

Hydro-geochemical characterization and Groundwater modelling of the subsurface around Ughelli West Engineered Dumpsite in the Western Niger Delta, Nigeria



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ABSTRACT: Geoelectric, geochemical investigation, and groundwater modelling were integrated in areas surrounding the Ughelli West Engineered dumpsite in the Western Niger Delta. The study focused on assessing the environmental impact of the dumpsite on its surrounding groundwater. The geochemical analyses revealed that the leachates generated from the dumpsite have significant potential to contaminate the surrounding environment. The BOD₅/COD ratio was less than 0.1, indicating that the dumpsite is old with stabilized leachate of low biodegradability and in the methanogenic phase of anaerobic degradation. The groundwater chemistry in monitoring wells outside the dumpsite and at other control sites showed no significant impact of the dumpsite on groundwater quality. Groundwater models showed groundwater flow in the north-western direction and significant vertical movement of contaminants up to depths of about 60 m beneath the dumpsite after a period of 3 years. The contaminant plume, however, had not moved considerably laterally away from the dumpsite. The location of the dumpsite within areas of low vulnerability due to the presence of clay/sandy clay between 1.3 and 6 m thick around the dumpsite limited the lateral migration of leachate in groundwater.

KEYWORDS: Dumpsite, Groundwater model, Vulnerability, Leachate, Infiltration

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I. INTRODUCTION

Groundwater resource is abundant in the Niger Delta region and is a major source for domestic and industrial use; however, the presence of contaminants in groundwater pose significant challenges to its search and usage. The Niger Delta is one of the world's largest petroleum region, and its importance lies in its abundant oil and gas reserves. The presence of oil companies and other related industries has caused population in the region to increase enormously; thus leading to high demand for potable water by the teeming population. The area has sufficiently thick aquifers comprising of porous and permeable sand with high transmissivity thus giving the Niger Delta region good to excellent groundwater potential. However, the huge waste generated by this growing population has an alarming detrimental effects on groundwater quality (Bate *et al.*, 2018).

Groundwater conditions in any environment is controlled by several factors such as the chemical composition of the infiltrating water at the point of recharge and the chemical composition of the host rock; such as the cementing material of the aquifer matrix. Others include water table, porosity/permeability of the aquifer, groundwater flow rate and the travel time of water through the vadose zone into the saturated zone. Anthropogenic activities; apart from these natural causes of contamination can also have an adverse effect on

groundwater quality (Akpoborie *et al.*, 2015). Leakages from septic tanks, sewage channels, and dumpsites are some established sources of subsurface contamination which has now become a major threat to groundwater resources (Kumari *et al.*, 2017; Rana *et al.*, 2018; Igboama *et al.*, 2022). This is because the subsurface, which serves as aquifers, is also the site for waste disposal. The prime effect of disposing waste directly into the subsurface or dumpsites without suitable liners is generation of leachate, which constitutes one prominent challenge related to groundwater exploitation (Adeolu *et al.*, 2011; Aweto, 2017; Aladejana *et al.*, 2018). One exquisite problem associated with dumping of wastes in the open is the spread of diseases. According to the World Health Organization (WHO 2011), about 80 % of all the diseases in a human being are water-borne.

Deterioration in groundwater quality of the Niger Delta has been linked to the shallow attributes of the aquifer, thus making them open qualitatively to chemical and biological contamination (Aweto 2012; Igboama *et al.*, 2022). Various studies have reported the deterioration of groundwater quality in the Niger Delta. Aweto *et al.* (2015) reported elevated total dissolved solids (TDS) in shallow aquifer due to anthropogenic activities; Okpara *et al.* (2021) observed that groundwater sources close to dumpsites are prone to contamination while Iwegbue *et al.* (2023) reported Cd, Fe and turbidity as major cause of deterioration of water quality. It has been observed

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that once groundwater quality is negatively affected due to presence of pollutants, it cannot be ameliorated by the removal of the source. This is because the pollutants in groundwater may persist for a significant long period of time even after the source of pollution had been removed (Cozzarelli, *et al.*, 2011; Bjerg, *et al.*, 2014). Therefore, it has now become crucial to monitor groundwater quality frequently and envisage means to protect it.

Modern dumpsites in emergent nations are designed with suitable liners which prevent leachate migration into groundwater. The dumpsite in the study area is lined, however, despite the compactness of the clay liners they may deteriorate after sometime due to numerous setbacks (Cossu & Stegmann, 2019). Shell Petroleum Development Company (SPDC 2005) had earlier reported compromise of liners and intense downward percolation of leachate has been recorded. In this present investigation, the groundwater surrounding the dumpsite was characterized to ascertain the effect of leachate percolation and dispersion using geophysical, hydro-geochemical, and groundwater modelling approaches.

II. MATERIALS AND METHOD

A. Location and Geology

The study area is the Ughelli West engineered dumpsite, located in the Uvwiamuge community, 10 km Southeast of Warri, in the Western part of the Niger Delta (Figure 1). It lies between longitudes 5° 51' E, 5° 53' E, and latitudes 5° 34' N, 5° 36' N. The subsurface geology of the area includes the Holocene Sombreiro – Warri Deltaic Plain deposits have been described and summarized in different studies (Akpoborie *et al.*, 2015, Ohwohere-Asuma *et al.*, 2018; Ohwohere-Asuma *et al.*, 2020). This deposit which is between 40 and 150 m thick, comprises of laterally homogenous fine to medium and coarse-grained sands with occurrences of little clays. Beneath the Sombreiro –Warri Deltaic Plain deposits are successions of sedimentary formations that include, from top to bottom: Oligocene – Pleistocene Benin Formation, Eocene – Oligocene Agbada Formation, and Paleocene – Eocene Akata Formation.

B. Resistivity Survey

Field resistivity measurements engaged the Schlumberger field procedure (Patra & Nath 1998). In the present work vertical electrical soundings were conducted using the ABEM SAS 1000 resistivity meter at sixteen (16) locations, as shown in Figure 1. Current electrodes (AB) separation ranged between 1 m and 200 m. The depth-sounding data were presented as sounding curves which were interpreted manually (Patra & Nath, 1998) and subsequently by computer iteration with *winResist Version 1.0* software (Vander Velpen, 2004). The electrical resistivity values of geoelectric layers facilitated the delineation of lithological units and identification of aquifer units (Aweto, 2019) with the aid of drillers log data from the area.

C. Aquifer Vulnerability

The Aquifer Vulnerability Index method was used to assess the vulnerability of the aquifer in the study area. This method evaluates the hydraulic resistance C in the aquifer; this

is equivalent to the travel time of contaminants through the vadose zone (Van Steempvort *et al.*, 1992). The hydraulic resistance in a year is determined by the expression given below:

$$\text{Log } C = \sum_i^n \frac{d_i}{k_i} \quad (1)$$

where d_i and k_i are the thickness and hydraulic conductivity of the vadose layers, respectively.

Hydraulic conductivity values of 3650 cm/y for sand, 0.365 cm/y for clayey sand, 0.0365 cm/y for sandy clay, and 0.000365 cm/y for clay as obtained from Aweto & Ohwohere-Asuma (2018) were used in this study.

D. Leachate and Groundwater Analysis

To examine the effect of leachate on the environment surrounding the dumpsite, water samples were collected at monitoring wells surrounding the dumpsite and other locations far from the dumpsite. At the same time, five (5) leachate samples from the collection systems were also collected. All samples collected were preserved and analysed using standard methods (APHA 2012; USEPA 2007). The parameters analysed in groundwater and leachate samples include pH, EC, COD, BOD₅, Ca, Mg, K, Na, SO₄, Cl, Pb, Cu, Cd, Zn, Cr, Ni, and Fe.

E. Groundwater Modelling

The package used for this work is MODFLOW, developed by the United States Geological Survey (McDonald & Harbaugh 1988). MODFLOW is capable of performing both steady-state and transient analyses based on the law of conservation of mass, which assumes that the groundwater flow rate into an aquifer equals the rate of flow out from the aquifer. The governing equation is given below:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - Q = S_s \frac{\partial h}{\partial t} \quad (2)$$

Where;

K_x, K_y, K_z = hydraulic conductivity along the x, y, and z axes which are assumed to be parallel to the major axes of hydraulic conductivity;

h = piezometric (hydraulic) head;

Q = volumetric flux per unit volume representing source/sink terms;

S_s = specific storage coefficient i.e the volume of water released from storage per unit change in head per unit volume of porous material.

