Heliyon 6 (2020) e04249

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Geological and geophysical assessment of groundwater contamination at the Roundhill landfill site, Berlin, Eastern Cape, South Africa

Seyi Mepaiyeda [a,*], Kakaba Madi [b], Oswald Gwavava [a], Christopher Baiyegunhi [c]

[a] Department of Geology, Faculty of Science and Agriculture, University of Fort Hare, Private Bag X1314, Alice 5700, Eastern Cape Province, South Africa
[b] School of Biological and Environmental Sciences, University of Mpumalanga, Private Bag X11283, Mbombela 1200, South Africa
[c] Department of Geology and Mining, School of Physical and Mineral Sciences, University of Limpopo, Private Bag X1106, Sovenga 0727, Limpopo Province, South Africa

ARTICLE INFO

Keywords:
Environmental science
Geology
Geophysics
Earth sciences
Hydrology
Geochemistry
Environmental assessment
Environmental pollution
Contaminants
Eastern Cape
Landfill
Leachate
Electrical resistivity
Chemical analysis

ABSTRACT

An integrated geological assessment of groundwater contamination was carried out to determine the nature of the subsurface as well as establish linkages between groundwater and contaminants in the vicinity of the Roundhill landfill, South Africa. Quantitative analysis involved measurement of physico-chemical properties of groundwater samples from two boreholes and a leachate pond within the landfill. Qualitative assessment involved combined measurements of electrical resistivity and time domain induced polarization (IP) across three profiles, using the double-dipole array. The physico-chemical analysis results show the presence of heavy metals (i.e.mercury, lead and arsenic) in groundwater samples in concentrations above the general acceptable limits. Perhaps, the high concentration of these metals could be due to the dumping of toxic and hazardous waste substances on the landfill, contrary to the landfill design and classification. Resistivity and IP pseudo-sections revealed a 4-layered earth structure and anomalous zones of resistivity ($\leq$112 Ω-m) and low chargeability ($\leq$1.25 ms) in the top layers. This is indicative of percolating leachate plume in the unsaturated zone. Despite the fact that layer lithologies and stratigraphy pose low risk to groundwater contamination, structural controls such as fractures in the bedrock are favourably disposed to the percolation of contaminants into the groundwater over time. Proper waste classification and inspection should be carried out on the landfill prior to waste disposal.

1. Introduction

South Africa has many recorded cases of pollution of water resources. Some health problems in man and animals can be attributed to the influence of environmental factors on water resources. Landfill waste often get decomposed or biodegraded over time and in the presence of infiltrating water, organic effluents known as leachate are formed. Leachate is toxic to the environment, human and animals. Leachate pollution affects three principal components of the environment namely, the atmosphere; through the release of greenhouse gases, the hydrosphere; through surface and groundwater contamination, and the lithosphere; through soil contamination. Unlike surface water, groundwater has limited ability to purify itself. The subsurface nature of groundwater makes it prone to a lot of misunderstanding and lack of effective management. However, the policies for management of surface water quality are well established, policy statements and strategies to manage the quality of groundwater resources is poorly developed in South Africa. There is a general lack of knowledge about groundwater, both about where it occurs and how to manage it so that its quality does not depreciate to unacceptable levels.

Groundwater pollution occurs as a result of a wide range of human activities such as acid mine drainage (AMD), agriculture, sanitation, industry, waste disposal and landfills. Landfill constituents are predominantly household waste. Other wastes come from shops, offices, chemical and manufacturing industries. These wastes largely contain toxic substances and as they are decomposed or biodegraded, with the presence of infiltrating water, organic liquid effluents known as leachate are produced. Leachate varies widely in composition, depending on many interacting factors such as composition and depth of waste, availability of moisture and oxygen, landfill design, operation and age (Reinhart and Grosh, 1998). Pollution by landfill sources can introduce pollutants such as nitrates, minerals, organic compounds, inorganic minerals, heavy metals, bacteria and viruses into groundwater, rendering them unsafe for human consumption (Sililo et al., 2001). The presence of bacteria and viruses can result in an outbreak of diseases such as diarrhoea, dysentery, cholera, typhoid, etc., which can lead to the loss of lives.

* Corresponding author.
E-mail address: 201714260@ufh.ac.za (S. Mepaiyeda).

https://doi.org/10.1016/j.heliyon.2020.e04249
Received 18 April 2019; Received in revised form 16 October 2019; Accepted 15 June 2020

In most parts of Africa, especially in South Africa, about 70% of landfills are unlined, hence they do not have groundwater protection, leachate recovery and/or treatment systems. In addition, there is general lack of inspection of the level of landfill leachate. The aim of this study is to determine the susceptibility to contamination of groundwater resource at the Roundhill landfill site using an integrated geological and geophysical approach and making recommendations on how to protect the aquifers from contamination. This will be achieved by ascertaining possible linkages of the groundwater chemistry with exotic substances from the landfill sites through qualitative and quantitative assessment of groundwater contamination.

1.1. Study area

The Eastern Cape Province is located on the south-eastern seaboard of South Africa (Figure 1). It covers an area of approximately 170 000 km^2, representing about 14% of South Africa's landmass (Statistics South Africa, 2003). Despite the existence of a range of alternative disposal

