Application of Electrical Resistivity and DRASTIC Models in the Study of Groundwater Contamination Risk in the Surroundings of the Hulene - B Waste Dump, Maputo, Mozambique

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Abstract

The contamination of groundwater by leachate migration around waste dumps is a growing challenge for maintaining the quality of water resources in urban centers. In this study the electrical resistivity method was applied, where six 400 m profiles were executed around the Hulene - B waste dump and then an inversion was performed by RES2D. The application of the electrical resistivity method allowed us to characterize in detail some of the fundamental aspects of the DRASTIC risk (estimating groundwater depth, characterizing the vadose zone and understand soil permeability) and to identify anomalous zones of possible fundamental contamination, which we grouped into two (i) anomalous lithological surfaces that we considered permeable and migrating leachate from the waste dump and (ii) anomalous zones in the subsoil and groundwater possibly contaminated. The computed DRASTIC index is very high for the area covered by profiles 2 and 6 (156 - 165) given the proximity of groundwater to the contaminating surface and the surrounding area consisting of very conductive materials. On profile 5 area the index is very low (96) due to the strong resistivity of the surface layers and the high depth at which groundwater was detected (> 40m). The area of profile 3 (further north of the dump) has also a low index (105) due to its distance from the contamination source (dump) and the strong resistivity of the lithological layers, indicating low permeability, in addition to the great depth (> 40m) at which groundwater were detected. Concerning profiles 1 and 4, despite presenting permeable materials at the surface (low resistivities), groundwater level was recognized at greater depth (> 40m), DRASTIC risk index was lower (115 - 125) than expected. The overall value of the DRASTIC index for the surrounding area of Hulene - B dump was estimated at 127, which represents a low overall vulnerability. However, the high vulnerability index values for the area covered by profiles 2 and 6, and given their relatively higher surficial altitude, suggest a strong groundwater contamination by horizontal dilution of leachates from the whole area surrounding of the Hulene - B waste dump.

Introduction

Urban areas are characterized by an excessive production of solid waste (González-Arqueros et al. 2021) which can often be deposited in areas not prepared for disposal or treatment, thus posing a risk of environmental contamination (Rathi et al. 2021), especially of soils and groundwater, which are described in many studies as extremely vulnerable (Boufekane et al. 2021). The concept of groundwater vulnerability first evolved in the early 1960s, with the aim of identifying areas prone to contamination (Saranya and Saravanan 2021). Groundwater vulnerability results not only from the properties of the groundwater flow system, but also from the proximity of contaminant sources, the character of the contaminant and other factors that can cause potential contaminants to reach groundwater resources as quickly as possible (Sresto et al. 2021). In urban areas, one of the main sources of groundwater contamination is leachate resulting from the decomposition of solid urban waste when deposited without treatment in unplanned locations such as waste dumps (Ghosh et al. 2021). Several non-invasive models have been developed to assess groundwater vulnerability in urban areas, of which geophysics in

particular electrical resistivity and the DRASTIC hydrogeological model are pointed out as the most relevant (El Mouine et al. 2021).

The electrical resistivity method has been prominent in locating buried hazardous waste as well as in identifying different sources of contamination in the subsurface environment (Kayode et al. 2019; Oum et al. 2021), being widely used in identifying areas of heavy metal contamination, contamination plumes (Liu et al. 2021), groundwater (Oum et al. 2021) and lithological variations (Kayode et al., 2019; Mepaiyeda et al. 2020). DRASTIC model was established by Aller (1987) with the American Environmental Model Protection Agency and the National Water Well Association. Seven hydrogeological parameters are included in the DRASTIC model (Aller 1987). These parameters constitute acronyms that form the term "DRASTIC" and include depth to water table, net area recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity (Aller, 1987). Conventionally, DRASTIC has been applied to map relatively large areas of groundwater vulnerability in urban areas (> 40 ha), according to Gemai et al. (2017) and Voudouris (2021). Shah et al. (2021), Arowoogun et al. (2021), Dhakate et al. (2021) and George (2021) shown it to be most effective when applied locally and combined with the electrical resistivity method to study the contamination plumes migration from different sources (Dumps, mines, cemeteries) and estimate groundwater vulnerability.

Nogueira et al. (2019) and Cendón et al. (2020) have described groundwater in Maputo City as vulnerable to contamination due to its hydrogeological context characterized by the proximity (to surface) of the groundwater level and the rapid expansion of the city without adequate planning and structured sanitation system. Recently, Bernardo et al. (2021), described that in the surroundings of the Hulene - B dump there is a strong risk of leachate migration through the adjacent lithologies and, consequently, the possible contamination of groundwater. This study aims to apply the electrical resistivity method and the DRASTIC model to estimate the risk of groundwater contamination by leachate in the area surrounding of the Hulene B waste dump, Maputo, Mozambique.

