# Use of Electrical Resistivity Tomography in Predicting Groundwater Contamination Due to Non-engineered Landfill

**Debaprakash Parida, Arindam Saha, and Ashim Kanti Dey**

**Abstract**  One of the major causes of groundwater contamination in urban areas is the flow of leachate from non-engineered landfills. Use of conventional test wells to predict the contamination is a cumbersome process. In this pilot study, a small-scale landfill having dimensions 4 m × 2.4 m × 0.6 m height was prepared to determine the efficiency of electrical resistivity tomography (ERT) in predicting groundwater contamination due to uncontrolled landfill. ERT survey was performed for five months, and the variations in groundwater contamination were observed. Water samples from the site were analysed for contaminant concentrations. The resistivity of the soil was found to be decreased considerably from around 200 to 20 Ω-m. This low resistivity zone ensured the presence of leachate flow followed by contamination of groundwater. The increased depth of low resistive zone below landfill evidenced the extended depth of groundwater contamination. Charts were prepared by correlating the contaminant concentrations in groundwater with the resistivity values. This chart may help in predicting the groundwater contamination and contaminant concentration using ERT, without making any borehole at a site. The study has evidenced the potential of ERT in predicting groundwater contamination.

**Keywords** Electrical resistivity tomography (ERT) · Leachate · Groundwater contamination · Non-engineered landfill

## 1 Introduction

Contamination of groundwater due to the leachate flow is a serious concern regarding the preservation of fresh drinkable groundwater in today's scenario. The presence of abandoned or existing non-engineered landfills poses threat to the fresh groundwater below the same land. Landfills are the facilities for the containment of wastes to safeguard the surrounding environment. Poorly maintained or improperly designed landfills impose adverse environmental effects on its immediate environment (Biswas

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et al. 2010). Many underground water sources are found to be severely affected by the uncontrolled dump sites. When rainwater percolates through the dump sites, it extracts toxic chemicals from the wastes. This toxic liquid that emanates from the dump sites is called leachate. Groundwater sources are more prone to contamination as the leachate percolates through the soil below the dump site. It is very difficult and time consuming to predict such contamination using only conventional methods. Moreover, conventional methods fail to provide full information on contamination of the whole site. Tracing of groundwater contamination is found to be more convenient with the use of geophysical techniques. Electrical resistivity tomography (ERT) method is more convenient than the other available geophysical methods to delineate the leachate plume emanating from the dump site (Lopes et al. 2012).

ERT is an advanced near-surface geophysical technique evolved to solve the complex field problems. This is a non-destructive method which does not need trenches, borehole (BH) and other destructive methods to serve the intended purpose. ERT survey needs a resistivity recording device and electrodes to determine the subsurface data including physical and geological characteristics (Abdul Nassir et al. 2000). Though this method is not very new, its extensive use in investigating the emerging environmental concerns needs to be explored to a greater extent. The depth of investigation can be increased by increasing the spacing between the electrodes along the resistivity profiles. A typical current flow pattern and potential distribution in a resistivity survey are shown in Fig. 1.

Geoelectrical resistivity method is based on the electrical property of the geomaterial to be surveyed. The knowledge of resistivity of various geomaterial is important in finding the composition of the earth material, moisture content, conductivity, etc. Resistivity imaging survey has played an important role in the field of applied geophysics for about last three decades. This technique was developed by Conrad Schlumberger in 1912, who performed the very first geological resistivity imaging experiment at Normandy. In 1915, Frank Wenner developed a similar idea in USA which offered a greater evolution to the field of applied geophysics in solving the difficult geological and geotechnical field problems. The theory of geoelectrical imaging is widely applied in the field of mining, hydrogeology, archaeological and engineering investigations. Knowledge of this technique has also proved to be very much effective in environmental and geotechnical investigation. Nowadays, geoelectrical imaging survey is mostly in use in various fields of civil engineering due to its interdisciplinary applications in subsurface investigation. Geophysicist

**Fig. 1** Current flow pattern and potential distribution in subsurface
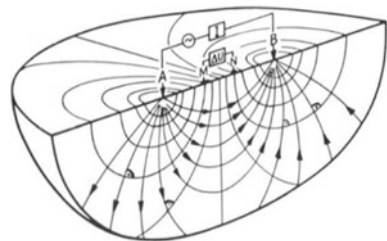
and geotechnical engineers have put their effort in implementing the geophysical technique as an easy, economic and cost-effective alternative to the conventional geotechnical methods being applied to the field of complex geotechnical, geological, environmental, geoenvironmental and hydro-geological problems.

The different types of array used during electrical resistivity tomography survey are Wenner array, dipole–dipole array, Wenner–Schlumberger array, pole–dipole array, pole–pole array. In comparison with Wenner array, the Wenner–Schlumberger array can better detect the horizontal subsurface resistivity variations. This array is suitable to characterize both horizontal and vertical structures as it is moderately sensitive to both types of structures. Wenner–Schlumberger array is the best choice between the dipole–dipole array and Wenner array where geological structures in both horizontal and vertical directions are expected in subsurface. In this research work, Wenner–Schlumberger array has been used as leachate will flow in both vertical and lateral directions.

This resistivity imaging method is not susceptible to the telluric noise which has a potential to affect the measured data observed at the site. This geophysical method is very much effective in observing both vertical and lateral variations in the subsoil properties. Electrical resistivity technique offers greater field productivity among other near-surface geophysical technique. The subsurface can be visualized in both 2D and 3D systems by the use of electrical resistivity imaging technique (Aizebeokhai 2010). Greater quality and reliability in subsurface resistivity data can be obtained through this technique. This technique measures the apparent resistivity data of the subsurface which is then processed, and inversion is carried out to get the true results. The observed resistivity of the subsurface material at the site is the apparent resistivity value. True resistivity values are obtained by the inversion of the apparent resistivity values using inversion software such as RES2DINV and RES3DINV in 2D and 3D resistivity survey, respectively.