The contaminant plume in the dumpsite was modelled for a stress period of 30 years. Transportation of solutes in the saturated zone is controlled by the advection-dispersion equation, which for a porous medium characterized by constant porosity pattern is given as follows:

$$\frac{\partial c}{\partial t} = - \frac{\partial}{\partial x_i} (c v_i) + \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial c}{\partial x_j} \right) + R_c \quad i, j = 1, 2, 3 \quad (3)$$

Where;

c = concentration of the solute;

R_c = sources or sinks;

D_{ij} = dispersion coefficient tensor;

V_i = velocity tensor.

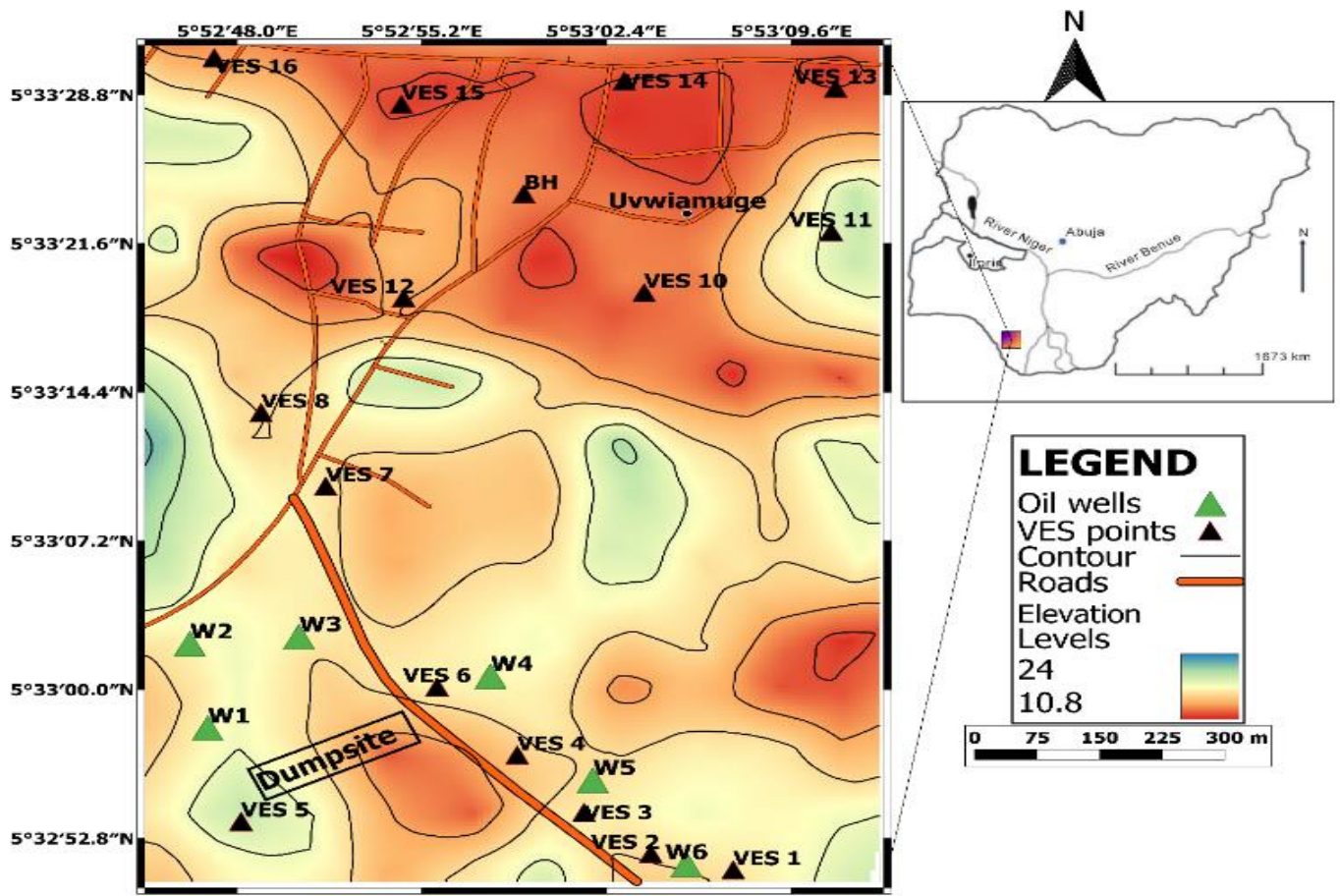


Figure 1: Map of the study area from digital elevation model

F. Conceptual model

The conceptual model grid approach was used to produce the groundwater-flow model. The model's grid consists of x, y, and z axes indicating width, length, and depth; $x = 1104$ m, $y = 1582$ m were estimated from the Digital Elevation Model (DEM) of the study area and $z = 80$ m from the borehole log of the area. Groundwater flow direction was determined from known hydraulic heads from wells. The DEM of the area was used as top elevation, and the borehole log was used to assign the remaining two layers. The hydraulic conductivity values of each layers were assigned from hydraulic conductivity values of different formations as provided by Guideal (2011). The Recharge rate of $638.46 \text{ mm/yr} = 0.001749 \text{ m/day}$ used for the model was estimated from the average annual rainfall of Warri between 2005 – 2015 (Oyerinde 2021).

Dispersion, longitudinal dispersivity, transverse and vertical dispersivity as estimated by Schulze-Makuch (2005) was used in this study. Longitudinal dispersivity was taken as 8.5 m, while transversal and vertical dispersivity were taken as 0.85 m and 0.085 m respectively.

III. RESULTS AND DISCUSSION

A. Isoresistivity and Vulnerability Map

In order to show the subsurface lithological distribution at various depths based on resistivity variations and vulnerability index, an isoresistivity and vulnerability maps were generated with the aid of SURFER 8 terrain and surface modelling

software (SURFER 2002). The results are shown in Figures 2 & 3.

The colours indicate the various lithologies and their resistivity range. The areas with blue colour having resistivity values ranging between 21 and $90 \Omega\text{m}$ indicate clay lithology. The areas with yellow colour having resistivity values ranging from 101 to $130 \Omega\text{m}$ indicate sandy clay and clayey sand lithology respectively. In contrast, the areas with red colour having resistivity values ranging between 180 and $1340 \Omega\text{m}$ represents sandy lithology. The isoresistivity map of Uvwiamuge at 5 m (Figure 2) showed that about 30 % of the area in the Southwest, Central, Northwest, and Northeast delimited with blue colour (VES 4, 5, 6, 11, 12, 15, and 16) is underlain by clay. The areas with yellow colour around VES 7 and 10, representing 26 %, are underlain by sandy clay and clayey sand, while the remaining 46 % (red colour) is underlain by sand. The isoresistivity map at 10 m and 20 m shows that the entire area is underlain by pervious sand, which serves as an aquifer.

The vulnerability of the aquifer to contamination was evaluated using the values of the logarithm of hydraulic resistance, as shown in Table 1.

The Aquifer Vulnerability Index defined three zones of vulnerability (Figure 3): low vulnerability (ruby red), moderate vulnerability (brown), and extremely high vulnerability (orange). The areas with low vulnerability constitute about 25 % of the entire area and lie within the Northern (VES 4, 5, and

6) and Southern (VES 12 and 15) parts. The dumpsite is located within the low vulnerability zone in the South, as shown in Figure 4. The aquifer in these areas is adequately protected from the surface and near-surface contaminants and hence not vulnerable. The areas with moderate vulnerability (representing about 19 % of the entire area) envelop the zones of low vulnerability as lithology changes from clays to sandy clays/clayey sand. The aquifer in the remaining 56 % of the area is highly vulnerable to contaminants because these areas are underlain by porous sand.

