao, M.D. Dogara, A. Danlami, E.E. Samson, Comparative assessment of half schlumberger configuration as an alternative method to the conventional schlumberger configuration at trade centre, mani-nissi village, Kaduna, Nigeria, SSRG Int. J. Applied Physics (SSRG-IJAP) – Volume 6 (3) (2019) 51–56, https://doi.org/10.14445/23500301/IJAP-V6I3P109.

[52] W.M. Telford, L.P. Geldart, E.R. Sheriff, Applied Geophysics, Cambridge University Press, 1990.

[53] N.E. Ekeocha, I.I. Okereke, S. Okonkwo, E.Electrical resistivity investigation of solid waste dumpsite at rumuekpolu in obio akpor L.G.A., rivers state, Nigeria, Int. J. Sci. Technol. 1 (11) (2012) 631–637.

[54] M.D. Dogara, J. Alao, H. Abdullahi, J. Ezekiel, J. George, Delineation of the geotechnical parameters within the Kaduna refining and petrochemical corporation layout, World J. Applied Physics 2 (3) (2017) 36–42, https://doi.org/10.11648/j.wjap.20170203.11.

[55] H.O. WHO, Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum, Licence, Geneva, 2017. CC BY-NC-SA 3.0 IGO, https://apps.who.int/iris/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1.

[56] A. Roychoudhury, S. Chakraborty, Effect of hydrogen sulfide on osmotic adjustment of plants under different abiotic stresses, in: M.N. Khan, M.H. Siddiqui, S. Alamri, F.J. Corpas (Eds.), Hydrogen Sulfide and Plant Acclimation to Abiotic Stresse," *Plant In Challenging Environments*, vol. 1, Springer, Cham, 2021, https://doi.org/10.1007/978-3-030-73678-1_5.

[57] S.L. Machado, Á.C. Santos, M. de Fátima Carvalho, L.A. Goes Damasceno, L.V. Almeida, A.B. dos Santos, Biogas production in a tropical landfill: long-term monitoring results and analysis of variables of influence, Environ. Monit. Assess. 193 (2021) 485, https://doi.org/10.1007/s10661-021-09248-y.

[58] K.O. Olomo, Assessment of groundwater vulnerability based on electrical resistivity—a case study in part of Dahomey Basin, southwestern Nigeria, Arabian J. Geosci. 14 (2021) 2125, https://doi.org/10.1007/s12517-021-08559-1.

[59] T.D. Aneesh, M.N. Archana, R.P. Krishna, T.J. Arun, S. Reji, Groundwater vulnerability assessment of an urban coastal phreatic aquifer in India using GIS-based DRASTIC model, Groundwater for Sustainable Devel. 19 (2022) 100810, https://doi.org/10.1016/j.gsd.2022.100810.

[60] K.H. Konan, I.K. Kouame, A. Noufe, J. Koffi, B. Kamagate, Analysis of the qualitative evolution of groundwater in the Abouabou area in the Port-Bou€et municipality (Abidjan, Cˆote d'Ivoire), Heliyon 6 (2020), e05268, https://doi.org/10.1016/j.heliyon.2020.e05268.