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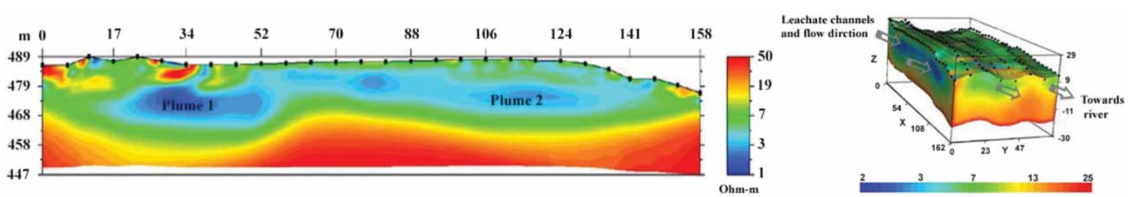
This study presents the use of direct current resistivity techniques (DCRT) for investigation and characterization of leachate-contaminated subsurface environment of an open solid waste dumpsite at Kandy, Sri Lanka. The particular dumpsite has no liner and hence the leachate flows directly to the nearby river via subsurface and surface channels. For the identification of possible subsurface flow paths and the direction of the leachate, DCRT (two-dimensional, three-dimensional and vertical electrical sounding) have been applied. In addition, the physico-chemical parameters such as pH, electrical conductivity (EC), alkalinity, hardness, chloride, chemical oxygen demand (COD) and total organic carbon (TOC) of leachate collected from different points of the solid waste dumping area and leachate drainage channel were analysed. Resistivity data confirmed that the leachate flow is confined to the near surface and no separate plume is observed in the downstream area, which may be due to the contamination distribution in the shallow overburden thickness. The stratigraphy with leachate pockets and leachate plume movements was well demarcated inside the dumpsite via low resistivity zones (1–3 Ωm). The recorded EC, alkalinity, hardness and chloride contents in leachate were averaged as 14.13 mS cm^{-1}, 3236, 2241 and 320 mg L^{-1}, respectively, which confirmed the possible causes for low resistivity values. This study confirms that DCRT can be effectively utilized to assess the subsurface characteristics of the open dumpsites to decide on corridor placement and depth of permeable reactive barriers to reduce the groundwater contamination.



Keywords: resistivity techniques; electrical conductivity; municipal solid waste dumpsites; leachate plume delineation; Sri Lanka

1. Introduction

Geophysical methods such as electrical resistivity (ER), electromagnetic, ground-penetrating radar, magnetic and induced polarization can be effectively used to obtain information on certain parameters in the subsurface for modelling of the underground physical characteristics.[1] Mainly, electromagnetic and electrical signals generated by artificial sources are used in these techniques. The non-destructive nature, cost-effectiveness and data reliability have made these techniques to be used extensively in various environmental applications such as modelling of groundwater flow patterns and identification of possible leakages of industrial waste and subsurface channels associated with dumpsites.[2–4] The detection of the location and extent of the contamination patches in dumpsites are very important for the purpose of evaluation and characterization enabling one to decide on suitable remedial measures.[5] The characteristic features of the landfill leachate or its plume such as resistivity/conductivity, dielectric constant, chargeability and magnetic susceptibility are engaged for effective use of the geophysical methods in landfills and its leachate studies.[5].

In 1968, for the first time, galvanic resistivities have been used to delineate a contaminant plume from an old landfill in West Chicago, USA.[6] Later, studies were focused on applying the geophysical techniques to characterize landfills and its contaminated plumes. For

