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ASSESSING THE IMPACT OF DUMPSITE LEACHATE ON GROUNDWATER DEVELOPMENT: CHALLENGES IN THE NORTHERN PART OF THE VOLTAIAN SEDIMENTARY BASIN, GHANA

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Abstract

Increase in population growth with a concomitant increase in economic activities, has seen the opening of many non-engineered dumpsites on the soil cover within the northern part of the Voltaian Sedimentary Basin (VSB). This is because non-engineered dumpsites are considered the cheapest and fastest way of waste disposal. However, the practice could have dire environmental consequences as toxic chemicals could be gradually leached into the shallow groundwater table resulting in contamination. To investigate the impact of the dumpsites on the shallow groundwater table, the electrical resistivity tomography technique (ERT) was deployed across some selected open (non-engineered) dumpsites in the Walewale municipality and Tamale metropolis in northern Ghana to map the possible flow of leachate below the subsurface. The results of the ERT sections revealed low-resistivity zones (< 20 Ωm) likely caused by migrating leachate from the waste piles or weathered clay soil underneath the dumpsites. This layer was interpreted as a possible leachate plume due to its spatial distribution and the comparatively low resistivity values relative to the background geology. The low-resistivity layers extend to depths averaging about 10 meters in the Walewale area which helped to define the vadose zone underneath the dumpsites. The geophysical results were corroborated with results from physicochemical and geoaccumulation index analysis of heavy metal concentrations on groundwater samples taken within a radius of 250 meters around the Walewale dumpsites. The study showed the concentration of total dissolved solids (TDS) and chloride (Cl^-) fell within the permissible limits stated by the Ghana Standard Authority (GSA) and World Health Organisation (WHO) for all the samples except for sample GB04 where the TDS concentration exceeded the WHO permissible limit. Likewise, the concentrations of heavy metals such as Pb, Zn, Cu, and Cr were within the threshold limit set by the GSA and WHO for all the samples. However, the concentrations of Cd in samples WF 01, GB 02, NY 01, and KB 01 and Fe in samples GB 02, KB 01, and GB 05 all exceeded the recommended threshold values advised by GSA and WHO for potable groundwater for domestic purposes. The appreciable high levels of Cd and Fe in some of the samples cited could be anthropogenic due to their proximity to the non-engineered dumpsites. The dumpsites consist of plastic materials and metallic components which are major sources of Cd and Fe respectively.

Keywords
Dumpsite, Leachate, Contamination, Anomaly, Groundwater, Voltaian Sedimentary Basin

Introduction

The prolonged droughts resulting from climate change significantly hinder groundwater development (Agodzo et al., 2023) in the northern part of the Voltaian Sedimentary Basin (VSB). Yet the few successful wells that serve as water supply sources for domestic and agricultural purposes appear to be under threat of contamination from indiscriminate dumping of rubbish directly on the soil cover. Open dumpsites in the basin are proliferating due to increasing economic activities, resulting in increased waste generation. This waste disposal system has been used commonly in developing countries because it is considered the cheapest and fastest way of waste disposal (Siddiqua et al., 2022). However, the negative impact caused by this system of waste disposal on the environment is dire as toxic chemical substances gradually get released into both the air and the ground. This undoubtedly has the greatest tendency of causing groundwater contamination and jeopardizing public health (Appiah et al., 2018). Leachates from solid waste disposal sites are one of the leading causes of groundwater pollution (Aboyeji and Eigbokhan, 2016; Boateng et al., 2019). A considerable amount of microbial, inorganic, and organic pollutants have been identified in groundwater across various studies from different parts of the world (Boateng et al., 2019; Christensen et al., 2001; Han et al., 2014; Liu et al., 2010; Rapti-Caputo and Vaccaro, 2006), and significant resources have been allocated to efforts aimed at addressing these problems. According to Akankpo and Igboekwe (2011), poor solid waste management has had a wide range of negative consequences, including bad aesthetics, environmental dangers, and contamination. Some of the most common waste materials frequently found at the dumpsite include; detergents, organic waste from kitchens, pesticides, waste from electronic materials, batteries, plastics, faeces, paints, insecticides, materials containing hydrocarbons, textiles, nylon, and scrap metals among others. These heterogeneous compositions result in an increased presence of pathogens, chemicals, biochemical, trace metals, non-metals, and other contaminants in waste sites, which can pollute groundwater (Igboekwe et al., 2021). Localities near waste disposal sites stand a higher risk of groundwater contamination because of the possible pollution source from the immediate dumping site. Such pollution of groundwater results in a significant risk to local groundwater resource users and to the natural environment (Nagarajan et al., 2012). In the VSB in particular where residents depend largely on groundwater as a result of the non-reliability of surface water sources caused by extreme temperatures and high evapotranspiration (Yidana et al., 2011), it is important to investigate and understand the likely impact that the possible formation and migration of leachates from the dumpsites could have on the development of the already scarce groundwater resources in the area. Although there is no documented evidence of leachate directly contaminating groundwater resources in the area, the alarming nature by which the open dumpsites are springing up should be a cause for worry. Arhin et al. (2020) stated that the increasing amount of heavy metals and trace elements concentrations in the soil in some communities in northern Ghana is posing a threat to groundwater development as they could eventually find their way into the shallow aquifers in the area. Also, an unpublished report of field activities under the DANIDA White Volta project (DWVP) managed by the University of Ghana, indicated the presence of maggots in a borehole located close to a solid waste dumpsite at a community known as Tinguli east of the Walewale township. Acheampong and Hess (1998) noted that the shallow aquifers which are particularly important in terms of water supply in VSB are vulnerable to contamination due to the permeable and fractured soil layer within the thin overlying vadose zone. The precariousness of the situation therefore shows the need to assess the risk posed by the dumpsites in the basin and findings of which could support the call on local authorities for the development and implementation of properly engineered landfills in the area.