This paper summarizes an extensive study on the effectiveness and applicability of the electrical resistivity technique in detecting the flow of contaminant at a contaminated site caused by a landfill by performing in situ investigations and laboratory experiments of collected groundwater from the observatory boreholes. The objective of this study is to correlate the resistivity values with contaminated groundwater parameters below a non-engineered landfill site.

## 2 Site Selection and Characterization

A municipal solid waste (MSW) dump was prepared within the NIT Silchar campus at a location 24.75 °N latitude and 92.79 °E longitude. From the meteorological data, it is observed that the average precipitation per annum is about 300 cm at the study area. The site was so chosen that the water table at that site is at a shallow depth from the ground surface. Flow of leachate from the modelled dump to the underlying groundwater was observed within a shorter time span as the groundwater table was at a shallow depth from the ground surface. For the selection of the site, resistivity

survey was carried out at three possible places in the campus after a preliminary investigation. The observed resistivity profiles at the sites, before selecting the final one, are presented in Figs. 2, 3 and 4. Among the possible sites available, the site 3 corresponding to Fig. 4 was finally selected as per the requirement of the experiment. There was no evidence of groundwater table at sites 1 and 2 for which these two were rejected for the proposed experimental work. Moreover, these two sites were filled soil where large amount of gravel and broken brick pieces were present. The selected site was at the foot of a stepped slope near a lake as shown in Fig. 5. The hydro-geological features at the site are presented in Fig. 6. The gravimetric flow of groundwater was along the slope of the natural ground surface towards the lake which was evidenced from the piezometric analysis of depth of groundwater in the observation wells at the site.
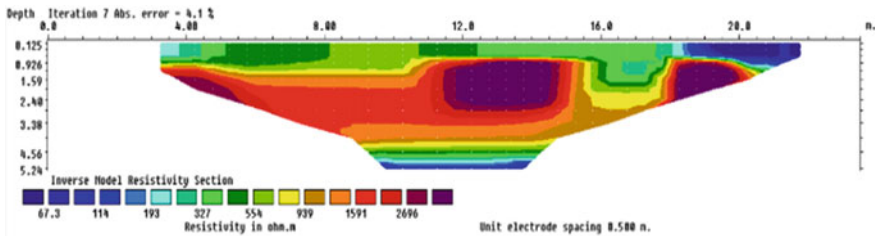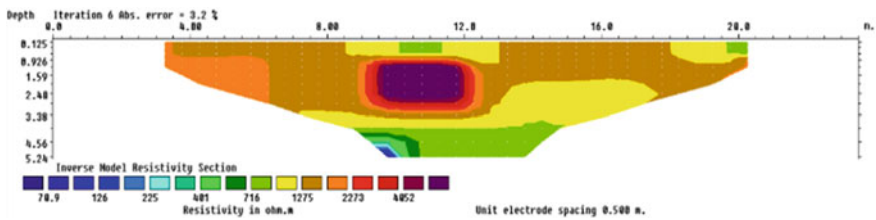


**Fig. 2** Resistivity profile at site 1



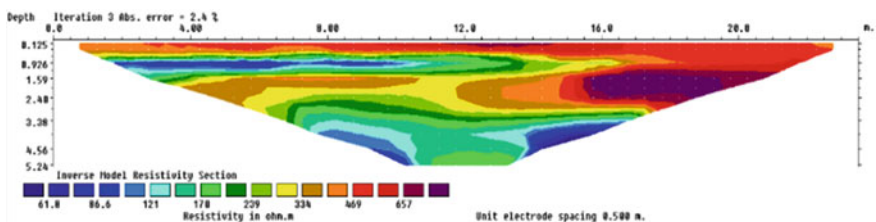**Fig. 3** Resistivity profile at site 2



**Fig. 4** Resistivity profile at site 3

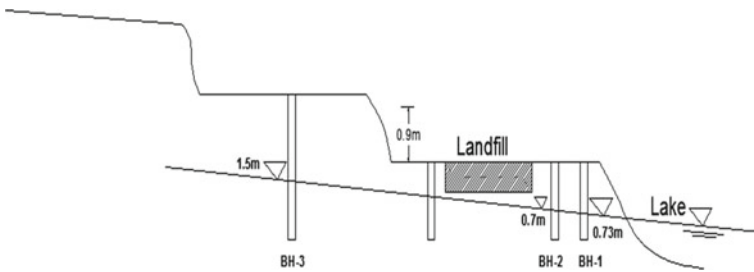**Fig. 5** Satellite image of the selected site



**Fig. 6** Hydro-geological features at selected site

## 3 Materials and Methods

### 3.1 Landfill Modelling and Waste Characterization

The MSW dump was prepared in November 2017. The depth of groundwater table was at 0.7 m from the ground surface. It was observed that silty clay soil was present at the site having coefficient of hydraulic conductivity of $3.174 \times 10^{-6}$ cm/sec.

A trench was prepared with size 4 m × 2.4 m × 0.6 m. The trench was made nearer to a lake. The prepared trench and the modelled MSW dump are shown in Figs. 7 and 8, respectively.

