

Research Article

Delineation of Leachate Plume and Subsurface Characterization Using Geophysical Method of Sisdol Landfill Site, Nepal

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Abstract

Leachate generated from landfill sites represents a major environmental threat, particularly to surface and groundwater resources. Conventional leachate monitoring using boreholes is a one-dimensional approach and does not adequately define the lateral and vertical extent of leachate plume migration. To address this limitation, an integrated geophysical and physico-chemical investigation was carried out at the Sisdol landfill site to delineate the depth and spatial extent of leachate plume migration. The study employed a two-dimensional electrical resistivity survey using Wenner and Wenner–Schlumberger array configurations, complemented by physico-chemical analysis of leachate and surface water samples. A total of six electrical resistivity survey lines were conducted within the landfill site, and five water samples were collected from upstream, on-site, and downstream locations. The resistivity images clearly distinguish leachate plumes, saturated and unsaturated waste zones, and the landfill base. The leachate exhibits very low resistivity values ranging from 0.47 Ωm to 6 Ωm , consistent with its high electrical conductivity of 35010 $\mu\text{S/cm}$. Physico-chemical analysis indicates elevated concentrations of heavy metals such as manganese, copper, zinc, nickel, iron, and lead in downstream water samples, while upstream samples remain uncontaminated. Lead concentrations exceeding permissible limits were detected at one downstream site. These findings confirm that the poorly managed Sisdol landfill site poses a serious risk to nearby water resources due to leachate percolation and direct discharge into the Kolpu Khola without proper treatment.

Keywords

ERT, Landfill Site, Leachate, Physico-Chemical Investigation, Geomorphologically

1. Introduction

1.1. Background

Nepal is a developing country. With economic development,

there's growth within the urban population annually. An increase in the urban population and a rise in the economic status of the people is causing an increase in the consumption of goods, which in turn increases the production of solid waste.

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The development of landfill sites always poses severe environmental problems in its vicinity and degraded the quality of soil, air, surface water, and groundwater. Dumping of solid waste inappropriately in an area can be the sole cause of the contamination of surface and groundwater through leachate infiltration, change in the natural soil properties which can be caused by contamination through direct contact of waste and mixing of leachate, the quality of the air get degraded by burning of wastes, flies and rodents in the dumping site can spread diseases, uncontrolled release of methane and other toxic gases by anaerobic decomposition and burning of waste [1]. People residing in the landfill vicinity are more affected by various activities happening in the landfill area. When the organic wastes get decomposed landfill sites produces unbearable foul smells and brings nuisance to people living in the vicinity of the landfill site. Problems are more serious in developing countries in comparison to developed countries, due to lack of technical infrastructures and manpower.

Among the various hazards generated from the landfill sites, leachate is the prominent one. Leachate production in the landfill site and its contamination with the groundwater and the surface water is a major threat to the ecosystem. Leachate is the viscous liquid that is formed with the degradation of organic substances with the mixing of other inorganic chemical constituents. The composition of the leachate varies with the age of the landfill site, seasonal variation, and the type of waste dumped in the site [2]. And the leachate from the landfill site contains both dissolved and suspended thousands of complex components. The chemical properties of the surface water and groundwater changes with infiltration of leachate. So, the concerned authority should make an effective solid waste management plan which has to be executed to conserve water resources and protect the environment. Unfortunately, in underdeveloped and developing countries, municipal solid wastes (MSW) is not appropriately disposed or managed [3].

Geomorphologically, the site has a concave hillside which was formed due to the continuous erosion by geomorphological agents. Sisdol landfill site was officially started operating on June 5, 2005, which was planned for short-term operation (2-3 years), is still receiving MSW from the Kathmandu Valley. The volume of leachate generation increases due to high rainfall in this region during the monsoon season.

With the development of the electrical resistivity survey and its ability to distinguish the host and target based on the resistivity offered by the substances, it has been widely used in hydrogeological surveys, mining areas, and geotechnical investigations and other environmental surveys [4]. The Electrical Resistivity method has been widely used for environmental monitoring studies like the modeling of groundwater flow patterns [5], delineating the hydrocarbon spills regions, identifying the region of marine water intrusion near coastal

regions [6], aerial survey of contaminant-filled trenches, delineating the leachate plume migration on landfill site [7]. The resistivity imaging technique is suitable in mapping the leachate plume migration since the leachate generated from the landfill has conductive nature [8]. Since landfills leachate has a relatively high conductivity than the surrounding materials, this makes the electrical resistivity tomography technique highly suitable for the detection of the leachate plume [9-11] as soluble ions in leachate plume will facilitate the flow of the electrical currents which in turn lowers the resistivity of the medium [12].

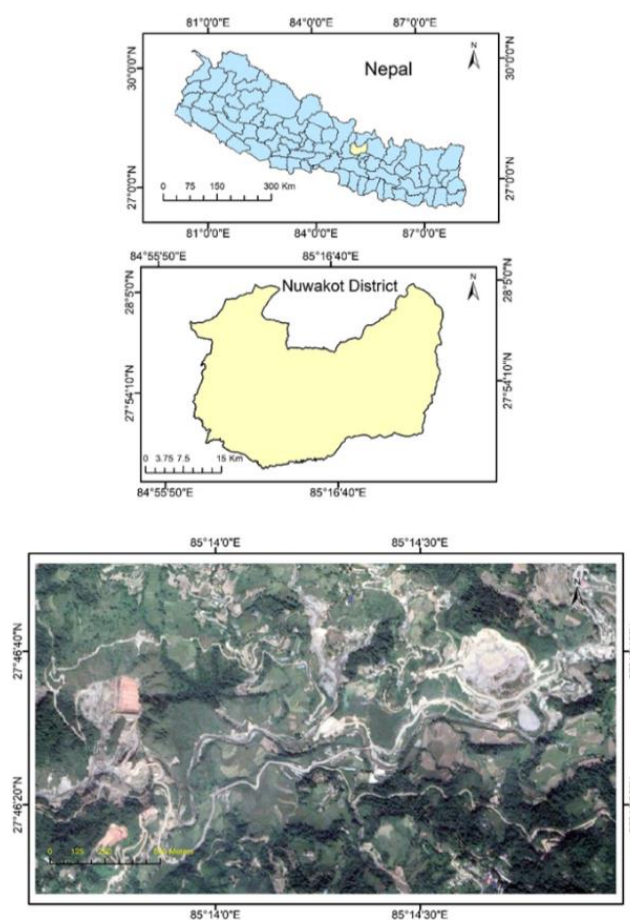


Figure 1. Study area.

1.2. Location and Accessibility

The study area is easily accessible via Balaju Bypass- Tinpi-Sisdol landfill site road. Public transport is available from Balaju Bypass to Tinpi. A motorable road is connected from Tinpi to the study area. Many tracks are connecting local villages that make the area accessible by motorbike and jeep. Figure 1. Figure 2 show the thickness of solid waste material.



Figure 2. Landfill site.

2. Methodology

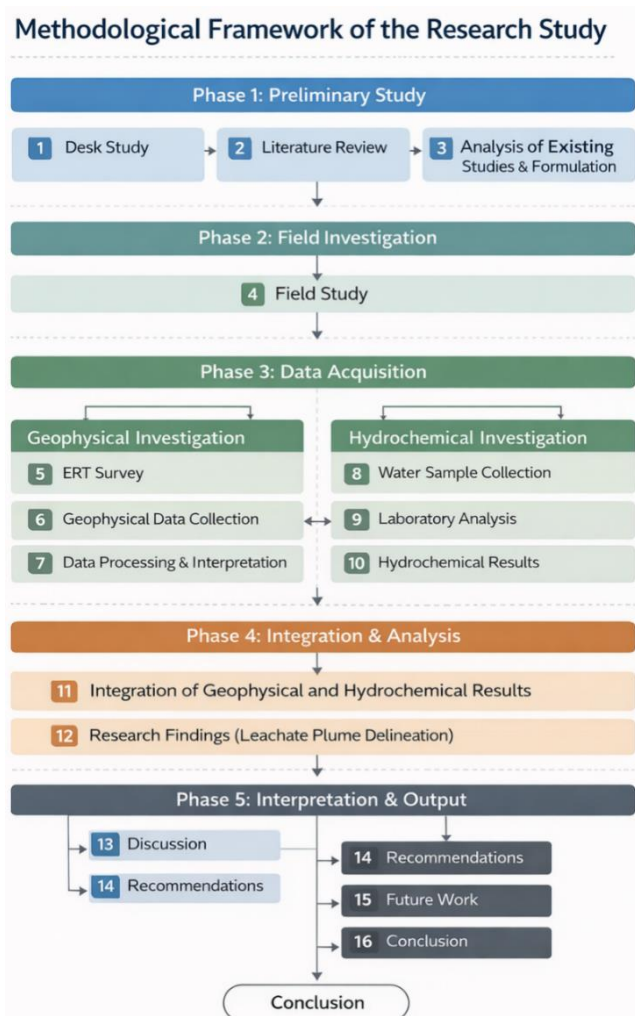


Figure 3. Flow chart of research study.

2.1. Wenner Array Configuration

This study, aimed at using an integrated approach inground

water and soil contamination at the selected twowaste dump sites is designed to involve two electrical resistivity field techniques, namely; In the Wenner array, potential electrodes are situated in between the current electrodes having equal a-spacing between electrodes. The electrode in the Wenner array for sounding is placed at equally incrementing a-spacing from the center of the array arrangement show in Figure 4. The current progressively passes into deeper layers, with a depth of investigation being equal to the distance between two consecutive electrodes. Depending upon the vertical conductivity variations of the subsurface, an apparent resistivity is calculated [13]. For the Wenner array, the geometrical factor is $G(k) = 2a$.

The apparent resistivity value ρ_a for this array is given by

$$\rho_a = 2\pi a \frac{V}{I}$$

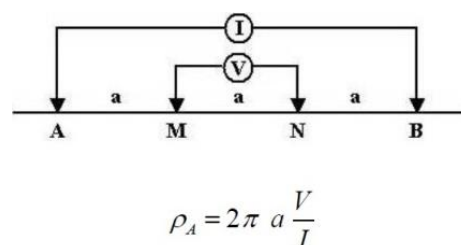


Figure 4. Wenner array Configuration.

In this method, a DC of known magnitude (I) is passed between the two outer (current) electrodes, thereby producing an electric field within the soil, whose pattern can be determined by the resistivity of the soil present within the field and the boundary conditions. The Wenner array is commonly used in profiling for lateral exploration of the ground, like soil testing, and sometimes VES for vertical exploration of the ground like defining horizontal layers [14].