The usefulness of surface geophysical methods in tackling a variety of challenges in dumpsite studies has continued to receive considerable attention. The non-invasive methods such as electrical resistivity tomography (ERT) have been identified as effective techniques for the proper characterization of dumpsites because they provide a good, fast, viable, and affordable means of obtaining spatially dispersed information (Kearey and Brooks, 1991) about contamination levels in the immediate environment and groundwater systems. The ERT techniques have been extensively used in groundwater contamination studies to identify leachate plumes (Iwmi et al., 2013). Leachate plumes spawned at a dumpsite contain appreciable levels of ionic concentrations and as such show low resistivity readings. The high ionic concentration makes most contaminants conductive hence the electrical method is a reliable choice for imaging and mapping contaminant zones generated from dumpsites (Ganiyu et al., 2015).

2D electrical resistivity methods and physiochemical analysis of groundwater samples were used in this study to characterize and highlight the possible imminent danger facing the development of groundwater in the near-surface (<100 m) of the VSB. This would be necessary to help reduce losses related to the continuous investment on groundwater exploration in the near-surface of the basin while emphasizing the need for alternative deeper sub-surface investigation as has been envisaged (Agyekum and Asare, 2016; Carrier et al., 2008; Mainoo et al., 2019) to hold the solution to address the continuous water scarcity in the basin.

Materials and Methods

Dumpsite Location

The study was conducted across three different dumpsites with two of them located in the Walewale municipality (Figure 1a) and one in the Tamale metropolis (Figure 1b). The dumpsites in the Walewale township are within the central part of the municipality surrounded by residential buildings (Figure 1a). Although there is no historical information about the dumpsites, they are believed to be among the oldest non-engineered sites in the area. Due to the long-time usage of the sites, it is anticipated that most of the degradable materials have been decomposed. The dumpsite to the north within the Walewale township is along a wetland and has adversely affected the watercourse creating a strong stench compelling local authority to start the decommissioning of the site. Nonetheless, residents are still disposing of domestic waste at the sites due to a lack of alternative refuse disposal sites. The third dumpsite that was investigated is located in the city of Tamale in a suburb known as Mosi-Zongo (Figure 1b). The Mosi-Zongo dumpsite just like the sites in Walewale receives all manner of waste materials including, medical waste, industrial waste, organic matter, metals, concrete, glass, fabric, clothes, old tyres, baby diapers, plastics, etc. The waste materials are deposited directly on the soil cover enabling easy leaching once the waste materials decompose.

According to Puopiel and Owusu-Ansah (2014), the daily waste generation in the Tamale metropolis is about 810 tons out of which only 216 tons are hauled daily. The backlog of about 594 tons subsequently ends up in open dumpsites such as the Mosi-Zongo dumpsite. The uncontrolled nature of solid waste disposal has become a concern and should be investigated to ascertain the likely impact the sites could pose on the development of groundwater resources which is already shrouded in difficulties in the area. The dumpsites investigated are non-engineered and open.

Geology and Hydrogeology

The geology underlying the Walewale and Tamale areas consists primarily of rocks belonging to the Bombouaka and Obosum groups of the Voltaian Supergroup (Figure 2). The Voltaian supergroup is made of lithologies such as sandstones, mudstones, shales, limestones, and conglomerates. The dumpsites in Walewale are underlain by a group of sandstones locally known as the Panabako sandstone formations. These sandstones are described as hard and resistive owing to their composition and geophysical characteristics (Aliou et al., 2022; Carney et al., 2010; Dzikunoo et al., 2020). Within

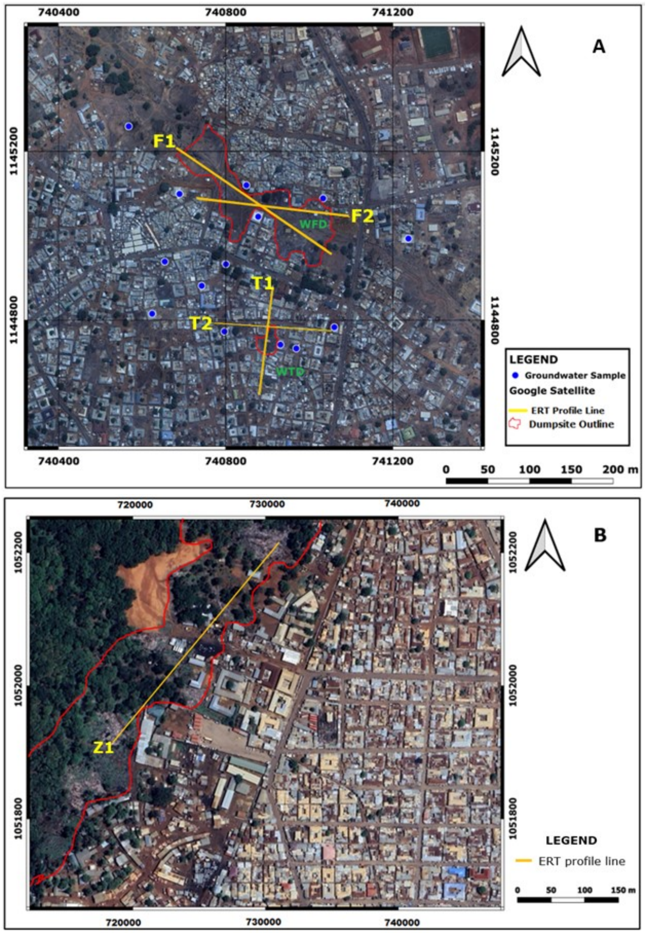

Figure 1. Satellite imagery showing dumpsite locations (marked in red) in the; (a) Walewale municipality