The trench was filled with discarded paper, food waste, cow dung, disposable plastics which were used to replicate the original MSW dumps. Cow dung was used as a waste material as it contains some minerals which cause groundwater contamination. Food waste attributes 40% of the total municipal solid waste in a
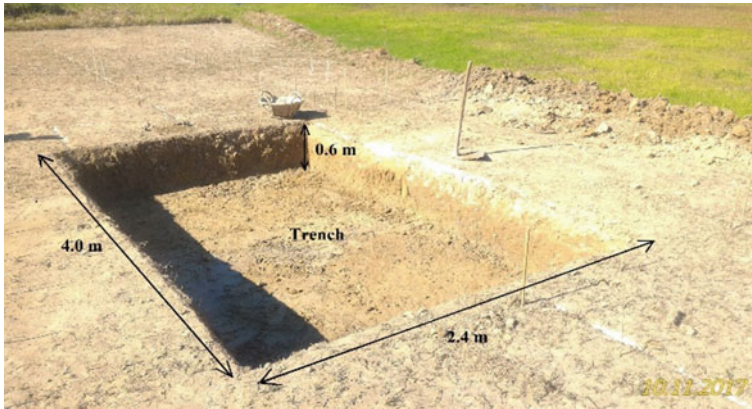
**Fig. 7** Trench prepared to accommodate the wastes



**Fig. 8** Model landfill at the site

landfill for which these were considered as the governing reasons for groundwater contamination at a landfill site. The model landfill was kept open to allow the rainfall and run-off to pass through wastes in the landfill followed by production of leachate from the model landfill. In the absence of rainfall, the landfill was watered on regular basis so as to produce leachate out of the landfill. It was observed that the top surface of the filled waste has been settled for an average depth of 16 cm which is due to the result of decomposition of organic waste in the dump.

## 3.2 Data Acquisition and Processing

Two ERT profiles on the downstream side, one on the upstream side and one on the landfill itself, were marked to conduct the resistivity survey along these profiles throughout the research period. The two downstream profiles were at a perpendicular distance of 0.5 and 1.5 m from the landfill, respectively, for profiles 2 and 3. A total of 48 electrodes were used at a spacing of 0.5 m resulting in a 23.5-m-long profile. Two- and three-dimensional resistivity tests were performed at every month to predict the groundwater contamination and visualize the flow of leachate from the model landfill. Positions of the ERT profiles near the model landfill are shown in Fig. 9.

   Through the arrangement, it was intended to measure the lateral as well as vertical spreading of the leachate below the model landfill. Resistivity survey was conducted throughout the research period along the predefined profiles from November 2017 to March 2018 at a regular interval. Accuracy of the electrode positions on the predefined profiles was ensured by inserting bamboo sticks inside the holes when no experiment was carried. Square grid pattern was used to arrange the electrodes for three-dimensional resistivity investigation surrounding the landfill. A spacing of 1.2 m was kept along X direction and that of along Y direction was kept 1.5 m. Syscal Junior-II was used as a multichannel resistivity measuring for the acquisition of data at the location. For optimization of input voltage, the instrument was equipped with automatic adjustment of output current value to result in a best measurement quality.

   A minimum of 3 stackings up to a maximum of 6 stackings were set with 99.5% confidence limit to get improved data quality during the experiments. For data acquisition, save energy mode was enabled with 800Vpp as maximum usable voltage. For the experiment, a total of three types of array configurations were used, e.g. Wenner array, dipole–dipole array and Wenner–Schlumberger array.



**Fig. 9** Model landfill at the site

The collected water samples were analysed for physicochemical parameters in laboratory. Efforts were made to correlate the observed physicochemical parameters of the contaminated groundwater with the true resistivity values. It was intended to determine the quality of the contaminated groundwater below and around the landfill by conducting resistivity survey without collecting the contaminated samples from the site for laboratory analysis. Three observatory wells, two on downstream side and the other on upstream side, were dug to monitor the contamination of groundwater and for collection of samples. The downstream boreholes were at 0.4 and 1.4 m away from the landfill, whereas the upstream borehole was at 1.2 m away from the landfill. To ensure the collection of the contaminated groundwater samples from the boreholes, the depth of observation wells was made 1.2 m from the ground surface. Resistivity imaging survey was carried out once in every month along predefined positions, and water samples were collected from the boreholes each time after the resistivity survey. As the natural slope of groundwater was towards the downstream side of the dump resulting in flow of the contaminated water towards the profiles 1 and 2 at the downstream side of the dump, the governing resistivity profiles are presented and analysed in the result and discussion section. The water quality parameters measured in the laboratory include alkalinity, pH, turbidity, sulphate, chloride, nitrate, iron, hardness, dissolved oxygen.

## 4 Results and Discussion

### 4.1 Resistivity Survey

Two-dimensional resistivity profiles were taken along the landfill at three different places. All the 2D ERT profiles at the site evidenced the depth of groundwater table at a shallow depth which was the main reason in choosing this site for the intended research work. ERT profiles 1 and 2 were at the downstream side of the landfill which was intended to capture the lateral flow of the leachate from the landfill towards the nearby lake. From the survey, it was known that the flow of groundwater was towards the profile 1 which was near a lake at the study site. It was observed from the profiles 1, 2 and 3 that the subsurface of the site is composed of clay, silt and sand. Analysis of the resistivity profiles indicated that the topsoil up to about 0.6-m depth was dominated by saturated clayey soil mixed with some portion of silt and the lower depth was dominated by the sandy soil which was later confirmed from the laboratory analysis of the soil samples taken from different depths. Generally, clayey soils have resistivity value within 100 $\Omega$-m. The resistivity values below 100 $\Omega$-m in the profiles 1, 2 and 3 were inferred as the presence of saturated clayey soil at the site. From the profile 3, the high resistivity values near the surface and at the left of the profile were inferred as the presence of red colour sandy clay. The resistivity values of the saturated clay at profiles 1, 2 and 3 were measured before and after dumping the waste in the trench for a comparative analysis. It was also intended to

observe the effect of leachate flow on the resistivity values those obtained in these profiles. Profile 3 witnessed the heterogeneity of the subsurface soil at the site.