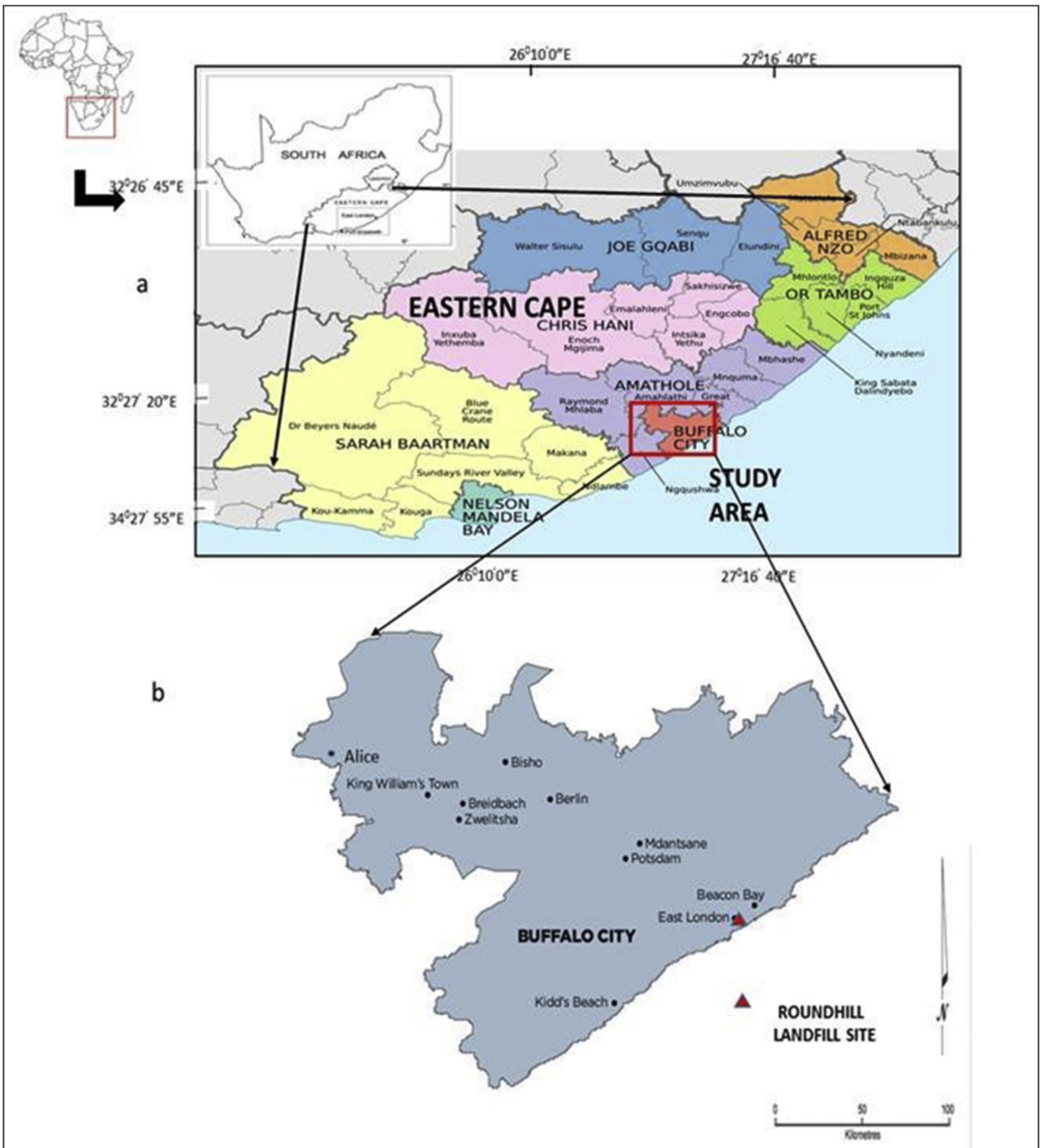

Figure 1. a. Map of the Eastern Cape Province showing the study area, b. Map of the study area showing the location of the Roundhill landfill.

technologies, waste management services in the province rely mainly on landfills and dump sites for the disposal of waste, which account for the majority of licensed waste facilities (SAEO, 2012). The Roundhill landfill site is located at a distance of about 4 km to the east of the Berlin and 30 km to the west of East London in the Buffalo City Metropolitan Municipality (Figure 2). The site is classified as a G; L; B+ (General; Large landfill; Leachate producing) based on the landfill classification system and it became operational in February 2006. The site serves as the regional landfill for the Amathole district and its environs, accepting about 600 tonnes of general waste per day. Based on the findings of the investigation carried out by DEAT (2001), it was revealed that there are 101 operational waste disposal sites in the Eastern Cape Province, 74 sites reported from questionnaires, 7 sites from permitting records and 20 sites estimated by projection. It is estimated that only 8% of landfills in the Eastern Cape Province complied with DWAF minimum requirements, 54% could potentially comply and 38% are currently unacceptable (DWAF, 1998).

The Berlin landfill, also known as the Roundhill landfill is strategically located on a watershed which occurred between the Nahoon and the Buffalo rivers. It is surrounded by small water bodies in form of artificial and natural dams. The drainage pattern in the area is northwards, towards the Nahoon River. The landfill site has well-constructed waste cells which are typically flat thus accounting for the gentle topography within the landfill area. The location of active cropland in the vicinity of the landfill site suggest a good groundwater potential in the area. Three groundwater monitoring boreholes (BH1–BH3) and a leachate pond were identified on the site (Figure 2). Two of the three boreholes had groundwater and the third borehole had no water. This is probably due to the shallow depth of the borehole and the dominance of dolerite exposures in the vicinity of the borehole (BH3).

2. Geology and hydrogeology

The Eastern Cape Province is geologically located within the Karoo Supergroup, which is believed to have developed from the Gondwana Supercontinent (Catuneanu et al., 1998). The Karoo Supergroup in the Eastern Cape Province of South Africa started with the deposition of the glacio-marine sediments of the Dwyka Group with stratigraphic thickness of about 600 m–700 m (Johnson et al., 2006; Baiyegunhi and Gwavava, 2016; Baiyegunhi et al., 2017a, 2017b). This formation is overlain by the Ecca Group (Prince Albert, Whitehill, Collingham, Ripon, Fort Brown and the Waterford formations), followed by the Beaufort Group (Koonap, Middleton, Balfour, Katberg and Burgersdorp formations) and Stormberg Group (Molteno, Elliot and Clarens formations) (Baiyegunhi et al., 2017a). The whole sequence of deposition is covered by the basalt and pyroclastic deposits of the Drakensberg Group (Table 1). The study area falls in the Beaufort Group, consisting of fine-grained sandstones and mudstones that show fining-upward sequence (Visser, 1995).