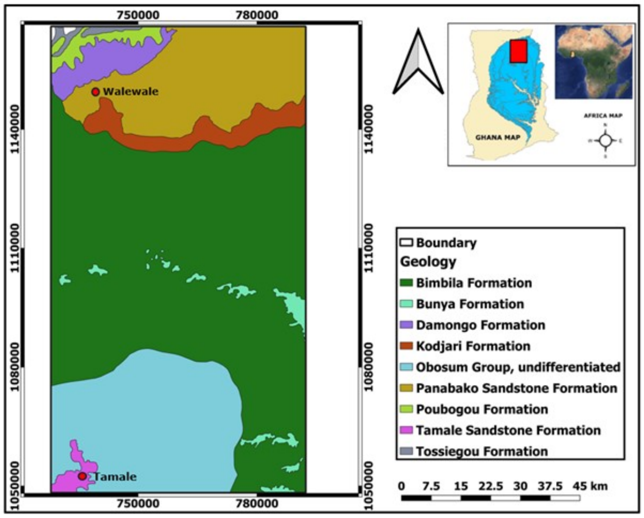

Figure 2. Surface geological map of the study area modified after Carney et al. (2010)

the study area, the rocks have undergone weathering to produce either a lateritic pan or sand at the top few meters (HAP, 2011). The Mosi-Zongo dumpsite overlies a formation of mudstones, siltstones and sandstones belonging to the Obosum group (Figure 2). While the mudstones and siltstones are claystones and should show relatively low resistivity readings when saturated, the Tamale sandstone formations are hard and resistive (Aliou et al., 2022; Mainoo et al., 2019), similar to the Panabako sandstones. Also, within the locality of the Mosi-Zongo dumpsite, weathering appeared extensive (Carrier et al., 2008; Yidana et al., 2020) with lots of sand making movement in and around the site difficult.

Hydraulic heads in the area are lowest at topographic low suggesting groundwater recharge rates ranges from high topographies to low topographies (Agyemang et al., 2024; Fetter, 2002). Aquifer yield in the area varies greatly due to numerous factors affecting the continuous groundwater movement laterally and in-depth (Carrier et al., 2008). As a result, secondary porosities and permeabilities generated by tectonic activities, weathering, and fracturing control the occurrence and flow of groundwater in the area (Carrier et al., 2008). Thus, the direction of groundwater movement in the region is determined by the orientation of the structural patterns. The primary orientation of the structures in the basin is NW-SE (Agyemang et al., 2024; Carney et al., 2010), which may have an influence on groundwater movement within the basin.

Data Acquisition

In this research, the 2-D electrical resistivity tomography (ERT) method was utilized to measure resistivity along designated lines at the dumpsites in the study area. The study employed the ABEM Terrameter LS, a cutting-edge data acquisition system for time-domain induced polarisation (IP), apparent resistivity, and spontaneous potential (SP) to image 2D resistivity data of the subsurface (ABEM, 2010). Electrodes were pegged at regular intervals of 5 m between adjoining electrodes spread over a distance of 400 m. The conventional Wenner and Schlumberger arrays were used to ensure the accuracy and uniformity of the apparent resistivity data of the subsurface during the surveys. The resistivity data were recorded and stored automatically by the Terrameter LS resistivity equipment. The 2-D ERT survey was intended to measure continuous lateral and vertical resistivity data along profile lines at the dumpsites to generate 2-D resistivity sections of the subsurface to examine and characterize the likelihood of leachate migration. The multi-electrode technique was employed primarily as a quality-control tool to authenticate the results and to establish the uniformity and accuracy of the data sets. The ABEM Terrameter LS resistivity equipment was connected with two 200 m long electrical cables at each side of the equipment for the study.

Data Processing and Inversion

The quality and veracity of the resistivity data used for the inversion were ensured through thorough monitoring and recording of parameters during the data collection. Also, post-acquisition data analysis and detailed examinations were performed to validate the data. In addition, an appropriate electrode configuration and arrangement that suited the measurement objective and anomaly of interest were deployed for good data quality. The data was processed and inverted us-

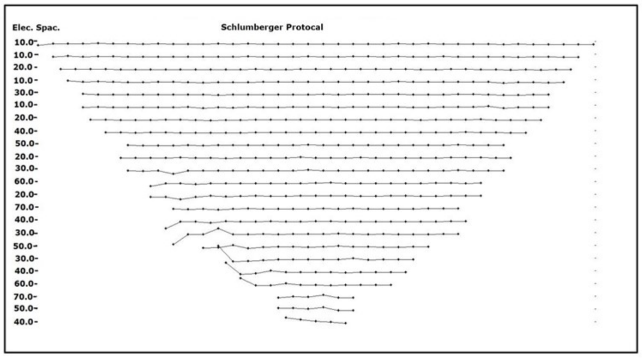

Figure 3. A typical example of the arrangement of data points in pseudo-section with the Schlumberger protocol

ing the RES2DINVx64 (Geotomo-Software, 2002). Bad data points which are usually recorded as negative values or spikes (Figure 3) (Raji and Adeoye, 2017) were eliminated from the rest of the data set using the edit tool after importing the data into the inversion software (Figure 3). This procedure is carried out to ensure that measured data with extremely high or extremely low resistivity values compared to the neighbouring point do not adversely affect the inversion (Mainoo et al., 2019). The bad data points (negative and or spikes) are likely due to poor ground-electrode contact resulting from hard surface or dry soil, failure of the relay cables to transmit current at one or more of the electrodes, or shorting across the cables due to very wet ground conditions. The starting model used for the inversion consists of blocks of apparent resistivities, generated automatically by the inversion application. The distribution and size of the blocks depend on the measured data with the last row of the block approximately matching the corresponding depth of investigation (Edwards, 1977). The damping factor utilised for the inversion was initially set at 0.1. However, it was increased to 0.3 in two of the inversion cases where the data appeared noisy. The apparent resistivity values were computed using a finite-difference modelling function, while the resistivity of the model blocks were determined using the non-linear smoothness-constrained least-squares optimization technique (Ganiyu et al., 2015; Griffiths and Barker, 1993). To optimize the resolution of the inversion routine, the cell size was set to half the electrode spacing, leading to an increase in the computational grid to about two times the electrode number. For all the inversion routines, root mean square (RMS) error ranges between 1.26% to 6.3%, which is below the recommended threshold of 5% (Loke, 2001), suggesting a good fit between the computed values and the observed data.