A 3D ERT survey was also carried out around the proposed trench area to get a better idea on the stratification of the site along the depth. The presence of saturated clayey soil as well as the groundwater table was also observed in the 3D survey. This 3D survey was also intended to observe its efficiency in capturing the leachate flow after dumping the waste into the trench.

The two-dimensional resistivity profiles were taken at an interval of one month, and the water samples were also collected at the same time so as to facilitate the development of correlation chart between the resistivity values and the water quality parameters. The resistivity values from each of the profiles were interpreted and are discussed in this section. Resistivity profiles along the predefined locations on each month and the water quality parameters representing each of the resistivity profiles on respective months are also presented in this section. Later, the water quality parameters and the resistivity values for the corresponding profile for corresponding months are correlated and presented in the following sections.

**Resistivity and Water Quality Data for Profile 1**. Resistivity survey was carried out for a period of five months from November 2017 to March 2018, and water quality parameters were also determined for each of the investigated months for profile 1. The resistivity profiles for each of the investigated months are presented in Figs. 10, 11, 12, 13 and 14, and the test results for water quality parameters are shown in Table 1.

After one month of dumping and watering the waste in the landfill, resistivity profile 1 which is 1.5 m away from the landfill at downstream side of landfill showed reduced value of resistivity from about 80 to 70 Ω-m which was suspected as a result of leachate intrusion. As there was no significant decrease in resistivity value in the subsoil, therefore it was suspected as very negligible intrusion of the leachate
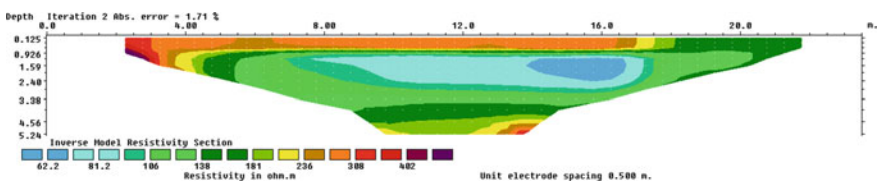


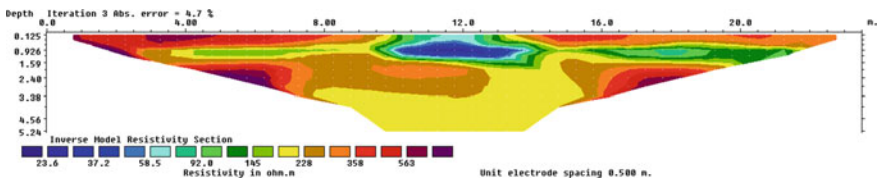**Fig. 10** Resistivity profile before filling the waste



**Fig. 11** Resistivity profile after one month of filling
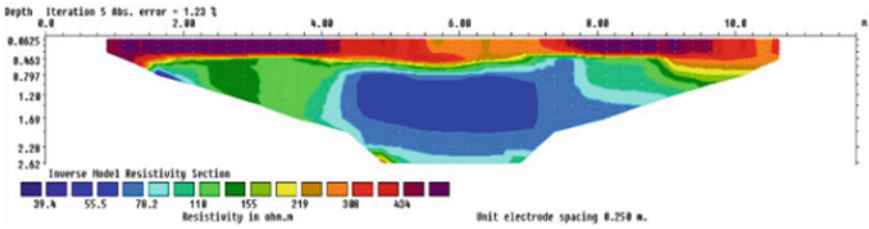
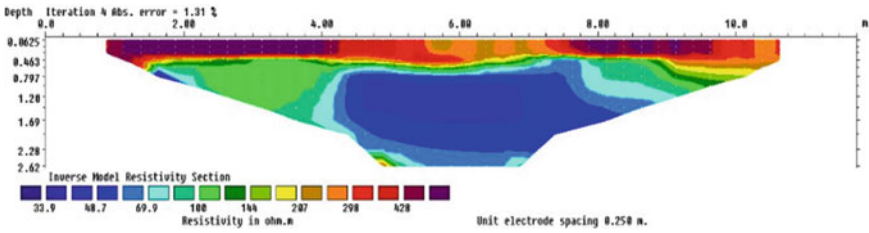**Fig. 12** Resistivity profile after two months of filling