The Berlin – East London area, which host or house the Roundhill landfill lies within the Balfour Formation, consisting of a fining upward sequence of greenish-grey sandstones with bands of darker mudstones. The Oudeberg, Daggaboersnek, Barberskrans, Elandsberg, and Palingkloof Members are the five members that make up the Balfour Formation (Table 1). These members are distinguished based on the lithological variation, which is characterised by the alternating sequence of sandstones and mudstones.

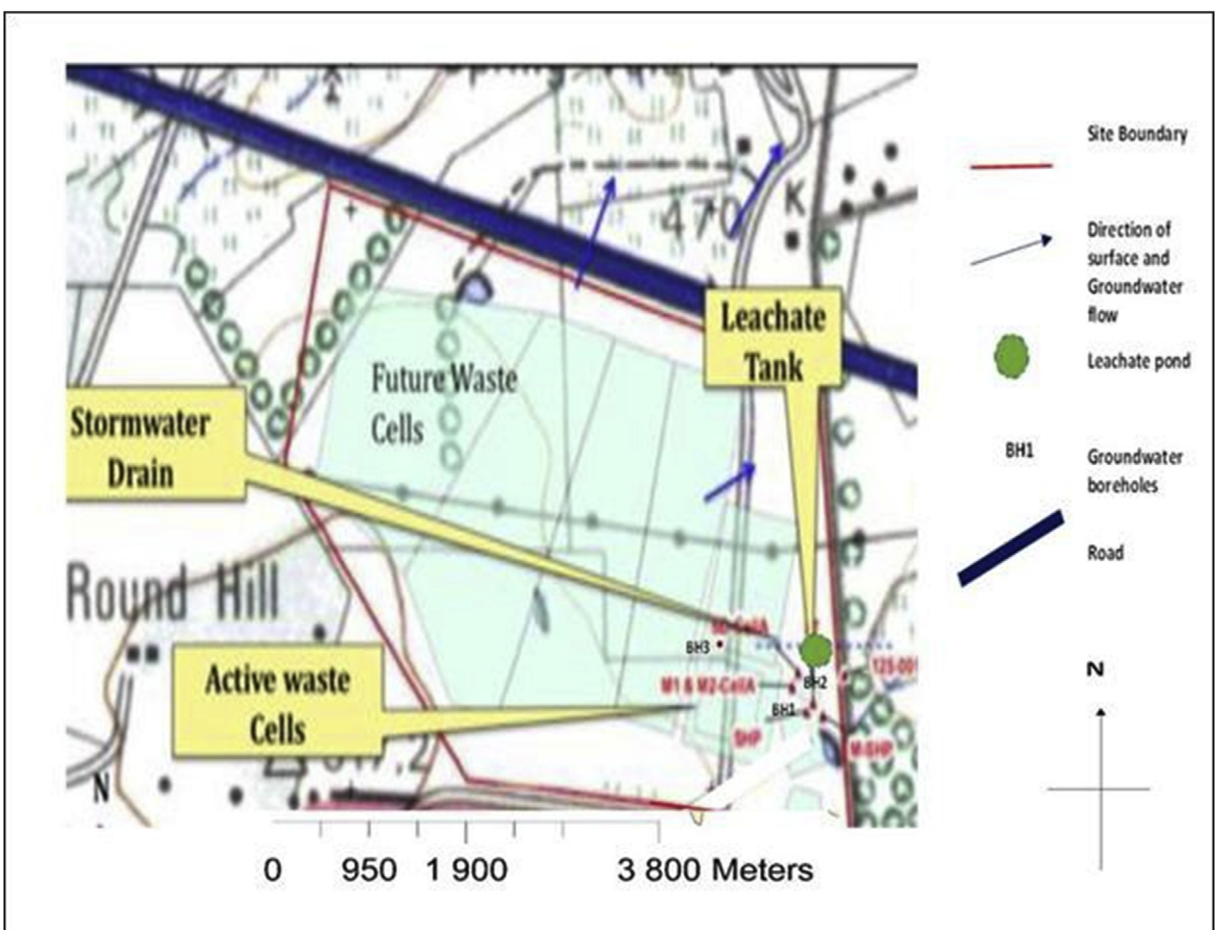

Figure 2. Locality map of the Roundhill landfill site.

Table 1. Lithostratigraphy of the Karoo Supergroup in the Eastern Cape Province compiled by the Council for Geoscience, South Africa.

SUPERGROUP	GROUP	SUBGROUP	FORMATION	MEMBER	LITHOLOGY
KAROO	STORMBERG		Drakensberg		Basalt, Pyroclastic Deposits
			Clarens		Sandstone
			Elliot		Mudstone, Sandstone
			Molteno		Sandstone, Khaki Shale Coal Measures
	BEAUFORT	TARKASTAD	Burgersdorp		Mudstone, Sandstone, Shale
			Katberg		Sandstone, Mudstone, Shale
		ADELAIDE	Balfour	Palingkloof	Mudstone, Sandstone, Shale
				Elandsberg	Sandstone, Siltstone
				Barberskrans	Sandstone, Khaki Shale
				Daggaboersnek	Shale, Sandstone, Siltstone
				Oudeberg	Sandstone, Khaki Shale
			Middleton		Shale, Sandstone, Mudstone
			Koonap		Sandstone, Mudstone
	ECCA		Waterford		Sandstone, Shale
			Fort Brown		Shale, Sandstone
			Ripon		Sandstone, Shale
			Collingham		Shale, Yellow Claystone
			Whitehill		Black Shale, Chert
			Prince Albert		Khaki Shale
			Dwyka		Diamictite, Tillite, Shale

The local geology of the Roundhill landfill site shows the predominance of the Daggaboersnek Member of the Balfour Formation in the Beaufort Group, comprising of a top layer of silty sandstone which is underlain by a clay layer (Baiyegunhi and Gwavava, 2016; Katemaunzanga and Gunter, 2009). A layer of weathered basement (sandstone) is below the clayey layer and it sits atop fresh bedrock of dolerite. The sandstone formation having poorly sorted framework with low permeability hosts the aquiferous zone. The presence of geological structures controls the occurrence of groundwater and its vulnerability to contamination. The identification of lineament structures and fractured zones can be used to determine the direction of groundwater flow (Salama et al., 1993; Baiyegunhi et al., 2019). The lineament map of the area showed SE- NW trending lineament, coinciding with the direction of groundwater flow about 200 m from the back of the landfill site (Figure 3). This indicates that the area around the landfill may have groundwater potential. This fact is corroborated by the dense vegetation, natural and artificial surface water sources found in the vicinity of the landfill. The average depth to the groundwater level as observed from the boreholes is about 50 m. The orientation of the lineament northwards in the direction of the Nahoon River located about 10 km away from the landfill poses a potential danger not only to the groundwater below but may serve as an excellent pathway for the drainage of possible leakages from the landfill.

