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Research article

Impact of leachate on quality of ground water around Chunga Landfill, Lusaka, Zambia and possible health risks

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ABSTRACT

We report the characteristics and possible impact of leachate on quality of groundwater in the Chunga Landfill area of Lusaka, Zambia. Water and leachate samples were collected within and around the landfill for analysis. The pH, biological oxygen demand (BOD), chemical oxygen demand (COD), nitrates, sulphates, chlorides for the leachate and groundwater samples were (6.6 ± 0.1 to 8.7 ± 0.0), (1.7 ± 0.3 to 1,569.6 ± 4.9 mg/L), (4.0 ± 0.0 to 10,378.5 ± 59.2 mg/L), (8.0 ± 0.0 to 37.7 ± 0.4 mg/L), (11.7 ± 0.0 to 273.1 ± 1.7 mg/L), (43.0 ± 1.2 to 974.2 ± 0.8 mg/L) respectively. Heavy metal concentration ranges were cadmium (0.004 ± 0.000 to 1.149 ± 0.021 mg/L, chromium (0.007 ± 0.000 to 2.699 ± 0.039 mg/L), copper (0.013 ± 0.002 to 0.246 ± 0.005 mg/L), lead (0.062 ± 0.005 to 2.591 ± 0.065 mg/L) and zinc (0.008 ± 0.001 to 2.032 ± 0.017 mg/L). The pH of the leachate (8.5 ± 0.0 to 8.7 ± 0.0) meant the landfill was in the methane fermentation phase. An indexing approach was used with the leachate pollution index (LPI) of 30.173, heavy metal pollution index (HPI) of 3,938.92. The heavy metal index (HMI) for copper, lead, chromium, cadmium and zinc were found to be 0.92, 1,124.19, 47.20, 994.17 and 1.48 respectively. Principal component analysis (PCA) showed that anthropogenic activities contributed to pollution with high loading values. Ash from continuous burning of the waste may provide alkalinity which reduces leachate BOD and COD. Results showed that the landfill has outgrown the designed cells capacity as not all leachate was collected by the under-drainage. Results also showed that lack of adequate landfill cover significantly increases rainfall infiltration thereby increasing volumes of leachate produced with a, hence potential for underground water contamination and a human health and environmental problem.

1. Introduction

Efficient waste management remains a global challenge, with direct human health impact (Parvin and Tareq 2021). Chunga Landfill in Lusaka is the only planned engineered landfill in Zambia (Muleya 2020) and construction started around 2005 with a life span of 25 years (Jica 2020) (Supplementary Information Figures S1, S3 and Table S2). By 2020, waste volume at the landfill was estimated at 761, 815 cubic metres, accounting for 6.5 percent of the total landfill capacity (Muleya 2020). This makes the landfill ideally to be still viable for few more years being estimated to be around 2034. Over the years, there has been an improvement in the technology for waste management albeit an increase in the amount of waste generated globally (Mudau 2012) as the population increases (Abdel-Shafy and Mansour 2018). Land availability for landfills is also fast diminishing as more people seek land for accommodation and business hence planners need to rethink waste management practices.

Waste at landfills is affected by either groundwater undercurrent or infiltration from rain resulting in contaminated water called 'leachate' (Mor et al., 2006). Leachates are highly concentrated aqueous discharges with a diverse composition of both dissolved organic matter; and inorganic compounds (Lee and Jones-Lee 1993; Christensen et al., 2001). Other than mining (Kaile and Nyirenda 2016), incorrect disposal of agricultural products (Malambo et al., 2019; Ziwa et al., 2020) is another means by which organic and inorganic compounds enter the environment and contaminate the ground and surface waters in Zambia. In a study near the Chunga landfill, Ngumba et al., (2020) reported that pharmaceutical drugs such as sulfamethoxazole were present in the

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influent and effluent waters in the mean concentration of 33,300 ± 1,890 ng/L and 30,040 ± 3,420 ng/L, respectively. Another study (Nyirenda et al., 2020) showed that these pharmaceutical products can persist in the waters and may lead to contamination. As more studies are being undertaken to check quality of water, methods for removal of heavy metals as well as soluble organic compounds are needed to safeguard quality of ground and surface waters (Nyirenda et al., 2021, 2022). This study aimed at uncovering the characteristics of the leachate and its impact on groundwater based on WHO (WHO 2011) water quality guidelines. Also reported in this paper are the possible health risks associated with heavy metal contamination as well as toxic anions such as nitrates found in the leachate and ground water. The main objective of this research was to carry out the physical chemical characterization of the leachate from Chunga landfill with respect to its impact on pollution of ground water of the surrounding area.

2. Materials and methods

2.1. Sampling site

The sample site lies between 15°20′26.17″-15°21′24.21″ S and 28°14′59.97″-28°16′12.32″ E. The leachate pond at 15°20′53.5″S 28°15′59.7″E was used as a reference point for sampling in the surrounding area. A total of 14 points were sampled in and around the landfill with the leachate pond being used as the reference point for all other points (Figure 1).

Sampling was done with an initial plan of monitoring wells which were placed for the same purpose yet are nonfunctional. So, a convenient method was used to ensure sites are as close to original sampling points as possible. Since the site was engineered before residential houses were built, much effort was done to include many places which surround the landfill. Parameters were fixed based on the ZABS standard for drinking water. Grab samples were collected in HDPE bottles and were closed with Teflon covered seals and cooled in cool boxes. They were transferred to a 4 °C fridge until analysis was done.

2.2. Analysis

Heavy metal analysis was done at the Zambia Agriculture Research Institute (ZARI) Lab using the Agilent microwave plasma atomic emission spectrophotometry (Agilent MP4210 MP-AES). Standard multi-element CRMs were purchased from Ultraspec, South Africa. Physical parameter analysis was done at the University of Zambia (UNZA), Civil and Environmental Engineering Laboratory. Fourteen sample points were selected and at each sampling point six samples were collected, and this translated to 84 sample samples. These were thoroughly mixed to yield a composite sample and analyzed at three different times to get means. This was done for the two sampling periods (August–September and November–December 2019). To ensure reliable results, quality control was performed on each instrument according to instructions before each test analysis. Details are explained in the supplementary material.

All samples were collected within a radius of 1,700 m from the landfill with the leachate pond being the point of reference. Analysis was done in conformity with methods for testing of water and wastewater, APHA 1998 (APHA 1998). Results were compared with standards from Zambia Bureau of Standards (ZABS 2010) and guidelines from World Health Organization (WHO 2011). Stata version 17 was used for calculating analysis of variance.

2.3. Pollution assessment by indexing

2.3.1. Leachate pollution index

The leachate pollution index (LPI) is one method among others used to express the state of the landfill and how much pollution has been caused. The LPI, a single number which ranges from 5 to 100 like a grade, articulates the complete leachate contamination potential of a landfill based on many leachate pollution parameters in a given time. As per this index a higher value indicates a poor environmental condition (Samal et al., 2020). Eq. (1) (Kumar and Alappat 2005) was used for calculating the individual leachate pollution indices from the three classes because not all the 18 pollutant parameters were used.

$$LPI = \frac{\sum_{i=1}^{m} w_i \ p_i}{\sum_{i=1}^{m} w_i} \quad (1)$$

where LPI is the weighted additive leachate pollution index; $m < 18$ and $\sum_{i=1}^{m} w_i < 1$; w_i is the weight for the ith pollutant variable; p_i is the subindex score of the ith leachate pollutant variable; m is number of leachate pollutant variables used in calculating LPI.