2.2. ERT Data Acquisition (Instrumentation)

The resistivity measurements are obtained by injecting a known value of Direct Current (DC) into the subsurface with the help of two current electrodes “transmitter” and the resulting voltage difference is measured with the help of two potential electrodes “receiver”. In this two-dimensional electrical resistivity survey, an array of stainless-steel electrodes spaced in a defined interval is placed in the ground where different combinations or arrays of transmitting and receiving electrodes are used Figure 5.

Dataacquisition is carried out by using equipment known under the brand name WDJ-4 Resistivity Meter (WDJD -4 Resistivity/IP equipment manufactured by BTKS), China. The instrument is fully automatic and designed to measure apparent resistivity as well as induced polarization of the subsurface materials. In the noisy area, the signal is significantly enhanced by stacking data measured in many cycles (4-10

stacks). It consists of three main units all housed in a single casing: the transmitter, the receiver, and the microprocessor. The electrically isolated transmitter helps to send out well-defined and regulated signal currents. The receiver discriminates the noise of the area and measures voltages correlated with transmitted signal current from the transmitter. Finally, the microprocessor of the instrument monitors and controls operations and calculates the results. The apparent resistivity is calculated automatically and displayed in digital form. The main task of 2D-ERT is to search for the best fitting electrical model of the subsurface that simulates the apparent resistivity very close to the observations. In 2D-ERT, the observed.



Figure 5. Resistivity data acquisition arrangement.

Pseudo-sections are first prepared from the raw field data. Pseudo-sections show the variation of resistivity in the subsurface, which has been affected by the electrode arrangement and relative apparent resistivity distribution in the subsurface. The inversion of the pseudo-section was carried out to get the best fitting model of true resistivity distribution. The location of the 2D ERT survey conducted in the field **Figure 6** explain ERT profile number with the starting and ending coordinates with length is given in **Table 1**.



Figure 6. Resistivity data acquisition arrangement.

Table 1. Details of 2D ERT Survey coverages.

Profile No.	Length (m)	Electrode spacing in (m)	Start		End		Profile Direction
			Longitude	Latitude	Longitude	Latitude	
ERT-1	195	5	85 °14'35.09"E	27 °46'38.45"N	85 °14'42.63"E	27 °46'39.82"N	West to East
ERT-2	195	5	85 °14'40.10"E	27 °46'34.68"N	85 °14'38.80"E	27 °46'39.79"N	South to North
ERT-3	245	5	85 °14'42.15"E	27 °46'33.92"N	85 °14'39.49"E	27 °46'40.32"N	South to North
ERT-4	245	5	85 °14'43.82"E	27 °46'35.46"N	85 °14'40.47"E	27 °46'40.12"N	South to North
ERT-5	145	5	85 °14'38.48"E	27 °46'34.15"N	85 °14'43.55"E	27 °46'36.10"N	West to East
ERT-6	94	2	85 °14'34.93"E	27 °46'37.24"N	85 °14'32.07"E	27 °46'37.12"N	East to West
Total Length			1119 m				

2.3. Data Processing

The raw 2D electrical resistivity data is processed using an iterative constrained least-square inversion method to create a

model of subsurface resistivity by inverting the apparent resistivity data with the RES2DINVx64 program. The RES2DINV software generates the optimum resistivity image of the investigation target with the inversion of apparent resistivity data after analyzing the filtered and processed data. The data files are stored in the RES2DINV DAT format as this

program uses this format. This program uses a least-square smoothness constrained inversion scheme by subdividing the subsurface into many blocks in order to determine the appropriate resistivity value for each block [15].

Bad data points in the data set can effectively be identified and filtered as they show the stand-out point in the profile drawn of the data for each data level. To remove negative resistivity values from the data set before the inversion of the data, exterminate bad datum points features in the RES2DINV software was used.

2.4. Water Sample Collection

Water samples were carefully collected from five different locations of the study area in PET bottles. The temperature and pH were measured in the field. The pH was measured in the field by using the portable pH meter. The collected samples were put in the standard cooler box and transported to the laboratory. The collected samples were stored in the cold container at 4 °C. Before analyzing the water samples, they were put outside the cooler box and allowed to stay for some time at room temperature. Then, the samples collected were used to analyze the changes in the water chemistry and to know the chemical constituents of the leachate. For the analysis of the leachate and the surface water characteristics, the standard examination methods were used [16]. In Table 2 show the coordinates of water sample location.

Table 2. Water sample location.

S. N	Water sample Location	Co-ordinates
1	Collected about 600 m upstream of Kholpu Khola from the landfill site.	27 °46'50.13"N 85 °14'52.06"E
2	Collected from a small gully near the road about 100 m towards north from the sisdol landfill site	27 °46'40.57"N 85 °14'50.45"E
3	Collected from the landfill site	27 °46'35.57"N 85 °14'46.73"E
4	Collected from the kholpu Khola after the leachate from the landfill site get mixed in the river	27 °46'29.76"N 85 °14'40.26"E
5	Collected at about 3 km downstream (near to banchare danda, proposed landfill site) from the sisdol landfill site	27 °46'26.40"N 85 °13'51.33"E

The leachate sample collected within the landfill site has the flow rate <1 l/s whereas other samples collected have the flow >1 l/s. A total of 24 different physical and chemical parameters are considered for the analysis Table 7. To determine the heavy metals in the leachate and the water sample, AAS

method was used. Water samples were collected from five (5) different locations based on field observations and several reconnaissance fields trips. The location of each sample collected and their respective geo-location (Coordinates) are given in Table 6 and Figure 8.

3. Results

3.1. Electrical Resistivity Data Processing, Analysis and Interpretation

The electrical resistivity survey in the sisdol landfill site was done on the 7th of March, 2021 and 17th December 16, 2021. A total of six (6) 2D resistivity survey was conducted using Wenner array and Wenner-Schlumberger array on the Sisdol Landfill Site. ERT 1 ERT 5 and ERT 6 are in the east-west direction and other remaining ERT 2, ERT 3, and ERT 4 are in the south-north direction. The arrangement of the ERT lines in the field is shown in Figure 8.

The 2D resistivity field data were processed employing RES2DINV inversion software developed by Geotomo software, which divides the subsurface into various blocks and uses a square inversion process to find each block value. The resolution of the ERT survey depends on the arrangement of the electrodes, the spacing between electrodes, the signal to noise (S/N) ratio, and the type of inversion algorithm [17]. The initial damping factor value selected for the inversion is 0.15 whereas the minimum damping factor value selected is 0.02. The higher damping factor value for the first layer is 5. The result of the 2D electrical resistivity tomography of the study area is given below.

3.2. Analysis of Obtained Data

Based on the geophysical investigation carried out in different part of the country by other researcher for infrastructure development project and study carried out in Sisdol landfill area, a site-specific correlation table is prepared which is presented in Table 3.

Table 3. Resistivity value along the ERT survey profile.

S.N.	Material	Resistivity (Ω m)
1	Leachate plume	0.4 to 6
2	Saturated waste	5 to 20
3	Dry waste	15 to 25
4	Fractured and weathered rock	20 to 400

3.3. Interpretation (Resistivity Tomograms)

The model section which is obtained by the data inversion

using RES2DINV software is presented as the resistivity tomogram section. These resistivity tomogram sections show the variation of modeled electrical resistivity along the lateral line of investigation and along with the depth of the section.

The variations observed in the sections are due to the change in the physical properties of the sub-surface geology and the hydro-geological phenomena. There is a significant relationship between electrode spacing and the depth of investigation [18]. It is a fact that the depth of investigation is always less than the spacing of an electrode.

Depending upon the depth of interest, the spacing between electrodes is usually three or more times to depth. The maximum achievable depth of investigation depends upon the spread of the survey lines, type of array used and is usually 20% of the total ERT array length (distance between the first electrode and the last electrode of the survey) [4].

3.3.1. ERT 1

ERT-1 was carried out at the top cap of the Sisdol Landfill Site. The total length of this traverse is 195 m with an electrode spacing of 5 m. Pseudo section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 1 is shown in Figure 7. The Representative Resistivity tomogram is present in Figure 8 and the interpretative section of the ERT 1 is shown in Figure 9.

The electrode configuration used for the data acquisition is Wenner-Schlumberger configuration. The lithological section can be interpreted as a multi-layered model, the lithology shows marked variation in lithology location and structure. A low resistivity value of less than 40 Ωm dominates in the area of survey, which indicates the presence of highly saturated mass. The top layer on the left part of the section with a resistivity value above 110 Ωm is interpreted as a local soil material.

The ERT profile runs from West to East, with the west side being the starting point of the survey. The profile starts at the middle of the road below which exposure of the rock was observed in the field.

In this profile, various lithologies ranging in resistivity value from 5 Ωm to 620 Ωm can be observed in the resistivity section. Very low resistivity value with resistivity below 10 Ωm is interpreted as the presence of leachate plume in the saturated zone at chainage 0+82 to 0+095 at depth of about 6 m and 0+131 to 0+166 at a depth ranging from 5 m to 10 m.

3.3.2. ERT 2

The total length of this profile is 195 m with an electrode spacing of 5 m. The ERT profile runs from South to North, with the Southside being the starting point of the survey. The profile starts just above the road and runs on through the pile of solid waste on the slope to the top of the landfill waste.

In this profile, various lithologies ranging in resistivity value from 1 Ωm to above 30 Ωm can be observed in the resistivity section. Pseudo-section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 2 is shown in Figure 10. The representative resistivity

tomogram is present in Figure 11 and the interpretative section of the ERT 2 is shown in Figure 12.

Resistivity distribution along line ERT-2 showed high resistivity values at the top and the low resistivity value of 1 Ωm to 5 Ωm showing the presence of conductive plume of leachate at ERT profile chainage 0+28 m to 0+52 m at depth of 5 m to 10 m, from chainage 0+83 m to 0+117 m at depth of 13 m to 10 m and from chainage of 0+143 m to 0+172 m at depth of 10 m.

The lithological section can be interpreted as a multi-layered model; the lithology shows marked variation. A low resistivity value of less than 4 Ωm can be seen in the profile area of the survey, which is interpreted as the presence of percolating leachate plume in highly saturated mass. The top layer on the left part of the section with a resistivity value of 5 Ωm to 20 Ωm solid waste material. From chainage 0+090 m at depth of 40 m to the chainage of 0+148 m at depth of 20m, is interpreted as a local clay mass.

