Research Article

Characterizing landfill leachate migration potential of a semi-arid duplex soil

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ABSTRACT

Leachate migration from open landfills is an environmental concern of developing cities. This study investigated the base soil-profile pedo-physical and chemical properties of the South African Sepane soil form or referred to as Cutanic Luvisol at the Bloemfontein southern landfill under the Mangaung municipality in the Free State Province. Six soil-profiles pedo-physical, exchangeable-cations and heavy metals concentrations were characterized from *in-situ*, core and loose soil-samples. The DTPA Test from a 5g air-dried soil extracted heavy metals. The soil profile was characterized by a layered Orthic-A, pedocutanic B- and C-horizons with lower horizons containing mean-total clay of 72%, bulk-density (≥ 1.5 gcm^{-3}) and saturated hydraulic-conductivity (Ks < 6mmhr^{-1}). Mean soil pH increased with depth from 6.4 to 6.8 along-side exchangeable-cations ranging from 19 to 2573 mgkg^{-1} in the order Ca > Mg > K > Na > S > P and Ca > Mg > Na > K > S > P for the respective A- and B-horizons. The Mg/K and (Ca + Mg)/K exceeded norm ratios. Soil-profile horizons had respective 44%, 34% and 22% heavy-metal distribution with mean content range of 0.001–37.3 mgkg^{-1} in the order Mn > Fe > Cr > Zn > Cu > As > Pb > Ni > Cd and Fe > Mn > Cr > Cu > As > Pb > Zn > Ni > Cd for the surface and subsurface horizons, respectively. Heavy-metal mean concentrations were below the norm except for *Cr* that was higher than 150% from upper horizons and posed serious risk to the near-surface environment. Soil profiles heavy-metal content and pollution-index was unpolluted (0.3–0.4), decreased with depth and reflected no subsurface pollution concerns. This study findings highlighted low internal-migration potential of clay soils and the need for understanding the sources and mode of migration of *Cr* at the landfill alongside continued monitoring.

1. Introduction

Municipal landfills lacking engineered hydraulic barriers or protective soil liners to contain leachate are a cause for concern to widespread pollution of the environment in most developing cities. Waste disposal occurs directly on the soil surface and by-products of decomposed waste are subject to leaching by rainwater accumulating below the landfill and eventually migrating into the soil profile, surface water and shallow groundwater table (Jegede et al., 2011; Shaikh et al., 2012; Donevska et al., 2013; Yazdani et al., 2015).

In the absence of leachate containment structures, the migration of leachate is highly dependent on the base soil profile physical and chemical properties controlling the movement and storage of water and solutes. Soil physical properties of particular important are the horizon layering sequence, depth, structure, texture and bulk density which in turn affect soil profile hydrology and hydraulic characteristics such as

permeability, saturated hydraulic conductivity (Ks), volumetric water content and field capacity also referred as drained upper limit (DUL) (Jegede et al., 2011; Mavimbela and van Rensburg, 2015; Mengistu et al., 2018). Soil chemical properties influencing the solute transport processes include pH, adsorption and ionic exchange which in turn are controlled by the type and amount of colloids (clay and humus) (Liaghati et al., 2003; Beukers, 2007; Rodríguez-Eugenio et al., 2018). Clays (<0.002 mm) are usually abundant under semi-arid conditions and has a major influence on soil-water and solute transport properties (Nelson et al., 2009; Wuana and Okieimen, 2011; Mana et al., 2017; Masindi and Muedi, 2018).

In the Free State, province of South Africa clay or duplex soil types constitute more than 10% of the provincial landscape (Hensley et al., 2006). These soil types contains clay content higher than 35% (USDA-NRCS, 2000; Hillel, 2004) and have been intensively studied under dryland agricultural land use and observed to be unsuitable for

field crop production especially under conventional systems (Hensley et al., 2000; Botha et al., 2012). Massive structure with swelling and shrinking properties and low permeability resulting to prolific runoff generation and water erosion were among the reasons (Hensley et al., 2006; Mzezewa and van Rensburg, 2011; Bothma et al., 2012; Mavimbela and van Rensburg, 2017). In landfill-waste management, clay soils and processed clay barrier lines are highly regarded for the lower Ks (Kutilek and Nielsen, 1994) essential for restricting leachate movement towards groundwater sources (Henry and Heinke, 2005; Jegede et al., 2011; Essien, 2013; Frikha et al., 2017). Although clays inhibit leachate migration, leachate can escape containment by moving along soil profile impervious layers and desiccated cracks (Jegede et al., 2011). This phenomenon of preferential flow adds to the complexity of leachate migration in soils (Liaghati et al., 2003; Beukers, 2007) and often raises concern about the effectiveness of landfilling clay soils in-situ. Low and erratic rainfalls and prolonged dry season of semi-arid areas favours the formation of soils with strong duplex and expansive characteristics (Hensley et al., 2006) and highly concentrated leachate plumes (Jegede et al., 2011). These attributes carries the potential to undermine the impervious nature of clays by giving rise to preferential flow that dramatically increase leachate migration (Jegede et al., 2011; Zgłobicki et al., 2018).

In this study, the investigation was about the leachate migration potential of duplex soil profiles found in an open landfill under the Mangaung metropolitan municipality (MMM) in the central Free State province of South Africa. The hypothesis was that the landfill solid waste is the source of leachate contamination of the underlying soil profiles. The objectives were firstly, to determine the soil profiles pedo-physical and chemical characteristics; secondly, to characterise the soil profiles exchangeable cations and heavy metals and thirdly, to determine the soil profiles heavy metal pollution index.