Eq. (2), reported by Kumar as Eq. (3) (Kumar and Alappat 2005) was used for calculating the overal LPI from Chunga Landfill.

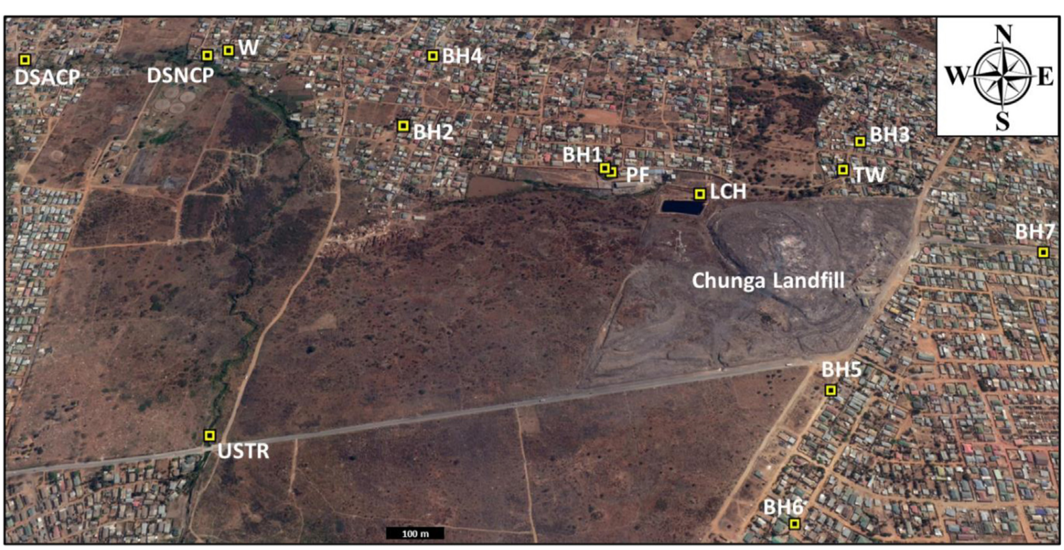

Figure 1. Aerial view of the sampling site. The sites are labeled in yellow. (BH) 1 to 7, tap water (TW), Plastic factory (PF), well (W), upstream of the Chunga ponds (USTR), Downstream after the Chunga ponds (DSACP), Downstream near the Chunga ponds (DSNCP) and leachate (LCH) respectively. The map was drawn with Google Earth Pro (version 7.3.3.7786 accessed on 24/06/2021). GPS Coordinates (Supplementary Table S1) were input in gpsvisualizer (https://www.gpsvisualizer.com) (Schneider 2021) and data output through Google Earth.

$$LPI = 0.232\ LPI_{or} + 0.257\ LPI_{in} + 0.511\ LPI_{hm} \tag{2}$$

where LPI_{or} is the sub-leachate pollution index organic component value; LPI_{in} is the sub-leachate pollution index inorganic component value; and LPI_{hm} is the sub-leachate pollution index heavy metal component value (Kumar and Alappat, 2005b).

2.3.2. Heavy metal pollution index

Heavy metal pollution index (HPI) provides the complex impact of an individual heavy metal on the quality of water (Rana et al., 2017; Sharma et al., 2020; Vasistha and Ganguly 2020, 2022). This parameter is calculated using Eq. (3) proposed by (Mohan et al., 1996).

$$HPI = \frac{\sum_{i=1}^{n} w_i\ Q_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

where, Q_i (represented in Eq. (4)) and W_i indicate the sub-index and unit weight assigned to the *i*th parameter and *n* denotes the number of parameters considered.

$$Q_i = \frac{|M_i - I_i|}{S_i - I_i} \tag{4}$$

where, M_i, I_i and S_i represent the heavy metal concentration in the sample, acceptable and permissible values respectively.

2.3.3. Metal index

The metal index (MI) was computed using Eq. (5) as proposed by (Dash et al., 2019).

$$HMI = \sum_{i=1}^{n} \left[P_i \times \frac{M_i}{S_i} \right] \times 100 \tag{5}$$

where, HMI is the heavy metal index, P_i is the weight assigned to each element from principal component analysis. M_i is the concentration of each element in solution, S_i is standard permissible concentration for each element and the subscript i is the *ith* sample.

2.4. Multivariate statistical analysis

Multivariate statistical analysis was performed on mean concentrations for all the parameters that were measured. In this study, the hierarchical cluster analysis (HCA), principal component analysis (PCA) and Pearson's correlation coefficient were used. This helps to reduce dimensionality and skewness and thereby highly useful in analyzing such large environmental data sets. The study reported a total of 13 parameters including pH, TDS, COD, BOD, sulfate, nitrate, chloride, copper, lead, cadmium, chromium, zinc and electrical conductivity. Extraction of factors was done using varimax rotation and derived principal components with eigenvalues greater than 1. The principal component method was used to study the distribution manner of individual association of the studied parameters in groundwater and the leachate. Cluster analysis was employed to classify the parameters on the basis of their similarities within a group. Hierarchical agglomerative cluster analysis provides a similarity relationship between heavy elements using a dendrogram. IBM SPSS version 29 was used for multivariate analysis. The Ward method of statistics was used to prescribe the agglomerative hierarchical clustering

procedure where the criteria for the set of clusters to integrates each step is based on the favorable value of an objective function.

3. Results and discussion

The leachate and water analysis were categorized into three, with physical parameters, chemical parameters and heavy metals for ease of analysis.

Tables 1 and 2 shows results for the two sampling periods, August–September modeling the dry period and November–December, modeling wet period respectively.

3.1. Electrical conductivity

Electrical conductivity of the samples was analyzed for two sampling periods with comparisons set against the permissible standard of 1500 μS/cm (ZABS 2010). For the dry period, contamination was noted for borehole 1, upstream, downstream after Chunga plant, with downstream near Chunga plant having the highest at 2,504.5 ± 0.6 μS/cm. The Well sample had the lowest recorded contamination of 851.5 ± 1.6 μS/cm. For the wet period, contamination was recorded for the upstream, downstream near Chunga plant, the Plastic factory, and the leachate point. The highest contamination was at the Plastic factory (3,941.3 ± 1.2 μS/cm) and the lowest at the Well sample (610.9 ± 0.5 μS/cm). Conductivity for the leachate for the two sampling seasons were 78,328.0 ± 5.4 μS/cm and 77,452.1 ± 2.7 μS/cm respectively. Other papers have recorded conductivities in the range of 1,405 ℧/cm (1,405,000,000 μS/cm) (Alam et al., 2020) indicating dissolved materials in the leachate. Mishra and Tiwary (Mishra et al., 2018) reported lower electrical conductivities than our study for two sites, Ramna and Karsara in the range of 4.55 and 12.57 mS/cm.