**Fig. 13** Resistivity profile after three months of filling
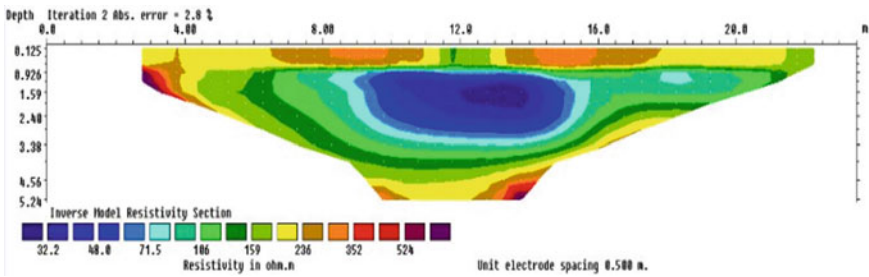


**Fig. 14** Resistivity profile after four months of filling

**Table 1** Physicochemical analyses of water samples for ERT Profile 1

| Parameters | Observed value | | | | |
|---|---|---|---|---|---|
| | November | December | January | February | March |
| pH | 6 | 5.8 | 5.1 | 5.3 | 5.5 |
| Turbidity (NTU) | 0.90 | 1.20 | 2.10 | 2.30 | 2.40 |
| Alkalinity (mg/l) | 10 | 40 | 30 | 26 | 22 |
| Chloride (mg/l) | 8.01 | 20.02 | 16.52 | 11.01 | 9.51 |
| Iron (mg/l) | 0.042 | 0.056 | 0.085 | 0.071 | 0.056 |
| Sulphate (mg/l) | 0 | 5.25 | 38.73 | 32.67 | 30.22 |
| Nitrate (mg/l) | 0 | 2.42 | 10.17 | 8.93 | 8.72 |
| Dissolved oxygen (mg/l) | 2 | 3.2 | 2.56 | 2.36 | 1.99 |
| Hardness (mg/l) | 38 | 52 | 40 | 54 | 42 |

transported through the saturated pores of clayey soil in the subsurface. The physic-ochemical analysis of the water sample, collected near this profile, witnessed very negligible increase in the contaminant concentration. The small reduction in the resistivity value below profile 1 was therefore discovered as a result of negligibly increased contaminant concentration in the groundwater. This change in resistivity value informed about the sensitivity of the resistivity survey in capturing the changes in contaminant concentration in the groundwater.

To detect the contaminated zone very minutely, the electrode spacing in the second month has been reduced to 0.25 m. The maximum depth of investigation is up to 2.62 m. ERT profile 1 conducted during the month of December has shown a drastic reduction in resistivity values. The resistivity of the contaminated zone is ranging between 50 and 55 $\Omega$-m, much lower than the resistivity before contamination. Physicochemical analysis has also shown increase in contaminant concentration. The width of contaminated zone is around 1.5 m, and the contaminated zone was about from depth 0.8 to 1.7 m. In third month, the resistivity value of the contaminated portion value decreased from the second month and was in the range of 40–45 $\Omega$-m. The wide contaminated zone was 3.13 m, and contaminated zone started from the depth of 0.84 to 2.28 m. There was some precipitation during the fourth month, which affected the changes in contaminant concentration in groundwater along with the leachate. It was observed that the contaminant concentration somehow reduced in the groundwater due to the precipitation. The resistivity survey also witnessed some similar effect due to precipitation. Most of the resistivity data were observed to follow the changes in the concentration of the physicochemical parameters of the groundwater. The area of the contaminated zone increases largely. There is rise in water table following the precipitation. The contamination zone started from a depth of 0.6 m and spread up to a depth of 3.1 m. The maximum depth of flow of leachate increased at subsequent months as predicted from electrical resistivity tomography. The variation of depth of groundwater table noted from observatory well 1 is also tabulated below. The variation of maximum depth of flow and the width of flow are presented in Table 2.

**Table 2** Groundwater table and resistivity details for ERT Profile 1

| Time | Depth of natural groundwater level (m) | Resistivity range of the contaminated zone ($\Omega$-m) | Width of contaminated zone (m) | Maximum depth of contaminated zone (m) |
|---|---|---|---|---|
| Before contamination | 0.7 | 70–75 | NA | NA |
| 1st month | 0.75 | 55–60 | 1.5 | 1.2 |
| 2nd month | 0.78 | 50–55 | 2.5 | 1.7 |
| 3rd month | 0.8 | 40–45 | 3.5 | 2.3 |
| 4th month | 0.65 | 45–50 | 5.5 | 3.1 |

**Resistivity and Water Quality Data for Profile 2**. Along profile 2, the resistivity survey was also carried out which is nearer to the landfill and the corresponding water quality parameters were also determined in the laboratory. Two-dimensional resistivity profiles along the profile 2 are presented in Figs. 15, 16, 17 and 18, and the test results for water quality parameters are presented in Table 3.

The physicochemical analysis of water samples witnessed more fluctuations in borehole 2 which was nearer to the landfill rather in the borehole which was away from the landfill. The parameters which were more affected by the contamination in borehole 2 include pH, acidity, alkalinity, chlorides, sulphate, nitrate, turbidity, hardness and iron. The pH value indicated the acidic nature of the groundwater where the value was reduced from 6.0 before contamination to nearer 5.5 after contamination. The parameter which was most influenced by the contamination was iron concentration. Iron concentration was increased from 0.042 mg/l before contamination to 0.959 mg/l after contamination, which informed about the sensitivity of iron contamination in the groundwater at the investigated site. Even within one month of waste filling, iron concentration exceeded its standard value of 0.300 mg/l recommended by the Indian standard code of practice for drinking water. Similarly, sulphate concentration was also more pronounced after the leachate being introduced in the groundwater.