2. Materials and methods

2.1. Site description

The solid waste landfill is located 10 km south central business district (CBD) of the MMM in Bloemfontein city also serving as the Free State provincial capital, and is situated between latitude 29*10′ 824″S and 29* 11′ 217″S and longitude 26*11′464″E and 26*11′ 924″E. The southern solid waste landfill (SSWL) has been in operation since 1993 (MMM, 2016) has a fenced surface area of 44 ha and lies within altitude of 1406 m and 1428 m. The landfill receives waste from the main CBD and surrounding suburbs, institutions and shopping centres. Disposed waste is, directly on the soil surface, levelled, compacted and covered with daily and intermediate cover soil liners to prevent rainfall infiltration and leachate production (Government Gazette, 2012). The landfill has a gentle west aspect slope bordered by the Johannesburg-Cape Town N1 highway and railway line. Vegetation was predominantly of dryland grasses and provided sparse and dense ground cover for high and low areas, respectively (Fig. 1). The lower end of the dumpsite has a 3 m high ridge which serve to prevent surface runoff or overland flow leaving the
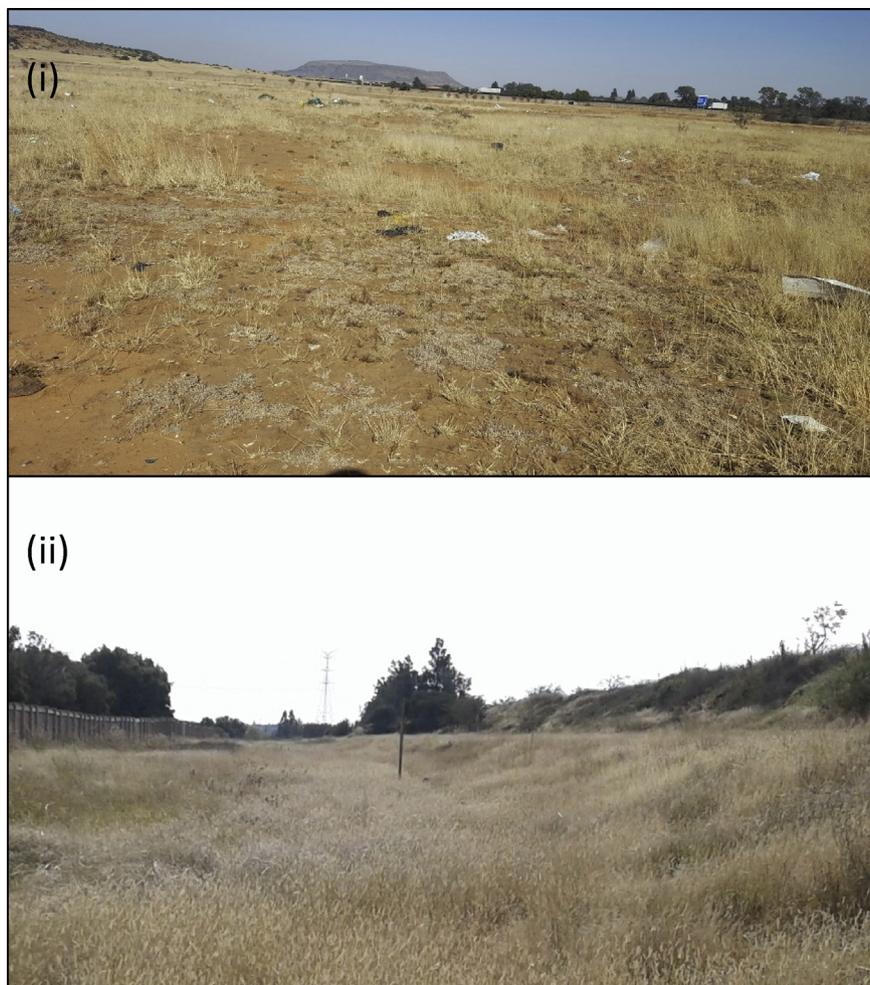

Fig. 1. Representative area with natural vegetation of excavated soil profiles 1 to 4 (i) and 5 to 6 (ii) at the Bloemfontein southern solid-waste landfill site.

landfill site. Mean monthly temperatures and rainfall patterns of the area's for the recent past decade is presented in Table 1 and showed the coldest and hottest months to be July and January, respectively, The effective rainfall season is from November to March.

2.2. Soil profile classification and sampling

Six soil-profile pits (Fig. 2) opened at various stations around the landfill were prepared and classified according to the Soil Classification Working Group (1991). Loose and undisturbed core soil samples were taken from soil profiles diagnostic horizons for physical and chemical analysis. The core sampler had an inner diameter of 105 mm and length of 77 mm.

2.3. Soil physical analysis

The Non-Affiliated Soil Analysis Work Committee (NASAWC) (1990) procedures were used in the analysis of particle size distribution (Pipette method), soil water contents and bulk density. Loose soil samples were air-dried, crushed and sieved using a 2 mm mesh to separate gravel and foreign material. The sand, silt and clay particle-size distribution were separated according to the order 2 to 0.05 mm, 0.05 to 0.002 mm and less than 0.002 mm, respectively. For the determination of gravimetric soil water content, soil samples were oven dried at 105 °C for a period of 24 h. The hanging water-column method was used to determine saturated hydraulic conductivity (Ks) and drained upper limit (DUL) of de-aired and pre-saturated core soil samples (Chimungu, 2009).

2.4. Soil chemical analysis

Soil pH (1:2.5 soil water suspension), S and P as well as exchangeable basic cations (Ca, Mg, K and Na) of soil profiles diagnostic horizons was determined using the standard method (NASAWC, 1990). The DTPA soil test (Lindsay and Norvell, 1978) determined heavy metals composition on 0.5 g subsamples including Cd, Cr, Cu, Fe, Pb, Zn, Ni, and Mn. The extractant consisted of 0.005MDTPA (diethylene triamine penta acetic acid), 0.1M triethanolamine, and 0.01M CaCl₂, with a pH of 7.3. The soil test constituted of shaking 5 g of air-dry soil with 20 ml of extractant for 2 h.

2.5. Statistical analysis

Soil profile physical and chemical properties constituted the major findings. Descriptive statistics including mean, standard deviation, maximum, median, and minimum values were determined. Ratios denoting heavy metal pollution index (PI) (Lee et al., 1998) of soil profiles and respective horizons was computed from detected concentrations and permissible screening norm values (South Africa Government Gazette, 2012). The PI ratio is given by the expression:

$$PI = \frac{1}{n}\left(\frac{M_1}{TL_1} + \frac{M_2}{TL_2} + \dots \frac{M_n}{TL_n} \right) \quad (1)$$

Where M_1, M_2 … M_n are the studied polluting heavy metal concentrations; TL_1, TL_2 … TL_n are the corresponding heavy metal permissible screening norm values; n is the total number of metals. Heavy metal PI for the A- (y_1), B- (y_2) and C- (y_3) horizons SP horizons were correlated (r) to

soil pH (x_1), clay% (x_2) and bulk density (x_3) (gcm^3) using the linear correlation coefficient (r) and is given by the expression (Gomez and Gomez, 1984):

$$r = \frac{\sum xy}{\sqrt{(\sum x^2)(\sum y^2)}} \quad (2)$$

Where $\sum xy$ represents the corrected sum of cross products of ith pair of X, the independent variable, and Y, dependent values; $\sum x^2$ and $\sum y^2$ corrected sum of squares for the respective independent and dependent variables.