Materials And Methods

2.1 Study area

The Hulene B waste dump is considered one of the largest in the country (Serra 2012), being located in Maputo city, the capital of Mozambique (Fig. 1a), on a residential area, the Hulene - B neighborhood, with approximately 27.996 inhabitants (Bernardo et al. 2022). The immediate around of the dump was densely populated until February 2018, and the fall of a large mass of waste caused the collapse of 32 houses and the death of 18 inhabitants, which led to the forced removal of the population within a radius of 50 m of the dump (VOA 2018; Serra 2012). The dump receives all types of waste produced in Maputo City (Serra 2012; Sarmiento et al. 2015). The height of the waste is estimated to be about 6 m to 15 m and occupies an area of ~17 hectares (Palalane 2008). The waste dump is in a former quarry with no previous preparation for waste reception (Ferrão 2006; Bernardo et al. 2022).

The Hulene B waste dump is inserted in the Mesocenozoic sedimentary basin of southern Mozambique (Afonso 1978) and is situated in a contact zone of two lithologies (Ponta Vermelha Formation and Malhazine), on a gentle dune slope with east-west orientation (Momade et al. 1996) (Fig. 1b). The Ponta Vermelha Formation (TPv) dates from the upper Pliocene to the lower Pleistocene, being composed in the upper part of ferruginous sandstones and red silty sands, which gradually change to yellow and whitish sands (Momade et al. 1996); at the surface this unit presents a red color, being poorly consolidated, and loose sands may appear (Cendón et al. 2020). The Malhazine Formation (QMa), from upper Pleistocene, consists of fine, poorly consolidated sands with whitish to reddish colors, fixed by vegetation because of successive consolidation processes (Momade et al. 1996).

The Hulene-B hydrogeological system is part of the Tertiary - Quaternary aquifer system (Cendón et al. 2020). The aquifer substrate is formed by a layer of clayey marl to grey clay (Cendón et al. 2020; Muchimbane 2010). In the surroundings of the Hulene-B dump the localized presence of the semi-impermeable layer (clayey sands), between the fine to coarse sand and the sandstones, causes the water circulation of these two sectors to continuously connect (Muchimbane 2010). There are places where the coarse sands lie directly on top of the clay layer, developing semi-confined conditions (Nogueira et al. 2019). The water level of the shallow wells varies between 1.5 and 9.3 m deep, with an average of 3.8 m (Cendón et al. 2020). Bernardo et al. (2021) used sections of electrical resistivity profiles between 2020 - 2021 and demonstrated that groundwater at the western boundary of the Hulene - B dump was at variable depths and at potential risk of being contaminated by leachate plumes resulting from vertical and horizontal migration, which, in the subsurface environment, were assigned ρ values from < 4.26 to $< 8.5 \Omega.m$. The hydraulic conductivity was estimated at 1 – 5 m/d (Muchimbane, 2010).

The predominant climate is of subtropical type, with two seasons: (a) hot and rainy period from December to March with more than 60% of the annual precipitation, with the highest concentration of precipitation in January (average 125 mm) and (b) dry and cold season from April to September with lower temperatures in June and July, as well as a weak and irregular precipitation, whose minimum values are recorded in August 12 mm. The average annual precipitation is 789,2 mm (INAM 2020). The prevailing winds are SE (Muchangos 1999).

2.2 Geophysical Studies (Electrical Resistivity)

The resistivity method is based on the electric current injected into the ground through a pair of electrodes (A and B - current electrodes) and the resulting potential difference between another pair of electrodes (M and N - potential electrodes) (Koda et al. 2017). The ground resistivity is calculated from the distances between the electrodes, applied current and measured potential difference, based on the Law of *Ohm* (Lau et al. 2019).