After the precipitation during March 2018, changes occurred in contaminant concentration in groundwater along with the leachate. It was observed that the contaminant concentration somehow reduced in the groundwater due to the precipitation. The resistivity survey also witnessed some similar effect due to precipitation. Most of the resistivity data were observed to follow the changes in the concentration of the physicochemical parameters of the groundwater. Resistivity survey also showed very less flow of leachate below the profile which was representative for the
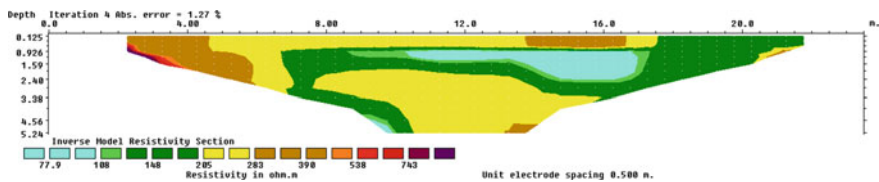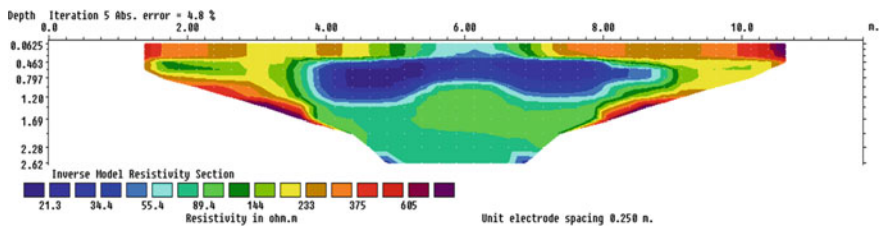


**Fig. 15** Resistivity profile before filling the waste



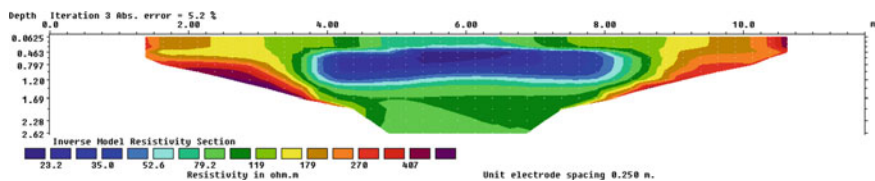**Fig. 16** Resistivity profile after two months of filling

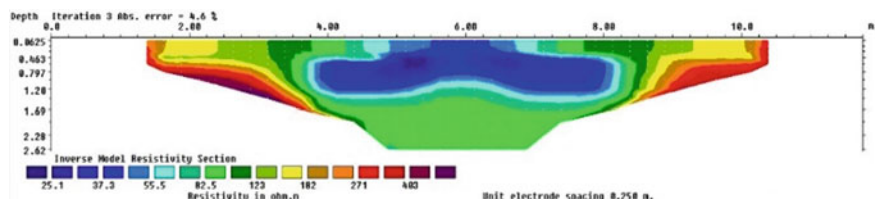**Fig. 17** Resistivity profile after three months of filling



**Fig. 18** Resistivity profile after four months of filling

**Table 3** Physicochemical analyses of water samples for ERT Profile 2

| Parameters | Observed values | | | | |
|---|---|---|---|---|---|
| | November | December | January | February | March |
| pH | 6.00 | 5.80 | 4.10 | 4.50 | 4.70 |
| Turbidity (NTU) | 0.90 | 2.20 | 5.70 | 8.80 | 7.40 |
| Alkalinity (mg/l) | 10.00 | 160.00 | 378.00 | 200.00 | 160.00 |
| Chloride (mg/l) | 8.01 | 93.10 | 77.59 | 68.58 | 52.56 |
| Iron (mg/l) | 0.042 | 0.776 | 0.776 | 0.987 | 0.959 |
| Sulphate (mg/l) | 11.23 | 20.86 | 160.00 | 167.87 | 150.98 |
| Nitrate (mg/l) | 3.06 | 12.50 | 42.60 | 45.90 | 42.65 |
| Dissolved oxygen (mg/l) | 3.153 | 2.956 | 2.365 | 2.266 | 2.069 |
| Hardness (mg/l) | 38.00 | 46.00 | 44.00 | 100.00 | 70.00 |

borehole 1 data. From the laboratory analysis of the groundwater, it was observed that the water sample collected from borehole 2, 0.5 m away from the landfill, was more contaminated than that of in borehole 1. Higher values of physicochemical parameters indicated degraded quality of groundwater in borehole 2. The variations of depth of groundwater table noted from observatory well 2 were also measured. The variation of maximum depth of flow and the width of flow are presented in Table 4.

**Three-Dimensional Resistivity Survey.** Two three-dimensional resistivity profiles were performed, one before the construction of landfill and another after one month of construction of landfill. The three-dimensional resistivity profile clearly showed the position of waste filled trench within 0.6-m depth. The waste has a resistivity

**Table 4** Groundwater table and resistivity details for ERT Profile 2

| Time | Depth of natural groundwater level (m) | Resistivity range of the contaminated zone (Ω-m) | Width of contaminated zone (m) | Maximum depth of contaminated zone (m) |
|---|---|---|---|---|
| Before contamination | 0.70 | 75–80 | NA | NA |
| 1st month | 0.72 | 40–50 | 4 | 0.9 |
| 2nd month | 0.75 | 30–40 | 4.1 | 1 |
| 3rd month | 0.77 | 20–30 | 4.2 | 1.2 |
| 4th month | 0.64 | 30–35 | 4.5 | 1.6 |

of 20–25 Ω-m. The flow path of leachate was clearly visible which was indicated by the reduced resistivity value within the depth of 0.6–1.29 m in Fig. 19. In this resistivity profile, it was also seen that the flow of leachate was towards the lake which was present at the downstream of the landfill. A little flow of leachate was observed beyond the depth of 0.6 m after one month of construction of landfill.