3. Results and discussion

3.1. Soil-profile pedological characteristics

Fig. 2 showed a representative soil profile of the South African Sepane soil-form belonging to the group D or Duplex land type (Soil Classification Working Group, 1991) also referred to as Cutanic Luvisols (World Reference Base for Soil Resources, 1998) excavated at the Bloemfontein Southern landfill. A total of six soil profile were studied as shown in Fig. 3 and had a characteristic orthic-A, pedocutanic-B and unconsolidated material with signs of wetness in the underlying C-horizon. The surface and sub-surface horizons had a respective weak apedal and moderate to strong sub-angular blocky structure with a clear transition illustrated by the corresponding light to dark brown pigments. The abrupt structural differences between the A- and B-horizons give rise to structural instability and inconsistency responsible for the formation of soil surface cracks illustrated in Fig. 2 (i) and (ii) during the dry period. These surface cracks can be as deep as 1 m (Hillel, 2004) and serve as preferential pathways for leachate into deeper layers of the soil profile (Jegede et al., 2011). However, these cracks close rapidly during rainfalls on expansive clay soils, an attribute that the local duplex soils inherited from the Karoo parent rock and red beds perforating the semi-arid areas of the province (Hensley et al., 2006). The low annual rainfall of about 450 mm and six months dry period shown in Table 1 implied that the soil profile cracks remain open for a significant period for leachate and waste materials to slough off into the cracks resulting to soil contamination as illustrated by SP2 in Fig. 3. This observation highlighted the concerns about open landfills and their impact on soil profile quality (Oostindie and Bronswijk, 1995; Zgłobicki et al., 2018).

Apart from having a common diffused transition the soil profiles lower horizons had noticeable hydro-pedological differences. According to Fig. 3 the C-horizon from SP1, SP2 and SP3 were chromic and calcic while from SP4, SP5 and SP6 were chromic and alcaic suggesting the latter had a higher water regime compared to the former. This analogy corroborate with the low elevation position of SP4, SP5 and SP6 shown in Fig. 1. Sediment deposit from surface runoff collecting in this area is responsible for the development of the overburden layer observed from SP5 and SP6 that confirmed that duplex soil were sensitive to water erosion (Mzezewa and van Rensburg, 2011). The C-horizon had a single grain to strong massive structure with yellow brown to grey pigment and common black to grey mottles. Mottling and greyic pigments formation implicated iron oxide reduction processes occurring under waterlogged conditions (Hensley et al., 2006). On the contrary, the light brown to pinkish white pigments observed from the lower horizons of SP1, SP2 and SP3 illustrated the presence of precipitated calcium carbonate and

Table 1
Bloemfontein mean monthly temperatures and rainfall patterns from 2004 to 2015.

Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max Temp (°C)	30.5	26.4	27.3	23.3	20.8	17.3	17.8	20.5	24.9	27.0	28.6	30.1
Min Temp (°C)	17.0	13.2	12.2	8.6	4.5	0.9	0.0	3.2	6.5	9.5	12.7	15.1
Rainfall (mm)	57.7	64.1	62.4	20.7	13.9	15.9	3.6	9.0	9.0	38.4	84.2	69.9
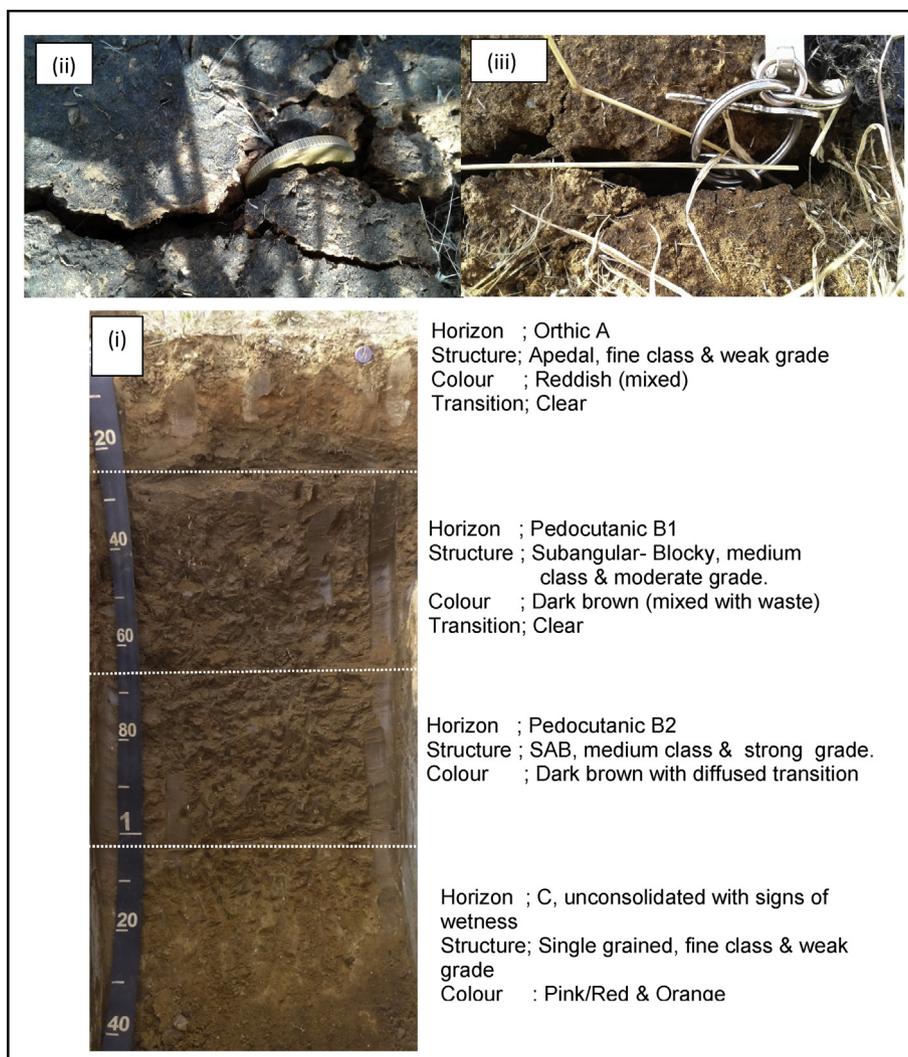
Fig. 2. Representative the Sepane soil-profile horizons (i) showing surface cracks with (ii) and without (iii) a pigmented leachate crust.

Fig. 3. Soil profiles showing the overburden (O), A-, B- and C- diagnostic horizons from the Bloemfontein southern landfill.

was indicative of a dry water regime and basic soil pH (Mavimbela and van Rensburg, 2017). Due to the impervious sub angular blocky structure of the pedocutanic B-horizon the underlying C-horizon remained dry even during rainfalls because of low infiltrability (Bothma et al., 2012) and hence, it developed a weak to moderate single grain structure.