The electrical resistivity of soils is a characteristic closely linked to the type, nature, and state of alteration of geological formations (Kayode et al. 2019). In areas of suspected groundwater contamination, the method has been employed for: (1) determining the depth of the groundwater table (Akhtar et al. 2021),

(2) determining the distribution of contamination zones and the direction of migration of pollutants; and (3) assessing the thickness of waste deposited in a landfill and (4) identifying possible leachate plumes (Koda et al. 2017; Adamo et al. 2020; Bernardo et al. 2022). In this investigation 6 electrical resistivity profiles were performed in May 2021, of which 4 were at the western edge of the dump and two profiles on the southern and northern borders respectively (Fig. 1a). Profile 3, north of the dumpsite, was applied to understand the possible migration of contaminants away from the dumpsite. ABEM SAS 4000 was used for the data acquisition resistor, including 4 rollers of 100 m cables with 21 outlets that connect to the same number of electrodes. The layout produced by this sequence of cables (100 m and 21 outputs) corresponds to the standard of the reading program hosted by the resistivimeter LUND Imaging System. Data acquisition employed a 50 Hz current frequency, using a multigradient protocol (GRAD4LX8 and GRAD4SX8), the GRAD4LX8 was selected because it provides dense coverage the nearby surface and adopts the Wenner-Schlumberger protocol (ABEM 2018). The electrode spacing for data acquisition was 5 m. All the electrodes take-outs were connected in the GRAD4S8 protocol. The resistivimeter automatically switches the electrodes to serve as current or potential pairs. After the readings, the data was transferred to the resistivimeter, which then takes the readings, 3 minimum and 6 maximums, to obtain the smallest error average between readings. The inversion of the electrical resistivity data obtained in the 6 lines was done based on the standards defined in the software RES2DINV3.59.106, namely: application of the smoothness constraint method in the resistivity values of the final model, calculation of the Jacobian matrix in each iteration, standard Gauss-Newton optimization method (Geotomo 2010). The interpretation of the profiles was based on the direction of each profile over the entire length (400 m)

2.3 Groundwater pollution risk index (DRASTIC)

The risk index of groundwater contamination in the surrounding of the Hulene B waste dump has been determined based on the DRASTIC model. This model has been commonly used in studies of areas where geographical, hydrogeological information is available and has been successfully applied in different regions (Anshumala et al. 2021; Shah et al. 2021). The model has been applied to determine the groundwater vulnerability index of the watershed (Aller 1987). The word DRASTIC is an abbreviation of initial letter of different parameters such as 'D' to depth to water; 'R' to net recharge, 'A' to aquifer media, 'S' to soil media, 'T' to topography, 'I' the impact of the vadose zone media, and 'C' to the hydraulic conductivity of the aquifer. Intrinsic vulnerability (IV) of groundwater is evaluated by the DRASTIC modelling terms of the DRASTIC Index formula which is given below:

$$\text{DRASTIC Index (IV)} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \text{ Eq. (1)}$$

where "r" is the rating value, and "w" is the weight assigned to each parameter. Each factor is assigned a relative weight ranging from 1 to 5 (Table 1). Each DRASTIC factor is divided into ranges that affect the contaminant potential. The range for each factor lies from 1-10 (Table 1). The DRASTIC model depends on seven boundaries or layers, which are utilized as input boundaries for modeling (Table 1). Thus, the interpretation of the index follows three categories: (i) indices below 135 denote a low vulnerability of the area; (ii) indices between 135 and 150 represent medium vulnerability and (iii) indices above 150 indicate

a high vulnerability of the site to groundwater-related environmental impacts (Aller 1987 and Ghosh et al. 2021). A recent systematization study on the application of the DRASTIC model to groundwater vulnerability assessment made by Voudouris (2021) showed that many studies applied the DRASTIC method for larger areas > 40 ha and combined it with ArcGIS (Persaud & Levison, 2021). However, recently Shah et al. (2021) applied DRASTIC and electrical conductivity to assess groundwater vulnerability in a small area in Safdar Abad Tehsil, Pakistan and demonstrated the role of lithologies of different resistivity in controlling contamination. In this study, the analysis covers an area of about ~ 32 ha.

The DRASTIC model results for each area covered by the electrical resistivity profile resulted from the combination of local hydrogeological information and interpretation of the resistivity models. For groundwater depth, we combined the data from Cendón et al. (2020) and Muchimbane (2010) which estimated groundwater depth in the study area between 1.5 and 9.3 m and were compatible with the model resistivity data for profiles 2 and 6 a weight of (9) was assigned and for the areas covered by profiles 3, 4 and 5 a depth > 40 m estimated according to the model resistivity data, weight (1). For the aquifer recharge network, we used the data from Momade et al. (1996) which estimates the average aquifer recharge for the Maputo region to be 165-185 mm/year. Thus, a value of 8 was assigned to the entire area surrounding the dump. The lithological substratum of the aquifer was classified as sandstone according to Momade et al. (1996) and assigned a weight of 9 for all areas. The vadose zone for the area covered by profiles 2, 4 and 6 received a classification of 9 because it is composed of sandy layers in all four profiles, which are proportional to the low electrical resistivity data of the upper layers of the profiles, in addition to the water table being at low depth (Cendón et al. 2020). Thus, for the area covered by profiles 3 and 5 a value of 4 was assigned, corresponding to sandstones, given the strong compaction of the upper layers and the high depth of the water table in both areas, well evidenced by the high resistivity in the upper layers of profiles 3 and 5. The area covered with the profile 1, given the heterogeneity of the resistivities of the surface layers, a weight of 6. The hydraulic conductivity was assigned a value of 2 and was assigned based on (Muchimbane 2010) data which estimates the hydraulic conductivity of the Hulene - B waste district at 1-5 m/day. Shah et al. (2021) and George (2021) demonstrated that groundwater vulnerability analysis using a combination of electrical resistivity and DRASTIC has successfully achieved good results and reduces generalizability in risk assessment.