3.2. Total dissolved solids (TDS)

Total dissolved solids for the dry period were above the ZABS limit of 1,000 mg/L in BH1, tap water from Lusaka Water and Sanitation Company (LWSC), upstream, downstream after Chunga plant, downstream near Chunga plant and the leachate pond. The highest concentration of 1,256.5 ± 1.4 mg/L was recorded at downstream near Chunga plant whilst the Well sample had the lowest concentration of 424.4 ± 0.8 mg/L. The sampling points at which contamination was occurred during the wet period were BH1, tap water, Plastic factory, BH7, upstream, downstream near Chunga and the leachate pond. The highest concentration of 1,480.3 ± 2.0 mg/L was at the Plastic factory and the lowest concentration of 300.6 ± 0.5 mg/L at the Well. The leachate concentrations were 39166.0 ± 3.8 mg/L and 38,751.5 ± 1.3 mg/L for the dry and wet period, respectively.

3.2.1. pH

The sampled points were all well within the permissible pH levels ranging between 6.5 and 8.0 for both respective periods apart for the leachate sample. For the dry period, the lowest pH was (6.6 ± 0.1) downstream near Chunga plant and the highest reading was (7.7 ± 0.0) downstream after Chunga plant. During the wet period, the lowest pH was (6.9 ± 0.0) upstream and the highest was (7.8 ± 0.0) downstream after the Chunga plant. The set standard is 6.5–8.0 according to ZS ISO 10523 normative of the Drinking Water Quality–Specification (ZABS 2010). The alkaline condition of the leachate (8.5 ± 0.0) and (8.5 ± 0.0) for the dry and wet periods respectively shows the landfill is in its old age (Mishra et al., 2018). This is representative of the landfill being in the methane fermentation phase as the findings were alkaline showing that the landfill is no longer in the acid formation phase (Joshi et al., 2018; Wijekoon et al., 2022). During this phase, the intermediate acids are consumed by methane forming bacteria and converted into methane and carbon dioxide.

3.3. Anions

The common anions we reported were the sulphates, nitrates and chlorides, parameters that have previously been monitored for Chunga river (Siwale and Bäumle 2011) which receives the bulk of contaminants from the leachate pond.

3.3.1. Sulphates

Only the leachate sample exceeded the permissible limit of 250 mg/L for both sampling periods at 272.1 ± 1.7 mg/L (Table 1).

3.3.2. Nitrates

For nitrates, only borehole 2 and the leachate at 10.7 ± 0.1 mg/L and 27.4 ± 0.6 mg/L respectively exceeded the permissible limit of 10 mg/L. Nitrates from the well, upstream, downstream after Chunga plant and

Table 1. Leachate water parameters for August and September 2019.

Site	Parameter							
	pH	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	Cl^- (mg/L)	BOD (mg/L)	COD (mg/L)	Conductivity (μS/cm)	TDS (mg/L)
BH1	7.0 ± 0.0	23.8 ± 1.0	5.1 ± 0.0	218.0 ± 1.9	2.4 ± 0.1	6.0 ± 0.0	1,661.3 ± 1.0	831.2 ± 0.8
BH2	7.1 ± 0.1	52.5 ± 0.5	10.7 ± 0.1	63.7 ± 1.2	2.7 ± 0.3	6.5 ± 0.0	890.9 ± 0.8	444.0 ± 1.4
TW	6.8 ± 0.1	33.3 ± 0.2	4.9 ± 0.0	116.7 ± 1.4	1.8 ± 0.3	4.5 ± 0.0	1,354.8 ± 0.4	679.6 ± 3.6
BH3	7.2 ± 0.0	51.4 ± 0.1	5.2 ± 0.1	53.0 ± 0.6	2.2 ± 0.4	4.9 ± 0.1	964.3 ± 1.6	481.4 ± 1.2
BH4	7.3 ± 0.0	66.2 ± 0.0	7.2 ± 0.0	70.9 ± 0.4	3.8 ± 0.2	9.0 ± 0.1	922.9 ± 1.3	465.4 ± 2.6
BH5	7.2 ± 0.0	56.8 ± 0.1	6.7 ± 0.1	67.7 ± 0.4	2.8 ± 0.4	7.7 ± 0.3	891.5 ± 1.6	445.3 ± 0.7
W	7.3 ± 0.0	11.7 ± 0.0	ND	43.0 ± 1.2	4.9 ± 0.2	12.3 ± 0.3	851.5 ± 1.6	424.4 ± 0.8
USTR	7.5 ± 0.0	28.2 ± 0.1	ND	118.2 ± 0.8	7.1 ± 0.1	14.0 ± 0.1	1,666.7 ± 0.8	834.8 ± 0.6
DSACP	7.7 ± 0.0	44.2 ± 0.1	ND	99.3 ± 0.7	8.9 ± 0.2	19.3 ± 0.6	1,734.6 ± 1.9	867.7 ± 2.0
DSNCP	6.6 ± 0.1	111.0 ± 0.3	ND	250.7 ± 0.5	60.3 ± 1.1	128.4 ± 1.1	2,504.5 ± 0.6	1,256.5 ± 1.4
LCH	8.5 ± 0.0	272.1 ± 1.7	27.4 ± 0.6	283.6 ± 1.9	1,569.6 ± 4.9	10,378.5 ± 59.2	78,328.0 ± 5.4	39,166.0 ± 3.8

downstream near Chunga plant were non-detectable. The wet period results showed that all samples that had detectable concentrations were above the permissible limit except the tap water sample which had a concentration of 8.0 ± 0.0 mg/L. Borehole 6 had the highest concentration of 37.7 ± 0.00 mg/L whilst the well sample, Plastic factory, leachate and downstream near Chunga plant had no detectable values. The ZABS standard (ZABS 2010) puts a 10 mg/L limit for nitrates. Nitrates have been implicated in many health effects including methemoglobinemia or (Blue Baby Syndrome) (Bouchard et al., 1992; Bryan and van Grinsven 2013).

3.3.3. Chlorides

Concentrations of chlorides in the dry period were all below the permissible 250 mg/L limit except for downstream near Chunga plant and leachate pond which had concentrations of 250.7 ± 0.5 mg/L and 283.6 ± 1.9 mg/L, respectively.

For the concentrations in the wet period, boreholes 4, 5, 6 and 7, the well and downstream after Chunga plant were within the permissible limit with the other sampling points having concentrations exceeding the set limits. Borehole 1 and downstream near Chunga plant had the highest concentrations of 304.6 ± 0.8 mg/L and 474.3 ± 0.7 mg/L, respectively.

3.4. BOD and COD

All BOD readings were within the set standards as only two samplings points downstream near Chunga plant 60.3 ± 1.1 mg/L and leachate 1,569.6 ± 4.9 mg/L exceeding the set limits in the dry period. All concentrations in the wet period well all within the set standards. All COD readings were within the set standards as only two samplings points downstream near Chunga plant 128.4 ± 1.1 mg/L and leachate 10,378.5 ± 59.2 mg/L exceeding the set limits in the dry period. All concentrations in the wet period well all within the set standards except for downstream near Chunga plant 96.0 ± 0.3 mg/L and leachate 102.4 ± 0.6 mg/L.

3.5. Heavy metals

Concentrations of heavy metals in the water samples were analyzed by use of the MP4210 MP-AES using multi-element standards (Ultraspec, South Africa). The heavy metal concentrations at each site are shown in Figure 2.