Groundwater Sampling and Analysis

Figure 4. (a & d) Some selected non-engineered open dumpsites (b & c) leachate collected in a trench at a dumpsite (e & f) some open hand-dug wells where groundwater samples were taken for analysis. At the background of the hand-dug wells are residential buildings and the open hand-dug wells where the samples were collected are approximately 20–250 m radius away from the dumpsites

Groundwater samples were collected from hand-dug wells and boreholes around the two dumpsites in the Walewale community (Figure 1a). In all, 14 samples were collected comprising 4 boreholes and 10 open hand-dug wells. The samples were collected within a 20–250 m radius from the dumpsites to investigate the possible influx of heavy metals and total dissolved solids (TDS) and to deduce the extent of migration of the metals away from the waste dumps. Some of the most significant pollutants found in leachate from waste dumps are heavy metals (Beinabaj et al., 2023; Carvajal-Flórez and Cardona-Gallo, 2019). Heavy metal concentrations in the groundwater samples were analysed using the atomic absorption spectrometry (AAS) technique at the Ecological Laboratory (ECOLAB) at the Geography Department of the University of Ghana. The basic principle of the AAS technique is based on the fact that free atoms in their ground state can absorb light at a particular wavelength which is explicit to only that element (Filho et al., 2012).

Also, the geoaccumulation index (Igeo) approach was used to evaluate the degree of contamination of heavy metals by comparing measured concentrations with pre-industrial levels. The geoaccumulation index (Igeo) is a widely used method for assessing the contamination status of sediments and water according to Muller (1969). Igeo is calculated using the equation:

$$\mathrm{Igeo} = \log_2\left(\frac{Cn}{1.5 \times Bn}\right) \tag{1}$$

where Cn is the measured concentration of the element, Bn is the geochemical background value for the element (a reference baseline concentration) and 1.5 is a constant factor used to account for possible variations in background data due to lithogenic effects.

Results and Discussions

Results

The pseudo-sections obtained from the inversion of the data are presented and discussed in the following sections.

Walewale Fogni Dumpsite (WFD)

Figure 5a shows the distribution of subsurface resistivity of the formation beneath Fogni dumpsite (WFD) near the old market in the Walewale community. The profile line (F1 in

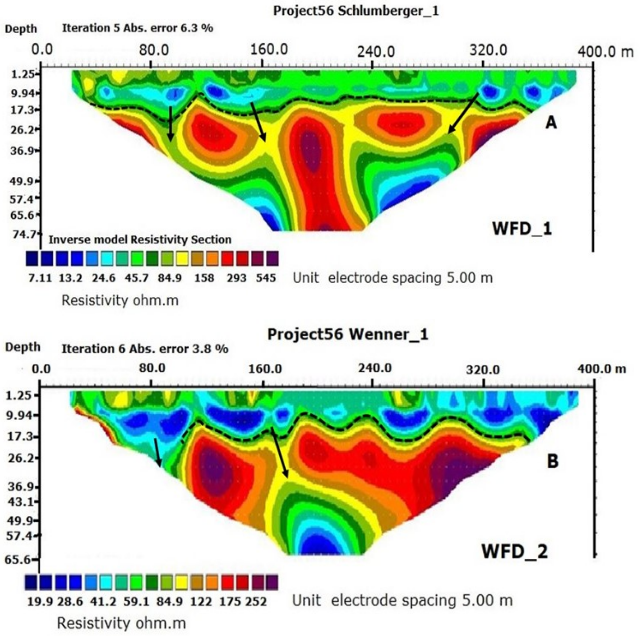

Figure 5. 2-D electrical resistivity pseudo-section showing variations in formation resistivity of Fogni dumpsite in Walewale (a) profile line A. The black arrow indicates a possible sub-vertical fracture that could facilitate the transportation of possible pollutants into deeper depths. The dashed line defines possible regolith boundaries underneath the profile

Figure 5a) at the dumpsite revealed a layer of low resistivity at an approximate depth of 10 m throughout the profile. Additionally, pockets of low resistivities were observed along the profile at the ground surface, at horizontal distances of 110 m–130 m, 320 m, and 380 m, and connected to the layer seen at 10 m depth. The low resistivity layer could be due to clay material from weathered bedrock or leachate plumes produced from decaying waste materials. This layer was identified as a potential leachate plume based on the resistivity values (<20 Ωm) (Ganiyu et al., 2015) and the spatial distribution. The pockets of low resistivities observed at the horizontal locations of 110–130 m and 320 m correspond to wastewater (Figure 4b) collected from the pile of waste materials, reinforcing the interpretation.

The pseudo-section in Figure 5b represents the inverted results of the second profile line (F2 in Figure 5a) at the WFD. At lateral distances of 115 m, 160 m–240 m and 320 m–380 m, an anomaly with low resistivity was observed. This low resistivity formation could be traced to an average depth of 15 m and extended across the entire profile, similar to the low resistivity layer observed in the first profile. The low resistivity anomaly appears to have infiltrated a little deeper in the second profile than in the first for the same waste dump. The low resistivity anomaly could be associated with clay materials or decomposed waste materials however, it was interpreted as a possible leachate contaminant from the dumpsite as the plume positions (160 m–240 m and 320 m) coincide with the surface location of leachate (Figure 4b) produced from the heap of waste materials at the site. Also, a formation with similar resistivity values occurred around 60 m depth and could be hydrologically connected to the possible leachate plume above via infiltration through a sub-vertical fracture (black arrows). Several migration pathways (black arrows) were observed, suggesting the shallow (<100 m) groundwater table in the region could be prone to contamination if already not present. The relatively high resistivity values were noted as locations of probably fractured bedrock as plastic waste materials in the area are not likely to be buried at such depths.