Three-dimensional resistivity data showed the resistivity values in three horizontal layers along the depth at the site. The resistivity data reflected to a great extent a similar type of soil and groundwater flow zones as in case of two-dimensional resistivity profiles at the same site. The groundwater zones were interpreted to be
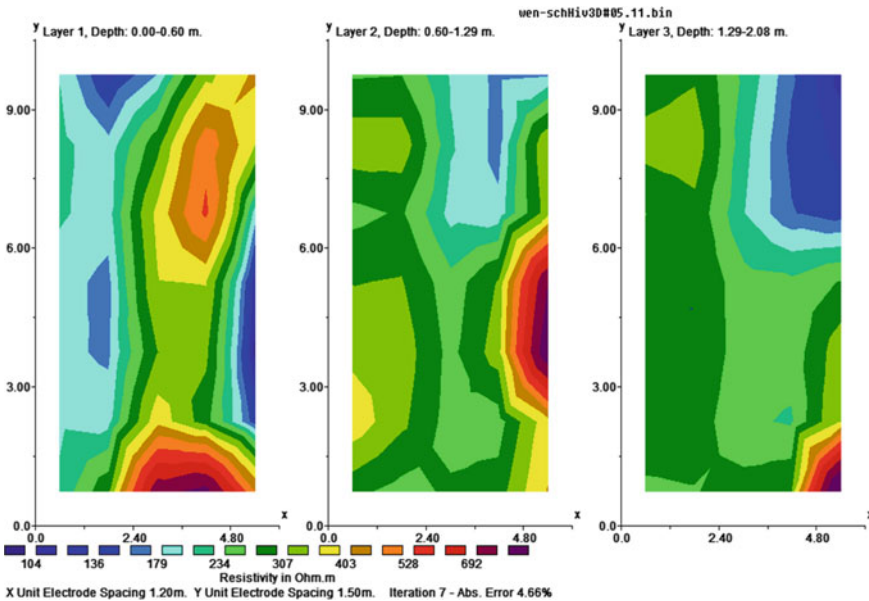


**Fig. 19** 3D resistivity profile before contamination
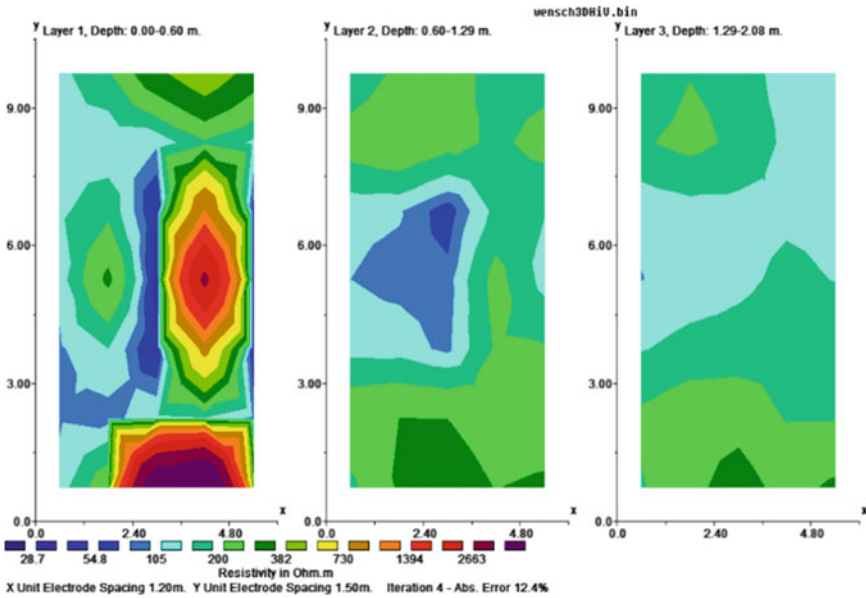
**Fig. 20** 3D resistivity profile after one month of filling

below 0.6-m depth which the two-dimensional resistivity data have shown earlier. The slope of the groundwater flow was found towards the lake, and the same data were observed during the investigation using piezometric analysis. From this profile, it was observed that a high resistive zone conforming the presence of gravelly area was present at the site which was also evidenced during the boring of the test wells (Fig. 20).
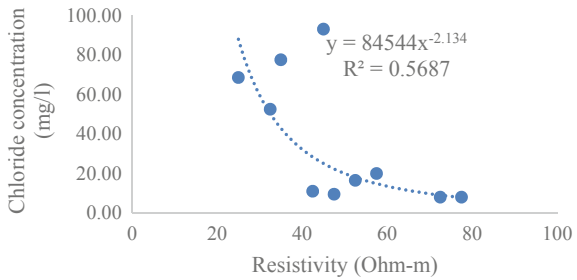
The three-dimensional resistivity profile after one month of contamination clearly showed the flow of leachate from the landfill to its downstream side towards the lake present at the site. The low resistive zone at the middle of the profile in second layer of the resistivity profiles is interpreted as the landfill, and the low resistivity zone surrounding the landfill was observed as the flow of low resistive liquid known as leachate originated from the landfill. The absence of low resistivity zone in the third layer of the resistivity profiles indicated that the flow of leachate from the landfill is limited to a depth of about 1.3 m in vertical direction. But the contaminated zone in the third layer was observed to be extended in horizontal lateral directions. Some high resistivity zones were also observed at the site from this resistivity profiles in case of the earlier resistivity profile.