3.2. Soil-profiles physical characteristics

Soil profiles physical properties were presented in Table 2. Four of the six profiles had clay content greater than 45% and were associated with the pedocunatic B- horizon of textural class ranging from clay to sandy

clay loam at depths of 20–80 cm. The low-lying SP6 had clay content of 53% and 46% for the respective A- and B-horizons with sand fraction not more than 45% in all its horizons. Soil horizons with clay content of at least 35% and in most cases not less than 40% belonged to the clay textural class because the clay content was significant to control physical and chemical properties. Due to the small size (<0.002 mm) of clay minerals, clay textured soils stick together forming an impervious soil matrix of various massive structures such as platy, prismatic and blocky structure. The latter corresponded to the sub-angular blocky structure of the Sepane pedocutanic B-horizons, with bulk density and Ks ranging from 1.38 to 1.54 g/cm^3 and 2.6 to 15,3 mm h^{-1}, respectively. Clayey soils usually have Ks lower than 0.04 mm h^{-1} (Kutilek and Nielsen, 1994). The higher Ks range suggested the Sepane pedocutanic B-horizon had a typical sandy clay to sandy loam texture an analysis that corroborated with the 47% average sand fraction (USDA-NRCS, 2000).

The orthic A-surface horizon had more variable clay content of 17–53%, bulk density of 1.15–1.54 g/cm^3 and Ks of 2.2–25 mm h^{-1}. On average, the surface horizon had clay and sand fraction of 30% and 57%, respectively. Apart from the SP6 with a clay texture, the soil profiles surface horizons had textural class ranging from sandy clay loam to sandy loam (USDA-NRCS, 2000). According Kutilek and Nielsen (1994), these textural classes have low to medium Ks of 3.6–36 mm h^{-1}, a range that described the infiltration capacity of the studied Sepane soil profile horizons. This result, therefore, implies that direct dumping of solid waste at the soil surface will have low to medium impact on the contamination of subsurface soil horizons. The 53% clay content, highest observed in this study, at the SP6 surface horizon was attributed to the deposition of sediments transported by surface runoff which collect at the lowest elevation where the profile was located. The surface overburden layer highlighted in SP6 was evident of sedimentation occurring in this area.

Increasing clay content in the subsurface horizon was coupled with densification which, increased bulk density of the underlying C-horizon ranging from 1.41 to 1.62 g/cm^3. This increase in bulk density with depth gave the Sepane soil-profile poor internal drainage properties characterised by DUL from 30 to 36 mm mm^{-1} for the C-horizon. Mavimbela and van Rensburg (2012) observed similar results on the Sepane soil-form. Poor internal drainage implied that leachate contamination of shallow groundwater table and aquifers leachate would be minimal. However, this function could have increased with elevation because the high elevated, soil profiles SP1, SP2 and SP3 had an average clay-content and bulk-density range 1.4–1.43 g/cm^3 for the low elevated SP4, SP5 and SP6. Clay minerals due to their low Ks (<0.04 mm h^{-1}) and internal

drainage (Kutilek and Nielsen, 1994) are increasingly used as barrier liners for containing leachate in sanitary landfills (Henry and Heinke, 2005; Frikha et al., 2017).

3.3. Soil-profile chemical characteristics

Tables 3, 4, and 5 presented soil pH, basic exchangeable cations (Ca, Mg, P, S, Na and K) and heavy metals (As, Cd, Cu, Cr, Fe, Pb, Mn, Ni and Zn) concentrations as well as the South African screening norm values (Government Gazette, 2012) and calculated pollution index for the respective soil profile horizons. Vertical soil profile distribution of exchangeable cations and heavy metals are illustrated in Fig. 4 (i) and (ii), respectively. The overall soil profile heavy metal distribution showed a decrease with depth (Figure S1 and S2) in contrast to exchangeable cations.

3.3.1. Soil pH and exchangeable cations

Mean soil pH for the Sepane soil profiles was 6.4, 6.5 and 6.8 for the respective orthic A-, pedocutanic B- and C- horizons. Observed soil pH range was approximately 6.0–7.4 and corresponded with the pH range 6–8 that favoured high degree of saturation of the exchange site with base forming cations (Hillel, 2004). Several of soil studies from solid waste landfills found similar soil pH range (Shaikh et al., 2012; Ogbonna et al., 2009). The increase in soil pH with depth was therefore not surprising given that it corroborated with the enrichment of basic forming exchangeable cations with a mean range of 24–2573 mgkg^{-1} in the order of abundance followed the trend $Ca > Mg > K > Na > S > P$ and $Ca > Mg > Na > K > S > P$ for the respective surface and subsurface horizons. Ololade et al. (2019) observed similar trends for soil profile horizons of sandy clay loam texture with mean pH of 6.6 from the drainage pathways of the Bloemfontein northern landfill. Higher Mg/K and $(Ca + Mg)/K$ mean ratios above the norm for all horizons confirmed the high enrichment of Ca and Mg associated with landfill contaminated soils (Shaikh et al., 2012). Decomposition of landfill waste is associated with the release of substantial quantities of organic matter and exchangeable cations and anions (Shaikh et al., 2012). Increased concentration of the major elements with depth corroborated with the abundance of clay content in the lower horizons amounting to approximately 72% of the soil profile total average clay content. This association was not surprising given that exchangeable cations like Ca dominate semi-arid soil colloidal complexes (Hillel, 2004) and was responsible for the basic pH of the lower horizons.

Table 2
Summary of soil profile physical and hydraulic properties.

Soil Profile	Horizons	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/cm3)	Qr [-]	Qs [-]	Ks (mm/hr)	DUL (mm)
1	A	17.10	10.55	72.35	1.44	0.12	0.46	8.3	0.25
	B1	46.57	8.75	44.68	1.49	0.14	0.44	15.3	0.29
	B2	45.69	12.50	41.81	1.49	0.14	0.44	15.3	0.29
	C	36.01	25.55	38.44	1.56	0.16	0.41	0.4	0.36
2	A	23.74	17.60	58.66	1.54	0.19	0.42	2.2	0.27
	B1	34.53	13.80	51.67	1.38	0.22	0.48	4.8	0.31
	B2	46.36	8.25	45.39	1.48	0.22	0.48	4.8	0.29
	C	31.77	13.35	54.88	1.62	0.20	0.39	2.6	0.31
3	A	36.75	7.90	55.35	1.34	0.11	0.5	25.0	0.24
	B1	36.14	12.20	51.66	1.54	0.20	0.42	3.1	0.30
	C	34.88	19.10	46.02	1.41	0.11	0.47	5.2	0.34
4	A	26.68	12.55	60.77	1.38	0.09	0.45	18.2	0.24
	B1	45.10	9.85	45.05	1.48	0.12	0.46	5.2	0.29
	B2	25.86	21.45	52.69	1.44	0.12	0.46	9.2	0.24
5	A	23.74	19.26	57	1.11	0.11	0.23	22.0	0.27
	B	38.00	11.00	51	1.49	0.12	0.24	3.2	0.31
	C	34.53	26.47	39	1.59	0.13	0.25	6.4	0.31
6	A	53.32	7.40	39.29	1.15	0.18	0.57	11.1	0.32
	B	46.37	8.90	44.73	1.51	0.22	0.43	2.6	0.33
	C	40.87	16.20	42.93	1.61	0.19	0.39	4.2	0.30

Qr: residual water content, Qs: saturated water content, Ks: saturated water content, DUL: drained upper limit.