Table 1
The weight assigned to DRASTIC parameters

Factor	Interval/Characteristics	Value (r)	Weight (w)
(D) Groundwater depth (m)	0 – 1.5	10	5
	1.5 – 4.6	9	
	4.6 – 9.3	7	
	9.3 – 15	5	
	15 – 23	3	
	23 – 30	2	
	> 30	1	
(R) Net Recharge (mm/day)	0 – 50	1	4
	50 - 100	3	
	100 - 175	6	
	175 – 250	8	
	> 250	9	
(A) Lithology	Massive Slate	1 – 3	3
	Igneous and metamorphic rocks	2 – 5	
	Altered igneous and metamorphic rocks	3 – 5	
	Thinly bedded successions of sandstones, limestones, and shales	5 – 9	
	Massive sandstones	4 – 9	
	Massive limestones	4 – 9	
	Sand and gravel	6 – 9	
	Basalts	2 – 10	
	Limestones and Karstics	9 – 10	
(S) Soil Type	Non-expansive clay	1	1
	Clay-French	3	
	Sandy siltstone	4	
	Franco	5	

Factor	Interval/Characteristics	Value (r)	Weight (w)
	Sandy frank	6	
	Expansive clay	7	
	Sandy soil	9	
	Soil with gravel	10	
	Thin soil	10	
(T)	0 – 2	10	1
Terrain slope (%)	2 – 6	9	
	6 – 12	5	
	12 – 18	3	
	> 18	1	
(I)	Clays and silts	1 – 2	5
Vadose Zone	Shales	2 – 5	
	Limestones	2 – 7	
	Sandstones	4 – 8	
	Limestones, sandstones and shales	4 – 8	
	Sands and gravels with significant silt and clay content	4 – 8	
	Igneous and metamorphic rocks	2 – 8	
	Sand and gravel	6 – 9	
	Basalts	2 – 10	
	Karst limestones	8 – 10	
(C)	1 – 4.1	1	4
Hydraulic conductivity (m/day)	4.1 – 12.2	2	
	12.2 – 28.5	4	
	28.5 – 40.7	6	
	40.7 – 81.5	8	
	> 81.5	10	

Results

3.1 Resistivity models and contamination risks

The resistivity models were analyzed to identify the possible influence of the dumpsite on groundwater contamination, thus we identified two anomalous zones reflecting the leachate transfer process: (i) contaminated lithologies that we consider as leachate migration sites to the groundwater media (ii) groundwater and surface water contaminated by leachate. For all profiles, the areas considered anomalous have been highlighted (dashed).

Profile 1

Profile 1, which extends from south to north of the dump (Fig. 2), is superficially characterized by high resistivity associated with rubble, house debris and compacted waste in non-wet environments from 0 to 35m. From 240 to 400m there are zones of rather heterogeneous anomalous resistivity, which we consider as zone of influence of the possible leachates ($< 15.0 - 10.7 \Omega.m$) from the dump and moving E-W (profile 2) and diluting with the surface waters causing their possible contamination ($< 8.56 - 6.85 \Omega.m$). At deeper levels between 30 and 56.5 m, anomalous zones are observed, which we consider as lithologies influenced by leachate ($15 - 10.7 \Omega.m$) and possible contaminated groundwater (> 45 m depth) by vertical migration of leachate ($< 8.56 - 6.85 \Omega.m$).