3. Materials and methods

Qualitative and quantitative methods were adopted in the assessment of groundwater vulnerability to contamination at the Roundhill landfill site. Quantitative method involves the measurement of the physico – chemical properties and elemental composition of collected water samples from groundwater monitoring boreholes in the vicinity of the landfill (Figure 4). This is to give an insight into the source and nature of contaminants at the landfill. Water samples were taken from two of the boreholes (BH 1 and BH 2) within the landfill site. The average depth of the boreholes and depth to the top of the water column was 60 m and 15 m, respectively. Parameters of the water samples such as temperature, pH, EC, TDS, salinity, turbidity were then measured. The physico-chemical properties of water samples obtained from the two boreholes (BH 1 and BH 2) and the leachate pond (LP) were measured at 25 °C and a control value for non-contaminated water. The level of contamination was determined by juxtaposing the results obtained with threshold values which are usually World Health Organization (WHO) standards.

The collected water samples were then digested in the laboratory by adding 5 ml of concentrated Nitric acid (HNO_3) to 100 ml of the well –mixed water sample (Ayenimo et al., 2005). The solution was evaporated to about 20 ml and another 5 ml conc. HNO_3 was added and the mixture was heated until the digestion was complete. The heavy metal composition in the water samples were then analysed using the Atomic Absorption Spectroscopy (AAS) in which standard solutions of the metals to be identified were prepared and different concentrations were prepared form the solution for plotting the calibration for the AAS analysis (Adeniyi et al., 2011). The concentration of the heavy metals were then compared to the general standard limits (USEPA, 1994). Qualitatively, geophysical assessment of groundwater contamination was done using the combined electrical resistivity and Induced Polarization measurements in the active waste cell (Figure 2) (adjacent cells 1 and 2 which were already covered with linings and cap material) along 3 traverses (X, Y and Z) at 40 m inter-traverse spacing (Figure 5). Instrumentation was done using the ABEM SAS 1000 Terrameter, in which apparent resistivity and time domain induced polarization were measured simultaneously. The Dipole-dipole array at $a = 10$ m, $N = 5$ and traverse length of 140 m was adopted. Time domain induced polarization was measured at initial delay of 0.01 s, base IP interval of 100 ms, variable output current mode with an acquisition time of 0.5 s and increment of 1. The obtained data values were interpreted using the DIPROfWIN inversion software.

4. Results and discussion

4.1. Water physico-chemical analysis

The obtained results were compared with World Health Organization (WHO) standards to determine the degree of contamination of the water samples. The summary of the results is presented in Table 2.

4.2. Atomic absorption spectroscopy (AAS)

The results of the heavy metal concentration in water samples obtained from the leachate pond (LP), and boreholes (BH 1) and (BH 2) is