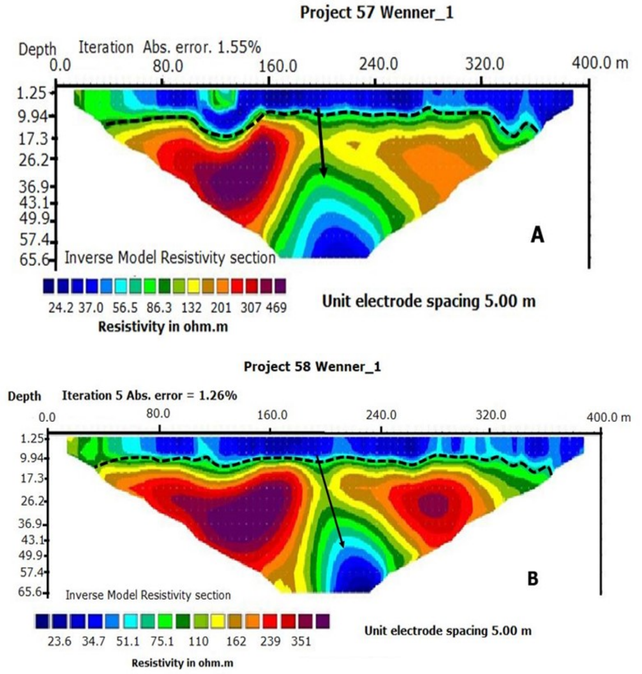

Figure 6. 2-D electrical resistivity pseudo-section showing variation in formation resistivity at the Tugbini dumpsite in Walewale community (profile A). The black arrow indicates a possible sub-vertical fracture that could facilitate the transportation of possible pollutants into deeper depths. The dashed line defines the regolith boundary underneath the profile

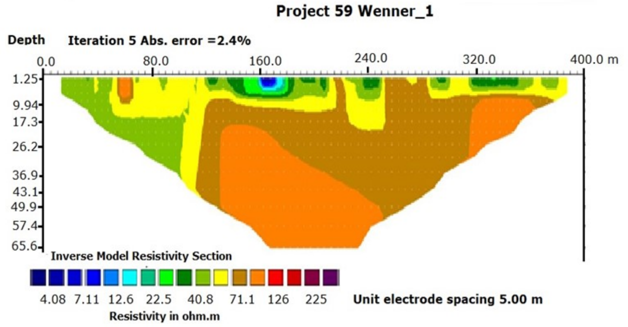

Figure 7. 2-D electrical resistivity tomography results of a dumpsite in the Mosi-Zongo community in Tamale

Walewale Tugbini Dumpsite (WTD)

The second dumpsite that was investigated is located in a suburb of Walewale known as Tugbini (Tugbini dumpsite). Two profiles (A and B) were laid in a north-south and east-west orientation respectively using the Wenner configuration. The

Table 1. Physico-chemical and heavy metal concentrations in groundwater samples compared with Ghana Standard Authority (2021) and World Health Organization (2022)

Sample	*Distance	TDS (mg/L)	Fe (mg/L)	Pb (mg/L)	Zn (mg/L)	Cd (mg/L)	Cu (mg/L)	Cr (mg/L)	Cl^- (mg/L)
WF 01	21 m	288	0.283	0.002	0.001	0.009	0.002	0.001	75.331
WF 02	250 m	279	0.001	0.002	0.006	0.002	0.003	0.001	53.175
WF 03	42 m	268	0.004	0.001	0.001	0.003	0.001	0.001	39.881
WF 04	85 m	156	0.002	0.002	0.001	0.002	0.002	0.006	26.588
WF 05	50 m	169	0.223	0.002	0.001	0.002	0.001	0.001	44.313
GB 01	–	393	0.001	0.004	0.001	0.002	0.001	0.001	66.469
GB 02	25 m	84	1.054	0.002	0.006	0.038	0.004	0.001	13.294
GB 03	211 m	470	0.001	0.002	0.004	0.002	0.002	0.001	16.839
GB 04	–	508	0.001	0.004	0.002	0.001	0.002	0.001	17.725
GB 05	64 m	179	0.410	0.002	0.001	0.002	0.001	0.001	53.175
NY 01	20 m	281	0.002	0.001	0.001	0.111	0.001	0.001	44.313
KB 01	35 m	53	1.150	0.002	0.001	0.034	0.001	0.001	31.019
GBN 1	112 m	165	0.007	0.002	0.001	0.004	0.001	0.002	35.450
TG 1	80 m	313	0.069	0.002	0.001	0.001	0.001	0.002	62.038
Standards									
GSA		500	–	0.01	10	0.003	2.0	0.05	250
WHO		500	0.3	0.01	5	0.003	2.0	0.05	250

*Distance: Present distance from sample wells to the dumpsite

pseudo-sections obtained after the inverse modelling of the profiles are presented in Figure 6a and Figure 6b. The topsoil beneath both profiles shows essentially very low resistivity anomaly (values <20 Ωm) along the entire profile lines in a similar fashion. These low resistivities could be attributed to leachate permeating from the heterogeneous waste materials, as the resistivity signatures of the underlying geology in the area are expected to return high readings (e.g. >200 Ωm) (Aliou et al., 2022; Carney et al., 2010; Ewusi et al., 2020). Due to space constraints, control profiles to investigate the migration path and extent of possible leachate movement away from the dumpsites could not be carried out. Data from this profile (control profile) usually serves as background values to guide the interpretation of data acquired over the dumpsites. Not having such data implies reliance on literature on resistivity survey in the same area. The dumpsites in the municipality are located right within populated areas surrounded by dense infrastructures (Figure 1a and Figure 4f). The sites are conveniently created by locals and are unregulated, hence making it difficult to find spaces wide enough to run control profile lines.