**Correlation of Resistivity Data with Water Quality Parameters**. Efforts were made to analyse the physicochemical parameters of each water sample collected from the boreholes over a period of five months and to correlate each parameter with the resistivity values corresponding to each observed month. Correlation charts are being prepared with electrical resistivity and the water quality parameters including pH,
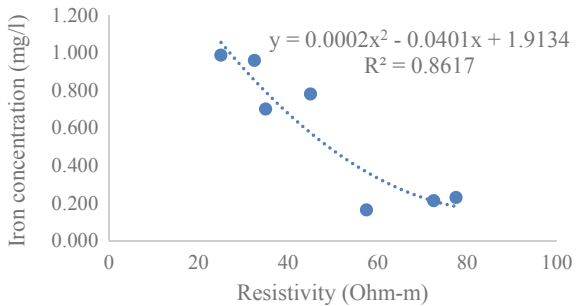
**Fig. 21** Correlation of resistivity with pH values



$$y = 0.04x + 3.0276$$
$$R^2 = 0.3419$$

pH value
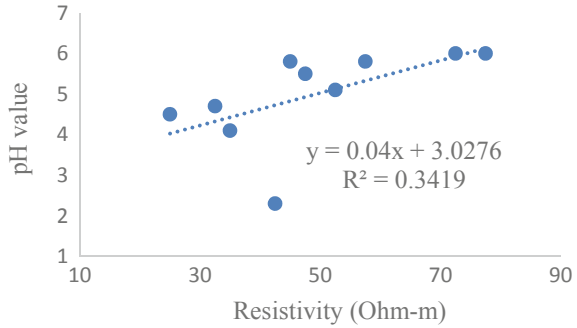
Resistivity (Ohm-m)

**Fig. 22** Correlation of resistivity with chloride



$$y = 84544x^{-2.134}$$
$$R^2 = 0.5687$$

Chloride concentration (mg/l)

Resistivity (Ohm-m)

**Fig. 23** Correlation of resistivity with iron



$$y = 0.0002x^2 - 0.0401x + 1.9134$$
$$R^2 = 0.8617$$
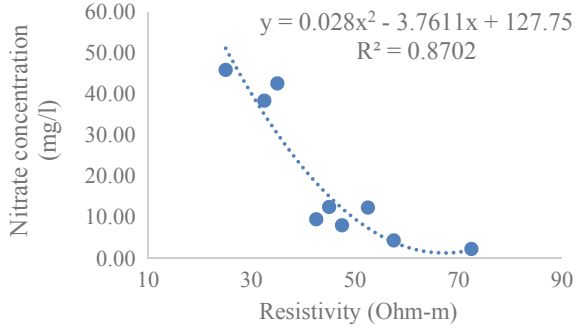
Iron concentration (mg/l)

Resistivity (Ohm-m)

chloride concentration, iron concentration, nitrate concentration, sulphate concentration and hardness concentration. The correlations of resistivity value with the water quality parameters are presented in Figs. 21, 22, 23, 24, 25 and 26.

## 5    Conclusions

Prediction and remediation of contaminated groundwater below a non-engineered landfill were the prime objectives of this research. Conventional method of solving the
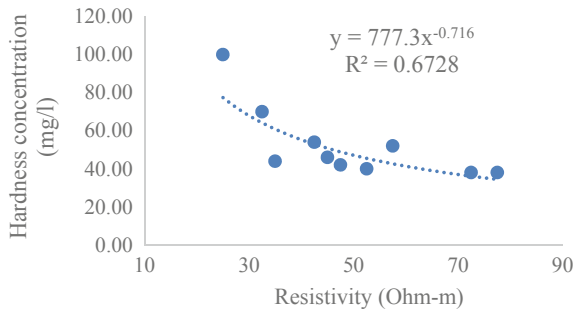
**Fig. 24** Correlation of
resistivity with nitrate

$$y = 0.028x^2 - 3.7611x + 127.75$$
$$R^2 = 0.8702$$

Nitrate concentration (mg/l)

Resistivity (Ohm-m)

**Fig. 25** Correlation of
resistivity with sulphate

$$y = 0.0761x^2 - 11.039x + 405.17$$
$$R^2 = 0.9073$$

Sulphate concentration (mg/l)
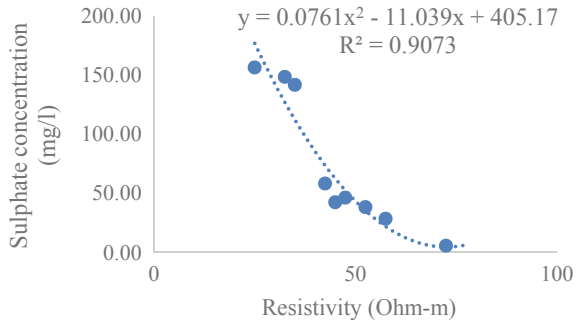
Resistivity (Ohm-m)

**Fig. 26** Correlation of
resistivity with hardness

$$y = 777.3x^{-0.716}$$
$$R^2 = 0.6728$$

Hardness concentration (mg/l)

Resistivity (Ohm-m)

concerned issues being found inefficient, the author has applied advanced geophysical techniques in solving the concerned issues of groundwater contamination. For this research work, electrical resistivity tomography was used to predict the groundwater contamination and to delineate the leachate plume below a landfill. The following conclusions can be drawn from this research work:

1. Resistivity survey accurately reflects the changes in contaminant concentrations in groundwater contaminated by non-engineered landfills.

2. The regression coefficient value of 0.87, 0.90 and 0.86 resulted from the correlation of resistivity value, respectively, with nitrate, sulphate and iron concentrations indicates the accuracy of the resistivity survey in determining the contaminant concentrations in polluted groundwater at a landfill site.
3. Non-engineered landfills have a great potential in contaminating the immediate environment within a very short period of time if no remedial measure is adopted.

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