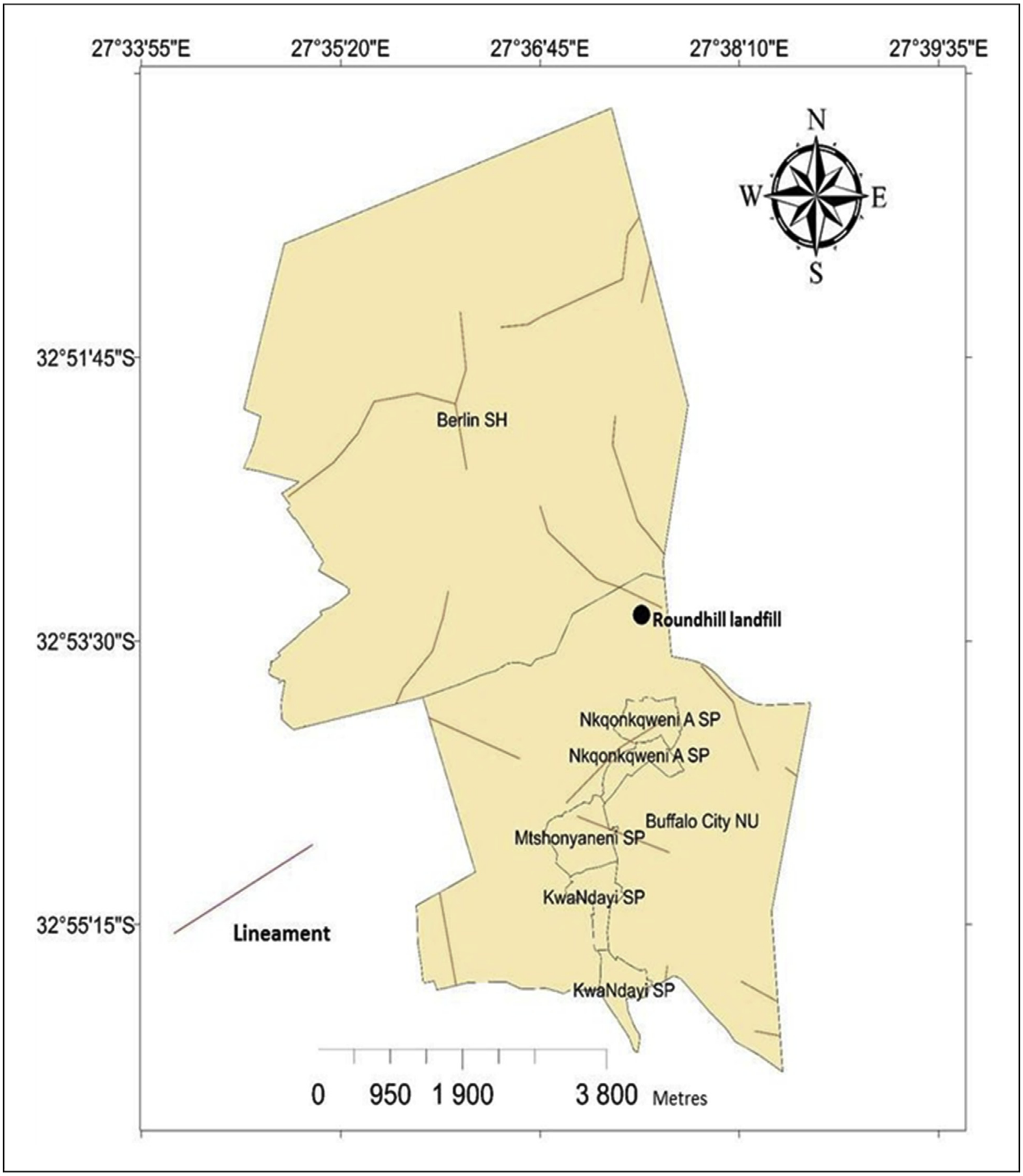

Figure 3. Local geological settings at the Roundhill landfill site.

shown in Table 3. The results were compared to the general standard limits of concentration in water samples, according to the United States Environmental Protection Agency (USEPA, 1994).

4.3. Electrical resistivity imaging and induced polarization

The pseudosections generated from the electrical resistivity and time – domain induced polarization measurements using the double-dipole array across three traverse lines are shown in Figures 6, 7, and 8.

The low salinity values of the water samples give an indication of their freshwater nature (low carbonates content). The positive values of the oxidation-reduction potential of water samples from BH 1 and BH 2 indicate an increase in their oxidizing properties thus making them unfit for human consumption (Table 2). The progressive increase in the total dissolved solid (TDS) values from BH 1 (265.5 ppm), located at the anterior end of the landfill to BH 2 (406.5 ppm) at the edge of the landfill, to the leachate pond (2126 ppm) located at the posterior end of the landfill is an indication of an increased percolation of the leachate with proximity to the landfill area and a migration of the contaminants, northwards in the direction of the groundwater flow. The high TDS values produce toxic effect on living organisms through high alkalinity and hardness thus causing living cells to shrink.

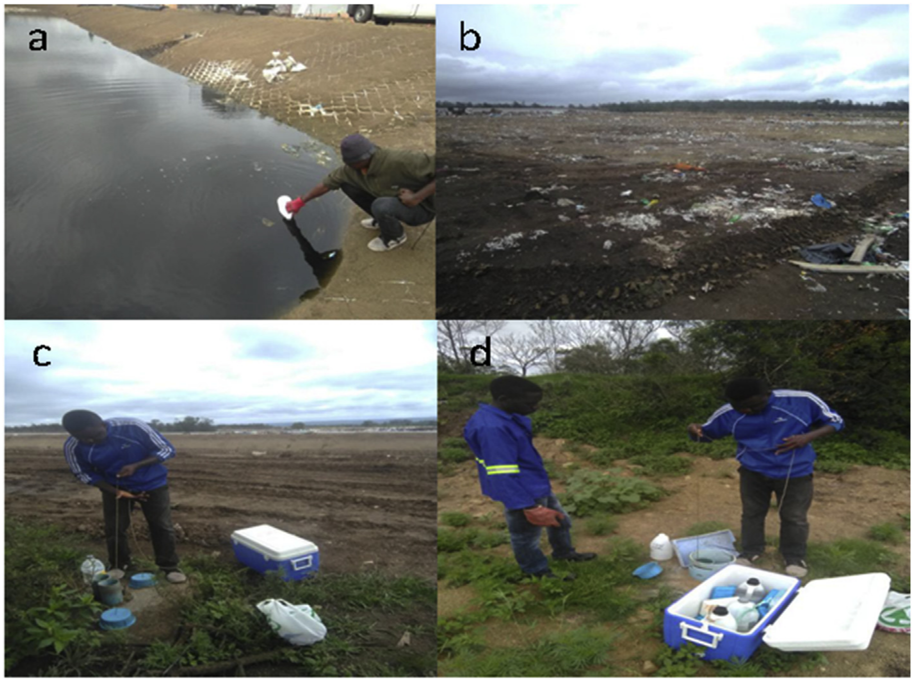

Figure 4. a. Leachate pond at the site, b. Surface composition of the landfill, c. Borehole (BH2) at the edge of the landfill, d. Dry borehole (BH3) at the back of the landfill.

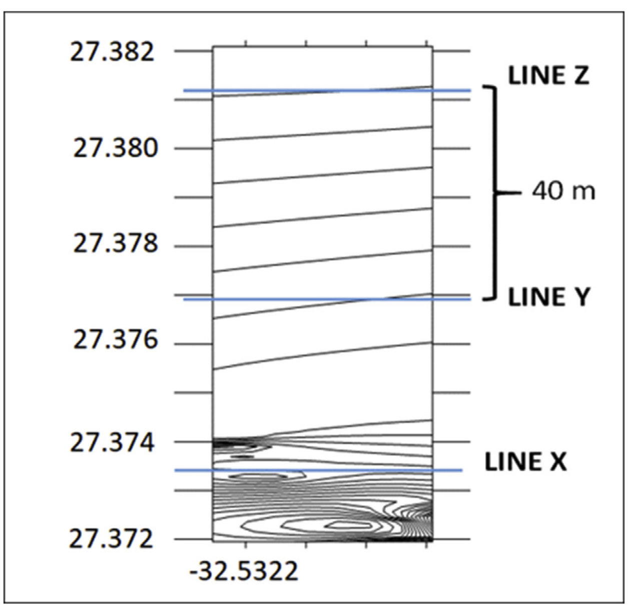

Figure 5. Geophysical data acquisition map of the Roundhill landfill.