3.3.3. ERT 3

The total length for this profile is 245 m using the Wenner configuration with an electrode spacing of 5 m. Wenner configuration is used as the electrical resistivity survey array. Pseudo-section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 3 is shown in Figure 13. The Representative Resistivity tomogram is present in Figure 14 and the interpretative section of the ERT 3 is shown in Figure 15.

The ERT profile runs from South to North, with the Southside being the starting point of the survey. The profile starts at the middle of the road below where the exposure of the highly weathered and fractured rock mass was observed in the field.

The lithological section can be interpreted as a multi-layered model, the lithology shows marked variation in lithology location and structure. A low resistivity value of less than 40 Ωm dominates in the area of survey, which indicates the presence of highly saturated mass. The top layer of the section with a high resistivity value represents a solid waste deposit.

In this profile, various lithologies ranging in resistivity value from 0.5 Ωm to 60 Ωm can be observed in the resistivity section. As per the objective of this survey, a very low resistivity value at ERT chainage 0+025 m to 0+075 m, 0+085 to 0+097, and 0+119 to 0+150, and 0+192 to 0+220. The pool of leachate was observed on the field in between ERT chainage 0+025 m to 0+030 m on the field which is also observed in the profile.

3.3.4. ERT 4

The total length for this profile is 245 m using the Wenner configuration with an electrode spacing of 5 m. The ERT profile runs from South to North, with Southside being the starting point of the survey.

Pseudo-section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 4 is shown

in Figure 16. The Representative Resistivity tomogram is present in Figure 17 and the interpretative section of the ERT 4 is shown in Figure 18.

In this profile, various lithologies ranging in resistivity value from $0.7 \Omega\text{m}$ to above $60 \Omega\text{m}$ can be observed in the resistivity section. very low resistivity value at survey profile chainage of 0+22 m to 0+42 m, 0+68 m to 0+97 m, 0+125 m to 0+152 m, and 0+190 m to 0+224 m, which is interpreted as leachate plume.

The lithological section can be interpreted as a multi-layered model, the lithology shows marked variation in lithology location and structure. The layer at the bottom from chainage 0+105 at depth of 38 m from the surface to 0+198 m at depth of 25 m from the surface of the section with a comparatively higher resistivity value which is interpreted as a highly fractured rock as the base of a landfill site.

3.3.5. ERT 5

The total length for this profile is 145 m using the Wenner configuration with an electrode spacing of 5 m. The ERT profile was acquired almost along east-oriented-oriented traverses.

Pseudo-section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 5 is shown in Figure 19. The representative resistivity tomogram is present in Figure 20 and the interpretative section of the ERT 5 is shown in Figure 21.

The ERT profile runs from West to East, with westside being the starting point of the survey. The profile starts at the middle of the road below which exposure of the rock was observed in the field.

The lithological section can be interpreted as a multi-layered model, the lithology shows marked variation in lithology locations and structure. A low resistivity value of less than $20 \Omega\text{m}$ dominates in the area of survey, which indicates the presence of highly saturated waste mass. In this profile, various lithologies ranging in resistivity value from $0.7 \Omega\text{m}$ to $45 \Omega\text{m}$ can be observed in the resistivity section. As per the objective of this survey, the very low resistivity value of less than $2 \Omega\text{m}$ at 27.5 to 63 at depth of 8 m, Resistivity less than $2 \Omega\text{m}$ is also observed from 0+093 to 0+137.5 m on the section, this is the place where a pool of leachate was observed on the field. This helps us to interpret the leachate plume based on the resistivity on the profile section.

3.3.6. ERT 6

The total length for this profile is 94 m using the Wenner configuration with an electrode spacing of 2 m. The ERT profile was acquired along north-south oriented traverses.

Pseudo-section of measured apparent resistivity, calculated apparent resistivity, and the inverse model of ERT 6 is shown in Figure 22. The representative resistivity tomogram is present in Figure 23 and the interpretative section of the ERT 6 is shown in Figure 24. The ERT profile runs from east to west, with eastside being the starting point of the survey. A low resistivity value of $50 \Omega\text{m}$ to $110 \Omega\text{m}$ dominates in the area of survey, which indicates the presence of highly saturated rock mass. The high resistivity value from $110 \Omega\text{m}$ to $530 \Omega\text{m}$ is interpreted as the fracture bedrock in the sisdol landfill. The exposure of the rock can be seen in the slope on the roadside, Figure 5 and the arrangement of the multicore cable and the electrodes for ERT 6 in shown in Figure 25.

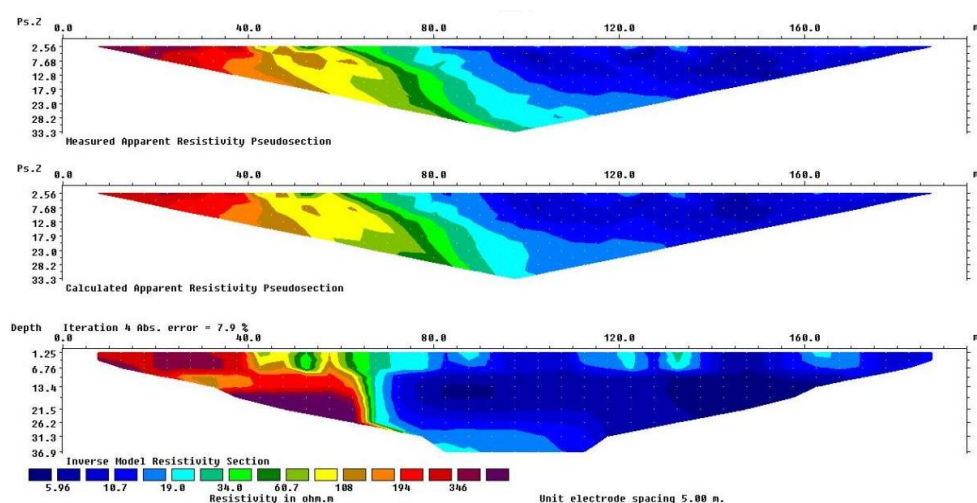


Figure 7. Pseudo section for the measured apparent resistivity, calculated apparent resistivity and inverse model ERT 1.

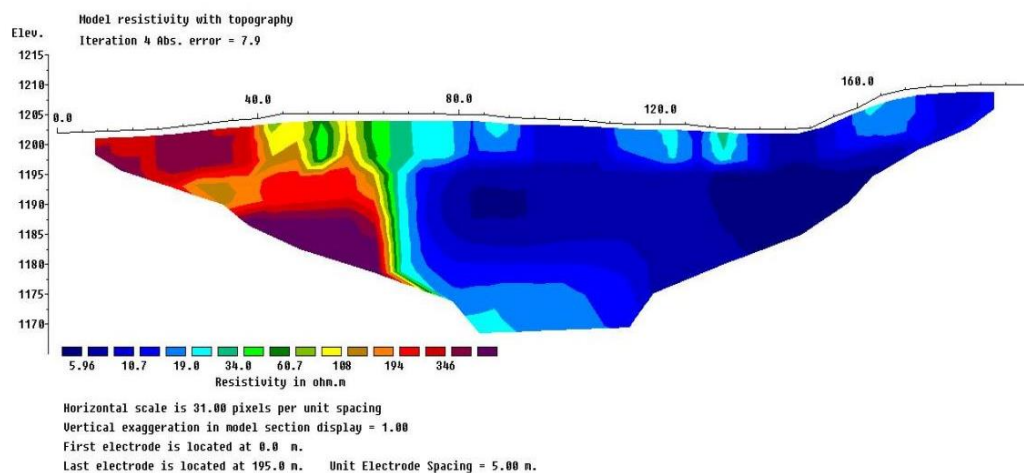


Figure 8. Resistivity image of ERT 1.

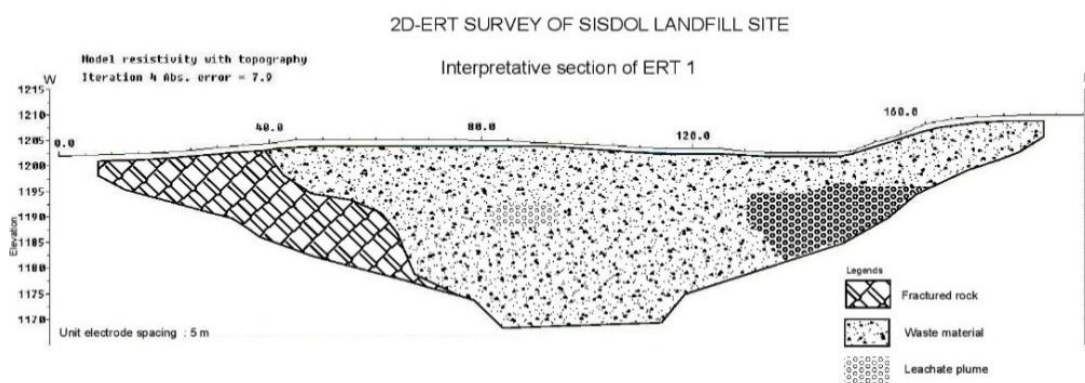


Figure 9. Interpretative section of ERT 1.

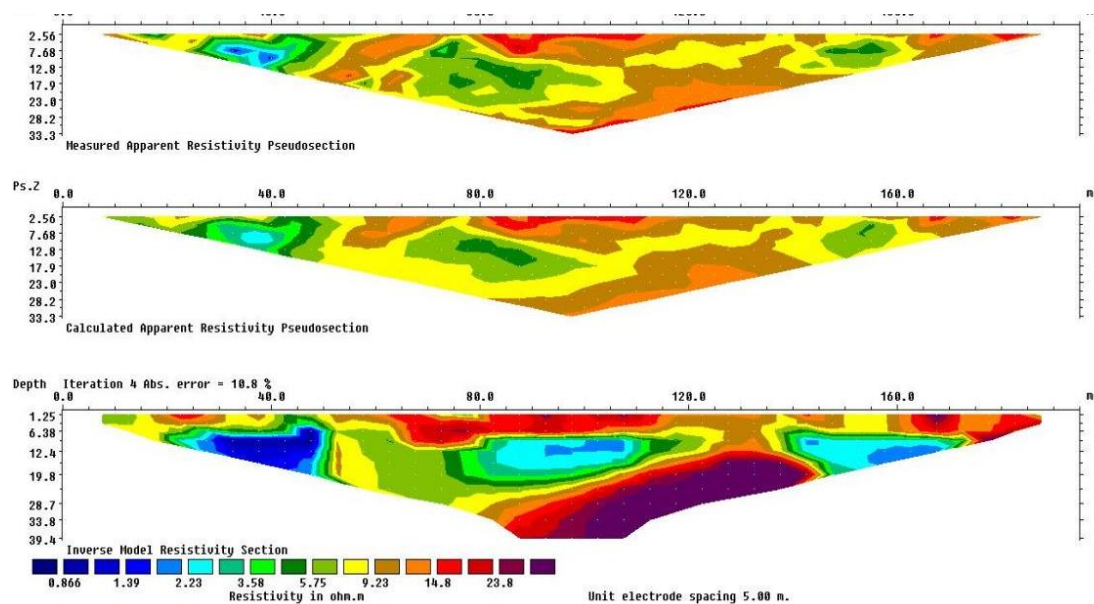


Figure 10. Pseudosection of measured apparent resistivity, calculated apparent resistivity and inverse model of ERT 2.