Table 3
Chemical properties of soil profiles (SP) surface 'Orthic' A-horizon.

Elements (mgkg^{-1})	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6	Min	Max	Mean	STD	Norm
pH (KCl)	5.83	7.44	5.52	6.57	6.53	6.51	5.52	7.44	6.4	0.3	-
Ca	1175.4	1166.1	1289	1060.4	2295.8	3924.9	1060	3924.9	1818.5	504.36	-
Mg	291.68	310.05	478.6	223.62	551.3	659.65	224	659.65	419.16	76.22	-
Na	63.31	69.95	76.01	35.84	79.46	72.52	35.8	79.46	66.18	7.09	-
K	154.2	119.09	137.7	131.03	275.04	456.35	131	456.35	212.23	59.24	-
S	20.82	26.49	34.83	21.79	59.07	65.09	20.8	65.09	38.02	8.67	-
P	22.2	20.6	20.6	22.2	26.8	30.6	20.6	30.6	23.83	1.8	-
Ca:Mg	2.46	2.29	1.64	2.89	2.54	3.63	1.64	3.63	2.58	0.3	1.5–4.5
Mg:K	**6.06**	**8.34**	**11.14**	**5.47**	**6.42**	**4.63**	**4.63**	**11.14**	**7.01**	1.06	3–4
(Ca + Mg)/K	**20.96**	**27.49**	**29.44**	**21.29**	**22.74**	**21.45**	**21**	**29.44**	**23.9**	1.63	10–20
Ni	1.65	0.56	1.91	1.18	2.42	1,32	0.56	2.42	1.51	0.29	91
As	1.86	3.81	3.06	4.18	5.09	4.87	1.86	5.09	3.81	0.54	5.8
Cu	3.12	1.38	1.45	0.79	0.44	8.76	0.44	8.76	2.66	1.4	16
Mn	57.22	14	21.2	15.04	18.72	23.2	14	57.22	24.9	7.25	740
Fe	41.56	6.64	50.6	29.50	48.56	46.72	6.64	50.6	37.26	7.51	-
Zn	2.28	1.14	0.5	1.12	2.56	5.32	0.5	5.32	2.15	0.78	240
Cr	**12,15**	**10.46**	**17.85**	**12.66**	**16.12**	**12.94**	**10.5**	**17.85**	**13,7**	1.23	6.5
Cd	0.1	0.01	0.01	0.01	0.02	0,04	0.01	0.10	0.03	0.02	7.5
Pb	1.66	2.32	1.88	2.58	2.06	3.36	1.66	3.36	2.31	0.27	20
Pollution index (PI)	0.32	0.31	0.44	0.36	0.44	0.45	0.31	0.45	0.39	0.03	-

PI < 1: unpolluted, PI > 1: polluted, bolded: concentration above norm.

Table 4
Chemical properties of soil profiles (SP) pedocutanic B-horizon.

Elements (mgkg^{-1})	SP 1	SP 2	SP 3	SP 4	SP 5	SP 6	Min	Max	Mean	STD	Norm
pH (KCl)	6.06	7.15	5.98	6.15	6.68	7.21	5.98	7.21	6.54	0.25	-
Ca	2304.7	3640.6	1420	1337.1	2040.3	3871.6	1337	3871.6	2435.8	486.83	-
Mg	910.09	900.81	641.9	613.92	474.05	744.39	614	910.09	714.2	76.7	-
Na	151.77	323.74	188.5	190.42	60.04	116.09	60	323.74	171.75	39.85	-
K	143.51	155.79	124.8	144.15	253.47	219.15	144	253.47	173.48	22.74	-
S	116.02	115.44	34.79	44.25	45.75	72.34	34.8	116.02	71.43	16.33	-
P	17	19	18.6	17.7	21.3	19	17	21.3	18.77	0.66	-
Ca:Mg	1.545	2.45	1.38	1.53	2.42	3.17	1.38	3.17	2.08	0.32	1.5–4.5
Mg:K	**20.23**	**18.89**	**15.76**	**13.64**	**6.31**	**10.89**	**6.31**	**20.23**	**14.29**	2.32	3–4
(Ca + Mg)/K	**51.5**	**65.69**	**37.41**	**34.42**	**21.22**	**45.42**	**21.2**	**65.69**	**42.61**	6.84	10–20
Ni	1.47	2.05	1.55	1.2	1.78	1.09	1.09	2.05	1.52	0.16	91
As	2.49	3.95	4.36	4.19	4.92	5.08	2.49	5.08	4.16	0.42	5.8
Cu	2.72	3.12	0.99	0.57	1.25	5.08	0.57	5.08	2.29	0.76	16
Mn	18.61	24.87	15	16.31	21.09	9.1	9.1	24.87	17.5	2.42	740
Fe	20.55	34.63	17.2	35.46	37.53	23.5	17.2	37.53	28.14	3.91	NA
Zn	0.58	2.15	0.44	0.51	2.11	0.72	0.44	2.15	1.09	0.36	240
Cr	**7.6**	**7.79**	**12.62**	**8.65**	**13.05**	**11.42**	**7.6**	**13.05**	**10.19**	1.1	6.5
Cd	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.003	7.5
Pb	1.72	2.79	1.62	1.85	2.09	2.93	1.62	2.93	2.17	0.25	20
Pollution index (PI)	**0.24**	0.29	0.36	0.28	0.39	**0.39**	0.24	0.39	0.32	003	-

PI < 1 = unpolluted; PI > 1 = polluted; bolded = concentrations above norm.