The elemental analysis of the water samples showed toxic concentrations of Cadmium (Cd), Mercury (Hg), Lead (Pb) and Arsenic (As) (Table 3). The concentrations are above the maximum contaminant level (MCL) (USEPA, 1994). The presence of these heavy elements suggest that toxic and hazardous wastes are being dumped on the landfill which is contrary to the designated landfill classification. The harmful effects of these heavy metals include environmental and health risks such as poisoning, cancer etc. Copper (Cu) and zinc (Zn) were within tolerable limits on the landfill, although fairly large concentrations have no known effect but can give a metallic or milky taste to the water samples.

Qualitative results of the geophysical assessment show a 4- layered earth system which is also corroborate by the geology with an average depth to the bedrock of about 20 m. Contaminant leachate plume were observed on Line X, revealing contamination to a depth of about 10 m through the top layers (Figure 6). A fractured bedrock which could serves as excellent pathways for the migration of contaminants into the groundwater below was also observed on line X (Figure 6). Chargeability values ranges from very low at the top surface (1.25 ms) to high values (1286 ms) at the bedrock across the pseudosections (Figure 7). Generally, across the sections, areas with low time domain chargeability values correspond to low resistivity on the sections (<112 Ω-m; Figures 6 and 7). This is interpreted to be percolating leachate plume in the unsaturated zone. The effectiveness of reducing ambiguities in interpretation through the combined electrical resistivity and induced polarization method was demonstrated on line Z (Figure 8), where anomalies on the IP sections (between 60 -100 m) were not detected on the resistivity pseudosections. This suggests the dense non aqueous nature of the contaminants on the IP section and low clay content in the top layer. The fractured plane of the bedrock is more obvious on line Z (Figure 8). The weathered to fresh basement zones were characterized by high resistivity and chargeability zones across the sections. This suggests that the basement layers lithology pose low risk to groundwater contamination.

5. Conclusions

The characterization of groundwater resources using an integrated geological and geophysical method was carried out to determine the extent of pollution and migration of pollutants due to a landfill in Berlin, near East London South Africa so as to proffer remediation methods for groundwater contamination and establish database for geological and geophysical environmental impact assessment. The results of the physico-chemical and elemental analysis show contamination of groundwater samples and migration of contaminants, northwards, in the direction of the groundwater flow. Heavy metal in water samples occurred in concentrations above the general acceptable limits. The possible source of these heavy metals are from toxic and hazardous waste being dumped on the landfill, contrary to the landfill design and classification, hence there should be proper waste classification and inspection of waste disposed at the landfill. The geophysical assessment indicates

Table 2. Physico-chemical parameters of water samples collected from the Boreholes BH 1 and BH 2 and the leachate pond (LP).

Parameter	Unit	Control (Dist. H_2O)	BH 2	BH1	LP	WHO standards
			Average	Average	Average	
	mVpH	-50.1	-17.0	-36.15	-59.5	
pH	pH	7.64	7.14	7.46	7.8	6.5–8.5
Oxidation – reduction potential	mVORP	84.5	105.3	136.75	-250.4	0–-400
Percentage Dissolved Oxygen	%DO	5.0	2.6	3.25	0.00	
Dissolved Oxygen	ppmDO	0.38	0.20	0.235	0.00	
Electrical conductivity	µS/cm	0	809	528	4245	500–000
	µS/cm^A	0	8400	554	4425	
	MΩ˙cm	0	0.0012	0.0019	0.0002	
Total dissolved solids	ppmTds	0	406.5	265.5	2126	500
Salinity	PSU	0	0.395	0.255	2.25	2–42
	σt	0	0.00	0.00	0.0	
Turbidity	TNU	0	12.7	8.95	42.65	
Temperature	°C	25.99	26.45	27.40	27.24	25
Pressure	psi	13.765	13.767	13.770	13.76	

Table 3. Heavy metal concentration in water samples from Boreholes BH 1 and BH 2 and the leachate pond (LP).

Metal	General limits (µg/L)	LP (µg/L)	BH 1 (µg/L)	BH 2 (µg/L)
Cadmium	5	338	15	18
Mercury	2	137	61	75
Lead	15	161	77	111
Iron	300	895	208	243
Copper	1,300	39	10	13
Zinc	5,000	97	22	37
Arsenic	10	112	8	17