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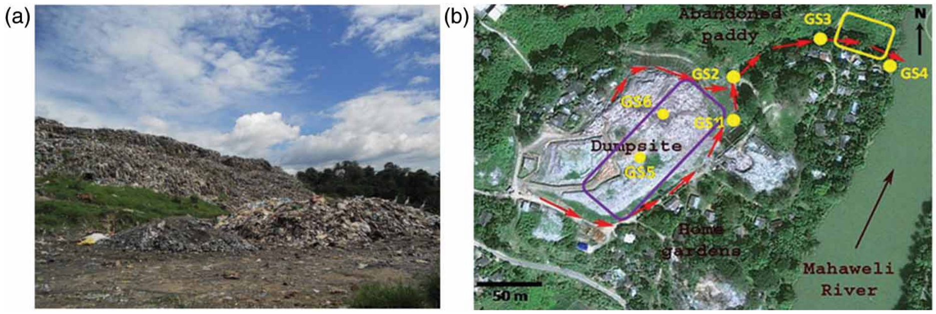

Figure 1. (a) View of the Gohagoda open solid waste dumpsite. (b) Schematic diagram of the leachate drainage channel (red arrows), leachate sampling points (yellow dots) and resistivity data acquisition area (yellow and purple rectangles for phases 1 and 2, respectively) at Gohagoda dumpsite.

instance, in 1990, some successful experiences on application of seismic reflection techniques for waste site evaluation/mapping of the overburden stratigraphy were reported.[7,8] The use of resistivity technique with seismic reflection on understanding the impermeable liner characteristics and for enlarging the landfill area at Hanko city in southern Finland was reported in 1993.[9] Resistivity surveys have since been applied extensively for characterization (i.e. understanding the natural barrier properties that are very crucial for avoiding pollutant contact to the groundwater) of future landfill sites.[4].

Among these geophysical techniques, the resistivity imaging method plays a major role in environmental monitoring studies. The conductive nature of the leachate generated by the landfill and their heterogeneous state of a landfill profile are very important characters on the mapping of open dumpsites and sanitary landfills.[1,10] For instance, ER studies had been reported in Nigeria and China highlighting their success in detecting the contaminant pathways from dumpsites.[5,11] Further, application of ER technique investigations has been reported on landfill leachate pollutants migration pattern in soil and groundwater at Sungai Sedu landfill site, Malaysia, emphasizing the relationship between the low resistivity values with most contaminated zones by landfill leachate.[12] However, very little attention has been paid to the use of this non-destructive and cost-effective technique aimed at understanding the landfill leachate contaminated subsurface environment associated with the open dumpsites with no liners. To find the best locations for the placement of permeable reactive barriers (PRBs) and to avoid groundwater contamination by landfill leachate, this technique is most useful.

The Gohagoda dumpsite, Kandy, is the main disposal site of urban garbage in the hill capital of Sri Lanka. It is a poorly maintained and ill-designed site where all types of municipal wastes have been accumulated into heaps of garbage over the last five decades (Figure 1(a)). The site is bounded by the longest river of the country, Mahaweli to the east, which is the major fresh water supplier for downstream communities for drinking, agricultural and sanitary requirements. This unprotected dumpsite with no leachate treatment facilities and no proper lining to prevent leachate flux into the river poses a major threat to the environment and to the end users of this fresh water source.[13,14] In addition, there is no cover material at the top of the dump for avoiding odorous emissions and light materials such as polythene debris to the surroundings. The high rainfall in the central hills is an added concern in the context of leachate control to the main river system. Previous studies found that uncontrolled landfills enhance the hydraulic contact between the leachate and groundwater sources increasing the contamination rate.[4] Similarly, the groundwater and surface water around the Gohagoda dumpsite area have been identified as being contaminated by the dumpsite leachate.[14,15] Therefore, it is very important to understand such environments/locations to avoid or minimize the pollution of ground or surface waters.

Characterizing the subsurface flow pattern of leachate towards the river is considered as one of the initial steps towards designing a treatment plant and/or controlling the leachate flux through PRBs into the river system. No information is available on the depth of the garbage heap that had accumulated over the last five decades due to the improper planning. The main objectives of this study are to identify the extent of contamination and distribution, to identify subsurface channels that may transport dumpsite leachate to the river and to observe the presence of any perched water pockets within the flow path and in the dump body with its subsurface environments. In addition, assessing the subsurface characters including depth to the bedrock of the dumpsite area is considered as a secondary objective. The data are used to suggest placement corridors for the PRBs.