3.3.2. Heavy metals

Heavy metals concentration except for *As* decreased with soil profile depth and was indicative of a negative association with high soil pH and clay content. Fig. 4 showed mean total heavy metal concentration of 44%, 34% and 22% for the A-, B- and C-horizons, respectively. The decline in heavy metal concentrations with depth and increasing clay content illustrated the low *Ks* and complex chemical reactions associated with clay colloidal properties influencing the state and fate of heavy metals (Liaghati et al., 2003; Beukers, 2007). The mean concentration of heavy metals ranged from 0.001 to 37.3 mgkg-1 in order of abundance followed the trend *Mn > Fe > Cr > Zn > Cu > As > Pb > Ni > Cd* for the surface horizon and *Fe > Mn > Cr > Cu > As > Pb > Zn > Ni > Cd* for the B-horizon. The C-horizon had a similar trend to the B-horizon with the difference being the exchange of positions between *Ni* and *Zn*. Heavy metals mean concentrations except *Cr* were lower than the South African norm threshold values suggesting that the soil profiles heavy metal contamination was below pollution levels. Heavy metals usually exist in the form of hydroxides, oxides, sulphides, sulphates, phosphates, silicates and organic compounds (Masindi and Muedi, 2018). For an acidic soil pH range, heavy metals are usually adsorbed and saturate the exchange site

at the expanse of exchangeable cations being released and leached (Hillel, 2004); a phenomenon attributed to the higher heavy metal concentration observed from the upper horizon with mean pH around 6.5. Decreasing heavy metal concentrations with depth was inversely related to the higher soil pH (>6.5) which corroborated with the sentiment that higher soil pH enhanced dissolution of heavy metals due to the formation of hydroxides (Wuana and Okieimen, 2011). In general, the low heavy metals concentration was indicative of the fact that the southern landfill was primarily a dumping site for municipal, domestic and institutional waste not industrial material (MMM, 2016). Similar findings were observed from the Municipal Bloemfontein Northern solid waste-landfills (Ololade et al., 2019).

Chromium concentration, over and above the 6.5 mg/kg norm, had soil profile mean values of 13.7, 10.2 and 7.2 mgkg-1 for the respective A-, B- and C- horizons. These high levels were a serious concern to the environment given that *Cr* was highly toxic to humans and animals even in minor quantities (Masindi and Muedi, 2018). Once it enters the food chain, *Cr* can cause damage to vital life-supporting tissues and organs including skin, kidneys, and brain as well as the respiratory, reproductive and digestive systems (Wuana and Okieimen, 2011; Masindi and Muedi,

Table 5

Chemical properties of soil profiles (SP) underlying C-horizon.

Elements (mgkg-1)	SP 1	SP 2	SP 3	SP 4	SP5	SP 6	Min	Max	Mean	STD	Norm
pH (KCl)	7.2	7.27	6.59	6.55	6.02	7.21	6.02	7.27	6.81	0,22	-
Ca	4539	3119	1617	1614	1448	3101	1448	4539	2573	549.11	-
Mg	892.24	876.2	704.6	670.94	578.72	978.97	579	978.97	783.61	69.13	-
Na	189.24	315.31	269.4	248.75	63.57	233.38	63.6	315.31	219.95	38.96	-
K	124.72	146.14	150.2	146.33	221.54	176.23	125	221.54	160.86	15.19	-
S	189.24	125.98	56.22	50.5	25.87	97.98	25.9	189.24	90.97	26.84	-
P	17.8	19.4	18.6	17.4	19	33	17.4	33	20.87	2.68	-
Ca:Mg	3.1	2.17	1.4	1.47	1.53	1.93	1.4	3,1	1,93	0,29	1.5–4.5
Mg:K	**22.93**	**19.22**	**15.03**	**14.7**	**8.37**	**17.8**	**8.37**	**22,93**	**16,34**	2,21	3–4.0
(Ca + Mg)/K	**94.06**	**60.94**	**36.08**	**36.26**	**21.15**	**52.2**	**21.2**	**94,06**	**50,12**	11,46	10–20
Ni	0.62	0.82	0.43	0.55	0.89	0.42	0.42	0.89	0.62	0.09	91
As	3.12	3.93	4.33	4.17	4.58	4.96	3.12	4.96	4.18	0.28	5.8
Cu	1.80	0.19	0.99	0.29	1.09	4.96	0.19	4.96	1.55	0.79	16
Mn	13.24	14.24	8.89	9.42	26.78	9.85	8.89	26.78	13.74	3.02	740
Fe	7.17	8.38	7.16	5.71	43.28	13.49	5.71	43.28	14.2	6.48	-
Zn	0.5	0.26	0.38	0.56	0.52	0.52	0.26	0.56	0.46	0.05	240
Cr	0.85	3.69	**10.93**	**6.62**	**12.51**	**8.31**	0.85	**12.51**	**7.15**	1.96	6.5
Cd	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	7.5
Pb	2.20	1.84	2.02	1.71	1.86	2.38	1,71	2.38	2.0	0.11	20
Pollution index (PI)	**0.11**	0.17	0.33	0.23	**0.37**	0.32	0.11	0.37	0.26	0.04	

PI < 1 = unpolluted; PI > 1 = polluted; bolded = concentrations above norm.
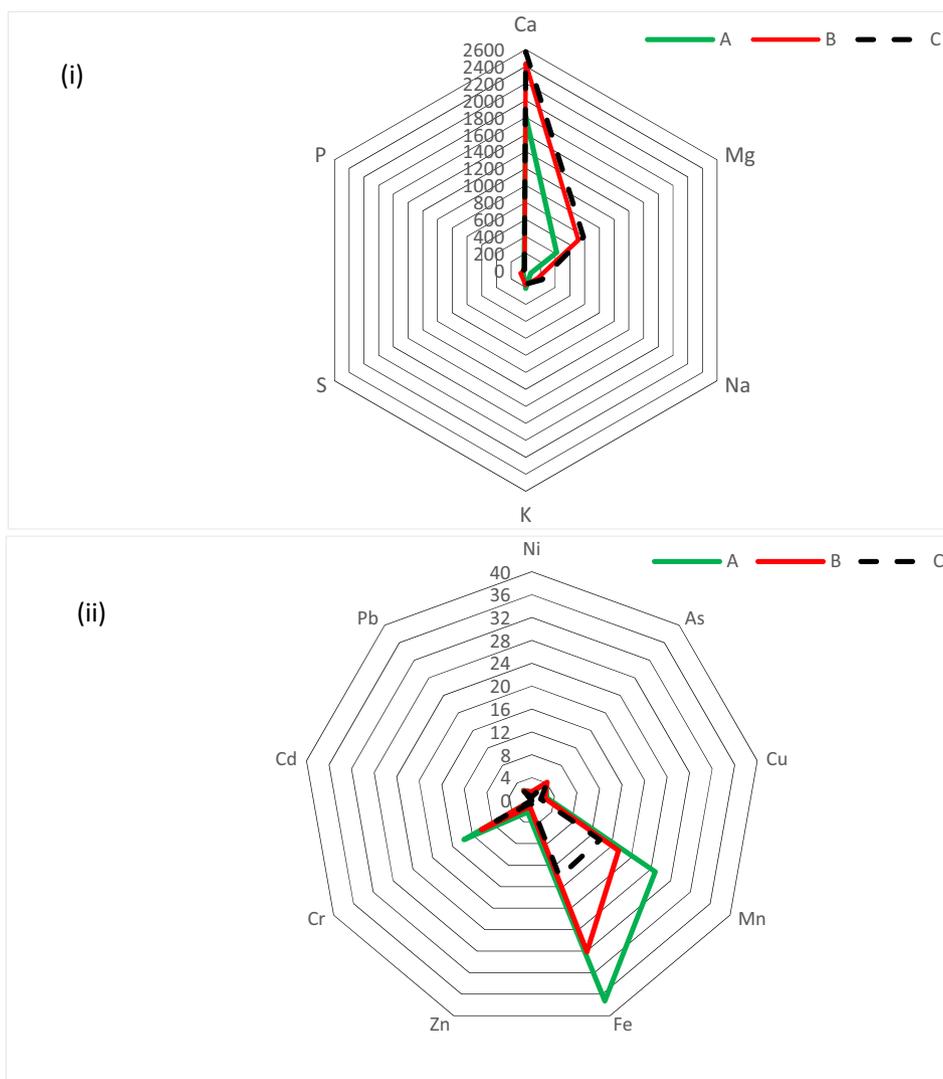