In the Walewale municipality, the low resistivity formations possibly induced by the infiltration of leachate into the weathered zone were used as the basis to estimate the regolith thickness for the area. The regolith thickness estimated ranges between 4 to 15 m and averages approximately around 10 m. This assessment is in line with Carrier et al. (2008) regolith thickness estimation of 6–11 m for the VSB. The weathered surfaces are clearly distinguished from the resistive bedrock along all profiles in the vicinity of the waste dump in the Walewale area making it possible to delineate the regolith thickness (curvy dash line). The base of the regolith, in particular, is described as an important source of groundwater in the area (Chegbeleh et al., 2009; HAP, 2011). Most of the hand-dug wells (Figure 4e and f) with depths ranging between 5–20 m (Carrier et al., 2008) which are predominantly used for domestic water supply in the area are completed within these regolith units making them prone to possible contamination as the leachate within this unit could slowly migrate over time due to groundwater abstraction gradient.

Tamale Dumpsite

The third dumpsite investigated is located in the Mosi-Zongo community behind a series of mechanic shops and close to a forest reserve (Figure 1b and Figure 4d) in the Tamale central business district. The inverse resistivity model of the site showed variations in resistivity ranging from 4–225 Ωm (Figure 7). At a lateral distance from 145 m to 180 m along the profile, a low resistivity anomaly with values less than 15 Ωm and at a depth of about 6 m is observed. This low resistivity anomaly occurred at the central part of the waste dump and directly underneath the peak of the waste pile. Such a location could be favourable for leachate formation as conditions such as temperature, humidity, and age could be right for the decomposition of the waste materials. Hence, such low resistivity anomalies could be associated with decomposed waste-producing leachate, which is gradually infiltrating into the soil cover. Some other low resistivity patches at relatively shallow depths along the profile were observed, except for a few places.

Analysis of Heavy Metal Concentrations

Table 1 shows the AAS analysis results of the 14 groundwater samples. The concentrations of each of the heavy metals, along with TDS and Cl^- in each of the samples, were compared with the recommended drinking water standards from the World Health Organisation (WHO) and Ghana Standard

Table 2. Calculated Igeo values of groundwater samples

Sample	Fe	Pb	Zn	Cd	Cu	Cr
WF 01	-0.669	-2.907	-12.873	1.000	-10.551	-6.229
WF 02	-8.814	-2.907	-10.288	-1.170	-9.966	-6.229
WF 03	-6.814	-3.907	-12.873	-0.585	-11.551	-6.229
WF 04	-7.814	-2.907	-12.873	-1.170	-10.551	-3.644
WF 05	-1.013	-2.907	-12.873	-1.170	-11.551	-6.229
GB 01	-8.814	-1.907	-12.873	-1.170	-11.551	-6.229
GB 02	1.228	-2.907	-10.288	3.078	-9.551	-6.229
GB 03	-8.814	-2.907	-10.873	-1.170	-10.551	-6.229
GB 04	-8.814	-1.907	-11.873	-2.170	-10.551	-6.229
GB 05	-0.134	-2.907	-12.873	-1.170	-11.551	-6.229
NY 01	-7.814	-3.907	-12.873	4.624	-11.551	-6.229
KB 01	1.354	-2.907	-12.873	2.918	-11.551	-6.229
GBN 1	-6.006	-2.907	-12.873	-0.170	-11.551	-5.229
TG 1	-2.705	-2.907	-12.873	-2.170	-11.551	-5.229

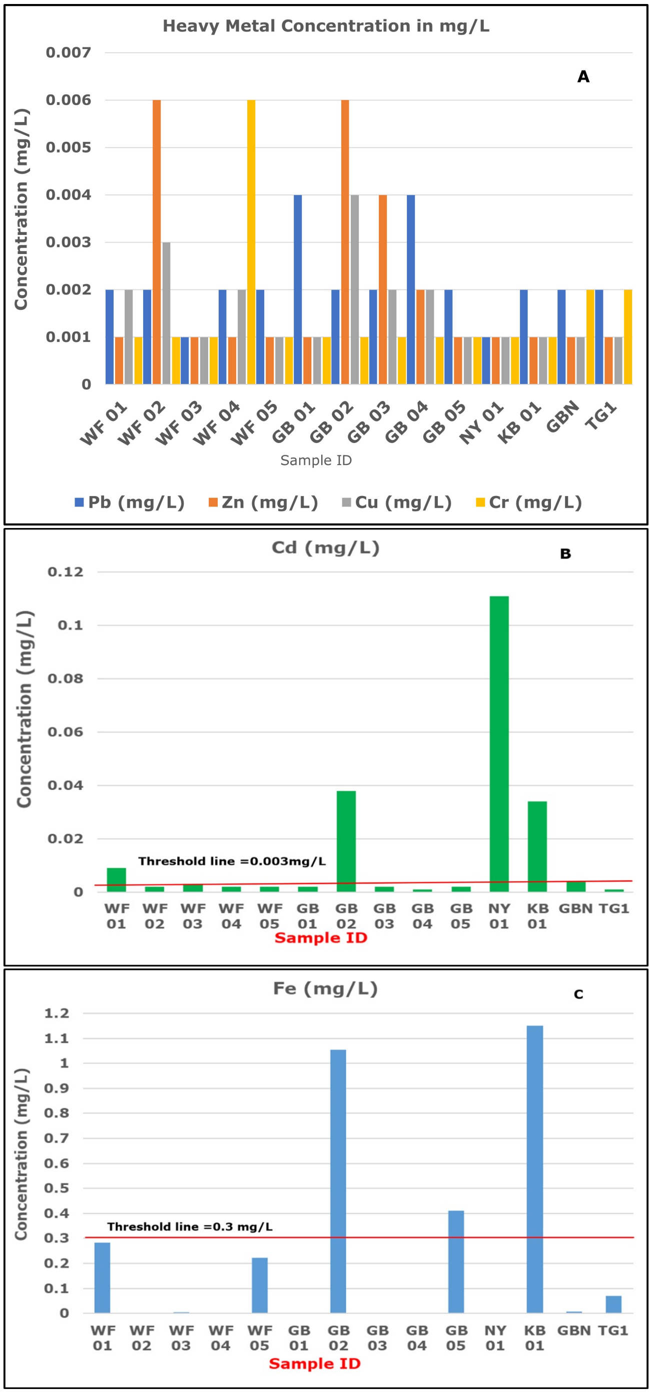

Figure 8. Bar charts of heavy metal concentrations versus sample ID showing which metal in which sample exceeds the recommended threshold values as suggested by GSA and WHO. (a) is a plot for Pb, Zn, Cr, and Cu

Authority (GSA). TDS values obtained from the analysed samples range from 53 mg/L to 508 mg/L. The TDS concentrations in most of the samples were lower when compared with safety standard values (Table 1) given by GSA and WHO (World Health Organization, 2022).