2. Materials and methods

2.1. Site description

The study area is the Gohagoda waste dumpsite; an aerial extent of 2.5 ha with coordinates of 7018$'$47.85$''$N and 80°37$'$19.02$''$E, with an average height of 460 m above the mean sea level. This site is in the Kandy suburbs,

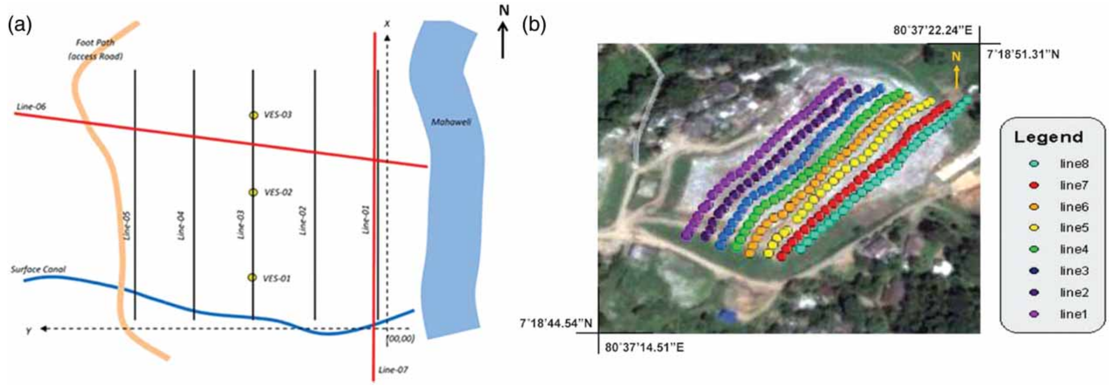

Figure 2. (a) A sketch of the survey plan for leachate-contaminated area (phase 1) with local coordinates. Black lines are to regular grid for 3D resistivity cube with 10-m line spacing and 40.5-m profile length. Two red lines are the traces for 67.5-m profiles. Yellow circles (VES-01-03) are locations for 1D resistivity survey. (b) The survey plan for existing dumpsite (phase 2) with respective coordinates. Lines 1–8 are to regular grid for 3D resistivity cube with 10-m line spacing and 158-m profile length.

Table 1. Errors, thickness and resistivities from 1D soundings.

		Layer 1		Layer 2	
VES #	RMS %	Resistivity	Thickness	Resistivity	Thickness
VES-01	3.0	18.6	3.4	613.8	–
VES-02	2.5	21.2	3.6	178.9	1.8
VES-03	2.5	25.7	5.1	422.4	–

Note: Resistivities and thickness are in Ωm and m, respectively. RMS, root mean-squared deviation.

hill capital of Sri Lanka, having an average annual rainfall of 2400 mm and typical tropical climatic conditions with warm and wet weather conditions. The study site is bounded by the river Mahaweli to the east with very little rock exposures but only weathered soil profiles. Drill logs revealed that the underlying hard rock of the dumpsite is hornblende-biotite gneissic rock of Kadugannawa Complex.[14].

This site receives municipal solid waste (MSW) from the Kandy city and suburbs since 1960s. The residential population of Kandy city exceeds 120,000 and being a tourist attraction, over 50,000 visitors use the city on a daily basis. About 130 t/day of MSW containing waste from slaughter houses, fish market, households and non-infectious hospital waste are being directly dumped without any sorting or pre-treatment.[16] Approximately 59% of disposed wastes consists of food waste, while garden trimmings, wood, polythene, cardboards and paper make-up 18%, 6%, 5%, 3% and 2% of the total waste mass, respectively.[17] Similar to all other MSW dumpsites in Sri Lanka, no Environmental Impact Assessment (EIA) or Initial Environmental Assessment (IEA) has been conducted prior to the site selection and no proper monitoring on the environmental effects. Unfortunately, due to lack of funds, the partially constructed leachate treatment system is not operational, thus very little actions have been taken on safeguarding the environment.