Profile 2

Profile 2, along W-E direction (Fig. 3), is quite heterogeneous, with high surface resistivities from 0 – 140 m, which represent for rubble, old house debris, waste buried in non-wet environment west of the dump, followed, from 140 m to 160 m, by a zone of possible migration of surface leachate into the subsurface environment, causing an extensive zone of subsurface anomalies, which we consider as lithologies contaminated by strong horizontal migration of leachate in the E-W direction ($16.8 - 7.99 \Omega.m$) and saturated zone and contaminated groundwater ($< 7.99 - 4.96 \Omega.m$) differentiated levels of semi-confinement of aquifers. From 245 m to 400 m of surface there are local anomalies and lithologies with high resistivities, corresponding to highly compacted waste with diverse moisture contents. At depths ranging from 30 to 160 m, semi-confined anomalies (< 8.35 m depth) and aquifers (> 10 m depth) separated by semi-saturated layers are noted, demonstrating the existence of a possible continuous connection between the two. These characteristics are described as conducive for groundwater contamination at various depths, mainly in the surroundings of the Hulene B dump, where surface leachate flows are noted that successively enrich the lithological layers ($< 16.8 - 7.99 \Omega.m$).

Profile 3

Profile 3 (Fig. 4) runs north of the dump in S-N direction to study the possible dynamics of groundwater contamination about 300 m away from the dump. The profile at surface level exhibits generally high resistivities, which alternate between rubble and highly compacted soils. At the deeper level (> 40 m) in

the southern end we note anomalous zones that we consider as contaminated lithologies ($< 15.95 - 9.95 \Omega.m$) and saturated zone and contaminated groundwater ($< 9.99 - < 7.43 \Omega.m$). We associate this anomaly with the horizontal and vertical migration of leachate described in profile 2.

Profile 4

Profile 4 runs NE-SW direction (Fig. 5). From starting point to 150 m, it presents in general high resistivities associated with compacted debris and rubble from old houses. From 150 m, below the surface, to the end of the profile, there is a continuous decrease in resistivity that is associated with the saturated and wet areas of the natural receiving basin where new waste deposits are observed, which are the localized source of production, dilution, vertical migration of leachates and groundwater contamination ($< 11.3 - 7.01 \Omega.m$). Between 300 and 340 meters, we note an area that we consider as vertical leachate migration points ($< 16.3 - 11.3 \Omega.m$) causing significant resistivity changes. At depth (6 – 56 m), we note a vast anomaly ($< 16.3 \Omega.m$) that we consider related to leachates that dilutes at great depth > 37.3 m causing possible groundwater contamination ($< 8.9 - 7.01 \Omega.m$).

Profile 5

Profile 5 runs in a west-east orientation, at the southern end of the dump (Fig. 6). The electrical resistivity results did not show significant change at the surface level and showed high resistivities associated with the compacted soils and rubble (including asphalt of the street where the profile was executed). This street besides being the southern boundary of the dump is an access to the interior of the Hulene-B neighborhood. Between 130 and 145 m (> 40 m depth) extends a resistive zone of low anomalous values, which are interpreted lithologies with influence of migratory leachates ($< 8.89 - 2.24 \Omega.m$) and possible water contaminated by the vertical movement of leachates ($< 0.95 - 0.403 \Omega.m$).

Profile 6

This profile runs at the eastern limit of the dump along S-N direction (Fig. 7), between the dump and Julius Nyerere Avenue (Fig. 9). From the starting point to 200 m (shallow), there are resistivities with average profile values ($> 44.4 - 119 \Omega.m$); these resistivities indicate soils with different levels of compaction and surface moisture that may be associated with various activities south of the dump. The resistivity $> 89.1 - 119 \Omega.m$ corresponding to a surficial but thick layer between 160 m to 200 m indicates compacted soils at the entrance of the dump. From 8.6 m depth deep wards, higher resistivity values ($> 119 \Omega.m$) are noted which may be related to the sandstone stratum with different levels of alteration that is typical of the red tip (TPv) formation (Momade et al. 1996; Nogueira et al. 2019). Onwards, in the northern direction, resistivity starts to decrease successively ($< 89.1 \Omega.m$) along thick layers with moisture levels that increase until saturated layers ($< 14.7 \Omega.m$). The saturated area occupies a large space and reveals the existence of an E-W groundwater flow parallel to the dune slope where the leachate is located. The groundwater contamination process at this point may be occurring horizontally due to leachate diffusion, causing localized anomalous resistivities ($< 14.3 \Omega.m$) close to the groundwater resistivity ($< 5.49 \Omega.m$). From 240 m, above the surface, resistivity begins to decrease, generating localized

anomalous zones in the subsurface, which are associated with vertical leachate migration, points the occurrence of two isolated "hot spots". Between 240 m and 280 m, below the first "hot spots", there is a tendency for a significant increase in resistivity that may correspond to less saturated layers up to the least conductive stratum $> 119 \Omega.m$. The data from this profile show the existence of two mechanisms of possible saturated zone and groundwater contamination ($14.7 - 3.65 \Omega.m$), which are (i) horizontal dilution in the south and center of the profile, (ii) vertical migration and retention of leachate in localized "hot spots".