B. Leachate and Groundwater Characterization

Groundwater samples were characterized to ascertain the extent of contamination by leachate from the dumpsite; results are shown in Table 2. P^H range in leachate is 7.2 – 8.5 while P^H range in boreholes outside the dumpsite is 6.2 – 7.5. Electrical conductivity of leachate is high (4220 – 5021 $\mu S/cm$) compared to range of 25 – 98 $\mu S/cm$ in boreholes outside the dumpsite. The concentration of chemical oxygen demand (COD) and biochemical oxygen demand (BOD₅) range in groundwater are 36.5 – 105 mg/L and 1.4 – 5.35 mg/L while values in leachate range between 881 – 917 mg/L and 62 – 75 mg/L respectively. The concentration of calcium, magnesium, potassium, sodium, sulphate and chloride in leachate are 33 – 54.2 mg/L, 10.6 – 25.4 mg/L, 180.1 – 806.3 mg/L, 207.6 - 522 mg/L, 225 – 803.2 mg/L and 207.6 - 522 mg/L respectively. The concentrations of calcium, magnesium, potassium, sodium, sulphate and chloride in mg/L were: 2.15 – 11.62, 2.37 – 8.28, 2.36 – 12.39, 1.52 – 6.44, 2.84 – 9.66 and 2.40 – 10.14 in groundwater samples.

Table 1 Relationship of aquifer vulnerability to hydraulic resistance (After Van Steempvort *et al.*, 1992)

The logarithm of the C	Aquifer vulnerability index
< 1	Extremely high vulnerability
1 – 2	High vulnerability
2 – 3	Moderate vulnerability
3 – 4	Low vulnerability
> 4	Extremely low vulnerability

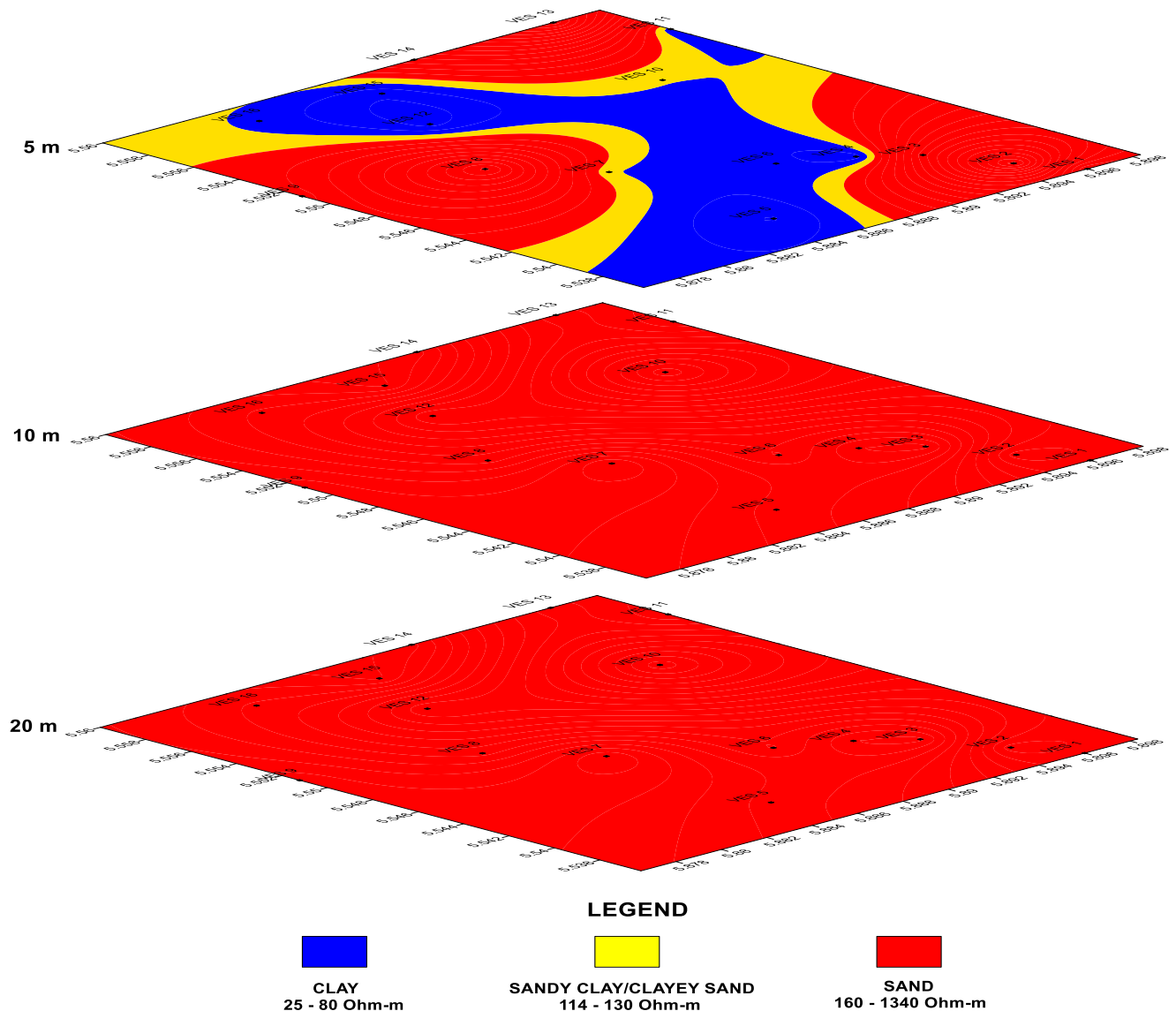


Figure 2: Isoresistivity map of the study area at 5m, 10m, and 20m

The results of heavy metal concentration in leachate showed concentration of Pb (0.80 – 2.10 mg/L), Cu (0.45 – 2.02 mg/L), Cd (0.09 – 0.10 mg/L), Zn (0.21 – 0.58 mg/L), Cr (0.062 – 0.27 mg/L), Ni (0.001 – 0.04 mg/L) and Fe (5.60 – 19.85 mg/L); whereas concentration in groundwater ranged from Pb (0.025 – 0.04 mg/L), Cu (BDL – 0.03 mg/L), Cd (BDL – 0.0015 mg/L), Zn (0.016 – 0.0014 mg/L), Cr (0.001 – 0.035 mg/L), Ni (BDL – 0.01 mg/L) and Fe (0.02 – 0.315 mg/L).

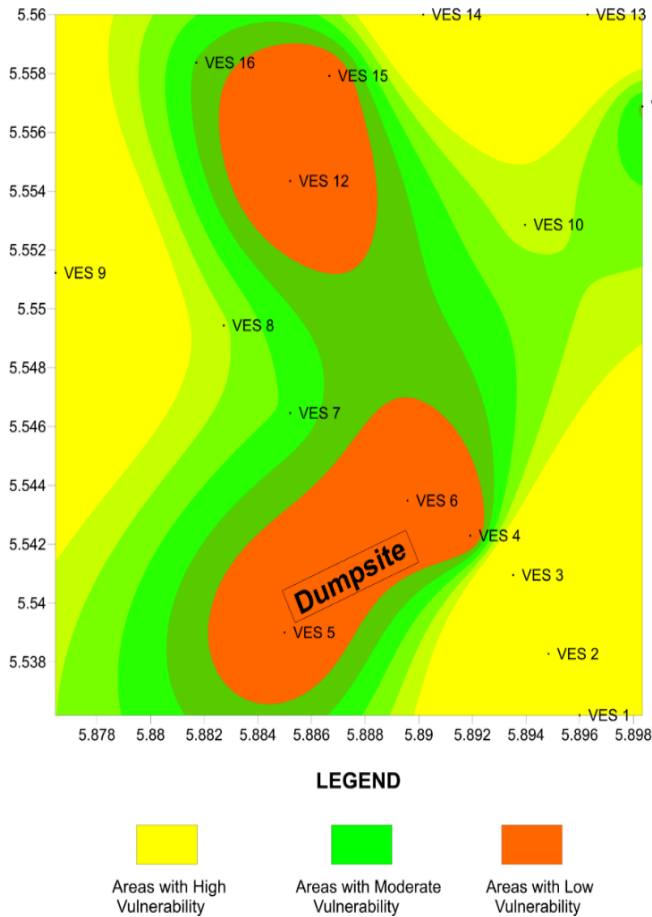


Figure 3: Aquifer vulnerability map of the study area

Table 2 Concentration of physicochemical parameters and heavy metal in leachate and groundwater