2.2. *Resistivity surveys*

The resistivity method has been considered as the best technique in assessing the subsurface characters of the dumpsite, possible flow patterns of the leachate and the subsurface formations, particularly the depth to the bedrock. However, the resistivity data obscured with the heavy rainfall occurred during the study at the dumpsite body.

2.2.1. *1D vertical electrical sounding (VES)*

One-dimensional (1D) VES is a standard resistivity sounding method that is designed according to the Schlumberger array. The depth of detection is controlled by the current electrode separation, and apparent resistivity values are measured for different electrode distances. In this survey, the maximum current electrode separation was kept at 100 m and the calculated apparent resistivity values were plotted on a double-log paper, against current electrode separation. Raw VES data were analysed in RESIST freeware that provides layer resistivity and respective thickness of the formations (ABEM Terameter SAS 300). In this particular survey, the main objective of the VES survey was to determine the depth of the bedrock and identify inversion parameters for two-dimensional (2D) resistivity imaging.

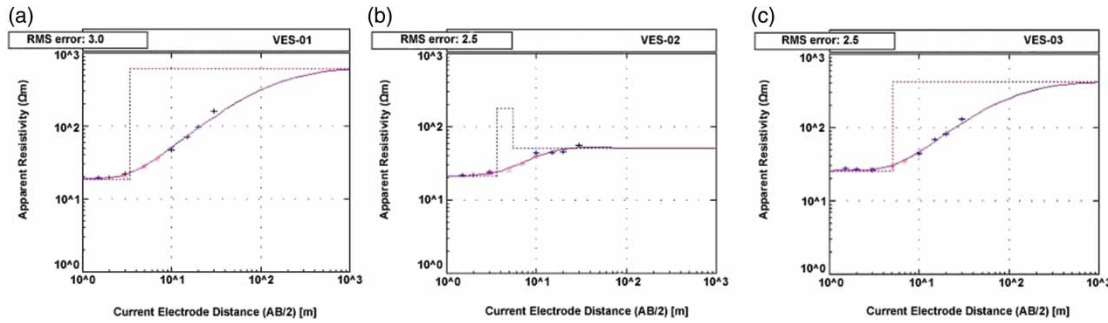

Figure 3. Vertical electrode sounding (VES) interpretation with true resistivity values. The subparts (a), (b) and (c) are related to the VES-01, VES-02 and VES-03, respectively (values are elaborated in Table 1).

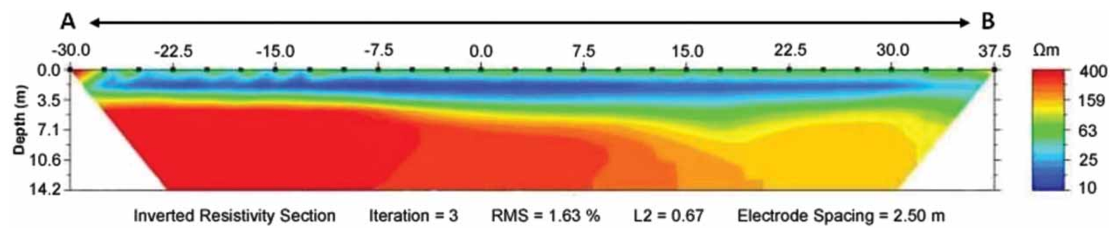

Figure 4. Resistivity image along the profile line-06. Data were acquired at 2.5-m electrode interval with 67.5-m total spread. The resistivity range is set at 400 and 10 Ωm maxima and minima and 400 Ωm is set as the lowest value for bedrock (partially weathered rocks).