3.5.1. Copper

The concentrations of copper in all the samples were well within WHO guidelines (WHO 2011) of 2 mg/L. Borehole 1 had the highest concentration of 0.037 ± 0.001 mg/L with borehole 3 having the lowest concentration of 0.013 ± 0.002 mg/L. The concentration in the leachate sample was 0.246 ± 0.005 mg/L, which was also within the acceptable limits but was relatively low compared to the concentrations of the other heavy metals in the leachate sample. High intake of copper can result in liver and kidney damage (Jing et al., 2016) over time leading to death whilst the short-term effects are stomach discomfort, vomiting and dizziness (Nalishuwa 2015).

Table 2. Leachate water parameters for November and December 2019.

Site	Parameter							
	pH	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	Cl^- (mg/L)	BOD (mg/L)	COD (mg/L)	Conductivity (μS/cm)	TDS (mg/L)
BH1	7.0 ± 0.0	116.3 ± 0.5	11.4 ± 0.4	304.6 ± 0.8	2.0 ± 0.0	4.0 ± 0.1	1,183.5 ± 3.5	592.2 ± 2.1
BH2	7.2 ± 0.0	50.4 ± 0.2	12.5 ± 0.1	229.2 ± 0.8	2.0 ± 0.0	4.4 ± 0.1	942.4 ± 0.8	476.3 ± 0.6
TW	7.1 ± 0.0	47.2 ± 0.0	8.0 ± 0.0	265.5 ± 1.1	1.9 ± 0.1	4.0 ± 0.0	1245.7 ± 1.1	623.2 ± 0.6
BH3	7.5 ± 0.0	45.5 ± 0.4	14.8 ± 0.2	136.1 ± 0.4	3.7 ± 0.3	6.5 ± 0.1	759.6 ± 1.4	380.3 ± 0.8
BH4	7.1 ± 0.0	44.2 ± 0.1	11.7 ± 0.0	74.6 ± 0.4	2.0 ± 0.0	4.0 ± 0.0	864.8 ± 0.7	432.4 ± 0.4
PF	7.0 ± 0.0	115.3 ± 0.5	ND	974.2 ± 0.8	2.0 ± 0.2	4.1 ± 0.1	3,941.3 ± 1.2	1,480.3 ± 2.0
BH5	7.4 ± 0.0	64.5 ± 0.2	23.7 ± 0.2	77.6 ± 0.4	2.3 ± 0.3	5.1 ± 0.2	736.1 ± 0.1	369.8 ± 0.3
BH6	7.3 ± 0.0	136.0 ± 0.5	37.7 ± 0.4	140.0 ± 0.2	2.0 ± 0.1	4.0 ± 0.1	989.5 ± 1.3	495.3 ± 1.1
BH7	7.5 ± 0.0	79.6 ± 0.1	22.5 ± 0.1	129.1 ± 0.8	1.7 ± 0.3	4.0 ± 0.0	1,026.8 ± 0.4	513.3 ± 0.9
W	7.5 ± 0.0	54.5 ± 0.1	ND	88.3 ± 0.2	3.4 ± 0.1	5.6 ± 0.4	610.9 ± 0.5	300.6 ± 0.5
USTR	6.9 ± 0.0	47.1 ± 0.1	25.6 ± 0.3	298.3 ± 2.4	5.4 ± 0.1	9.5 ± 0.1	1,874.3 ± 0.9	636.7 ± 1.5
DSACP	7.8 ± 0.0	51.3 ± 0.1	17.4 ± 0.2	191.5 ± 0.6	5.5 ± 0.0	12.6 ± 0.1	936.4 ± 1.4	424.8 ± 0.4
DSNCP	7.5 ± 0.0	154.8 ± 0.2	ND	474.3 ± 0.7	35.9 ± 0.2	96.0 ± 0.3	2,061.6 ± 0.9	783.7 ± 1.2
LCH	8.7 ± 0.0	ND	ND	ND	67.3 ± 0.3	102.4 ± 0.6	77,452.1 ± 2.7	38,751.5 ± 1.3

ND: Non-Detectable.

3.5.2. Cadmium

All samples exceeded the permissible limit by ZABS and WHO of 0.003 mg/L with Borehole 6 having the highest concentration of 0.089 ± 0.004 mg/L and borehole 3 having the lowest concentration of 0.004 ± 0.000 mg/L just above the allowable limit. The leachate sample had a concentration of 1.149 ± 0.021 mg/L and the average concentration of cadmium being 0.1194 mg/L. The principle physiological effects of cadmium are bone damage, chronic kidney disease, cancer and hypertension (Adedapo and Adeoye 2014). It is also very toxic towards aquatic life (Kumar and Singh 2010; Kaile and Nyirenda 2016).

3.5.3. Chromium

Only the leachate sample and borehole 1 exceeded the permissible limits. The set standard by Zambia Bureau of Standards (ZABS 2010) and World Health Organization (WHO 2011) is 0.05 mg/L with the borehole 1 sample having a concentration of 0.233 ± 0.006 mg/L. The leachate sample concentration was 2.699 ± 0.039 mg/L which is significantly higher than the allowable limits with the average being 0.228 mg/L. Chromium is known to be carcinogenic at high concentration, though its deficiency is of even higher nutritional concern (DesMarias and Costa 2019). Oxidation states of chromium under environmental conditions ranges from the less toxic trivalent chromium (III) to the hexavalent chromium (VI), which is more toxic and damages the liver, gastrointestinal track, kidney and the lungs.

3.5.4. Lead

Lead concentration was above permissible limits in all the samples that were taken. The allowable set limit by both ZABS and WHO is 0.01 mg/L with borehole 6 having the highest concentration of 0.660 ± 0.007 mg/L and the lowest being the tap water supplied by the LWSC having a concentration of 0.062 ± 0.005 mg/L. The leachate sample had an average lead concentration of 2.591 ± 0.065 mg/L. Lead has many toxic effects on human health with infants and children the most vulnerable (Bose-O'Reilly et al., 2018). Lead poses neurodevelopmental challenges for children and causes kidney problems and high blood pressure in adults (Pena and Rollins 2017; Yabe et al., 2020).

3.5.5. Zinc

Zinc concentrations in all the samples were well within the permissible ZABS and WHO limit of 3 mg/L with the highest concentration found upstream near the Chunga plant of 0.037 ± 0.003 mg/L and the lowest concentration at borehole 4 of 0.008 ± 0.001 mg/L. The leachate had a zinc concentration of 2.032 ± 0.017 mg/L and an average concentration 0.1936 mg/L was recorded. Zinc is essential to man (Prasad and Bao 2019; Singh and Dubey 2019; Chasapis et al., 2020) but if ingested in gross amounts has an emetic effect (Solomons and Schümann 2017).