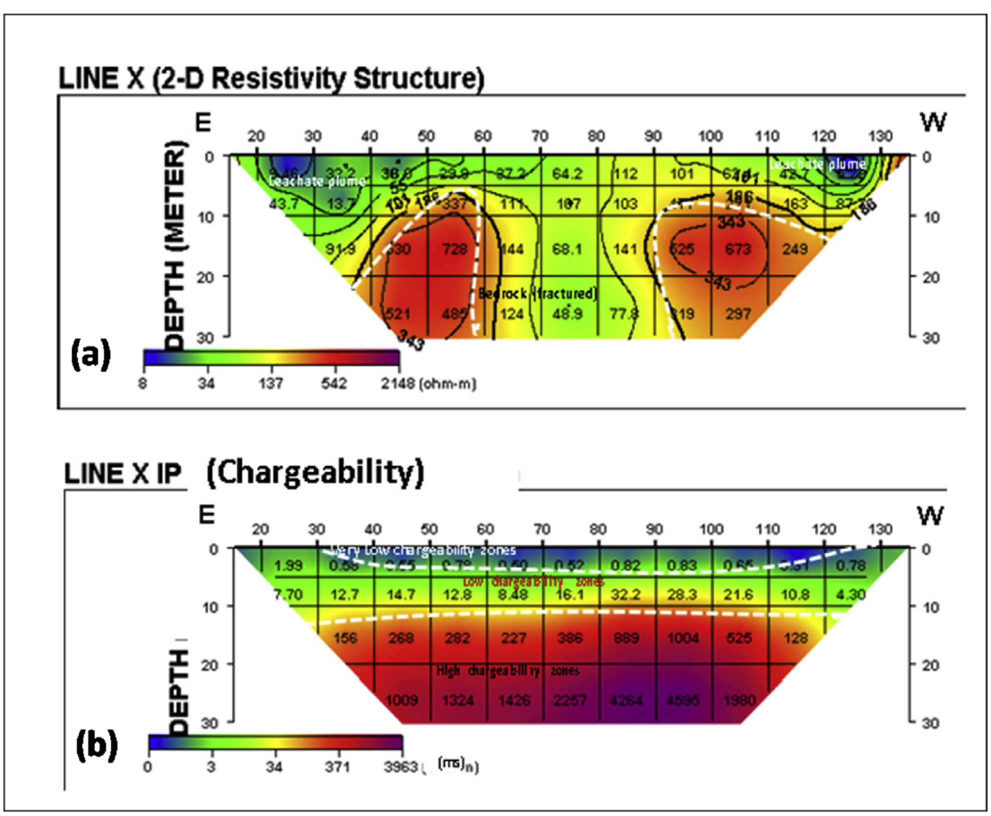

Figure 6. a. Dipole-dipole resistivity pseudosection along line X, b. Induced polarization section along line X.

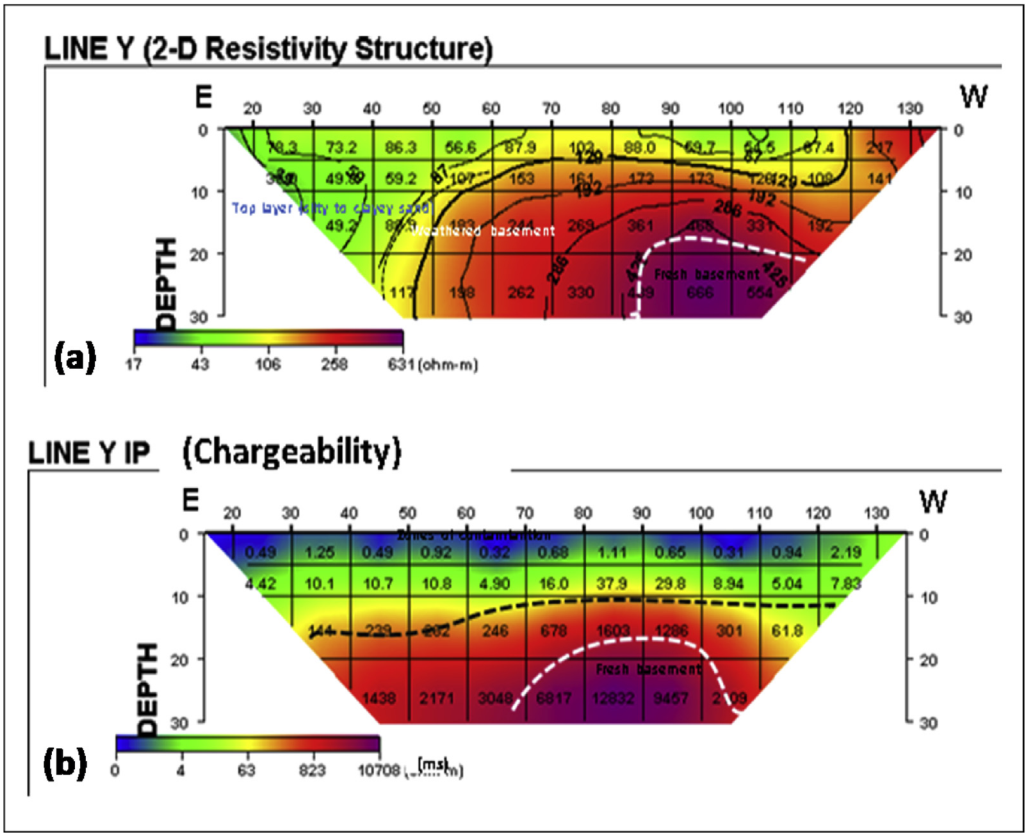

Figure 7. a. Dipole-dipole resistivity pseudosection along line Y, b. Induced polarization section along line Y.