2.2.2. *2D and 3D imaging*

Two-dimensional imaging was conducted along the selected profiles as outlines in Figures 1(b), 2(a) and 2(b) for leachate contaminated area and dump, respectively, parallel lines, enabling to synthesize a three-dimensional (3D) cube from 2D data. Raw data were acquired according to Schlumberger–Wenner combined array both with high lateral and vertical resolutions. Multi-electrode system with 28 electrodes was considered for this survey, and 233 data blocks were acquired at each and every profile as raw data with Advanced Geosciences, Inc. (AGI) Mini-Sting system. Data processing was conducted in AGI software by introducing appropriate inversion parameters derived by VES outcome.

In almost all occasions, raw data perfectly matched with mathematical model indicating high reliability of the resistivity technique for this survey. As the surface layers have very low resistivity and bedrock displays a high contrast, in all inversion processes the RMS values were kept below 5%.

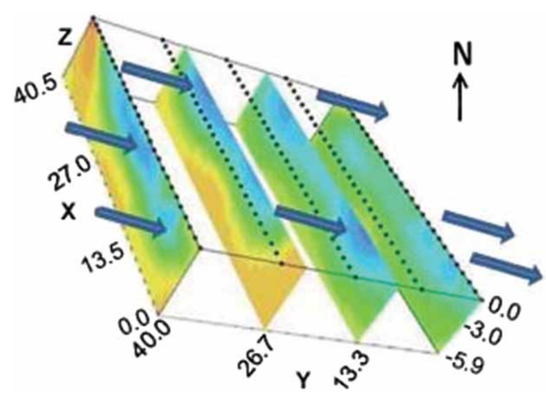

Figure 5. Two-dimensional imaging profile at leachate-contaminated area at Gohagoda dumpsite. Sliced section normal to *y*-axis and normal to *z*-axis indicates the flow patterns. The sections normal to *z*-axis reveal that the leachate flow is at very shallow level and limited to 3-m level. Blue arrow shows the leachate flow direction towards the river.

2.3. *Characterization of dumpsite leachate*

To understand the quality of the dumpsite leachate, the leachate was collected at six sampling points of the drainage channel (GS1–4) and existing MSW dumping area (GS5–6) from the Gohagoda open dumpsite parallel to the resistivity survey period (Figure 1(b)). The GS1–4 sampling points were selected based on the topography, natural streams pattern and proximity to the dumpsite, whereas the GS5–6 points were selected to capture the physico-chemical characteristics of the fresh waste-derived dumpsite leachate. The leachate samples were collected by a hand pump to the distilled deionized water rinsed sample bottles. The pH was measured using ROSS sure-flow combination epoxy body electrode at field site. Afterwards, the samples were immediately transferred to the laboratory at 4°C condition. Recommended procedures were performed to characterize the collected leachate samples for basic physical and chemical constitutes.[14] The EC and chloride concentrations were measured directly with an Orion star series conductivity meter (5 STAR, Environmental Instruments, USA). The alkalinity and hardness were measured as described by William.[18].