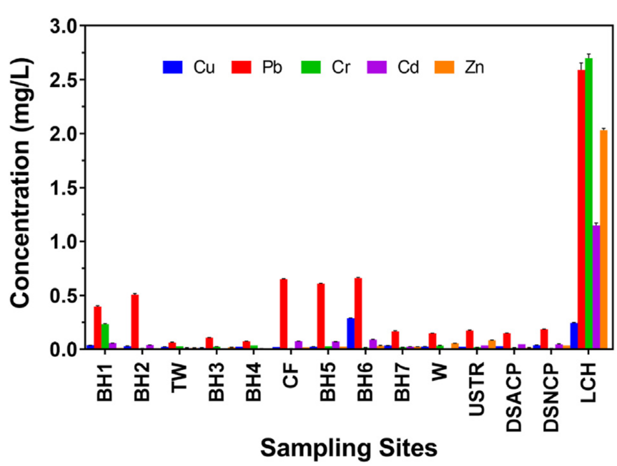

Figure 2. Heavy metal distribution in the water samples from the boreholes (BH) 1 to 7, tapwater (TW), Plastic factory (PF), well (W), upstream of the Chunga ponds (USTR), Downstream after the Chunga ponds (DSACP), Downstream near the Chunga ponds (DSNCP) and leachate (LCH) respectively. The heavy metals were analysed by the Agilent Technologies 4210 Microwave plasma Atomic Emission Spectrophotometer. Values were expressed as means ± SD.

3.6. Chemical composition of leachate

The chemical composition of the Chunga landfill is quite diverse in that there is a significant variation in the concentration of the respective parameters. Leachate quality is greatly influenced by many factors such as waste age (Hussein et al., 2019) and seasonal weather variations (Bhalla et al., 2013). Supplementary figure S4 shows the typical black colour of the leachate at the time of sampling. The Chunga landfill construction started in 2005 with fully fledged operations starting in 2007 with an operational lifespan ending in 2022. This will place the landfill in the methane fermentation stage going into the maturation stage of its lifespan (Jica 2020; Muleya 2020).

Most of the sulphates and nitrates are converted to sulphides and nitrites respectively in this phase which explains why the concentrations of the sulphates recorded were all within the permissible set standards by WHO as most would have been converted. The nitrates were still considerably above the permissible limit in the wet period which may have resulted due to the first wave of rains bringing new nitrates in the leachate pond from the landfill. Only the leachate sample was above the set standard in the dry period for sulphates and nitrates.

Chloride is a conservative parameter which is independent of refuse decomposition and its availability in the leachate is mainly depended on or attributed to the nature of the waste deposited at the landfill. Therefore, the amounts of chlorides in the findings can be explained by studying the type of waste being received at the landfill. The findings show that the amounts of chlorides increased in the dry period compared to the wet period which may have resulted from waste containing more chlorides being deposited more during the dry period.

The BOD and COD values recorded in the leachate were significantly different ($p = 0.0000$) between the dry and wet period with values of 67.3 ± 0.3 mg/L and 102.4 ± 0.6 mg/L respectively during the wet period, 1,569.6 ± 4.9 mg/L and 10,378.5 ± 59.2 mg/L respectively. BOD and COD values are used to measure the organic content of the leachate and studies have shown that there is a constant decrease in concentrations over time (Ehrig 1989; Inglezakis et al., 2018). The continuous burning of the waste pile reduces the BOD and COD levels with the ash from the burning (Supplementary Information Figure S2 (c), (d) and 3) providing alkalinity and carbon absorption, which reduces several metal constituents from leaching. A decline in the concentrations of BOD and COD of the leachate over time can be attributed to a combination of reduction in organic contaminants available for leaching and the increased biodegradation of the organic compounds. The BOD/COD ratio obtained during the dry period of 0.15 compares with other studies that show a reduction in the biodegradability in the leachate and ascribe to the biodegradability that is taking place in the landfill (Fatta et al., 1999).

Electrical conductivity is used as an indicator of the abundance of dissolved inorganic species or the total concentration of ions (Al-Sabahi et al., 2009). The recorded values of electrical conductivity in Chunga leachate are relatively high in both the dry and wet periods with readings of 78,328.0 ± 5.4 μS/cm and 77,452.1 ± 2.7 μS/cm respectively showing a high presence of ions in the leachate. The EC values at Chunga are higher than values recorded in previous studies (Tatsi and Zouboulis 2002) which maybe explained in that the leachate in the pond does not have a recirculation system in place. The only system available is evaporation in the leachate pond though it was established that the leachate that collects in the pond does not evaporate quickly enough even during peak summertime. Leachate recirculation is an option in leachate management as it is reported to improve the quality of the leachate through stabilization of the landfill and enhancement of biogas production (Li et al., 2020; Budihardjo et al., 2021; Kumar and Reddy 2021).

The high levels of TDS in both sampling periods indicate presence of high suspended matter and high dissolved organic matter in the leachate. The concentrations of 39,166.0 ± 3.8 mg/L and 38,751.5 ± 1.3 mg/L for the dry and wet period respectively are very similar to each other but are relatively higher as compared to other studies (Hussein et al., 2019). This is due to the ponding which happens in the leachate pond as the leachate does not get evaporated completely. The figures are expected to be much higher that the readings recorded in a wastewater treatment plant.

The heavy metals copper (0.246 ± 0.005 mg/L and zinc (2.032 ± 0.017 mg/L concentrations were relatively low compared to those of cadmium, chromium and lead. Both copper and zinc were well within the WHO guidelines and the major factor is the type and composition of the waste that is deposited at the Chunga landfill. With the major sources of zinc being discharges of smelter slag waste and mine tailings it explains why the concentrations are relatively low as there are no such active operations near the landfill. The low concentrations recorded can be attributed to commercial products such as fertilizers and wood preservatives that may have found themselves to the landfill. Similarly, copper concentrations are low attributing to waste being deposited at the landfill that has little copper constituents.

Findings show that chromium (2.699 ± 0.039 mg/L) was above the WHO acceptable limit in the leachate sample. Major sources of chromium at the landfill are waste generated from leather tanning and paint production industries. Though the amounts of chromium are significantly higher in wastewater sewers going to the wastewater treatment plants in solution form, waste from these industries is still deposited at the landfill explaining the high concentration recorded.

Lead (2.591 ± 0.065 mg/L) and cadmium (1.149 ± 0.021 mg/L) are the most prevalent heavy metals in the leachate sample with respect to the WHO allowable standards. A study by Nyirongo around Chunga gardens (Kunda 2020) revealed that the concentrations of Cd, Cu, Pb and Zn were beyond the maximum permissible standards for their samples based on WHO guidelines. These results clearly show a bioaccumulation pattern of heavy metals and there is need for interventions to safeguard the health of people staying and conducting agricultural activities near the landfill.

3.7. Leachate pollution index

The coefficients 0.232, 0.257 and 0.511 are fractional summations of the pollutant weights (Table 3). The sub index score were read and estimated from Supplementary Information Figures S5, 6 and 7 (Kumar and Alappat 2005).

The overall LPI was found to be 30.173. This value compares with results for the PP and SW landfills (Kumar and Alappat 2005) of 36.48 and 39.04 respectively. Other studies have shown that the LPI for active landfills is usually much higher than those which are closed (Hussein et al., 2019).

3.7.1. Heavy metal pollution index (HPI)

Table 4 shows the heavy metal concentrations at different sample sites. The distances for each site were measured relative to the leachate pond which was assigned zero meters.

Table 4 shows the mean heavy metal concentrations of the five analytes (ppb). The permissible values were sourced from the ZABS standard (ZABS 2010). The maximum allowable concentration and highest desirable values were adopted from (Lotfi et al., 2020).

The HPI was found to be 3,938.92 far much higher than the proposed value of 100 (Dey et al., 2021).