	Minimum	Maximum	Mean + SD	Minimum	Maximum	Mean + SD
pH	7.2	8.5	7.7 ± 0.72	6.2	7.5	6.8 ± 0.47
EC	1120.0	4221.0	2281.0 ± 1690.1	25.0	98.0	52.86 ± 26.02
TDS	459.0	2400.0	1187.7 ± 1057.0	15.3	364.8	135.63 ± 198.55
COD	581.0	1169.0	899.0 ± 294.99	36.50	105.0	84.13 ± 38.67
BOD ₅	65.0	124.7	93.64 ± 29.92	1.40	5.35	2.89 ± 1.48
Ca	33.0	54.2	70.40 ± 47.65	2.15	11.62	6.63 ± 3.50
Mg	10.6	25.4	18.57 ± 7.46	2.37	8.28	4.63 ± 2.22
K	180.1	806.3	398.6 ± 353.38	2.36	12.39	5.61 ± 3.56
Na	207.6	522.0	381.23 ± 159.76	1.52	6.44	3.60 ± 1.85
SO ₄	225.0	803.2	593.0 ± 319.77	2.84	9.66	5.63 ± 2.38
Cl	186.9	964.0	501.83 ± 409.12	2.40	10.14	6.30 ± 2.70
Pb	0.80	2.10	1.41 ± 0.65	0.025	0.04	0.014 ± 0.023
Cu	0.45	2.02	1.25 ± 0.88	BDL	0.03	0.017 ± 0.015
Cd	0.09	0.10	0.08 ± 0.03	BDL	0.02	0.0059 ± 0.009
Zn	0.21	0.58	0.38 ± 0.19	0.006	0.09	0.23 ± 0.033
Cr	0.062	0.27	0.16 ± 0.10	0.001	0.035	0.014 ± 0.015
Ni	0.001	0.04	0.024 ± 0.02	BDL	0.01	0.0055 ± 0.0064
Fe	5.60	19.85	11.85 ± 7.28	0.02	0.315	0.095 ± 0.10

BDL – Below detection limits.

C. Groundwater flow and Contaminant model

The groundwater of the study area flows in the Northwest direction (Figure 4). The hydraulic head ranged from 6.62 – 6.78 m; groundwater infiltrates into subsequent layers from the top layer and tends to change its course of direction toward the residential area in the Northwest.

MT3D package was used to model the contaminant in the dumpsite for three periods of stress: 1 year (365 days), 14 years (5114 days), and 30 years (10,950 days). Using steady-state condition and initial concentration of 11.85 mg/L for Fe (from geochemical analyses of leachates from the dumpsite). Typical infiltration of iron in leachate in the study area is shown in Figures. 5 – 8.

The models (Figures 5 - 8) show an increase in impact area with depth, indicating that the liners could not limit plume migration. After 365 days, figure 6 showed the localized area of leachate that had infiltrated into deep layers up to 26 m with concentrations of Fe ranging from 1.0 - 6.3 mg/L; after 5114 days (Figure 7), it had penetrated depths of about 40 m with concentrations ranging from 1.0 - 7.1 mg/L. The plume infiltrated to depths of 60 m after 10950 days, with concentrations ranging from 1.0 - 7.9 mg/L. The average concentration of Fe in the leachate after 10950 days is 7.1 mg/L has the potential to contaminate surrounding groundwater. According to (Sykes *et al.*, 1982; Cozzarelli *et al.*, 2011; Bjerg *et al.*, 2014), contaminant plumes can persist in groundwater after the source has been removed.

D. Contaminants spread in the aquifer

The lateral spread of Fe and Pb introduced by the leachate into the aquifer is shown in Figures 10 and 11 as mass function. The mass of Fe introduced at the dumpsite is 13,800 mg, while Pb is 16,200 mg; at 130 m away from the dumpsite, the masses of Fe and Pb detected were 1,440 mg and 172 mg, respectively. This further reduced as the plume moved 220 m away to 56 mg for Fe and 6.8 mg for Pb. At a distance of about 340 m away from the dumpsite, the mass of Fe was 0.56 mg, while that of Pb was 0.48 mg. The diminishing mass of Fe and Pb with distances away from the plume has shown the impact of the attenuation process on the transport of the leachates from the plume.