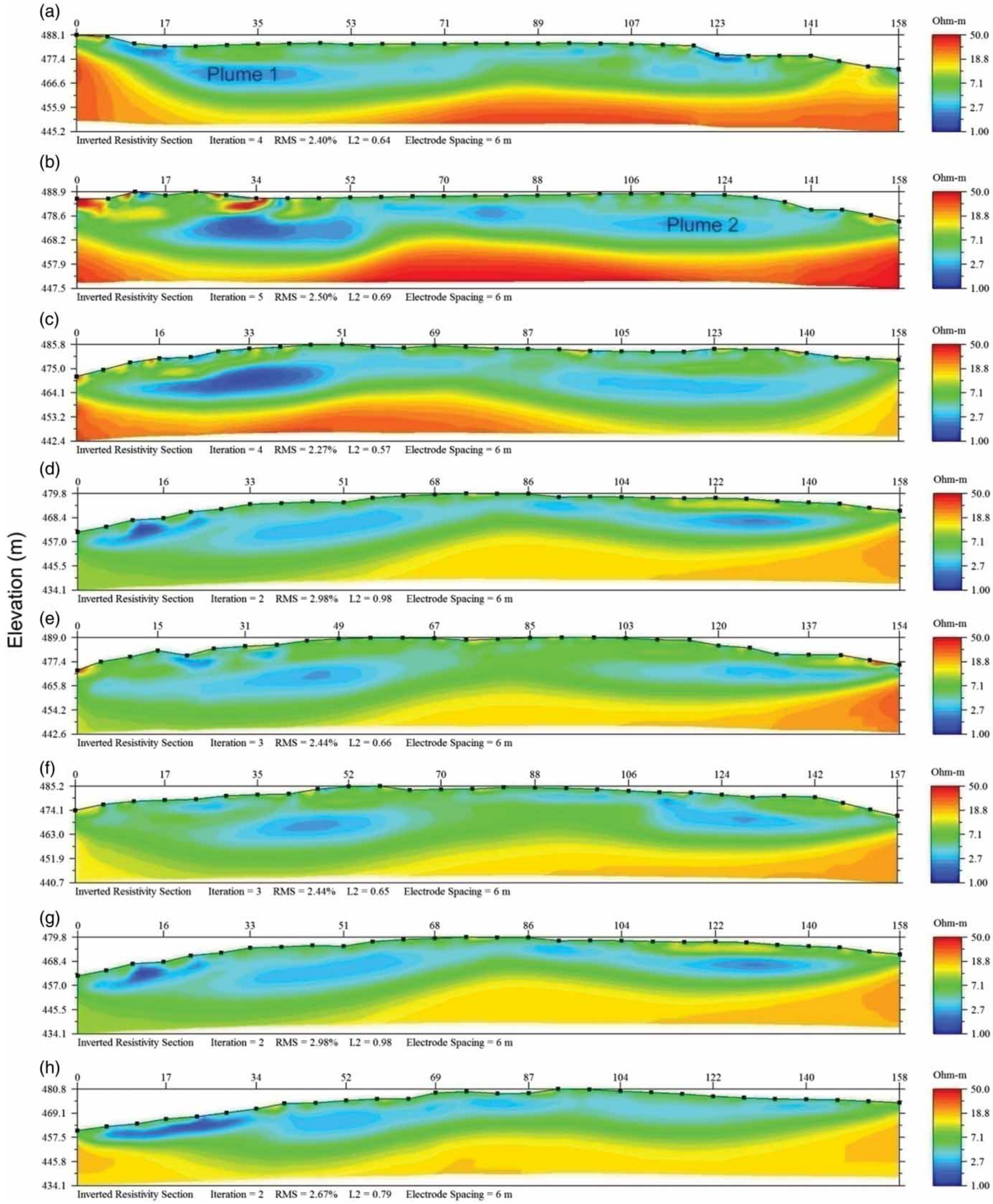

Figure 6. (a–h) Resistivity profile images along the profile line-01 to line-08, respectively, on the dumpsite. Data were acquired at 2.5-m electrode interval with 158-m total spread.

3. Results and discussion

3.1. Geophysical investigations from leachate-contaminated soils

All related data were collected in different phases. The 1D VES sounding data confirmed that the bedrock in the downstream area is about 3- to 5-m deep and have a simple two-layer earth model (Table 1 and Figure 3).[14,19] Moreover, the depth to the bedrock showed an increase/dip towards the river with a gentle slope. According to the resistivity pseudo-sections, gradual and concentric