Individual site HPI ranged from 326.90 to 34,006.69 for BH3 and Leachate pond samples respectively (Figure 3).

Table 3. Pollutant weights and sub index scores for the 18 pollutants contributing to LPI.

Index	Parameter	Weighted Factor (w_i)	Pollutant Conc.	Sub Index Value (p_i)	w_ip_i
	BOD5	0.263	1,570	36	9.468
LPI_{or}	COD	0.267	10,379	75	20.025
	Summation	0.530			29.493
	LPI_{or}				55.647
	pH	0.214	9	30	6.420
LPI_{in}	TDS	0.195	39,166	90	17.550
	Cl^-	0.187	284	7	1.309
	Summation	0.596			25.279
	LPI_{in}				42.414
	Total Cr	0.125	2.70	12.5	1.563
LPI_{hm}	Pb	0.123	2.59	25	3.075
	Zn	0.110	2.03	5	0.550
	Cu	0.098	0.25	5	0.490
	Summation	0.456			5.678
	LPI_{hm}				12.451

All results were reported in mg/L except for pH.
Values in this study were comparable to other studies(Alam et al., 2020).

3.7.2. The heavy metal index

The heavy metal index (HMI) determination used the approach of (Dash et al., 2019). The MI for copper, lead, chromium, cadmium and zinc were found to be 0.92, 1,124.19, 47.20, 994.17 and 1.48 respectively. These values were far much above compared to other similar studies (Abou Zakhem and Hafez 2015; Sharma et al., 2020).

Table 5 shows the classifications based on heavy metal index values (Dash et al., 2019). The results shows that copper, chromium and zinc were below 50 implying the water was fit for consumption but on the other hand, lead and cadmium levels were far much higher than permissible limits categorizing the water as unsuitable for drinking as HMI values were higher than 300.

Clearly it shows that there is heavy pollution in and around the Chunga landfill compared to other sites. This may augment the view that due to perennial fires, the lining of the landfill has been compromised.

3.7.3. Multivariate statistical analysis

Three principal component analyses (PCAs) and Hierarchical cluster analyses (HCAs) were obtained for the Chunga Landfill sampling site with an Eigenvalue greater than unity and at a total cumulative variance of 92.622% in the data set. Table 6 shows the principal components. The Kaiser-Meyer-Olkin (KMO) test value was 0.559 an indicator for good sampling adequacy. Barlett's test of sphericity revealed a high significant value of $p < 0.001$ which proves that correlation matrix is a nonidentity matrix.

Table 6 shows the total variance of 13 parameters including pH, TDS, COD, BOD, sulfate, nitrate, chloride, copper, lead, cadmium, chromium, zinc and electrical conductivity. Three principle components were obtained and used to describe the pollution potential surrounding the Chunga Landfill.

Table 7 shows the loading values of the rotated component matrix. The rotation method employed was Varimax with Kaiser Normalization.

3.7.3.1. Principle component 1. Principle component 1 was mainly influenced by the high loading values of cadmium, BOD, zinc, conductivity, COD, TDS, Chromium and lead. It was moderately affected by sulphate and copper while chloride, nitrate and pH affected the component least.

3.7.3.2. Principle component 2. Principle component 2 was mainly affected by nitrate and copper while lead, chromium, cadmium, COD, TDS, conductivity, zinc, BOD and pH loading values affected the results in a moderate manner.

Table 4. Mean heavy metal concentrations (ppb).

Element	Mean Value (Mi)	Standard permissible value (S_i)	MAC	Highest desirable value (I_i)	Unit Weightage (Wi)	Sub Index (Q_i)	$W_i \times Q_i$
Cu	60.890	1,000	1,000	2,000	0.0010	193.91	0.19
Pb	462.072	10	2	-	0.1000	4,620.72	462.07
Cr	226.186	50	50	-	0.0200	452.37	9.05
Cd	118.755	3	3	-	0.3333	3,958.50	1,319.50
Zn	177.430	3,000	5,000	5,000	0.0003	241.13	0.08
					$\sum W_i = 0.45$		$\sum W_i{*}Q_i$ 1,790.89
						HPI	3,938.92

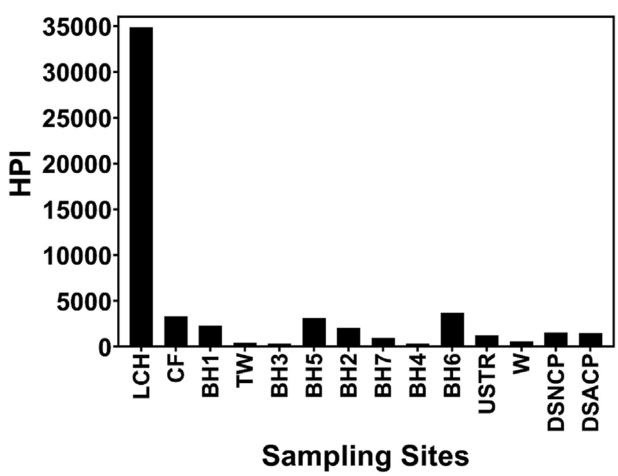

Figure 3. Shows the individual Heavy metal Pollution indices. The leachate (LCH) had a very high value while the rest of the sites ranged about 330–3700. These values reported here compare with those reported by (Dey et al., 2021) with the exception of the leachate pond water.

Table 5. Water quality classifications based on HMI values.

Range of HMI values	Category
HMI <50	Excellent
50 ≤ HMI <100	Good
100 ≤ HMI <200	Poor
200 ≤ HMI <300	Very Poor
HMI≥300	Unsuitable for Drinking

3.7.3.3. Principle component 3. Component 3 was mainly characterized by the high loading value of pH. Chromium, BOD, TDS, zinc, COD and conductivity were affected almost by the same margin.

The component matrix and the total variance of the 13 parameters in this study are shown in Table 6 and Figure 4.

3.7.3.4. Hierarchical cluster analysis. A hierarchical cluster analysis of parameters resulted into three major clusters (Figure 5).

The sites were also clustered together and produced three distinct clusters (Figure 6).

The distantly put single site cluster of the leachate can be explained by the unusually high concentration of the heavy metals as seen by the high conductivity values.

3.7.4. Correlation coefficient analysis

A correlation analysis matrix revealed that there was heavy correlation between many metal to metal and metal to nonmetal parameters as shown in Table 8.

With the exception of copper (0.598), all other metals had a very strong positive Pearson Correlation coefficient with conductivity. Lead ($r = 0.940$), chromium ($r = 0.997$), cadmium ($r = 0.996$) and zinc ($r = 0.998$) respectively. Our results are in agreement with similar studies done on groundwater analyses done on sites near landfills (Sharma et al., 2020).