The sample GB 04, however, showed a TDS value slightly higher than both the GSA and WHO safety values. Likewise, the concentration of Cl^- in all the samples was below the recommended threshold limits (250 mg/L) suggested by both (GSA and WHO) for potable groundwater. It is known that Cl^- can be used as an indicator of anthropogenic contamination in groundwater (Castaneda et al., 2012; Grisey and Aleya, 2016) but this was not the case in the present study, which showed low values (Table 1). For the heavy metals, the concentrations of Pb, Zn, Cu, and Cr, in all the samples fall within the permissible limits reported by both GSA and WHO (Figure 8a). However, the concentrations of Cd in samples WF 01, GB 02, NY 01, KB 01, and GBN 1 (Figure 8b) and Fe in samples GB 02, KB 01, and GB 05 (Figure 8c) exceeded the recommended threshold values set by the WHO for potable groundwater intended for domestic use.

Table 2 shows the geoaccumulation index, a heavy metal index which is used to evaluate heavy metal contamination in groundwater and other geochemical samples. The samples are analyzed for degree of contamination based on the Igeo classification (Table 3). The Igeo values for Fe vary across the samples, with most values falling below 0 (Igeo ≤ 0), indicating uncontamination. However, two samples, GB 02 and KB 1 exceed the limit of 1 (1.2279, 1.3536 respectively), placing them in the moderately contaminated level ($1 <$ Igeo ≤ 2). Per the Igeo value of sample GB 05 (-0.134), it is very close to the threshold limit and therefore requires extra monitoring. For Pb, the Igeo values are consistently negative, ranging from -3.91 to -1.91 across all samples. These values place every sample within the uncontaminated level. The consistency suggests limited anthropogenic input of Pb into the water system. Zn also shows a negative pattern, with most samples recording a value of -12.873. These extremely low values indicate that all the locations are uncontaminated with respect to Zn. Cd presents the most significant variability in Igeo values, indicating a clear contamination issue in four of the samples. Many samples have negative values (Igeo < 0) making them uncontaminated. In sample WF 01, Cd is noted to be uncontaminated to moderately contaminated ($0 <$ Igeo ≤ 1). The Igeo values increases in samples KB 01 (2.9175), GB 02 (3.078), NY 01 (4.624), placing them in class 3, 4 and 5, respectively (Table 3). Thus, suggesting moderate to heavy contamination degree of cadmium, which could proba-

Table 3. Classification of Igeo values

Geoaccumulation Index Class (Igeo)	Value Range	Contamination
0	Igeo $\leq$ 0	Uncontaminated
1	0 < Igeo $\leq$ 1	Uncontaminated to moderately contaminated
2	1 < Igeo $\leq$ 2	Moderately contaminated
3	2 < Igeo $\leq$ 3	Moderately to heavily contaminated
4	3 < Igeo $\leq$ 4	Heavily contaminated
5	4 < Igeo $\leq$ 5	Heavily to extremely contaminated
6	Igeo > 5	Extremely contaminated

bly be due to anthropogenic sources. In samples WF 03 and GBN 1, the proximity of the Igeo values to the background values requires monitoring. Cu values across all samples are negative as shown in Table 2, indicating no sign of copper contamination. This suggests that copper amounts, if present, are either minute or quickly adsorbed. Cr values are also negative (Igeo < 0) which signifies that all the groundwater samples are uncontaminated with respect to chromium. The contrast between these samples and others suggests localized contamination rather than a widespread issue.

Discussion

Spatial Analysis

Leachate from the dumpsite is a highly polluted liquid containing ionic constituents thereby making it very conductive (Nagarajan et al., 2012; Wijekoon et al., 2022). The decomposition of waste and formation of leachate is primarily influenced by factors such as high temperatures, humidity, and age of waste materials (Bernardo et al., 2022). Apart from humidity which varies significantly throughout the year in the area, temperatures remain high thus favouring the decomposition and formation of leachate from the waste dumps. Due to the high compositional heterogeneities of the dumpsites, interpreting their resistivity sections can be complex. This is because high resistivity values could result from buried plastic waste materials or the bedrock below the waste dump. Similarly, low resistivity values could be caused by weathered bedrock or seeping leachate plumes. As such, delineating resistivity patterns relative to the waste positions and proper understanding of the underlying geology is essential for adequate interpretation. Ordinarily, resistivity profiles at the fringes of the dumpsite overlying a duricrust soil should not be characterised by a significant decrease in resistivity signatures unless the formations underneath have been infiltrated with a contaminant plume such as leachate (Appiah et al., 2018). The geologic formation beneath the WFD is reported to have resistivity values ranging from 250 Ωm and exceeding 1000 Ωm at some locations (Aliou et al., 2022); however, the resistivity signatures reported for the layer at the near surface are rather low (<250 Ωm), and that could be attributed to the influence of leachate permeating into the subsoil. The leachate plume appears to spread gradually within the overburden throughout the profile. The low resistivity layer identified as a contaminant plume (with values less than 20 Ωm) is likely to migrate vertically with time when sub-vertical fractures and effective permeabilities are encountered.