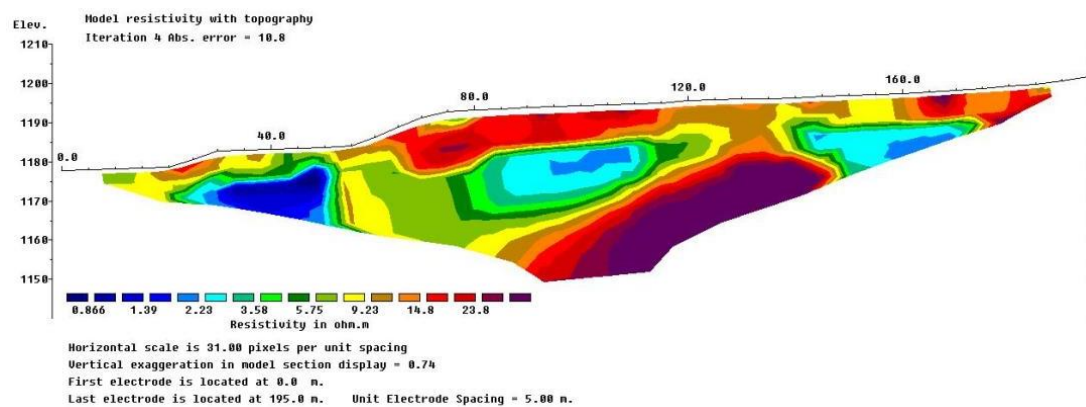


Figure 11. Resistivity image of ERT 2.

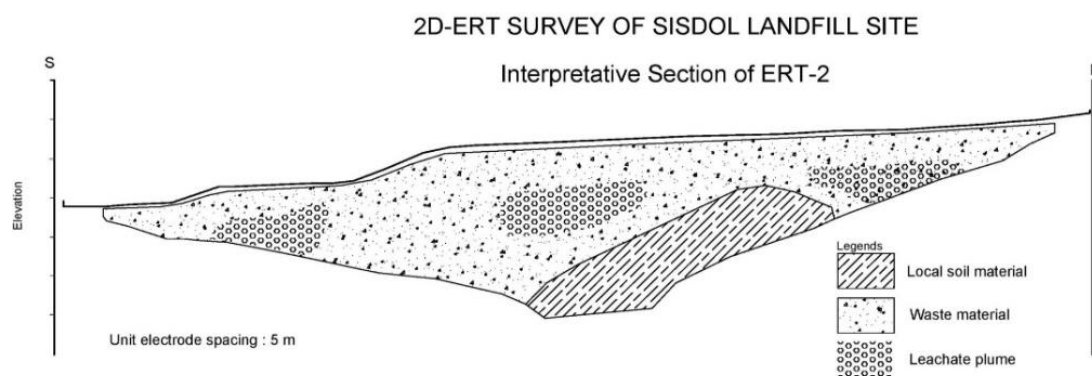


Figure 12. Interpretative section of ERT 2.

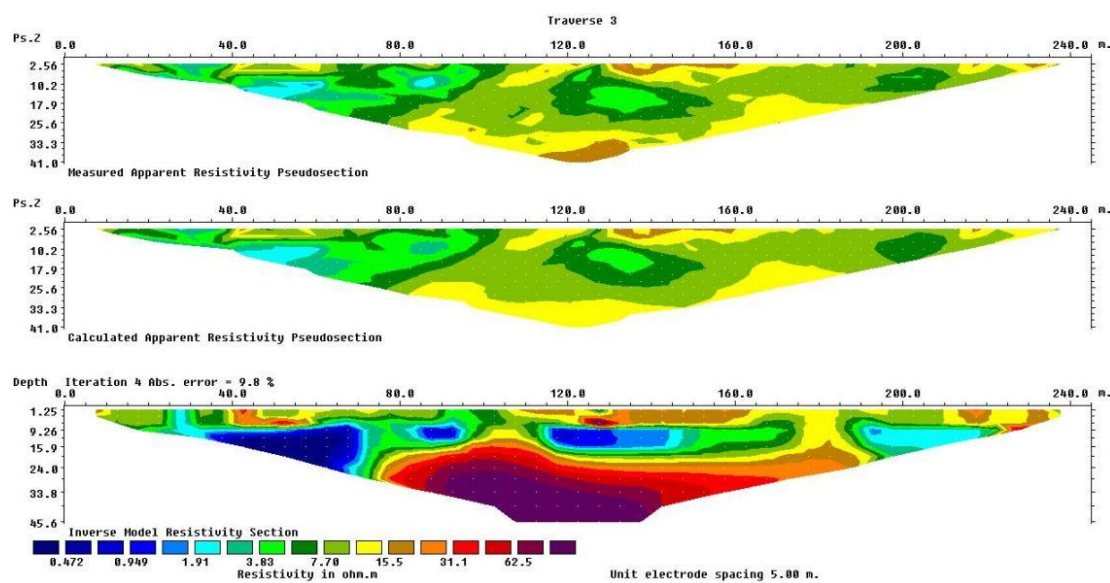


Figure 13. Pseudosection for measured apparent resistivity, calculated apparent resistivity and inverse model of ERT 3.

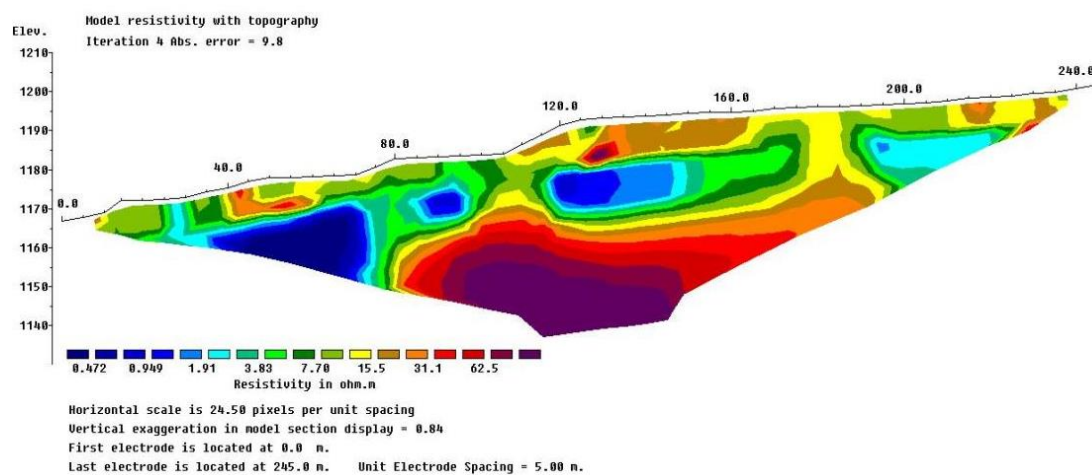


Figure 14. Resistivity image of ERT 3.

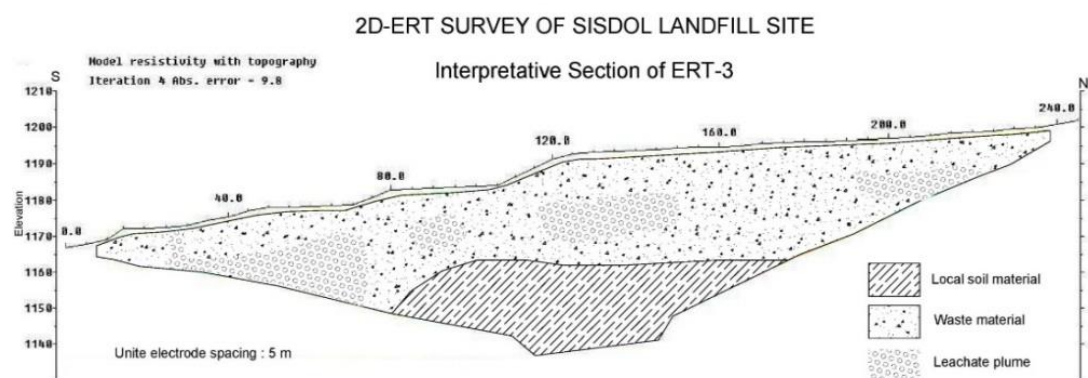


Figure 15. Interpretative section of ERT 3.

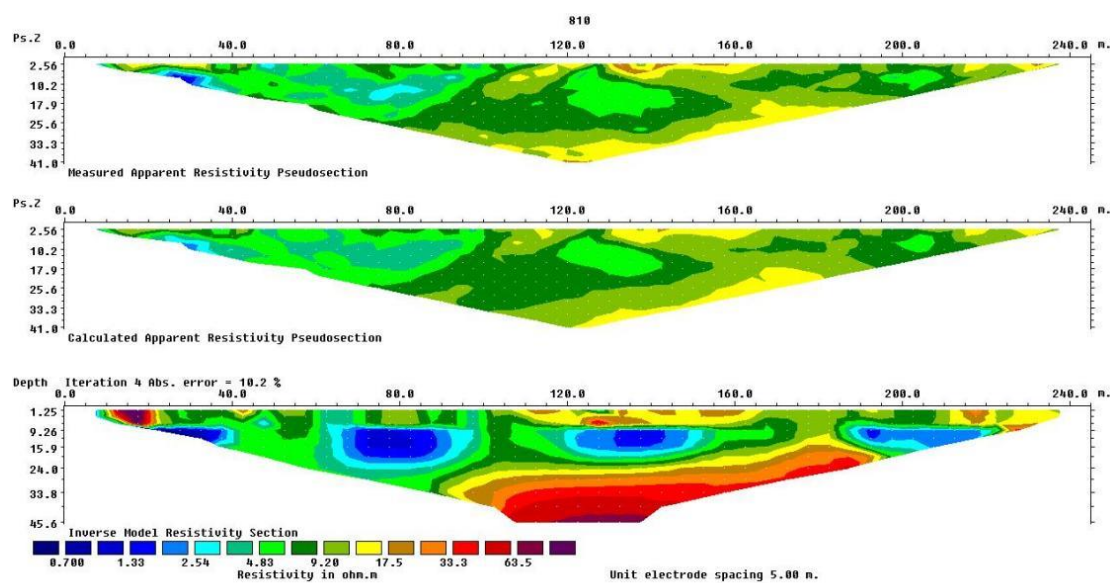


Figure 16. Pseudosection for measured apparent resistivity, calculated apparent resistivity and inverse model ERT 4.