3.2 Risk of Groundwater Vulnerability (DRASTIC)

The values of the DRASTIC index for the whole area are systematized in Table 2. The assessment of the area covered by profiles 1, 3, 4 and 5 showed low vulnerability to groundwater contamination (125 - 96) as groundwater is at greater depths and the surface lithologies have higher resistivity values, which reduces vertical infiltration of contaminants. However, horizontal migration of leachate at greater depths may affect groundwater at the southern boundary of the area covered by Profile 3 and southwards to the area covered by Profiles 1 and 5. For the area covered by profile 4, the risk becomes even greater as the surface area concentrates the leachate-enriched surface waters and the subsurface substrates exhibited low electrical resistivities ($< 16.8 \Omega.m$) demonstrating vertical migration of leachate to greater depths. In the area covered by Profile 2, the relatively steep relief (gentle dune slope) significantly reduces the vertical movement of contaminants, generating a greater horizontal flow of leachate in the surface layers in E-W direction, which may subsequently cause vertical migration of contaminants to groundwater at shallower depths ($< 6 m$), thus the risk was estimated to be high (156). The area covered by profile 6, was classified as having a very high vulnerability (165) to groundwater leachate contamination as the groundwater is at a shallower depth ($< 3 m$) and the surface lithological layers are less resistive ($< 59.2 \Omega.m$) and the relief is flat, which demonstrates optimal conditions for leachate infiltration. The overall risk value of vulnerability across the whole area of was estimated to be 127 representing low vulnerability. However, the high values of vulnerability index of the area covered by profiles 2 and 6, and given their relatively higher altitude, suggest strong groundwater contamination by horizontal dilution of the whole surrounding area of the dump.

Table 2
Parameter values considered in the DRASTIC Index.

Factor	Characteristics of the surroundings of the waste dump	P 1	P2	P3	P4	P5	P6	Mean
D	Depth of groundwater level	5	45	5	5	5	45	18.3
R	Recharge capacity	32	32	32	32	32	32	32
A	Sandstone	21	21	21	21	21	21	21
S	Sandy soils	9	5	9	9	5	9	7.6
T	Plan, soft dune and interdune depression	10	5	10	10	5	10	8.3
I								
C	Sands	30	40	20	40	20	40	31.6
	Hydraulic conductivity	8	8	8	8	8	8	8
DRASTIC index:		115	156	105	125	96	165	127
<i>P – Profile</i>								

3.3 Descriptive statistics of the values of electrical resistivity and DRASTIC index

The electrical resistivity values of the areas covered by the profiles were projected with the vulnerability index values (Table 3).

Table 3
mean, maximum, minimum, standard deviation of resistivity and DRASTIC index

ID	MIN	MAX	MEAN	STDV	DRASTIC
P1	8.64	42.36	20.78	5.72	115
P2	5.37	119.1	20.22	9.31	156
P3	10.12	50.8	31.01	7.3	105
P4	6.98	41.19	18.1	4.64	125
P5	1.04	477.1	37.35	31.86	96
P6	3.06	207	49.2	32.78	165
<i>P – Profile</i>					

In general, the areas covered by profiles 2 and 6 were classified as having a high DRASTIC index. For profile 2, the average resistivity values were 20.22 Ω .m, which demonstrates the predominance of lower resistivities across the entire surface area of the profile, demonstrating that the lithologies are generally