3.8. Impact of leachate on groundwater quality

Analysis of the groundwater around the Chunga landfill revealed that the landfill has an impact on the groundwater. The pH of the groundwater sampled around the landfill ranged from 6.6 ± 0.1 to 7.8 ± 0.0 in both periods with most of the recorded readings being above pH 7. This shows a slight alkaline range with not many fluctuations in the readings between the dry and wet period, respectively. As the landfill is in the

Table 6. Total variance explained in component matrix for Chunga Landfill.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	8.964	68.953	68.953	8.964	68.953	68.953
2	1.820	14.004	82.957	1.820	14.004	82.957
3	1.256	9.665	92.622	1.256	9.665	92.622
4	0.509	3.919	96.540			
5	0.284	2.188	98.728			
6	0.105	0.810	99.539			
7	0.052	0.398	99.936			
8	0.006	0.050	99.986			
9	0.001	0.008	99.994			
10	0.001	0.005	100.000			
11	2.280E − 05	0.000	100.000			
12	1.288E − 06	9.907E − 06	100.000			
13	3.752E − 07	2.886E − 06	100.000			

Table 7. Rotated component matrix.

	Component		
	1	2	3
Cd	0.991	0.097	0.044
BOD	0.987	0.074	0.112
Zn	0.986	0.077	0.109
COND	0.985	0.083	0.108
COD	0.984	0.094	0.108
TDS	0.984	0.089	0.110
Cr	0.981	0.099	0.114
Pb	0.960	0.100	-0.120
SO_4^{2-}	0.757	-0.332	-0.074
Cu	0.656	0.389	-0.532
Cl^-	0.063	-0.914	-0.243
NO_3^-	0.191	0.859	-0.230
pH	0.293	0.070	0.894

methane producing phase with most of the sulphates and nitrates converted to sulphites and nitrites within the landfill, it can be seen through the sulphates findings which are low in all the sampled groundwater for both sampling periods. All the sulphate findings were within the permissible WHO limits. The nitrate concentration in the dry period was low with only BH2 having a reading above the set limit with a concentration of 10.7 ± 0.1 mg/L. There is a significant increase in the concentration of the nitrates in the wet period with only the tap water sample not having a concentration above the set standard of 10 mg/L. Though not totally attributed to the landfill, concentrations are expected to increase in the wet period due to lower temperatures and increased moisture content which favors aerobic conditions in the groundwater and surrounding soils. These conditions increase the conversion of nitrites to nitrates in the soil and groundwater. BH4, BH6 and BH7 have high levels of nitrates in the wet period which suggest that despite not being the direction of the reported groundwater flow, they still fall within the landfill leachate plume.

Chloride is one of the major indicators for contamination as it does not readily absorb onto soil, and it rarely occurs naturally in groundwater thus marking the landfill as the major source of the chloride found in the groundwater around with concentrations ranging from 43.0 ± 1.2 mg/L to 250.7 ± 0.5 mg/L in the dry period and 74.6 ± 0.4 mg/L to 974.2 ± 0.8 mg/L in the wet period. The range is higher than findings by (Reinhard et al., 1984) and (Abiriga 2017) whose concentrations were mainly <100 mg/L. The concentrations in the dry period were all below the permissible limit with the highest being downstream near Chunga plant having a concentration of 250.7 ± 0.5 mg/L which basically on the set standard. The concentrations in the wet period were higher that the dry period with all samples recording higher concentrations in the wet period. BH1, tap water, Plastic factory, upstream and downstream near Chunga plant all having concentrations higher than the set standard. These points are all located in the direction of the groundwater flow. The well value is low despite being in the same area as the other points recording high concentrations and this is due to the depth of the Well as (Christensen et al., 2001) reports that density and concentration of Cl^- increases with depth of the groundwater. The BOD and COD values for both the dry and wet periods were very low with the BOD/COD ratio having an average of 0.15 in the dry season and 0.6 in the wet season respectively. All the findings were within the permissible limits and were lower than findings in previous studies.

The electrical conductivity of the groundwater samples ranged from 851.5 ± 1.6 μS/cm to 2,504.5 ± 0.6 μS/cm with BH1, upstream, downstream after Chunga plant and downstream near Chunga plant

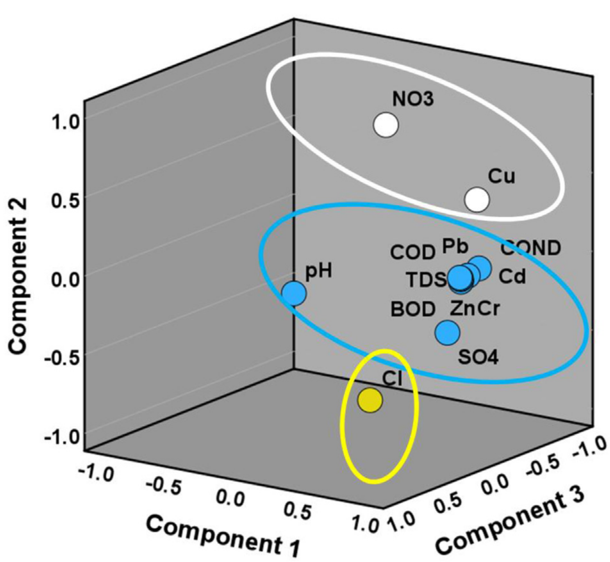

Figure 4. Rotated component matrix with varimax normalized for Chunga Landfill. The 13 parameters were grouped into 3 major clusters. The single parameter chloride (yellow), copper and nitrate (white) and the pH, BOD, zinc, sulphate, lead, chromium, COD, TDS, conductivity and cadmium (cyan) clusters respectively.

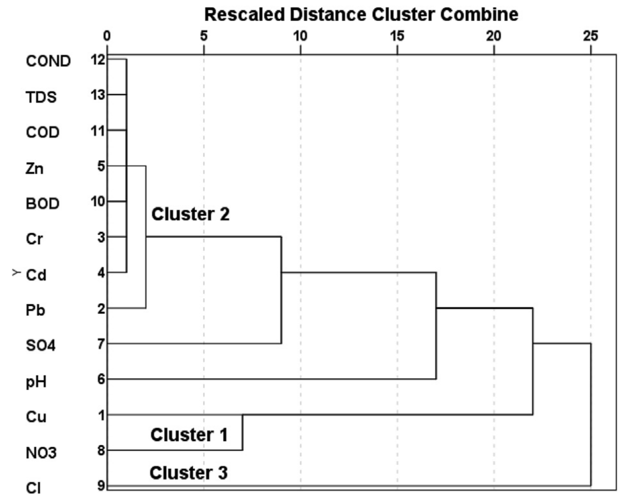

Figure 5. Hierarchical dendogram of the 13 variables. Ward linkage method was used for cluster analysis.

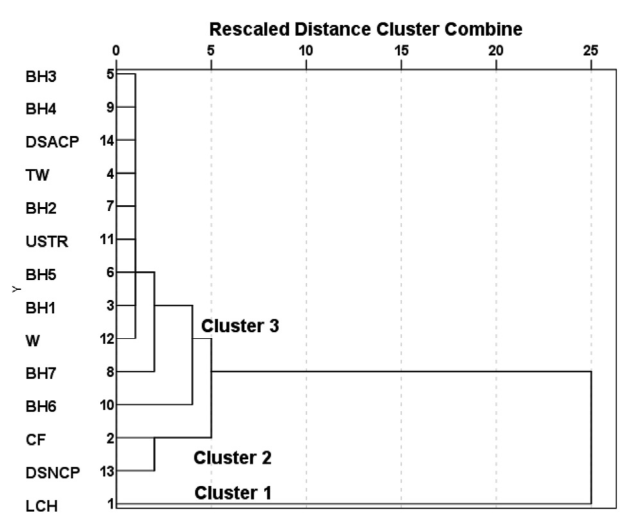

Figure 6. Hierarchical dendogram of the 14 sample sites. The Ward linkage method was used for cluster analysis.