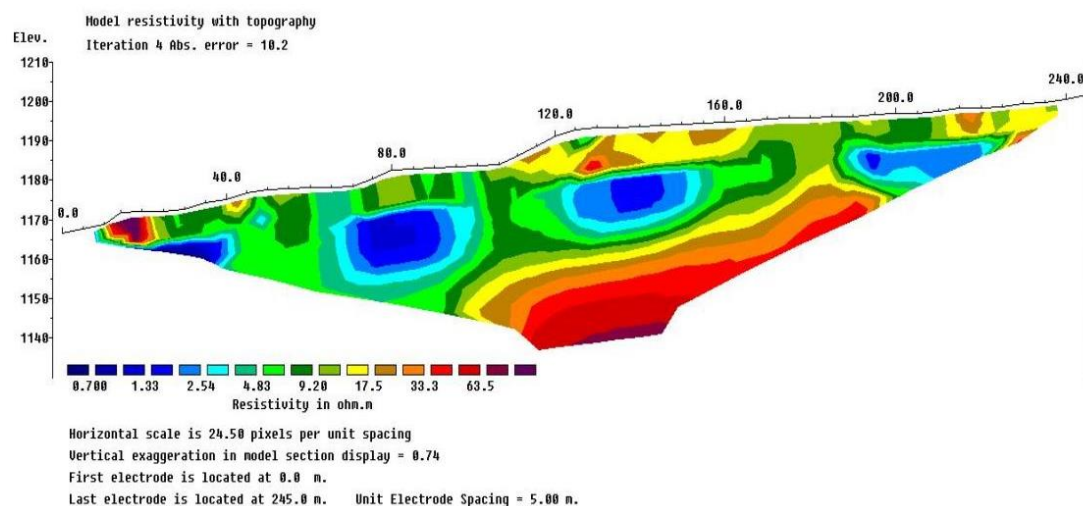


Figure 17. Resistivity image of ERT 4.

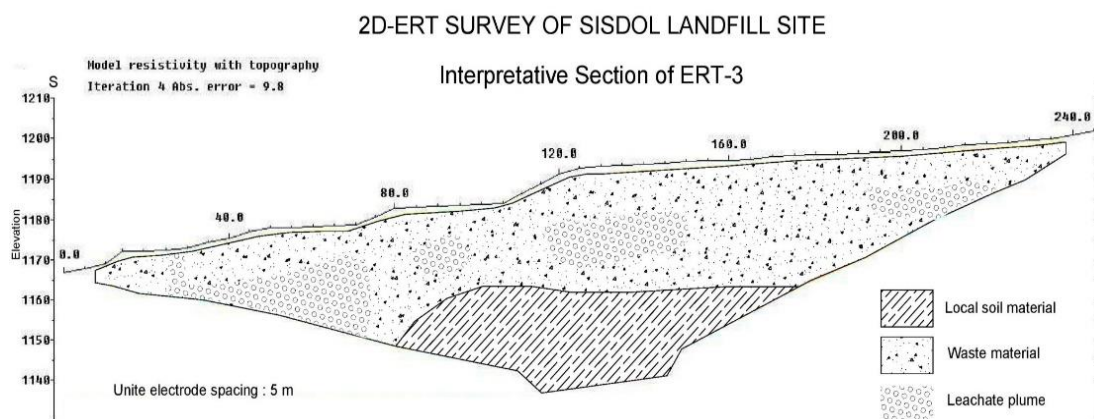


Figure 18. Interpretative section of ERT 4.

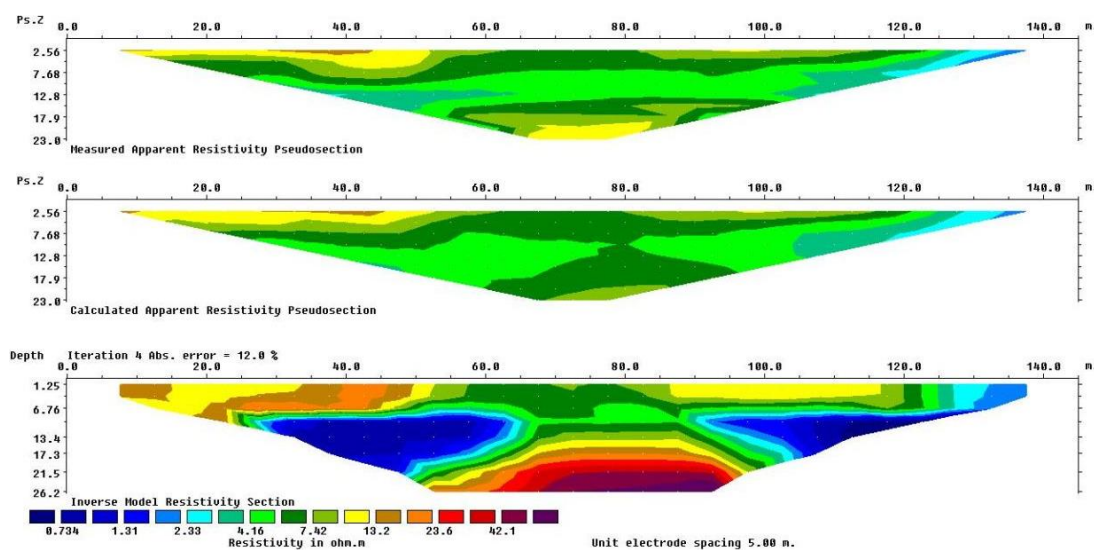


Figure 19. Pseudosection for measured apparent resistivity, calculated apparent resistivity and inverse model of ERT 5.

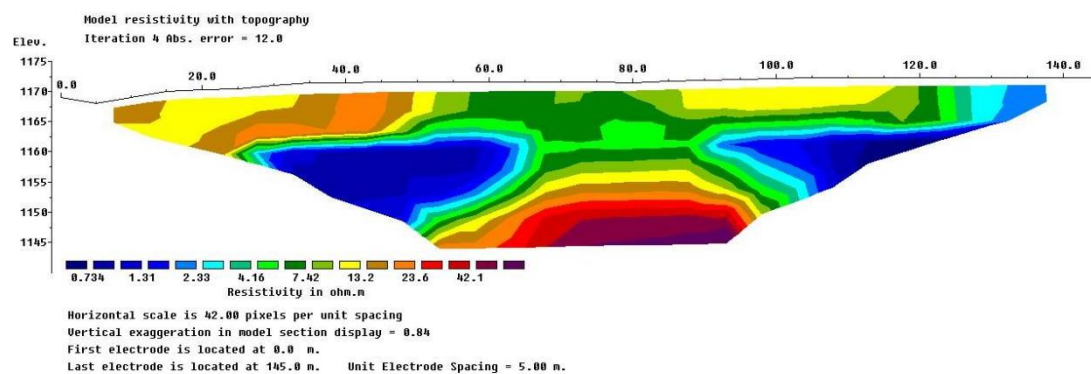


Figure 20. Resistivity image of ERT 5.

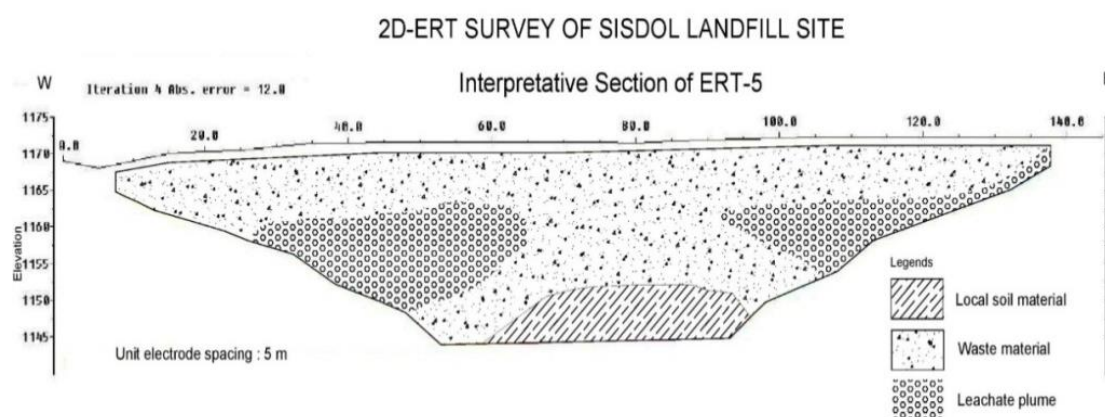


Figure 21. Interpretative section of ERT 5.

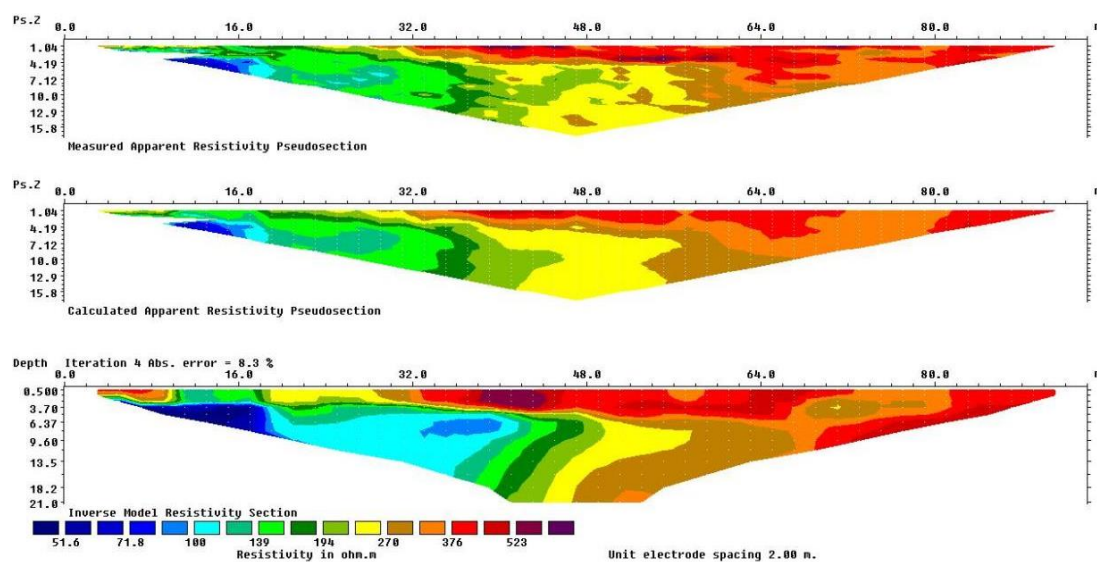


Figure 22. Pseudosection for measured apparent resistivity, calculated apparent resistivity and inverse model of ERT 6.