porous in addition to the shallow groundwater depth. The area covered by profile 6 had an average of 49.2 $\Omega.m$, minimum of 3.06 $\Omega.m$ and maximum of 207 $\Omega.m$. The mean resistivity value was relatively higher but presented a much higher standard deviation 32.78, which demonstrates a heterogeneity of the resistivity values, marked by less resistive surface lithological surfaces, i.e. porous lithologies and low depth of groundwater, which may allow a greater migration of leachates and groundwater contamination. These characteristics were determinant in the high DRASTIC risk index. The areas covered by profiles 1, 3, 4 and 5 presented a low DRASTIC risk and the resistivity values were quite heterogeneous. Thus, the area covered by Profile 1 showed heterogeneities of surface and subsurface anomalies that may be associated with vertical and horizontal migration of contaminants with minimum resistivity values of 5.37 - 8.64 $\Omega.m$. The Profile 3 area, showed an average resistivity of 31.01 $\Omega.m$, with a minimum value of 10.12 $\Omega.m$ and maximum of 50.8 $\Omega.m$. These data demonstrate the predominance of high resistivity values, which is translated by the reduced predominance of resistive surfaces that are interpreted as less permeable substrates. The minimum resistivity at great depth 10.12 $\Omega.m$ may be indicating the existence of a saturated area or the localized influence of the horizontal migration of contaminants described in profile 2. The area of profile 4, showed an average resistivity of 18.1 $\Omega.m$, a minimum of 6.98 and a maximum of 41.89 $\Omega.m$, which demonstrates the strong predominance of conducting surfaces and porous lithology, which are relevant factors in leachate migration and groundwater contamination, which can be justified by the high value of DRASTIC risk. The area covered by profile 5, presented an average resistivity of 37.35 $\Omega.m$ and minimum of 1.04 $\Omega.m$ and maximum of 477.1 $\Omega.m$. The low DRASTIC values in the areas of profiles 1, 3 and 5 resulted from the combination of two factors (i) the high resistivities prevailing in the surface lithologies that are generally impermeable, which greatly reduces the risk of vertical migration of leachate to deep layers, (ii) the greater depth at which the resistivities interpreted as groundwater are located. For profile area 4, only the groundwater depth factor was crucial for the low DRASTIC risk because the superficial layers are less resistive and therefore permeable.

In general, the statistical data showed that the zones whose profiles presented a high average resistivity, the DRASTIC risk was lower (Profile 3 and 5) (Fig. 8). Exceptionally, the area of profile 6 showed a very high DRASTIC risk with relatively high average resistivity values than (1 and 3) due to its high standard deviation and to the predominance of resistivities between < 14.71 $\Omega.m$ and 3.65 $\Omega.m$ in a large strip of surface that we associate to migration points of leachate to the underground waters that are located at low depth than in all profiles. However, in the areas of profiles 1 and 4, despite the lower mean resistivity value 20.4 – 18.1 $\Omega.m$, the great depth of groundwater determined the low DRASTIC risk.

Discussion

The resistivity data presented by the area covered by profiles 1,2, 4 and 6, with a predominance of surface and groundwater resistivity anomalies, are described in many studies as revealing leachate migration(Parvin and Tareq, 2021) and groundwater contamination(El Mouine et al. 2021),mainly in areas surrounding non-isolated dumps where leachate can freely circulate through the adjacent lithologies and subsequently affect vadose zone and the groundwater (Wysocka et al.2017). Surface circulation and leachate infiltration is well evidenced in profiles 2 and 4 by surface and subsurface resistive anomalies, which are described as indicative of contamination(Netto et al. 2021). The typology

of the soils (sandy and non-compacted) covering all profiles with strong concentration of resistive values and high DRASTIC index are described as optimal for leachate infiltration at great depths (Wong et al. 2017;Chetri et al. 2021).The zone covered by profile 6, besides showing an extensive layer of low resistivities ($< 14.7-3.65\Omega \cdot m$), which in similar studies in the around of dumps were considered as saturated zone and groundwater contaminated by leachates(Brahmi et al. 2021;Adamo et al. 2020), shows also, to the north, two localized points of resistive anomalies, which are called "hot spots" (Ololade et al. 2019;Marques et al. 2021) resulting from vertical migration and localized accumulation of contaminants (Feng et al. 2021; Marques et al. 2021), or may be associated with the confined aquifer system that has been described in this zone as quite vulnerable to contamination given its proximity to the surface and the sandy characteristics of the vadose zone(Cendón et al. 2020). In turn, the resistivity data of profile 3 and 5 characterized by high resistivities, being described as low permeability of contaminants(Gemail et al.2017), because in areas surrounding waste dumps they may be revealing less permeable compacted surfaces (Udosen 2021).Our profile 3 is located far from the waste dump ($> 350 m$), which reveals that contaminants may not be reaching this range. Morita et al. (2021) and Oum et al. (2021)demonstrated that the increase in resistivity moving away from the dumpsites shows a significant decrease in contamination, due to the attenuating role of soils and groundwater. The location of the groundwater at great depths in the area covered by profiles 1, 3, 4 and 5 has been described in similar studies as a determinant in the low risk of contamination(George 2021), which partly explains the low DRASTIC risk in these areas.Paul et al. (2021) and Boumaiza et al. (2021)mentioned that the depth of groundwater and the characteristics of the infiltration zone are the most important factors determining the DRASTIC risk.Shah et al. (2021),Nasri et al. (2021) and Gemail et al. (2017)integrated electrical conductivity and DRASTIC data and concluded that the areas of highest DRASTIC index around the dumps generally exhibit high electrical conductivity associated with the migration of contamination through adjacent lithologies that may subsequently reach groundwater. The high DRASTIC vulnerability risk of the area covered by profiles 2 and 6, which in topographic terms are in the high and transitional zone, may constitute evidence of contamination by horizontal groundwater flow.The spatial projection of the DRASTIC Vulnerability Index in the surrounding of the Hulene - B dump was shown to be high to the east and north of the dump (with high and transient relief) and low to the south and west of the dump (low elevation, except for the southern area which is transient) (Fig. 9).However,Blarasin et al. (2021)and Tan et al. (2020)have reported that contamination of the upper levels of the water table leads to the dispersion of contaminants to large areas.