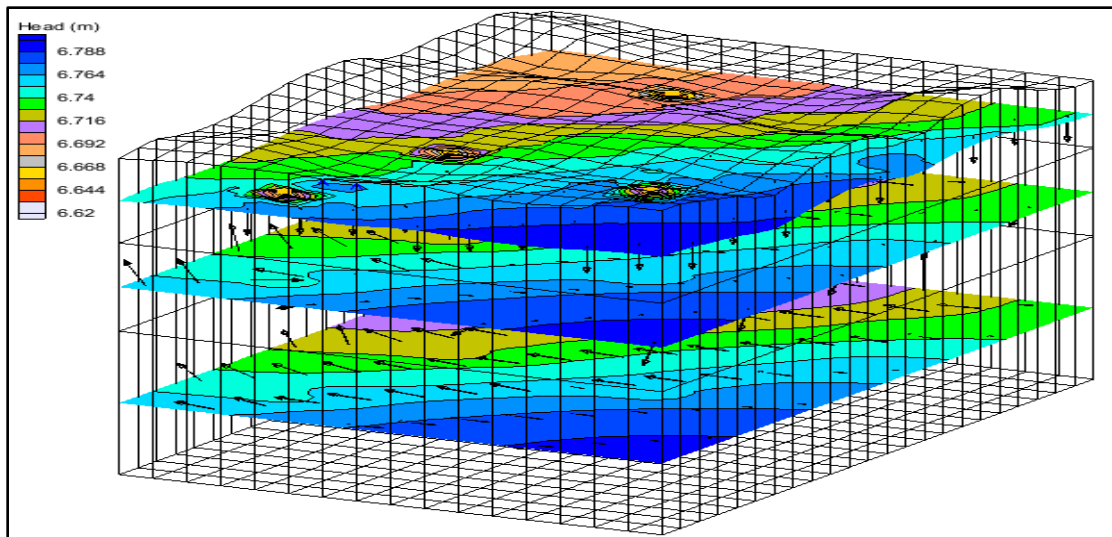


Figure 4: Groundwater flow direction in the study area

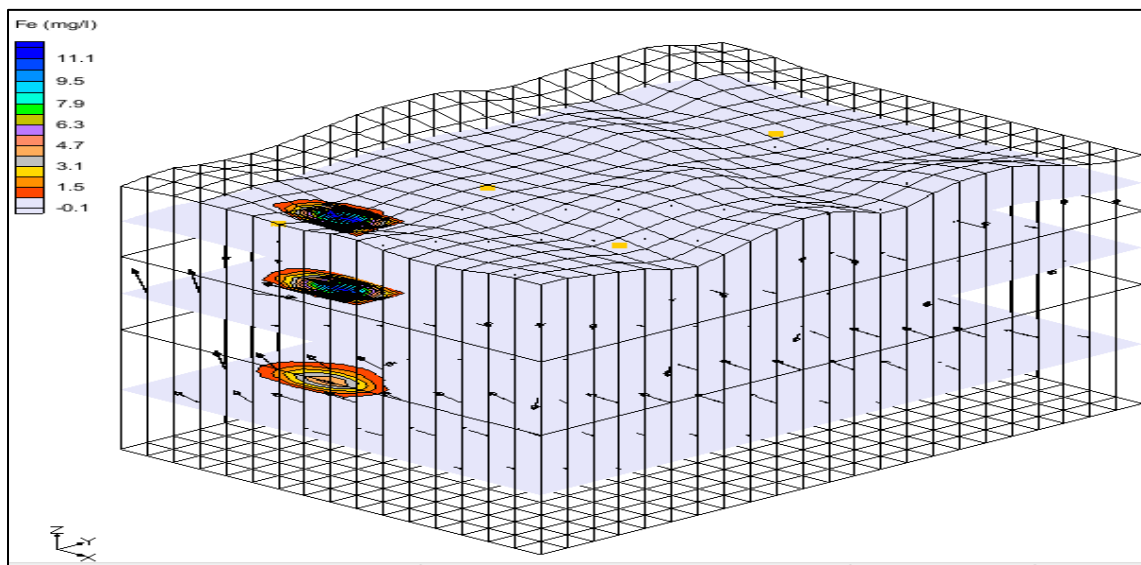


Figure 5: Infiltration of Fe in leachate beneath the dumpsite

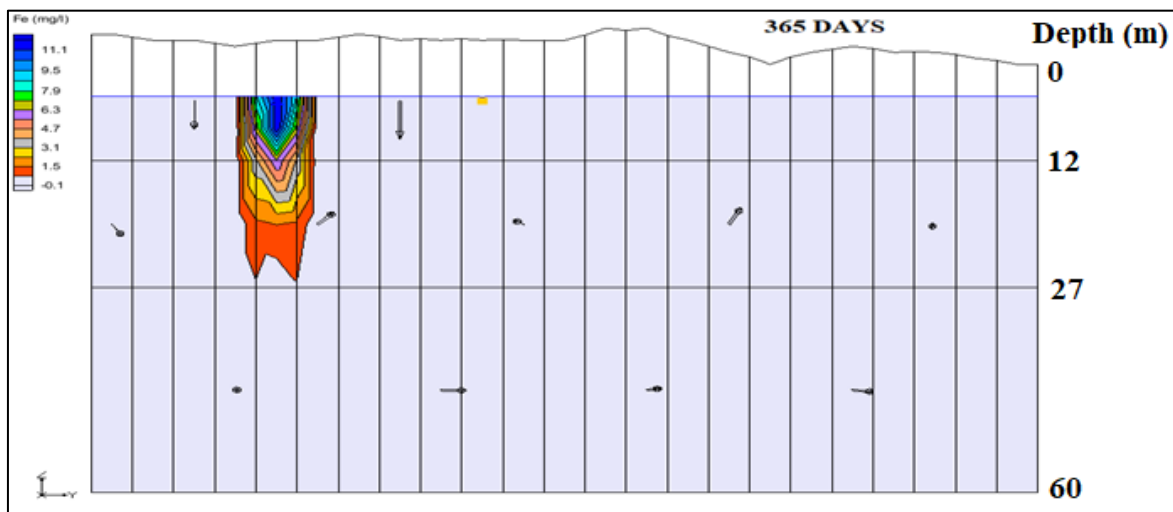


Figure 6: Infiltration of Fe in leachate after 365 days

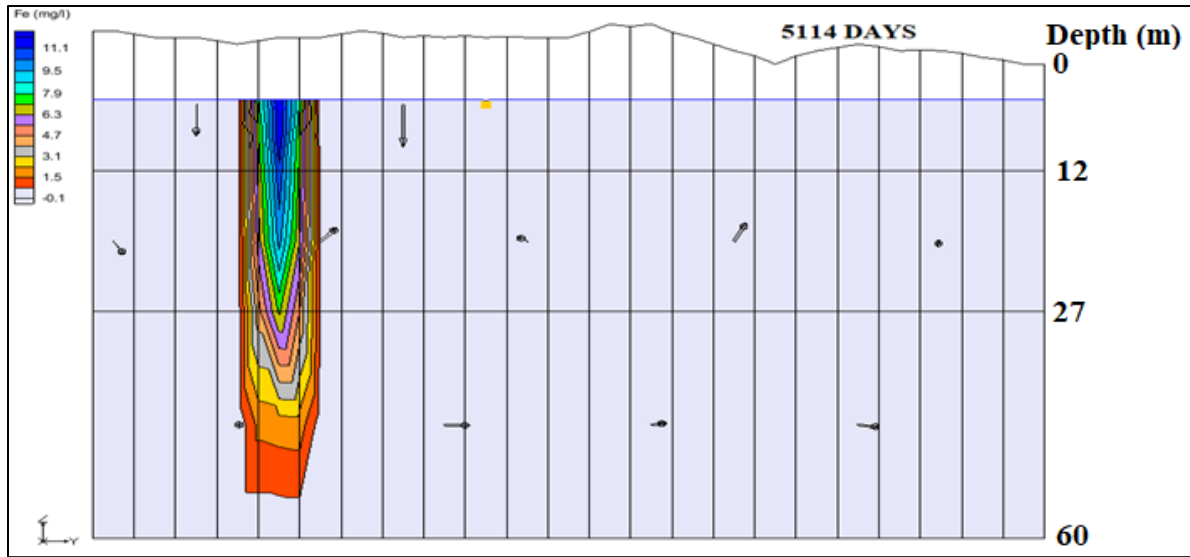


Figure 7: Infiltration of Fe in leachate after 5114 days

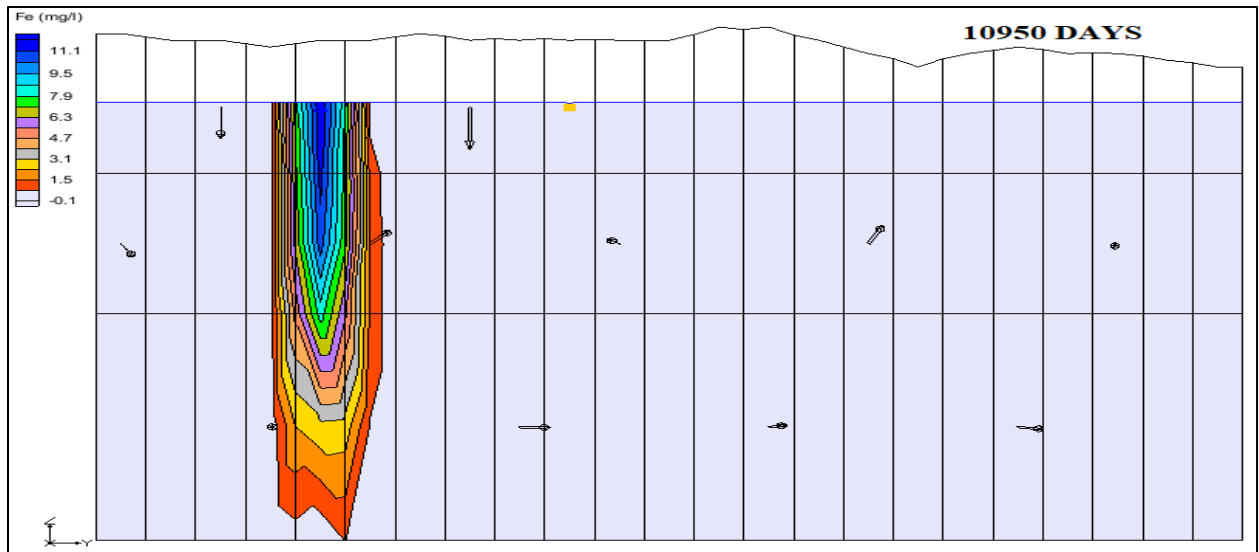
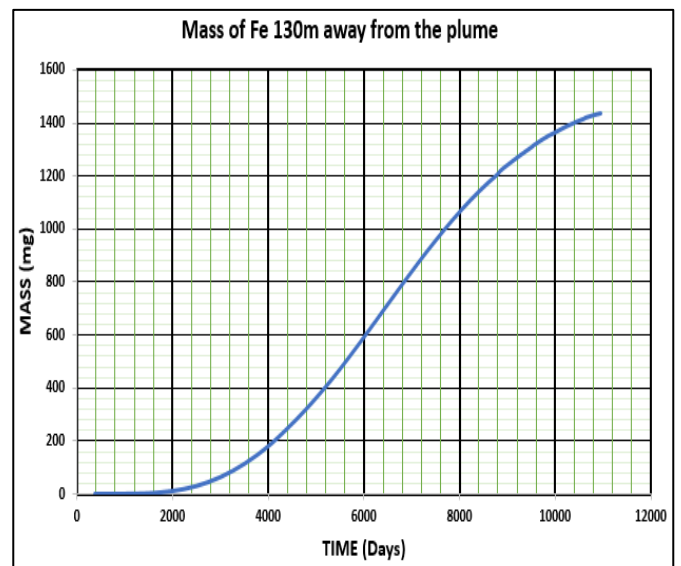
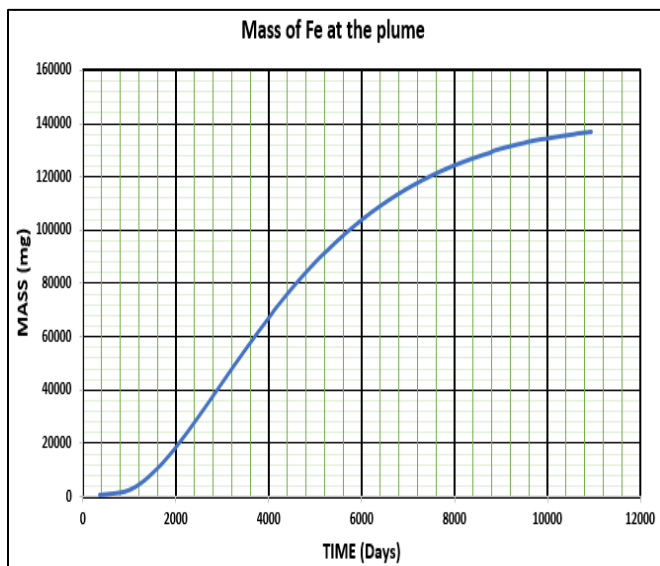