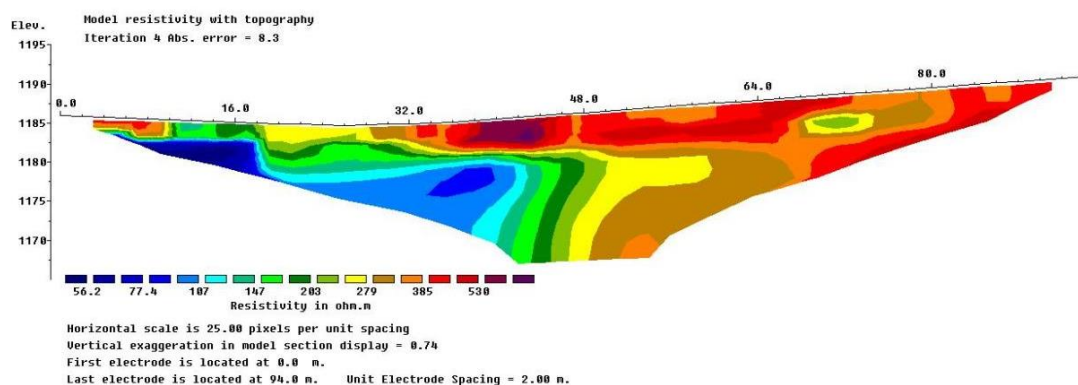


Figure 23. Resistivity image of ERT 6.

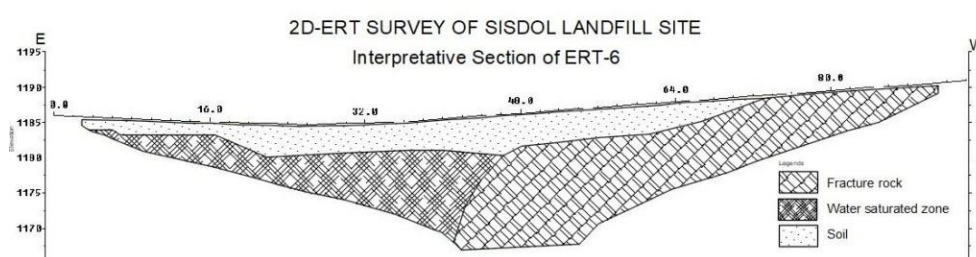


Figure 24. Interpretative section of ERT 6.

3.4. Physico-Chemical Analysis of Leachate and Water Samples

In this study, samples were collected on February 20, 2021 A.D. Samples were taken from five different locations in and

around the Sisdol Landfill Site which has been operating since 2005, and 24 measurements of physical and chemical parameters were analyzed. Table 4 show the basic characteristics like Temperature, pH, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Dissolved Solids (TDS).

Table 4. Leachate Characteristics at Sisdol landfill site.

Parameters	Standards	Site 1	Site 2	Site 3	Site 4	Site 5
Temperature		19	19	19	19	19
pH	6.5-8.5*	8.47	7.98	8.35	8.06	8.08
Conductivity	1500	194	203	35010↑	725	512
Turbidity	5(10)	2.37	8.87	1875↑	2595↑	896.00↑
Total Dissolved Solids (TDS)	1000 mg/L	100	103.3	17320↑	375.6	270.6
Total Hardness as CaCO ₃ (mg/L)	500 mg/L	88	116	790↑	188	208
Calcium Hardness as CaCO ₃ (mg/L)		20.04	21.64	769.54	52.10	164.33
Magnesium Hardness as CaCO ₃ (mg/L)		67.96	94.35	20.46	135.89	43.67
Chloride Content (mg/L)	250 mg/L	22.72	15.62	3031.70↑	71	53.96
Iron Content (mg/L)	0.3(3) mg/L	0.50↑	2.00↑	17↑	40↑	13.00↑

Parameters	Standards	Site 1	Site 2	Site 3	Site 4	Site 5
Arsenic Content (mg/L)	0.05 mg/L	ND	ND	ND	0.01	0.025
Parameters	Standards	Site 1	Site 2	Site 3	Site 4	Site 5
Ammonia (mg/L)	1.5 mg/L	0.2	15↑	12.5↑	50↑	50↑
Nitrate (mg/L)	50 mg/L	8	8	50	ND	10
Total Alkalinity as CaCO ₃ (mg/L)		190	60	24200	650	250
Total Acidity as CaCO ₃ (mg/L)		5	10	900	100	75
Free CO ₂ (mg/L)		ND	8.8	4840	88	110
Sulphate (mg/L)	250 mg/L	0.29	0.41	108.44	42.23	20.73
Biological Oxygen Demand (BOD) mg/L		89.20	24.33	81.09	186.5	16.22
Chemical Oxygen Demand (COD) mg/L		205.60	50.33	23506	574	351.5
Copper (mg/L)	1 mg/L	ND	ND	0.294	ND	0.045
Manganese (mg/L)	0.2 mg/L	ND	ND	2.344	0.847↑	2.85↑
Nickel (mg/L)		ND	ND	0.402	0.01	0.138
Lead (mg/L)	0.01 mg/L	0.01	ND	0.14	ND	0.21↑
Zinc (mg/L)	3 mg/L	0.01	ND	0.6248	0.0342	0.156

Electro Conductivity, Turbidity, Ammonia, Nitrate, Arsenic content, Chloride Content, Total Hardness as CaCO₃, Calcium Hardness as CaCO₃, Magnesium Hardness as CaCO₃, Iron Content, Arsenic Content, Total Alkalinity as CaCO₃, Total Acidity as CaCO₃, Free CO₂, Sulphate, Copper, Manganese, Nickel, Lead, Zinc have been determined at National Academy of Science and Technology (NAST). Atomic Absorption Spectroscopy method is used to analyses the heavy metals in the sample.

3.5. Leachate Characteristics

3.5.1. pH

Leachate generally has pH in the range of 4.5 to [19]. The pH of a young landfill site leachate has a pH less than 6.5 whereas the pH of the old landfill site is higher than 7. [20]. The bar graph, Figure 25, gives data about the pH value of samples collected from five different locations in and near the sisdol landfill site along kholpu Khola. The pH value ranges from 7.98 to 8.47 pH units. It is clear that the pH is higher than 8 except for site 2.

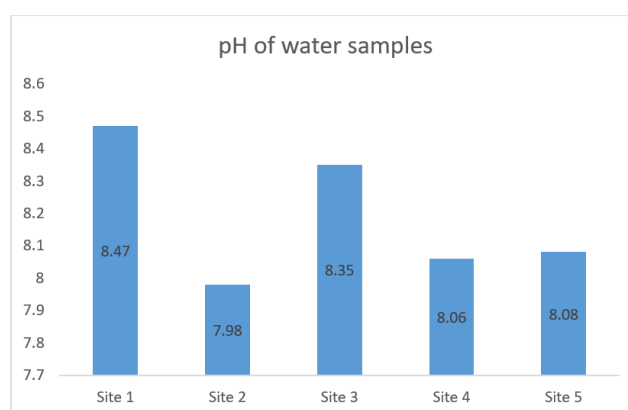


Figure 25. Distribution of pH values of five different samples.

3.5.2. TDS and Conductivity

Total Dissolved Solids measures mainly inorganic salts and dissolved organics. It measures the extent to which minerals are dissolved in the water and also higher concentration can change both the physical and chemical characteristics of the water [21]. The value of the TDS ranges from 100 mg/L to 17320 mg/L Figure 26, except for site 3 the value of the TDS is within the limit of Nepal drinking water quality standard, 2062. The conductivity of the leachate is 35010 micro siemens which is very high than the standard limit.

3.5.3. BOD and COD

Biological Oxygen Demand (BOD) is the measurement of the amount of oxygen required or consumed for the microbiological decomposition of organic material in water in 5 days. The higher value of BOD indicates the low quality of water with less amount of dissolved oxygen available in the water.

The BOD value ranges from 16.22 mg/L to 186 mg/L.

The COD value ranges from 50.33 mg/L to 23506 mg/L. The highest COD value is observed in the leachate sample from the sisdol landfill site and the COD value from site 4 and site 5 is comparatively high to site 1 and site 2, [Figure 27](#). Higher COD level in the sample is also evidence of the presence of inorganic and organic contaminants in the water.

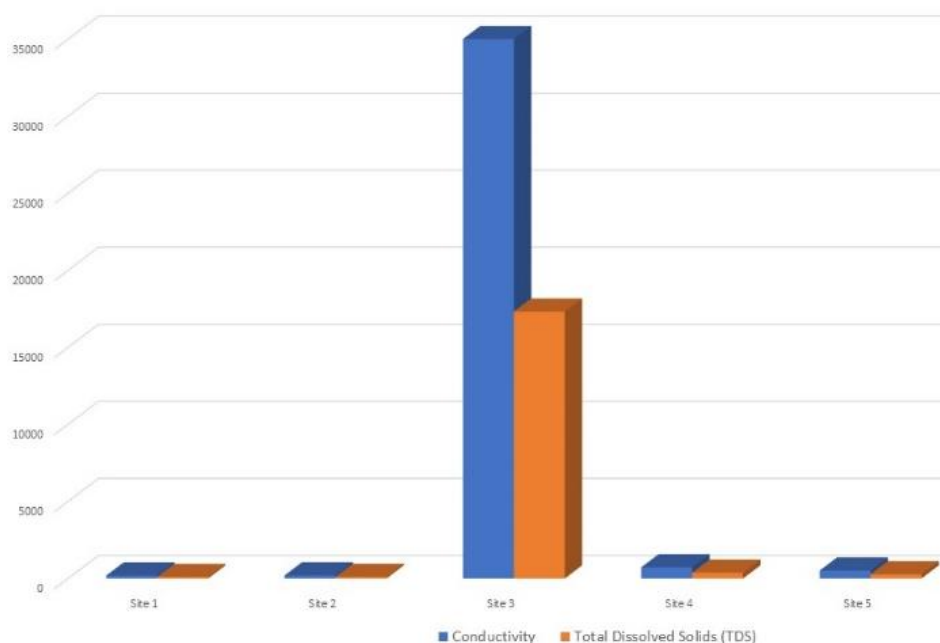


Figure 26. Conductivity and total dissolved solids in water samples.