Conclusions

In this study, the combination of electrical resistivity models and the DRASTIC method proved effective to describe the hydrogeological particularities, estimate in detail the groundwater vulnerability and identify areas of possible leachate contamination in the surroundings of the Hulene - B dump. Thus, the areas covered by profiles 1, 2, 4, and 6 showed strong indications of possible groundwater and surface water contamination by leachate, because the low resistivity values presented in several extensions of the profiles are revealing of surfaces with possible migration or installation of contaminants, besides being

typical of permeable surfaces, which is a factor to consider in the vertical migration of leachate. Thus, in these areas, the DRASTIC index was very high for the area covered by profiles 2 and 6 (156 - 165) given the proximity of groundwater to the contaminating surface and the surrounding area consisting of very conductive materials (sandy soils), while for profiles 1 and 4, despite presenting permeable materials at the surface (low resistivities), groundwater was interpreted at a greater depth (> 40m) and the DRASTIC risk index was lower (115 - 125). In profiles 5 the index was very low (96) due to the strong resistivity of the surface layers and the high depth at which groundwater was detected (> 40m). The area of profile 3 further north of the dump also had a low index (105) due to its distance from the contamination (dump) and the strong resistivity of the lithological layers, indicating low permeability, in addition to the great depth (> 40m) at which the anomalies interpreted as groundwater were detected.

The overall value of the DRASTIC index for the surrounding area was estimated at 127 which represents a low overall vulnerability. However, the high values of vulnerability index of the area covered by profiles 2 and 6 and given their relatively higher altitude, suggest strong groundwater contamination by horizontal dilution of the whole surrounding area of the dump.

The results suggest the need for further studies with quantitative methods to validate the possible contamination in areas of suspected contaminant migration into groundwater. The results of this study recommend:

- To assess contamination monitoring thru installation of piezometers in the anomalous areas (groundwater) that could help understand the pattern of aquifer dynamics and temporal levels of contamination.
- An inventory of all the wells around the dump and temporal chemical quantification of the water could be done to understand the periods of high groundwater contamination and design appropriate methods to minimize the risks for the local.

Declarations

Ethical Approval: Authors state no potential conflicts of interest, and that research did not involve Human Participants and/or Animals.

Consent to Participate: All authors agreed to participate.

Consent to Publish: All authors consent to publish.

Author Contributions: Conceptualization, B.B. and F.R.; methodology, B.B.; software, B.B.; validation, B.B., C.C. and F.R.; formal analysis, F.R.; investigation, B.B.; resources, B.B.; data curation, B.B.; writing—original draft preparation, B.B.; writing—review and editing, B.B. and F.R.; visualization, B.B.; supervision, F.R. and C.C.; project administration, F.R.; funding acquisition, B.B. and F.R.. All authors have read and agreed to the published version of the manuscript.

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Figures

Figure 1

(a) Location, Profiles, (b) Geology, Topography. Adapt. Bernardo et al. (2021) and Momade et al. (1996).

Figure 2

Electrical resistivity model of profile 1. Adapt. Bernardo et al. (2021)

Figure 3

Electrical resistivity model of profile 2. Adapt. Bernardo et al. (2021)

Figure 4

Electrical resistivity model of profile 3. Adapt. Bernardo et al. (2021)

Figure 5

Electrical resistivity model of profile 3. Adapt. Bernardo et al. (2021)

Figure 6

Electrical resistivity model of profile 5.

Figure 7

Electrical resistivity profile 6

P – Profile

Figure 8

Electrical resistivity values (minimum, maximum, mean, standard deviation) and DRASTIC Index

Figure 9

Spatial projection of the DRASTIC Vulnerability Index in the surrounding of the Hulene - B Waste dump.