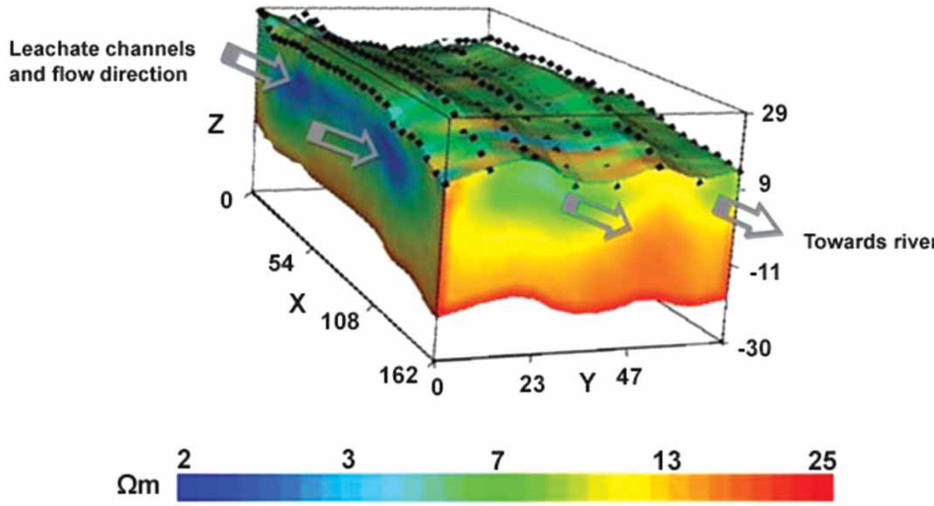

Figure 7. Three-dimensional cube synthesized from 2D imaging profile (a–h) obtained from the dumpsite. The section normal to *y*-axis and normal to *z*-axis indicates the flow patterns. The sections normal to *z*-axis reveal that the leachate flow is limited to around 10-m level.

weathering is well apparent in the subsurface. Closer to the river, the bedrock has weathered substantially with concentric layers. In addition to the identified natural geological features, subsurface channels and perched water accumulations could be well described due to the dumpsite leachate movement across the studied area. For instance, apart from the surface channel at the edge of the study area, a few subsurface channels possibly carrying leachate were identified (Figures 4 and 5).

3.2. *Geophysical investigations of the dump body*

Accordingto the resistivity values of the profiles 1–8 that are shown in Figure 6, low resistivity zones are clearly seen (1–2.7 Ωm). The results from the physico-chemical characterization of the leachate and samples from the top of the dumpsite confirmed high concentration of dissolved solids indicating a possible reason for the low resistivity values.[6] High degree of leachate accumulation at the near-surface is the possible cause for the low resistivity at this location. The movements of the plumes area are approximately 20–48 and 100–130 m on the horizontal scale from northwest to southeast direction (Figures 6 and 7). Within the depth detection limits of this survey, at about 40 m, there were no indications of the bed rock. The increment of resistivity values with depth reveals the degree of compaction of waste.

In detail, examining the profile 1 of Figure 6(a), the main leachate plume movement (Plume 1) beginning from the top of the dumpsite and spreading in both north-west and south-east directions along the dumpsite was observed. The plume spreads from approximately 17 m up to 53 m towards north-west direction on the horizontal scale with around 14.5-m depth on the vertical scale from the surface of the dump. Interestingly, visual sights of draining leachate at similar heights at south-east and north-west embankments in dumpsite further confirm the geophysical findings. Moreover, it was noted that the main plume (Plume 1) combines with the leachate collected at a surface location at around 100 m on a horizontal scale. In addition to this main leachate plume, a separate plume was observed at 110–120 m horizontally with approximately at 15-m depth limits (Plume 2).

Table 2. Monitoring data for leachates in Gohagoda open dumpsite (GS1–4 value ranges).

Constituents	GS1	GS2	GS3	GS4
pH	7.76	8.16	8.30	8.65
EC	13.86	31.40	4.55	3.20
Chloride	423	723	311	63
Alkalinity	1448	39606	3960	725
Hardness	285	2241	771	15
COD	2480	3020	730	610
TOC	1450	1830	410	370

Note: Results in mg/L unless pH; conductivity in mS/cm^{-1}.