Figure 8: Infiltration of Fe in leachate after 10950 days



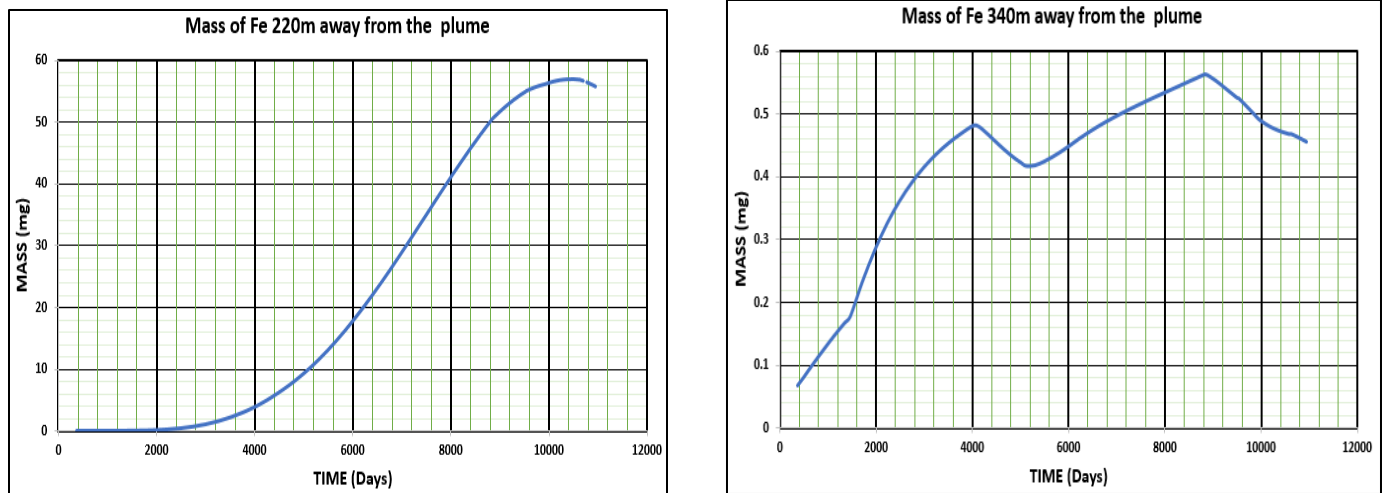


Figure 10: Mass of Fe in the aquifer unit around the plume, 130 m, 220 m, and 340 m away from the plume

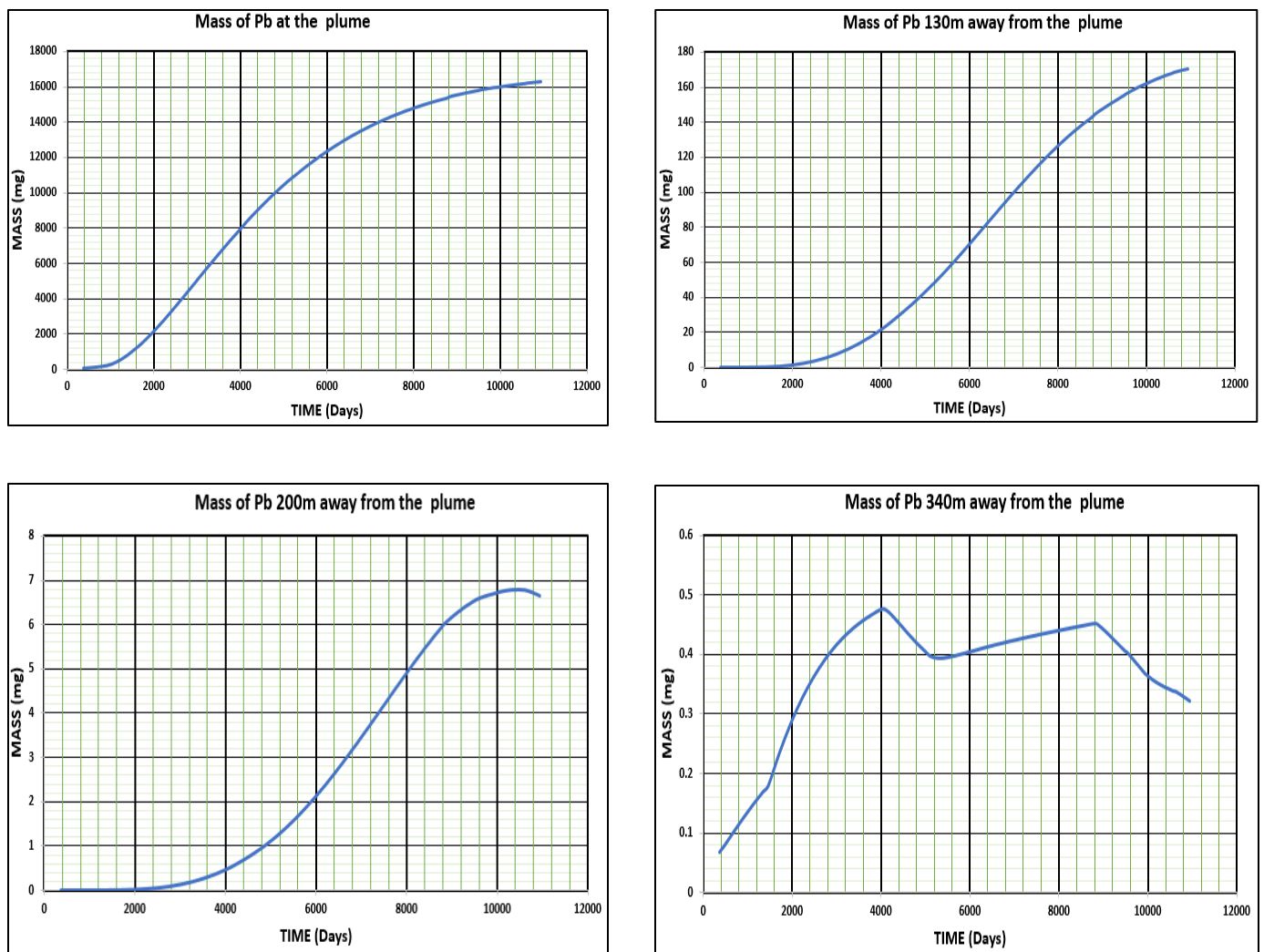


Figure 11: Mass of Pb in the aquifer unit around the plume, 130 m, 200 m, and 340 m away from the plume

The soil (clays/sandy clays/clayey sand) surrounding the dumpsite in the study area tends to filter the leachates as it spreads a process known as natural filtration.