Table 8. Shows the correlation analysis of the 13 parameters studied. The correlation coefficients in bold showed very high correlation above 0.9 for various parameter combinations.

	Cu	Pb	Cr	Cd	Zn	pH	SO_4^{2-}	NO_3^-	Cl^-	BOD	COD	COND	TDS
Cu	1.000												
Pb	0.698	1.000											
Cr	0.600	**0.939**	1.000										
Cd	0.643	**0.963**	**0.993**	1.000									
Zn	0.604	**0.934**	**0.993**	**0.994**	1.000								
pH	−0.177	0.177	0.368	0.315	0.365	1.000							
SO_4^{2-}	0.502	0.666	0.649	0.672	0.677	0.261	1.000						
NO_3^-	0.537	0.316	0.232	0.256	0.210	−0.019	−0.042	1.000					
Cl^-	−0.215	0.021	−0.056	−0.033	−0.043	−0.220	0.348	−0.607	1.000				
BOD	0.601	**0.935**	**0.995**	**0.995**	**0.999**	0.367	0.681	0.208	−0.042	1.000			
COD	0.604	**0.939**	**0.996**	**0.996**	**0.999**	0.360	0.659	0.224	−0.057	**0.999**	1.000		
COND	0.598	**0.940**	**0.997**	**0.996**	**0.998**	0.360	0.657	0.218	-0.042	**0.999**	**1.000**	1.000	
TDS	0.599	**0.939**	**0.997**	**0.996**	**0.998**	0.362	0.655	0.222	−0.048	**0.999**	**1.000**	**1.000**	1.000

having readings above the acceptable limit. During the wet period, the range was 610.9 ± 0.5 μS/cm to 3941.3 ± 1.2 μS/cm with the Plastic factory, upstream and downstream near Chunga plant all having recordings above the acceptable set standard. The EC is affected by the presence of inorganic dissolved solids such as calcium, magnesium, chlorides, sulphates and nitrates with the levels of conductivity increasing as the levels of salinity also increase. The sampling points which recorded high concentrations of chlorides showed high levels of electrical conductivity. The Plastic factory which had the highest recorded concentrations of chlorides also had the highest recorded electrical conductivity of 3,941.3 ± 1.2 μS/cm while the Well which had very low concentration of chlorides had low electrical conductivity of 610.9 ± 0.5 μS/cm. The salinity recorded at the Plastic factory was high justifying the high electrical conductivity recorded. Any sudden increase in conductivity in groundwater is an indication of pollution showing that new ions have been newly introduced in the water.

The WHO guideline of 500 mg/L was used to check whether the levels of TDS recorded were acceptable or not, with values that were above 900 mg/L considered very high. In the dry period findings for BH1, tap water, upstream, downstream after Chunga plant and downstream near Chunga plant were above 500 mg/L with downstream near Chunga plant having the highest reading of 1,256.5 ± 1.4 mg/L. During the wet period BH1, tap water, Plastic factory, BH7, upstream and downstream near Chunga plant recorded high readings with the Plastic factory having the highest reading of 1480.3 ± 2.0 mg/L.

The zinc and copper concentrations were all within the set limits for the groundwater sample which follows the leachate pond sample which also had zinc and copper concentrations that were under the set limit. This shows that the waste that is deposited at the landfill has very little zinc and copper constituents.

Findings show that only BH1 had a concentration of chromium that was higher than the standard of 0.05 mg/L with a concentration of 0.233 ± 0.006 mg/L which is relatively high compared to the other samples. BH1 is relatively close to the landfill but findings do not show similar results for the Plastic factory that is located near BH1. The other sampled groundwater had low concentrations of chromium.

Contamination of the groundwater was mainly from lead and cadmium with samples having concentrations that were above the set standards for lead and cadmium, respectively. For lead the highest concentrations were at the BH1, BH2, the Plastic factory, BH5 and BH6 with concentrations of 0.395 ± 0.009 mg/L, 0.506 ± 0.012 mg/L, 0.650 ± 0.004 mg/L, 0.607 ± 0.004 mg/L and 0.660 ± 0.007 mg/L, respectively. This can be explained in terms of location of these sampling points that recorded high concentrations were either relatively close to the landfill, located in the direction of groundwater flow or located within the landfill leachate plume. BH3 and tap water showed lower concentrations as they were away from the direction of groundwater flow and outside the landfill leachate plume despite being in proximity with the landfill. Treatment of the tap water may also have further reduced the lead content in the sampled water. The concentrations of lead in this study were higher than those recorded in other studies (Christensen et al., 2001). The leachate sample had a lead concentration of 2.591 ± 0.065 mg/L which is significantly higher that the set standard pointing to the landfill as the major source of the lead contamination in the groundwater that is around the landfill.

Cadmium levels in the groundwater were high with BH1 (0.057 ± 0.001 mg/L), Plastic Factory (0.075 ± 0.000 mg/L) and BH5 (0.071 ± 0.001 mg/L) having the highest concentrations. This is attributed to the proximity of these sampling points to the landfill while BH3 (0.004 ± 0.000 mg/L) and BH4 (0.007 ± 0.000 mg/L) having the lowest concentrations though these were still above the acceptable limit. The results of the study were higher than the findings from other studies (Hussein et al., 2019). This may prompt further testing and were possible removal methods such as activated carbon filters (Nyirenda et al., 2022).

4. Conclusion

Operation of the Chunga landfill has compromised the groundwater quality in and around the landfill area, evidenced by the presence of inorganic material that was detected in the leachate and groundwater. The major pollutants in the groundwater were cadmium, lead, nitrates and chlorides generated from the leachate produced from the landfill. Seasonal variations have an impact on the concentrations of specific pollutants with chlorides ($p = 0.0006$) and nitrates ($p = 0.0001$) increasing in concentration in the wet period which resulted in higher electrical conductivity showing higher concentration of ions in the wet season. The leachate pollution index of 30 shows that there is potential for contamination of groundwater sources from the landfill. Findings showed that distance also significantly ($p = 0.002$) affected the concentrations of the pollutants (Supplementary Information Table S4) with the sampling points that were near the landfill having high concentrations especially those located within the landfill leachate plume and in the reported direction of groundwater flow. Further a multivariate analysis has provided information on the state of the leachate as well as surrounding ground water. The HPI of 3938.92 was found to be far much higher than the recommended value of 100 further enhancing our conclusion on the potential of pollution and contamination of the groundwater near the landfill. Physical and geochemical attenuation greatly affect the pollutants as they are transported. At the time of writing this manuscript, there was no published data to use as a baseline for comparisons hence we believe, information and data presented here offers a detailed baseline for future studies. Information generated here is very important for policy makers to streamline operations at Chunga landfill to offset potential health risks arising from contaminated ground and surface waters as reported elsewhere (Kunda 2020; Ngumba et al., 2020). Notwithstanding this, other sources of groundwater pollution around Chunga landfill may be from increased deep borehole drilling for residential water supplies.

Declarations

Author contribution statement

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

Philip Mwamba Mwansa: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

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