An extended pattern of the main leachate plume movement can be examined at profile 2 in Figure 6(b). Hence, similar low resistivity values were noted at the same depth, where Plume 1 was identified. However, the main plume has been isolated as a separate pocket as shown in Figure 6(b). Moreover, Plume 2 can be identified as a more developed unit in profile 2. In addition to these plume movements, high resistivity spots (at 50 Ωm) have been identified at the dumpsite surface on the horizontal scale in profiles 3–5. These high resistivity spots are probably due to non-conductive materials that are present in the near-surface of the dumpsite such as rubber scraps and plastics.[6] As a most common landfill leachate management practice, landfill leachate is flushed out from the landfill site. In this sense, exact location of the perched leachate pockets in a particular landfill would provide information to the leachate management experts for its management. For instance, the leachate flushing well locations and its depth can be decided by analysing the resistivity images of the dump body. Hence, the acquired 2D resistivity results from Gohagoda dumpsite can be effectively used for the determination of the leachate flushing wells during its rehabilitation process.

3.3. *Characteristics of the leachate*

The chloride concentration, alkalinity, hardness ranged from 68 to 723; 725 to 39,606 and 15 to 2241 mg L^{-1}, respectively, during the study period. Further, the observed pH, EC, COD and TOC ranged between 7.76 to 8.65; 3.2 to 31.4 mS cm^{-1}; 610 to 2480 mg L^{-1} and 370 to 1450 mg L^{-1}, respectively (Table 2). In general, the analysed parameters showed a decreasing trend from GS1 to GS4 suggesting possible infiltration and attenuation of particular ions by soils. However, high concentration of chloride, alkalinity and hardness was reported at the GS2 point. This may be due to the accumulation of wastewater rich in ions from a nearby piggery. Moreover, the leachate collected from GS5 and GS6 points showed high concentrations of analysed parameters than the leachate collected from the channel. For instance, the chloride concentration ranged 3200–8300 mg L^{-1}at the GS5 point in the dumpsite. Previous characterization studies have reported that this leachate comprises high concentrations of heavy metals and inorganic ions.[14,20,21] It is well understood that the ER of soils is dependent upon various factors such as soil type, water content, saturation and pore fluid property.[22] In addition, the collection of landfill leachate that consists of various ions shows a decrease in ER.[4,22] Therefore, the recorded high EC, alkalinity, hardness and chloride in leachate confirmed that the resistivity survey data for leachate contaminated in the paddy field area and in the existing dump body.[1].

4. Conclusions

The main objective of the present study was to understand the subsurface characteristics of the dumpsite leachate-contaminated area of the existing dump at Gohagoda open dumpsite. The vertical electrode sounding (1D) and 2D techniques were applied to the leachate contaminated soils and existing dumpsite. The dumpsite leachate flows directly to the river Mahaweli from Gohagoda dumpsite and is characterized by a plunging basin towards the river. According to both 1D and 2D soundings, the bedrock was identified at a depth of 3–5 m in the downstream. In addition, downstream, the leachate flow is almost confined to the near surface and the flow pattern may have been influenced by the river water inflow beneath the 3-m level diluting the perch water influx. The flow patterns in the subsurface are partially controlled by the depth to the bedrock. The 2D resistivity data obtained from the dump body revealed that there is lateral and vertical migration of the dumpsite leachate mainly towards the river side. These movements could be further described as two plumes commenced from the top of the dumpsite and then moved down in both southeast (river side) and in northwest directions. Therefore, it can be concluded that the application of resistivity technique in characterizing the subsurface of the dumpsite is highly effective and reliable results can be obtained. Accordingly, the embankment at the southeast and northwest sides of the dump body can be constructed with compacted soils or liners to avoid leachate migration to the outside of the dumpsite as an initial step to avoid leachate contamination. In analysing the bedrock characteristics and subsurface flow movements of leachate, a corridor to the PRB can be located up to 3-m depth and up to 34-m length along the survey line 5 at the leachate-contaminated paddy field area.

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