Fig. 4. Soil profile horizons mean (i) exchangeable cations and (ii) heavy metal concentration distribution.

2018). Chromium enrichment levels was generally higher than the norm from the upper A-and B- horizons from all soil profiles and from the C-horizon for the low-lying SP3, SP4, SP5 and SP6. Lower mean *Cr* concentration were from SP1 and SP2 occupying landfill high elevation positions. The high *Cr* levels from the low-lying soil profiles suggested the landfill as a possible source of contamination and surface runoff being the likelihood to be the primal mode of migration through sediment transport. Various work has pointed out that migration of *Cr* from contaminated sites was via transportation of surface-water runoff sediments (Smith et al., 1995; Wuana and Okieimen, 2011). The surface horizons *Ks* mean range of 2–25 mmhr^{-1} justified the sentiment earlier in this study that the Sepane soil form was of low permeability with high runoff generative potential attributed to the higher downslope enrichment of *Cr* in particular.

3.3.3. Pollution index

Pollution index (*PI*) were computed from the combined concentration contributions of all measured heavy metals for the respective soil profile horizons with the exception of *Fe* because its South African norm limits was not available. Computed *PI* did not exceed 0.5 (Tables 3, 4, and 5) from all soil profiles horizons illustrating that the combined heavy metal concentrations were below the pollution levels. However, the higher *PI* range (0.31–0.45) observed from surface horizons reflected the soil surface as the first point of entry or contamination. The general increase in *PI* with downslope soil profiles point out to gravitational influence involved in the migration of heavy metals especially by surface runoff due to low permeability ($Ks \leq 25$ mm h^{-1}) of the Sepane soil form. The unpolluted level of *PI* supported the notion that the waste disposed at the landfill was of low heavy metal content (Ololade et al., 2019). In addition, to the low heavy metal content of the waste disposed at the landfill the low *PI* corroborated with the long-term low annual average rainfall (Table 1; 449 mm) which was suggestive of seldom occurrence of surface runoff or overland flow. However, ongoing climatic variability and global warming can bring atmospheric conditions that exacerbate high intensity rainfalls and proliferation of surface runoff and water erosion in landfills resulting to downslope migration of soluble and particulate contaminants.

4. Conclusion

This study investigated the leachate migration potential of six soil-profiles of a duplex soil-form underlying the Bloemfontein southern landfill. The soil profile was characterised by an orthic A-, pedocutanic B- and C-horizon with corresponding clay content of 30%, 42% and 34%, bulk density of 1.33, 1.49 and 1.54 gcm^{-3}, and saturated hydraulic conductivity of 14.5, 5.7 and 4.7 mmhr^{-1}, respectively. The lower horizons higher clay and bulk density was indicative of the soil profiles moderate to strong duplex properties. This was evident from the abrupt changes in chemical properties between the surface and lower horizons with the latter having double the amount of exchangeable cations compared to the surface horizons. The opposite was true for the heavy metal concentration that had a corresponding soil-profile horizon distribution of 44%, 32% and 22%. This distribution was reflective of the underlying soil-profile low internal leachate migration potential. Findings from the analysis of heavy-metal concentrations and pollution index showed no pollution concerns except for *Cr* that was 150% over and above the 6.5mgkg^{-1} norm from the upper soil profile horizons. This was a cause for concern given the *Cr* high toxicity to humans and animals, and therefore understanding *Cr* sources and mode of migration alongside continued monitoring was proposed.

Declarations

Author contribution statement

Sabelo Wesley Mavimbela: Conceived and designed the experiments;

Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Olusola O Ololade: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Johan J Van Tol: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Makhosazana P Aghoghovwia: Analyzed and interpreted the data; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Additional information

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References

Beukers, J., 2007. Fixation of Cadmium, Copper, Nickel, and Zinc in Soil; Kinetics, Mechanisms and its Effect on Metal Bioavailability. Ph.D. thesis.

Botha, J.J., Van Rensburg, L.D., Anderson, J.J., Van Staden, P.P., Hensley, M., 2012. Improving maize production of in-field rainwater harvesting technique at Glen in South Africa by addition of mulching practices. Irrig. Drain. 61 (Suppl. 2), 50–58.

Bothma, C.B., Van Rensburg, L.D., Le Roux, P.A.L., 2012. Rainfall intensity and soil physical properties influence on infiltration and runoff under infield rainwater harvesting. Irrig. Drain. 88 (Suppl. 2), 41–49.

Chimungu, J.G., 2009. Comparison of Field and Laboratory Measured Hydraulic Properties of Selected Diagnostic Soil Horizons. MSc thesis. University of the Free State, South Africa, pp. 26–50.

Donevska, K., Jovanovski, J., Jovanovski, M., Pelivanoski, P., 2013. Analyses of environmental impacts of non-hazardous regional landfills in Macedonia. J. Sustain. Dev. Energy Water Environ. Syst. 1, 281–290.

Essien, O.E., 2013. Foundation soil's properties at old dumpsite under short-term restoration from effect of municipal solid waste disposal. Int. J. Eng. Res. Technol. 2 (2), 1–7.