The P^H value of leachate indicates alkaline conditions; the alkaline nature of leachate from dumpsites has been reported by Obasi *et al.* (2012) and Agbashie *et al.* (2020). According to (Gautman & Kamar, 2021 and Lindamulla *et al.*, 2021), alkalinity is typical of dumpsite leachate during the phase of waste stabilization. The leachate's BOD₅ (75 mg/L) and COD (881 mg/L) are relatively low. The BOD₅/COD ratio measures the biodegradability (Dincer, 2020) and age of the dumpsite (Alvarez – Vazquez *et al.*, 2004; Lindamulla *et al.*, 2021). The BOD₅/COD ratio, less than 0.1, indicates that the dumpsite is old and in the methanogenic phase of anaerobic degradation. This is usually characterized by old and stabilized leachate with low biodegradability. The dumpsite in the study area is over 28 years old, and according to (Yadav & Dikshit, 2017), old dumpsite produces stabilized leachate with relatively low COD and low biodegradability.

The chemical composition of groundwater from monitoring wells and other wells in the control sites showed great contrast with the leachate composition. A lower concentration of major cations, anions, and heavy metals was observed in groundwater. The result shows that groundwater in wells around the control sites had very low electrical conductivity and COD values, which may be due to the absence of leachate. Heavy metals concentration in the four monitoring wells outside the dumpsite and at other control sites were below the maximum contamination limits for drinking water by the Standard Organization of Nigeria (SON, 2007), except iron which exceeded the limits of 0.3 mg/L in some localities. This may be unrelated to impact from the dumpsite, studies by Etu-Efeotor & Odigi (1983); Ngah & Nwakwoala. (2013); Nwakwoala *et al.* (2016) and Okiongbo *et al.* (2020) revealed a preponderance of high iron content in some aquifers of the Niger Delta, which is linked to the geology of the area. According to Etu-Efeotor & Odigi (1983) and Okiongbo *et al.* (2020), the high iron content in these aquifers is sequel to leaching of ferruginised regolith overlying the aquifers. This study showed that the leachate had a higher concentration of chemical constituents in orders of several magnitudes above concentration in groundwater at the control sites. Thus, it is evident that the decomposed wastes and leachate have the potential to contaminate the underlying aquifer.

Groundwater models show infiltration of contaminants into successive layers beneath the dumpsite and spread laterally northwest in the direction of groundwater flow. However, the contaminant plume had not moved considerably far from the dumpsite. Substantial differences were observed in the distribution of plumes at a different distance away from the dumpsite after a stress period of 30 years. The mass of Fe and Pb reduced considerably from 13,800 mg and 16,200 mg at the dumpsite to 0.56 mg and 0.48 mg, respectively, at 340 m away from the dumpsite. When leachate from a dumpsite mixes with groundwater in the aquifer, it gradually mixes with the non-contaminated flow. This results in dilution of contaminants plume leading to reduction of concentration or mass of contaminants owing to hydrodynamic dispersion.

Studies by Akudo *et al.* (2010); Aladejana *et al.* (2018); Ameloko *et al.* (2018) have shown that leachate from dumpsites is a known source of chemical loading to domestic groundwater. Comparatively low contents or none of these chemicals have been introduced into the groundwater surrounding the dumpsite. This suggests that there is no noticeable influence of leachate from the dumpsite on the concentration of chemical constituents of groundwater. This can be adduced to low contents of major cations, anions, and heavy metal contents in groundwater below the stipulated standard permitted by regulatory bodies. The clayey lithology (1.3 – 6 m thick) around and beneath the dumpsite probably acted as an effective aquiclude that prevented lateral migration of possible contaminants in the groundwater zone.

IV. CONCLUSION

The geophysical study at Uvwiamuge revealed that the lithological successions are mostly sand, thus giving 56 % of the study area an extremely high vulnerability status. The chemical composition of the leachate showed high cations, anions, and heavy metals content, several orders of magnitude higher than groundwater. This indicates the potential of the leachate from the dumpsite to contaminate the surrounding groundwater. However, the low concentration of these chemical constitutions below the maximum contamination limits set by World Health Organization (WHO) revealed no significant groundwater contamination. Based on the modelling, the contaminant plume had neither expanded nor moved considerably from the dumpsite. The clays between 1.3 and 6 m thick around the dumpsite in the southern part probably acted as affective aquiclude preventing significant vertical migration of contaminants in groundwater.

AUTHOR CONTRIBUTIONS

K. E. Aweto conceived and designed this study. **K. E. Aweto, O. Ohwohere-Asuma and G. Ovwamuedo** acquired the groundwater samples and resistivity data. **P. C. Atiti** performed groundwater modelling. **K. E. Aweto** wrote most parts of the manuscript, **O. Ohwohere-Asuma and G. Ovwamuedo** wrote the hydrogeochemistry aspect. **K. E. Aweto and O. Ohwohere-Asuma** edited the manuscript.

REFERENCES

- Agbeshie, A. A.; R. Adjei; J. Anokye and A. Banule. (2020).** Municipal waste dumpsite: Impact on soil properties and heavy metal concentrations, Sunyani, Ghana. *Scientific African*, 8, e00390.
- Adeolu, A. O.; O. V. Ada; A. A. Gbenga and O. A. Adebayo. (2011).** Assessment of groundwater contamination by leachate near a municipal solid waste landfill. *African Journal of Environmental Science and Technology*, 5(11), 933 – 940.
- Akpoborie, I. A.; K. E. Aweto and O. Ohwohere – Asuma. (2015).** Urbanization and major ion hydrogeochemistry of the shallow aquifer at Effurun – Warri Metropolis, Nigeria. *Environment and Pollution*, 4(1), 37 – 46.
- Akpoborie, I. A.; O. A. Ekakite and E. O. Adaikpoh. (2000).** The Quality of Groundwater from Dug Wells in Parts of the Western Niger Delta. *Knowledge Review*, 2(5), 72 – 75.