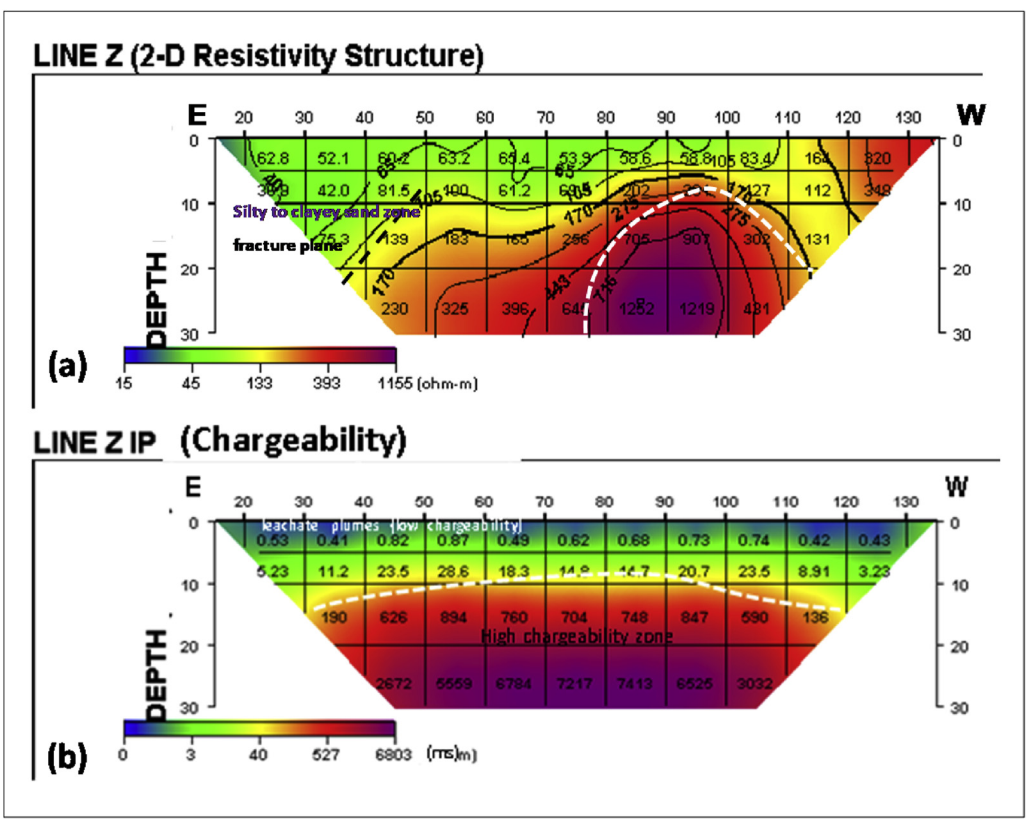

Figure 8. a. Dipole-dipole resistivity pseudosection along line Z, b. Induced polarization section along line Z.

contamination by leachate to a depth of about 10 m across three profiles and a depth to the bedrock of about 20 m. Anomalous zones of low resistivity correspond to low chargeability values, indicating percolating leachate plume in the unsaturated zone. A general observation across the pseudosections revealed that while the layer lithologies and stratigraphy poses low risk to groundwater contamination, the presence of structural controls such as fractures in the bedrock may be favourably disposed to the percolation of contaminants into the groundwater below over time.

Declarations

Author contribution statement

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

K. Madi: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

O. Gwavava: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

C. Baiyegunhi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors wish to acknowledge the following for their contributions towards the research;

- The Buffalo City Metropolitan Municipality (BCMM) for granting access permits to the landfill site.

- The Applied and Environmental Microbiology Research Group (AEMREG), University of Fort Hare, South Africa for the physico-chemical analysis carried out in this research.

- The Department of Minerals and Petroleum Resources Engineering, Kogi State Polytechnic, Lokoja, Nigeria for geophysical data acquisition.

- The Govan Mbeki Research and Development Centre (GMRDC) of the University of Fort Hare is appreciated for logistic supports.

References

Adeniyi, A.A., Owoade, J.O., Shotonwa, I.O., Okedeyi, O.O., Ajibade, A.A., Saliu, A.R., Olawore, M.A., Ope, K.A., 2011. Monitoring metals pollution using water and sediments collected from EbuteOgbo River catchments, Ojo, Lagos, Nigeria. Afr. J. Pure Appl. Chem. 5 (8), 219–223.

Ayenimo, J.G., Adeeyinwo, C.E., Amoo, I.A., 2005. Heavy metal pollutants in Warri. Kragujevac J. Sci. 27, 43–50.

Baiyegunhi, C., Gwavava, O., 2016. Variations in isochore thickness of the Ecca sediments in the Eastern Cape Province of South Africa, as deduced from gravity models. Acta Geol. Sin. 90 (5), 1699–1712.

Baiyegunhi, C., Liu, K., Gwavava, O., 2017a. Sedimentation rate and subsidence history of the Southeastern Karoo Basin, South Africa, using 1D backstripping method. Arabian J. Geosci. 225 (10), 1379–1402.

Baiyegunhi, C., Liu, K., Gwavava, O., 2017b. Diagenesis and reservoir properties of the permian Ecca Group sandstones and mudrocks in the eastern Cape province, South Africa. Minerals 88 (7), 1–26.

Baiyegunhi, C., Gwavava, O., Liu, K., Baiyegunhi, T.L., 2019. An integrated geophysical approach to mapping and modelling the Karoo dolerite intrusions in the southeastern Karoo Basin of South Africa. J. Eng. Appl. Sci. 14 (9), 1885–1911.

Catuneanu, O., Hancox, P.J., Rubidge, B.S., 1998. Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa. Basin Res. 10, 417–439.

DEAT. Department of Environmental Affairs and Tourism, 2001. Disposal Sites for Hazardous and General Waste in South Africa. Baseline Study in Preparation for the National Waste Management Strategy for South Africa, pp. 1–20.

DWAF. Department of Water Affairs and Forestry, 1998. Minimum Requirements for Waste Disposal by Landfill, Second Edition, pp. 1–40.

Johnson, M.R., van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H. de V., Christie, A.D.M., Roberts, D.L., Brandl, G., 2006. Sedimentary rocks of the Karoo Supergroup. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.L. (Eds.), The Geology of South Africa. Geological Society of South Africa, Johannesberg/Council for Geoscience, Pretoria, pp. 461–499.

Katemaunzanga, D., Gunter, C.J., 2009. Lithostratigraphy, sedimentology and provenance of the Balfour Formation, Beaufort Group in the Fort Beaufort Alice area, eastern Cape province, South Africa. Acta Geol. Sin. 83 (5), 902–916.

Reinhart, R.D., Grosh, C.J., 1998. Analysis of Florida Municipal Solid Waste Landfill Leachate Quality. Florida Centre for Solid and Hazardous Waste Management, pp. 1–78. Report number 97(3).

SAEO, 2012. Chapter 9 – Waste Management – Draft 2. South Africa Environment Outlook, pp. 1–49.

Salama, R.B., Farrington, P., Bartle, G.A., Watson, G.D., 1993. The role of geological structures and relict channels in the development of dry land salinity in the wheat-belt of Western Australia. Aust. J. Earth Sci. 40, 45–56.

Statistics South Africa, 2003. Census 2001: Census in Brief, pp. 1–34. Report No. 03-02-03.

Sililo, O.T.N., Saayman, I.C., Fey, M.V., 2001. Groundwater Vulnerability to Pollution in Urban Catchments. A Report to the Water Research Commission. WRC Project No. 1008/1/01.

USEPA. United States Environmental Protection Agency, 1994. Water Quality Standards Handbook. Second Edition, pp. 49–52. EPA 823-B-94 005a.

Visser, J.N.J., 1995. Post-glacial Permian stratigraphy and geography of southern and central Africa: boundary conditions for climatic modelling. Palaeogeog., Palaeoclimatol., Palaeocol. 118, 213–243.