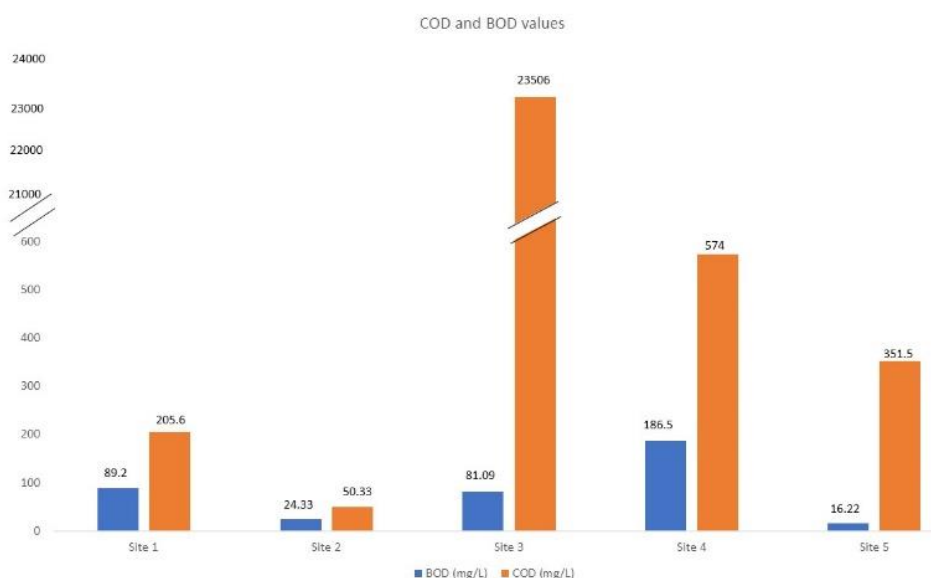


Figure 27. BOD and COD value of collected samples.

3.5.4. Heavy Metals

In high concentrations, heavy metals pose a threat to the

ecosystem. The concentration of heavy metals in the water doesn't only depend on the anthropogenic factors but also increases by the natural causes. In landfill sites, the concentration of the heavy metals in the sample depends on the age of

the landfill. During earlier stages of the landfill site, the concentration of the heavy metals is high because of higher metal solubility due to low pH of the leachate by the production of organic acids [22].

The bar diagram gives data about the presence of heavy metals like copper, manganese, Nickel, Lead, and Zinc in water samples. The Copper content ranges from 0.045 mg/L to 0.294 mg/L which are traced in samples collected from site 3 and site 5, Zinc content ranges from 0.01 mg/L to 0.6248 mg/L, which is high in site 3 with 0.6248 mg/L and lowest in site 1 with 0.01 mg/L, Figure 28.

Manganese content ranges from 0.847 mg/L to 2.85 mg/L, which is higher than the standard value of 0.2 mg/L. The volume of manganese found in site 3 is 2.344 mg/L where as in site 4, manganese is found to be 0.847 mg/L. The highest amount of manganese contamination is found in site 5 with the value of 2.85mg/l of volume. Manganese contamination is found in site 3, site 4 and site 5, which confirms the Kholpu khola contamination with the leachate from the Sisdol landfill site as manganese is not detected in the site upstream from the Sisdol landfill site. Lead is found in site 1 having value 0.01 mg/L and in site 3 and 5 with value of 0.14 mg/L and 0.21 mg/L respectively which is more than the standard value of 0.01 mg/L of Nepal drinking water quality standard. The Iron content ranges from 0.5 at site 1 to 40 mg/L at site 4.

3.5.5. Chloride Content

The concentration of the chloride depends on the age of the landfill site. The concentration of chloride for earlier stage landfill site ranges between 200-3000 mg/L and the concentration decreases to 100-400 for the older (5 to 10 years) landfill site [23]. The bar diagram, Figure 29, clearly shows that chloride content value in the five different samples is under the Nepal drinking water quality standard except for the leachate sample collected from the landfill site.

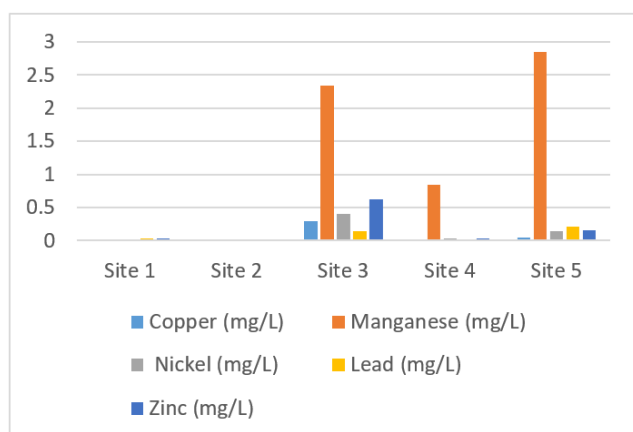


Figure 28. Heavy metal content in water samples.

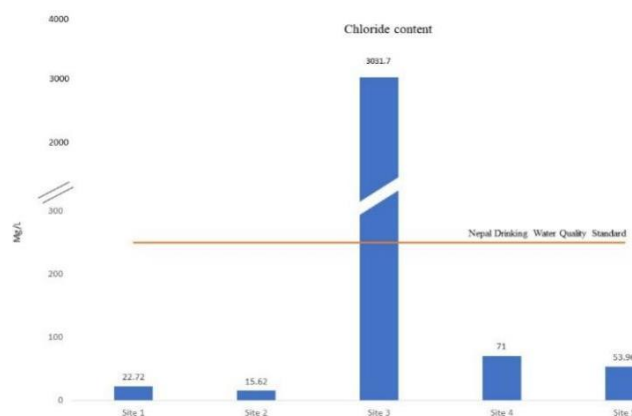


Figure 29. Chloride content in collected samples.

4. Discussion on the ERT Results

Non-invasive geophysical investigation method- 2D electrical resistivity method; was conducted in Sisdol landfill sites to locate the leachate plume within the subsurface. This method was chosen for its ability to locate the highly conductive leachate plume inside the landfill site. ERT survey was deployed in landfill site to map variations in the moisture content and the underlying subsurface condition along the line of investigation. Analysis of six 2D ERT sections suggests that some part in the section has very low resistive value and some have a high resistive value which helps to understand the landfill properties and the leachate plume in the landfill site.

The ERT 1 shows the contrast in the resistivity between the uncontaminated rock mass on the left part of the section to the surveyed waste deposited part of the Sisdol landfill site.

In ERT 2, a low resistivity value of less than 4 Ωm can be seen in the profile area of the survey, which is interpreted as the presence of percolating leachate plume in highly saturated mass. The top layer on the left part of the section with a resistivity value of 5 Ωm to 20 Ωm solid waste material. From chainage 0+090 m at depth of 40 m to the chainage of 0+148 m at depth of 20m, is interpreted as local soil mass in which the conductive fluid is percolated.

In ERT 3 section, various lithologies ranging in resistivity value from 0.5 Ωm to 60 Ωm can be observed. A very low resistivity value at ERT chainage 0+025 m to 0+075 m, 0+085 m to 0+097 m, and 0+119 m to 0+150 m, and 0+192 m to 0+220 m. The pool of leachate was observed on the field in between ERT chainage 0+025 m to 0+030 m on the field which is also observed in the profile.

In ERT 4 section, various lithologies ranging in resistivity value from 0.7 Ωm to above 60 Ωm can be observed. The very low resistivity value of 0.7 Ωm to 3 Ωm at survey profile chainage of 0+22 m to 0+042 m, 0+068 m to 0+097 m, 0+125 m to 0+152 m, and 0+190 m to 0+224 m is interpreted as leachate plume.

In ERT 5, the very low resistivity value of less than 2 Ωm from chainage 0+027.5 m to 0+063 m at depth of 8 m, and from 0+093 m to 0+137.5 m on the section is confirmed to be

the leachate plume as latter one is the place where a pool of leachate was observed on the field.

In ERT 6, the low resistivity value is found at a depth of 3 to 5 m from ert chainage 0+004 m to 0+045 m which is interpreted as a water saturated zone. The region having high resistivity value is interpreted as a fracture bedrock. The top layer is interpreted as a soil.

The very low resistivity value ranging from 0.4 to 6 Ω m in the section shows the leachate plume. The electrical conductivity of the water sample is an important indicator of the number of materials dissolved in the sample. The conductivity value of the leachate sample collected from the sisdol landfill site is 35010 μ S/cm which is a very high conductivity value, this, in turn helps to confirm the very low resistivity value as 0.28 Ω m of leachate. The resistivity value of the subsurface leachate plume in the inverse model is slightly higher than the resistivity value of the leachate sample due to the influence of overlying soil and waste materials.

ERT sections reveal that the leachate is found to be in a patch over the section. The leachate plume delineated in the inverse model suggests that the leachate plume is being accumulated in the subsurface and then migrated when it gets oversaturated. The inverse models indicate a presence of internal bund forming the leachate patches. The deep blue color in the inverted resistivity models is the accumulative leachate in the landfill site. This makes it easier to identify the leachate plume and delineate the contaminant plumes [24].

The electrical conductivity of the water sample is an important indicator of the number of materials dissolved in the sample. The high EC in the water collected downstream of the landfill site is an indication of its effect on the water resources.

4.1. Site 1

The water sample contains Iron Content beyond the standard at the time of analysis. The electrical conductivity is 194 micromhos/cm. The value of total dissolved solids (TDS) is 100 mg/L which is under the permissible limit.

Chemical oxygen demand (COD) 205.6 mg/L. Biochemical oxygen demand (BOD) is also 89.2 mg/L. Total alkalinity is at 190 mg/L. The total hardness of the sample at this site is 88 mg/L. Calcium hardness and magnesium hardness are at an average of 20.04 mg/L and 67.96 mg/L respectively (Table 8). The sulphate content is found to be 0.29 mg/L. The average chloride content in the sample is 22.72 mg/L.