In Figure 6a, the low resistivity anomaly formed a bowl-shaped structure at a horizontal distance between 80 m to 150 m and was observed at depths of about 15 m. The structure is interpreted as a leachate plume which has infiltrated from the surface beneath the waste dump. The continuous infiltration of the leachate plume was probably curtailed by a resistive body occurring just below the migrating fluid, and perhaps resulting in the accumulation of the leachate in the form of a bowl-shaped structure as observed. At the centre of the waste body, both profiles revealed a deep-lying low resistivity anomaly with similar resistivity values (<20 Ωm) as those observed within the overburden. The deep-lying anomaly could be possibly saturated clay materials or a contaminant plume conceivably connected to leachate observed in the topsoil via infiltration, as its position coincides with what seems to be a fracture (black arrow) formed by the displacement in the resistive body (Figure 6 and Figure 6b).

At the Tamale dumpsite, the resistive areas near the surface at the waste dump could represent compact debris consisting of non-biodegradable materials possibly buried at shallow depths. The range of resistivity value distribution of the profile is low compared to the resistivity of the profiles around the Walewale area. The relatively low resistivities are reflective of the geology of mudstones and siltstones (Carney et al., 2010) underneath the profile. The mudstones and siltstones form part of the Obosum group of the Voltaian supergroup and have been described by Mainoo et al. (2019) and Carney et al. (2010) to have relatively low resistivity. Mudstones contain over 50% of clay materials (Aplin et al., 1999) which can limit fluid flow in the subsurface and that perhaps explains the restricted spread of the leachate pool (blue) beneath the waste body. Where possible, groundwater quality assessment around these waste dumps should be performed to gauge any likely movement of the pollutants away from the dumpsites. The mudstones and siltstones intercalate with thin beds of sandstones locally referred to as the Tamale sandstones at some locations in the area.

Groundwater Quality

Though the source of the heavy metals can be geogenic, there is the possibility that the relatively high concentration levels of Cd and Fe observed in some of the samples and confirmed by Igeo calculations could be anthropogenic due to their proximity to the waste dump. Leachate from dumpsites contains several heavy metals including Cd and Fe which when infiltrated into the groundwater system, could increase their concentrations. According to the World Health Organization (2022) report, the main source of Cd in drinking water is wastewater (e.g. leachate) released into the environment. Cd is widely used in the steel and plastics industries (Luparello et al., 2011). Plastics constitute a large proportion of the materials in the waste dumps (Figure 4), potentially serving as a significant source of Cd in the area. The high concentrations of Cd observed in some samples and supported by Igeo calculated values, could be attributed to the gradual leaching and infiltration of the metal into the shallow groundwater table. Long-term consumption of Cd through food, water, and air can lead to its accumulation in the kidneys, causing kidney disease and fragile bones (Genchi et al., 2020). One such case is Itai-Itai disease, a severe health condition caused by chronic cadmium poisoning, which affected residents of Toyama Prefecture in Japan during the 20th century (Aoshima, 2016; Inaba et al., 2005; Kasuya et al., 1992). Fe is one of the most abundant metals in the Earth's crust (Wedepohl, 1995) and, as a result, occurs naturally in freshwater systems (Hem, 1985). It is also identified as a major component in leachate due to its presence in various waste materials and the reductive dissolution of iron oxides in landfills (Christensen et al., 2001). The concentration of Fe was noted to be within the permissible limit given by WHO except for 3 samples (Figure 8c and Igeo values in Table 2). The relative distances of the wells from which the 3 samples with relatively high Fe concentrations were taken are closer to the dumpsites hence the high concentrations could probably be due to the contribution of Fe from leachate from the waste dumps. High concentration of Fe in water leads to overload (Adams et al., 2005; Taher and Saliba, 2017) which can cause diabetes, hemochromatosis, stomach problems, and nausea (Hossain et al., 2023). However, based on the TDS and Cl^- assessment, it suggests that the water is health risk-free and could be safe for consumption.

In addition, it has previously been reported that certain heavy metal concentrations found in vegetables cultivated in the Tamale metropolis surpass WHO permissible limits (Ametepey et al., 2018), albeit the report did not directly link their findings to leachates from dumpsites. The trends as revealed by the resistivity sections and groundwater sample analysis indicate the gradual migration of the leachates from the dumpsites, suggesting an imminent risk as many rural communities source water from locally hand-dug wells and boreholes most of which produce marginal yield. As the waste dump ages and produces more leachate and the abstraction and withdrawal of groundwater continue, the potential likelihood of groundwater contamination within the shallow sub-surface is heightened as leachate migration will increase due to suction pressure. With developmental quest high on the government agenda, coupled with increasing economic activity, solid waste generation will only increase thus making the situation more precarious.

Conclusion

The application of the ERT technique aided the acquisition of data from some selected dumpsites which have been useful in deriving depth and lateral information about the waste bodies. The determination of the extent of incursions of contamination plumes and the delineation of preferential migration pathways of leachates have been investigated for remediation and regulation. The delineated conductive fluids identified as leachate steadily spread across the loose overburden within the vicinity of the waste dump. Analyses of the profiles at the dumpsites in the Walewale municipality revealed the possible migration of leachate plumes to depths beyond the weathered zone. The results of the ERT clearly defined the regolith thickness along the profiles of the survey area which agrees with what has been suggested by earlier researchers in the basin. The existence of subvertical fractures in the weathered zone will only aid the migration of the leachate from these hybrid waste dumps over time putting the already scarce shallow groundwater table in danger of being contaminated.

The physicochemical analysis carried out indicated a high concentration of cadmium (Cd) and iron (Fe) in groundwater in the area. The high concentrations of these heavy metals could be due to the gradual movement of leachates from the dumpsites into the shallow water below. The application of the geoaccumulation index also asserts the degree of contamination of Cd and Fe in the study area. Although these observations were made in a smaller number of samples and more evidence may be needed to reach a definite conclusion, it is still a wake-up call for well-meaning authorities to act to avert any future problems.

It would therefore be impractical to continue investigating the shallow part of the basin given the imminent threat and the low success rate for siting productive wells. Instead of committing resources to further explore the shallow subsurface (<100 m), which has been widely established to have low potential, efforts could be redirected toward investigating the deeper subsurface, which is suggested to have a higher likelihood of yielding high-productivity wells in the area.

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