- Akudo, E. O.; G. U Ozulu and L. C. Osogbue. (2010).** Quality Assessment of groundwater in selected waste dump site areas in Warri. *Environmental Research Journal*, 4(4), 281 – 285.
- Aladejana, J. A.; O. O. Odeyemi; M. N. Tijani and I. Hassan. (2018).** Integrated assessment of leachate concentration in soil underlying Amuloko Open Waste Dumpsite, Ibadan, Southwestern, Nigeria. *Journal of Mining and Geology*, 54(1):1 – 12.
- Alvarez – Vazquez, H.; B. Jefferson and S. Judd. (2004).** Membrane bioreactors vs. conventional biological treatment of landfill leachate: a brief review. *Journal of Chemical Technology and Biotechnical*, 79, 1043 – 1049.
- Ameloko, A. A.; E. A. Ayolabi; E Enaworu and E. Bolujo. (2018).** Assessment of leachate contamination of groundwater around the Igbenre Ekotedo dumpsite, Ota, Southwest Nigeria. *Petroleum and Coal*, 60(5), 890 – 902.
- American Public Health Association, APHA. (2012).** Standard Methods for Examination of Water and Wastewater. 22nd Edition, Washington, DC.
- Aweto, K. E. (2012).** Hydrogeological deductions from geoelectric and downhole geophysical data in Okpara Inland, Western Niger Delta Nigeria. *Middle-East Journal of Scientific Research*, 11(1), 100 – 105.
- Aweto, K. E. (2017).** Groundwater contamination indications derived from electrical resistivity imaging and single-point resistance log. In *Proceedings of the 4th Delta State University Faculty of Science International Conference*, 110 – 115.
- Aweto, K. E.; I. A. Akpoborie and Ohwohere – Asuma, O. (2015).** Characterization of groundwater quality from surface geoelectric: The case of the Sombreiro – Warri Deltaic plain aquifer, Western Niger Delta, Nigeria. *Journal of Environment and Earth Science*, 5(8), 5 – 12.
- Aweto, K. E. and Ohwohere – Asuma, O. (2018).** Assessment of Aquifer vulnerability index at Oke-Ila, Southwestern Nigeria using Vertical Electrical Sounding. *Journal of Geography, Environment and Earth Science*, 16(2), 1 – 11.
- Aweto, K. E. (2019).** The efficiency of resistivity method in delineating lithologic units of the Quaternary deposits of the Niger Delta. *FUW Trends in Science & Technology Journal*, 4 (2): 446 – 451
- Bate, G. C.; M. N. Mkhwanazi and Simonis, J. (2018).** The effects of population growth on groundwater quality of a sandy rural catchment. *Transactions of the Royal Society of South Africa*, 73, (3), 1 – 11. DOI:10.1080/0035919X.2018.1533901
- Bjerg, P. L.; H. J. Albrechtsen; P. Kjeldsen; T. H. Christensen and Cozzarelli, I. M. (2014).** The biogeochemistry of contaminant groundwater plume arising from waste disposal facilities. In Holland, H. D. & Turekian, K. K. (Eds). *Treatise on geochemistry*, 2nd Edition, Oxford: Elsevier, pp 573 – 606.
- Cossu, R. and Stegman, R. (2019).** Solid waste landfilling: Concepts, processes and Technology. Elsevier, pp 501 – 509. <https://doi.org/10.1016/C2012-0-02435-0>.
- Cozzarelli, I. M.; J. K. Böhlke; J. R. Masomer; G. N. Breit; M. M. Lorah and M. L. W. Tuttle. (2011).** Biogeochemical evolution of a landfill leachate plume, Norman, Oklahoma. *Ground Water*, 49, 663 – 687.
- Dincer, A. R. (2020).** Increasing BOD5/COD ratio of non-biodegradable compound (reactive black 5) with ozone and catalase enzyme combination. *SN Applied Science*, 2, 736. <https://doi.org/10.1007/s42452-020-2557-y>.
- Etu – Efeotor, J. O. and Odigi, M. I. (1983).** Water supply problem in Eastern Niger Delta. *Journal of Mining and Geology*, 20(1), 182 – 192.
- Gautam, P. and Kumar, S. (2021).** Characterization of hazardous waste landfill leachate and its reliance on landfill age and seasonal variation: a statistical approach. *Journal of Environmental Chemical Engineering*, 9, 4, 105496.
- Guideal, R.; A. E. Bala and Ikpokonte, A. E. (2011)** Preliminary estimates of hydraulic properties of Quaternary Aquifer in N'Djamena Area, Chad Republic. *Journal of Applied Sciences*, 5(4), 542 – 548.
- Igboama, W. N.; O. S. Hamed; J. O. Fatoba; M. T. Aroyehun and Ehiabhili, J. C. (2022).** Review article on impact of groundwater contamination due to dumpsites using geophysical and physiochemical methods. *Applied Water Science*, 12, 130. <https://doi.org/10.1007/s13201-022-01653-z>
- Iwegbue, C. M. A.; T. K. Faran; P. O. Iniaghe; J. O. Ikpefan; G. O. Tesi; G. E. Nwajei and B. S. Martincigh. (2023).** Water quality of Bomadi Creek in the Niger Delta: assessment of some physicochemical properties, metal concentration, and water quality index. *Applied Water Science*, 13, 36. <https://doi.org/10.1007/s13201-022-0184-2>.
- Kumari, P.; N. C. Gupta and A. Kaur. (2017).** A review of groundwater pollution potential threats from municipal solid waste landfill sites: assessing the impact on human health. *Avicenna Journal of Health Engineering*, 4(1), e11525.
- Lindamulla, L.; N. Nanayakkara; M. Othman; S. Jinadasa; G. Herath and V. Jegatheesan. (2022).** Municipal solid waste landfill leachate characteristics and their treatment options in tropical countries. *Current Pollution Reports*, 8, 273 – 287. <https://doi.org/10.1007/s40726-022-00222-x>.
- McDonald, M. and Harbaugh, A. W. (1988).** A modular Three-Dimensional finite differential groundwater flow model. In: *Techniques and water resource investigations*, Book 6, US Geological survey, 588pp
- Ngah, S. A. and Nwakwoala, H. O. (2013).** Iron (Fe²⁺) occurrence and distribution in groundwater sources in different geomorphologic zones of Eastern Niger Delta. *Archives of Applied Science Research*, 15(2), 266 – 272.
- Nwakwoala, H. O.; N. Egesi and C. C. Agi. (2016).** Analysis of the water resources of the Kaiama area of Bayelsa State, Eastern Niger Delta. *International Journal of Environmental Science and Technology*, 1(2), 7 – 12.
- Obasi, N. A.; E. I. Akubugwo; O. C. Ugboogu and G. Otuchristian. (2012).** Assessment of physico-chemical properties and heavy metals bioavailability in dumpsites along Enugu-Port Harcourt Expressway, South-east, Nigeria. *Asian Journal of Applied Science*, 5, 342 – 356.
- Ohwohere-Asuma, O.; K. E. Aweto and F. C. Chukwuma Felix Ugbe. (2018).** Lithofacies identification and multivariate analysis of groundwater chemistry in coastal

aquifers in Koko area of the Western Niger Delta, *Hydrology*, 6, 31, doi: 10.3390.

Ohwohere-Asuma, O.; F. I. Chinyem; K. E. Aweto and R. Iserhien-Emekeme. (2020). The use of very low-frequency electromagnetic survey in the mapping of groundwater condition in Oporoza-Gbamaratu area of the Niger Delta. *Applied Water Science*, 10, 164. <https://doi.org/10.1007/s13201-020-01244-w>

Okiongbo, K. S.; K. K. Oboshenure and A. R. C. Amakiri. (2020). Investigation of lithological control of iron enrichment in groundwater using geophysical techniques in Yenagoa, Southern Nigeria, *SN Applied Science*, 2, 107. <https://doi.org/10.1007/s42452-019-1876-3>

Okpara, D. A.; M. Kharlamova and Grachev, V. (2021). Proliferation of household waste irregular dumpsites in Niger Delta region (Nigeria): unsustainable public health monitoring and future restitution. *Sustainable Environmental Research*, 31, 4. <https://doi.org/10.1186/s42834-020-00077-1>

Oyerinde, O. O. (2021). Analysis of decadal rainfall and temperature trend in Warri, Nigeria. *European Journal of Environment and Earth Sciences*, 2(2), 15 – 18.

Patra, H. P. and Nath, S. K. (1998). Schlumberger Geoelectric sounding in Ground Water. Principles, Interpretation, and Application. A. A. *Balkema Publishers, Brookfield*, 183pp.

Rana, R.; R. Ganguly and A. R. Gupta. (2018). Indexing method for assessment of pollution potential of leachate from non-engineered landfill sites and its effect on ground water quality. *Environmental Monitoring and Assessment*, 190(1), 46. <https://doi.org/10.1007/s10661-017-6417-1>

Schulze-Makuch, D. (2005). Longitudinal dispersivity data and implications for scaling behaviour. *Groundwater*, 3, 443 – 456.

SPDC (2005). Subsurface investigation of soil and underground water contamination at Ughelli West Engineered Dumpsite, Shell Petroleum Development Company Technical Report, Warri. 79pp.

SON (2007). Nigerian Standard for Drinking Water Quality, Standards Organisation of Nigeria, NIS 554 Abuja, 30pp

SURFER (2002). Contouring and 3D surface mapping for scientists and engineers. Golden Software Incorporation, Colorado, USA, 619pp.

USEPA (2007). Method 9045D: Soil and waste pH, part of test methods for evaluating solid waste, Physical/Chemical Methods, United States Environmental Protection Agency

Van Stempvoort, D.; L. Ewert and L. Wassenaar. (1992). Aquifer Vulnerability Index A GIS – compatible method for groundwater vulnerability mapping. *Canadian Water Resources Journal*, 18:25 – 37.

Vander Velpen, B. P. A. (2004). winReisist Version 1.0. M.Sc. Research project ITC, Delft, Netherland.

WHO (2011). International Standards for Drinking Water. 4th Edition, World Health Organisation, Geneva, 27, Switzerland.

Yadav, J. S. and Dikshit, A. K. (2017). Stabilized old landfill leachate treatment using electrocoagulation. *Environment Asia*, 10, 1, 25 – 33. Doi:10.14456/ea.2017.4