The Iron content in the sample is 0.5 mg/L which is higher than the standard value of 0.3 mg/L (3 mg/L, when the alternative is not available).

4.2. Site 2

The water sample contains Iron Content and Ammonia beyond the standard at the time of analysis.

The electrical conductivity is 203 micromhos/cm. The value of total dissolved solids (TDS) is 103.3 mg/L. Chemical

oxygen demand (COD) on a given sample is 50.33 mg/L. Biochemical oxygen demand (BOD) is 24.33 mg/L. Total alkalinity as CaCO_3 is at 60 mg/L. The total hardness of the sample is 116 mg/L. Calcium hardness and magnesium hardness are at an average of 21.64 mg/L and 94.35 mg/L respectively (Table 8). The sulphate content is found to be 0.41 mg/L. The chloride content in the sample has a value of 15.62 mg/L than the standard limit of 250 mg/L.

The Iron content in the sample is 2 mg/L which is higher than the standard value of 0.3 mg/L (3 mg/L, when the alternative is not available).

4.3. Site 3

The water sample contains Conductivity, Turbidity, TDS, Total Hardness, Chloride Content, Iron Content, and Ammonia beyond the standard at the time of analysis.

The Electrical conductivity of the sample is 35010 micromhos/cm. The Total Dissolved Solids (TDS) of the sample is 17320 mg/L. The relatively high values of the electrical conductivity and TDS indicate the presence of inorganic materials in the sample collected from the landfill site. The increase in salinity due to an increase in TDS concentration also increases the level of toxicity in the water by bringing change in the ionic composition.

Chemical oxygen demand (COD) on average was more than ninety-four times as high at 23506 mg/L (standards = 250 mg/L). The value of Biochemical oxygen demand (BOD) is of 81.09 mg/L (permissible limit = 30 mg/L). The ratio of COD/BOD gives the value of 0.00345. The presence of high values of COD and low value of BOD and a low ratio of COD/BOD indicates that the sample contains a high amount of non-biodegradable materials. A low ratio of COD/BOD is likely to occur in the leachate sample collected from the landfill site as the landfill site has been in operation for more than 15 years. The low ratio of COD/BOD is evidence of the reduction of organic pollutants that are leaching in landfills over the period.

Total alkalinity and Total Acidity as CaCO_3 of the sample collected at the landfill site is 24200 mg/L and 900 mg/L respectively. The total hardness of the leachate samples is above the limit at an average of 790 mg/L (standard value: 500 mg/L). The calcium hardness and magnesium hardness of the sample are 769.54 mg/L and 20.46 mg/L respectively (Table 8). The sulphate content is found to be 108.44 mg/L which is less than the prescribed limit of 250 mg/L. The chloride content in the samples is higher at 3031.70 mg/L which is twelve times higher than the prescribed limit of 250 mg/L.

The leachate sample collected from the landfill site shows the presence of heavy metals like copper, manganese, Nickel, Lead, and Zinc. The Copper content is 0.294 mg/L, Zinc content is at 0.6248 mg/L and Manganese content is at 2.344 which is higher than the standard value of 0.2 mg/L. The Iron content in the sample is 17 mg/L which is higher than the standard value of 0.3 mg/L (3 mg/L, when the alternative is

not available).

4.4. Site 4

The water sample contains Turbidity, Iron Content, Ammonia, and Manganese beyond the standard at the time of analysis.

The electrical conductivity of the sample is 2595 micromhos/cm which is very high than the standard value. Chemical oxygen demand (COD) on average was more than two times as high at 574 mg/L (disposal standards = 250 mg/L). Biochemical oxygen demand (BOD) of the sample tested is 186.5 mg/L (permissible limit = 30 mg/L). The presence of high values of COD and BOD indicates organic strength. Total alkalinity as CaCO_3 is at 650 mg/L. Total hardness as CaCO_3 of the leachate samples is 188 mg/L. Calcium hardness and magnesium hardness were at an average of 52.10 mg/L and 135.89 mg/L respectively (Table 8). The sulphate content is found to be 42.23 mg/L. The chloride content in the samples is at 71 mg/L. The sample also shows the presence of some heavy metals like Manganese, Nickel, and Zinc. The manganese content is found to be 0.847 mg/L which is four times higher than the standard value of 0.2 mg/L whereas Nickel and Zinc content is 0.01 mg/L and 0.0342 mg/L respectively.

The Iron content in the sample is 40 mg/L which is higher than the standard value of 0.3 mg/L (3 mg/L, when the alternative is not available).

4.5. Site 5

The water sample contains Turbidity, Iron Content, Ammonia, Manganese, and Lead beyond the standard at the time of analysis.

Chemical oxygen demand (COD) of the sample is high at 351.5 mg/L (disposal standards = 250 mg/L). The biochemical oxygen demand (BOD) of the sample is 16.22 mg/L. The presence of high values of COD to low BOD indicates the increase in inorganic strength. Total alkalinity was at 250 mg/L. The total hardness of the leachate sample was above the limit at an average of 208 mg/L. Calcium hardness and magnesium hardness were at an average of 164.33 mg/L and 43.67 mg/L respectively (Table 8). The sulphate content was to be 20.73 mg/L. The chloride content in the samples is at 53.96 mg/L. The presence of Arsenic is also detected in this sample having a content of 0.025 mg/L where the permissible value is 0.05 mg/L of Nepal Drinking water quality standard.

The Iron content in the sample is 13 mg/L which is higher than the standard value of 0.3 mg/L (3 mg/L, when the alternative is not available).

The sample also shows the presence of some heavy metals like Manganese, Nickel, and Zinc. The manganese content is found to be 2.85 mg/L which is fourteen times higher than the standard value of 0.2 mg/L whereas Nickel and Zinc content is 0.138 mg/L and 0.156 mg/L respectively. A higher amount

of lead (Pb) is also detected in the sample containing about 0.21 mg/L which is twenty-one times higher than the permissible limit of 0.01 mg/L.

From Table 8, it is clear that a very high concentration of various chemicals is found on the leachate collected from the landfill site and the river water downstream. The leachate sample collected from the landfill site consists of high amounts of COD and BODs. Chemical oxygen Demand (CODs) is high in the landfill site sample which is due to the age of waste deposited. Similarly, heavy metals, Iron content, Lead, Nickel, Zinc shows evidence in the sample from the site.

5. Conclusions

Sisdol landfill site is one of the biggest landfill sites in Nepal. The Sisdol landfill site of the Nuwakot district is now a non-engineered open dumpsite situated on the hillside slope.

In this study, the electrical resistivity method is used to image the subsurface waste, geology of the area and helps to delineate the leachate plume of the landfill site. The following are the conclusions reached after this study.

The study reveals that the dumpsite consists of leachate plume, saturated waste material, dry waste material and weathered and fractured rock layer. ERT method is an effective method of detecting the leachate plume in the landfill site because there is high resistivity contrast between the leachate plume region to its surrounding region which helps in distinguishing the region of contamination. There is a contrast in resistivity because leachate has a high concentration of organic and inorganic chemicals leached from the municipal wastes dumped in the landfill site and leachate sample has the resistivity value of 0.28 Ω m.

During the study, some parts in the inverse models of the study show a very low resistive value and some have a high resistive value which helps to understand the landfill properties and the leachate plume in the landfill site. The very low resistivity value ranging from <1 to 2 Ω m in the section shows the leachate plume. Whereas the high resistive value on the left side of the ERT 1 is the fractured, weathered bedrock. The high resistive value overlying the low resistivity contaminated zone in the ERT 2, ERT 3, ERT 4, and ERT 5 represents the old unsaturated waste in the survey line.

In the present context, the landfill site lacks leachate collection and treatment facilities. Therefore, the leachate generated in the landfill site eventually ends getting mixed in the river and degrades the quality of the water. The samples obtained from the study area have a pH of 7.98 to 8.35 and have a very high electrical conductivity due to the high concentration of the major inorganic components. A higher pH value indicates that the landfill site is matured. The BOD and COD values of the leachate and the water samples collected downstream are much higher, this indicates the existence of organic and inorganic pollutants in the water decreasing its natural properties [25]. High concentration of TDS, Turbidity, Iron content, Ammonia, manganese, lead, etc. in the sample shows that the

quality of the water resources downstream of Kolpu Khola from the landfill site is highly deteriorated and is not suitable for domestic purposes. Also, the presence of Cl^- , Ammonia, and COD is evidence of the leachate presence in the sample collected 4 km downstream from the landfill site. As there is no other reason for the high concentration of these pollutants in the water, it is concluded that the leachate released from the landfill site into the river is the sole cause for the deterioration of the quality of water near the sisdol landfill site.

The 2D-electrical resistivity survey in the area and the physico-chemical analysis of the water samples from the study area proves the movement of the leachate from the sisdol landfill sites. The leachate plumes are delineated in the resistivity inverse model below the waste pile which also confirms that the electrical resistivity technique for delineating leachate migration is appropriate.

6. Recommendations

KMC needs to gear up its waste collecting, handling, controlling, and monitoring techniques to reduce the impact on the water resources and the surrounding environment. Leachate produced in the landfill site is a major threat to the environment. Many factors affect the leachate composition such as surface water, rainwater, type of waste dumped, etc. So, it is strongly recommended that the following may be taken into consideration in the future.

- 1) It is advised for the leachate treatment in the site as per the regulation.
- 2) Immediate research on the groundwater contamination by the leachate generated from the landfill site has to be done.
- 3) It is suggested to the KMC to segregate the waste to reduce the organic waste in the landfill so that leachate generated will be less.
- 4) A periodic study of the landfill site and its vicinity with a physico-chemical analysis of the GW and the surface water has to be done to know the impact of the leachate on the water resources of the area.

Abbreviations

2D	Two Dimensional
APHA	American Public Health Association
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CDG	Central Department of Geology
DHM	Department of Hydrology and Meteorology
DMG	Department of Mines and Geology
EC	Electrical Conductivity
ERT	Electrical Resistivity Tomography
GPS	Global Positioning System
KMC	Kathmandu Metropolitan City
LMC	Lalitpur Metropolitan City
MBT	Main Boundary Thrust

MCT	Main Central Thrust
MFT	Main Frontal Thrust
MSW	Municipal Solid Waste
STDS	South Tibetan Detachment System
SW	Solid Wastes
TDS	Total Dissolved Solids
VES	Vertical Electrical Sounding
ha	Hectare
l/s	liter per Second
m	Meters

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Conflicts of Interest

The authors declare no conflicts of interest.

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