Frikha, Y., Fellner, J., Zairi, M., 2017. Leachate generation from landfill in a semi-arid climate:A qualitative and quantitative study from Sousse, Tunisia. Waste Manag. Res. 00 (0), 1–9.

Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research. John Wiley and Sons, New York, pp. 100–120.

Government Gazette, 2012. Draft National Norms and Standards for the Remediation of Contaminated Land and Soil Quality (Notice No. 233, 2012). Government Gazette 35160:561, March 19 (Regulation Gazette No. 59, 2008). DEAT, Pretoria.

Henry, J.G., Heinke, G.W., 2005. Environmental Science and Engineering, second ed. Prentice Hall of India Pvt Ltd., New Delhi, pp. 567–618.

Hensley, M., Botha, J.J., Anderson, J.J., van Staden, P.P., Du Toit, A., 2000. Optimising Rainfall Use Efficiency for Developing Farmers with Limited Access to Irrigation Water. Research Commission Report No. 878/1/00. Pretoria, South Africa.

Hensley, M., Le Roux, P.A.L., du Preez, C.C., van Huyssteen, C., Kotze, E., Van Rensburg, L.D., 2006. Soils: the free state agricultural base. S. Afr. Geogr. J. 88, 11–21.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Academic Press, New York, pp. 100–200.

Jegede, S.I., Osazuwa, I.B., Ujuanbi, O., Chiemeke, C.C., 2011. 2D electrical imaging survey for situation assessment of leachate plume migration at two waste disposal sites in the Zaria basement complex. Adv. Appl. Sci. Res. 2 (6), 1–8.

Kutilek, M., Nielsen, D., 1994. Soil Hydrology. CATENA VERLAG, Cremlingen, p. 370.

Lee, J., Chon, H., Kim, K., 1998. Migration and dispersion of trace elements in the rock-soil plant system in areas underlain by black shales and slates of the Okchon zone. Korea. J. Geochem. Explor. 65 (1), 61–78.

Liaghati, T., Preda, M., Cox, M., 2003. Heavy metal distribution and controlling factors within coastal plain sediments, Bells Creek Catchment, Southeast Queensland, Australia. Environ. Int. 29, 935–948.

Lindsay, W.L., Norvell, W.A., 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Sc. Soc.of Am. J. 42 (3), 421–428.

Mana, S.C.A., Hanafiah, M.M., Chowdhury, A.J.K., 2017. Environmental characteristics of clay and clay-based minerals. Geo. Ecol. Landscapes 1 (3), 155–161.

Mangaung Metropolitan Municipality, 2016. Integrated Waste Management Plan: Review of Integrated Waste Management Plan; Final Report. Mangaung Metropolitan Municipality, Bloemfontein.

Masindi, V., Muedi, K.L., 2018. Environmental Contamination by Heavy Metals. Chapter 7. IntechOpen Access Books, pp. 1–133.

Mavimbela, S.S.W., Van Rensburg, L.D., 2012. Estimating hydraulic conductivity of internal drainage for layered soils in situ. Hydrol. Earth Syst. Sci. 17 (11), 4349–4366.

Mavimbela, S.S.W., Van Rensburg, L.D., 2015. In situ evaluation of internal drainage in duplex soils of the Tukulu, Sepane and Swartland forms. South Afr. J. Plant Soil (xx-xx), 1–12.

Mavimbela, S.S.W., Van Rensburg, L.D., 2017. Characterizing infiltration and internal drainage of South African dryland soils. Earth Surf. Landforms 42 (3), 414–425.

Mengistu, A., Mavimbela, S.S.W., Van Rensburg, L.D., 2018. Characterisation of the soil pore system in relation to its hydraulic functions in two South African aeolian soil groups. S. Afr. J. Plant Soil 1–10.

Mzezewa, J., Van Rensburg, L.D., 2011. Effects of tillage on runoff from bare clayey soil in a semi-arid ecotope in the Limpopo province of South Africa. Water S.A. 37 (2), 65–172.

Nelson, S.S., Yonge, D.R., Barber, M.E., 2009. Effects of road salts on heavy metal mobility in two eastern Washington soils. J. Environ. Eng. 135 (7), 505–510.

Non-Affiliated Soil Analysis Work Committee, 1990. Handbook of Standard Soil Testing Methods for Advisory Purposes. Soil Sc. Soc. of South Africa, Pretoria.

Ogbonna, D.N., Kii, B.L., Youdeowe, P.O., 2009. Some physico-chemical and heavy metal levels in soils of waste dumpsites in Port Harcourt Municipality and Environs. J. Appl. Sci. Environ. Manag. 13 (4), 65–70.

Ololade, O.O., Mavimbela, S.S.W., Hansen, R., Makhadi, R., 2019. Impact of leachate from northern landfill site in Bloemfontein on water and soil quality: implications for water and food security. Sustainability 11 (15), 1–19.

Oostindie, K., Bronswijk, J.J.B., 1995. Consequences of preferential flow in cracking clay soils for contamination-risk of shallow aquifers. J. Environ. Manag. 43, 359–373.

Rodríguez-Eugenio, N., McLaughlin, M., Pennock, D., 2018. Soil Pollution: a Hidden Reality. FAO, Rome, p. 142.

Shaikh, P.R., Bhosle, A.B., Yannawar, V.B., 2012. The impact of Landfill on soil and groundwater quality of the Nanded city, Maharashtra. Researcher 4 (7), 56–63.

Smith, L.A., Means, J.L., Chen, A., et al., 1995. Remedial Options for Metals-Contaminated Sites. Lewis Publishers, Boca Raton, Fla, USA.

Soil Classification Working Group, 1991. Soil Classification: a Taxonomic System for South Africa. Memoirs on the Agricultural Natural Resources of South Africa no 15. Department of Agricultural Development, Pretoria.

USDA-NRCS, 2000. Soil Texture Calculator. United States Department of Agriculture, National Resources and Conservation Service. www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167. (Accessed 21 May 2019).

World Reference Base for Soil Resources, 1998. World Soil Resources. FAO Report No 84. Food and Agricultural organisation, Rome.

Wuana, R.A., Okieimen, F.E., 2011. Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecol. 1–20.

Yazdani, M., Monavari, M., Omrani, G.A., Shariat, M., Hosseini, M., 2015. Municipal solid waste open dumping, implication for land degradation. Solid Earth Disc. 7, 1097–1118.

Zgłobicki, W., Telecka, M., Skupiński, S., Pasierbińska, A., Kozieł, M., 2018. Assessment of heavy metal contamination levels of street dust in the city of Lublin, E Poland. Environ. Earth Sc. 77 (774), 5–11.