Detecting leachate plumes and groundwater pollution at Ruseifa municipal landfill utilizing VLF-EM method

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A B S T R A C T

A Very Low Frequency-Electromagnetic (VLF-EM) survey was carried out in two sites of domestic waste of old and recent landfills. The landfill structures lie on a major highly fractured limestone aquifer of shallow groundwater less than 30 m, which is considered as the main source of fresh water in Amman–Zarqa region. A total of 18 VLF-EM profiles were conducted with length ranges between 250 and 1500 m. Hydrochemical and biochemical analysis of water samples, taken from wells in the region, has also been conducted. The integrated results of previous DC resistivity method of the same study area and the outcomes of the 2-D tipper inversion of VLF-EM data proved the efficiency of this method in locating shallow and deep leachate plumes with resistivity less than 20 Ω m, and enabling the mapping of anomalous bodies and their extensions down to 40 m depth. The sign of groundwater contamination was noticed in many surrounding wells resulting in the high number of fecal coliform bacteria and total coliform bacteria and the increase in inorganic parameters such as chloride (Cl). The pollution of groundwater wells in the landfill area is attributed to the leachate bodies which flow through the upper part of Wadi Es Sir (A7) or Amman–Wadi Es Sir Aquifer (B2/A7). Furthermore, several structural features were detected and the direction of local groundwater movement has been determined. The structural features have been found to have critical effects on the flowing of leachate plume towards north-northeast and west-southwest of the potable aquifer in the area.

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1. Introduction

The study area is located between 247.5–251.95 E and 156.3–159.2 N according to the local grid; this corresponds to longitude 36° 2’ 16”–36° 3’ 4.71” E and latitude 32° 0’ 12.98”–32° 0’ 37” N in the international grid (Fig. 1). The area of domestic waste dumping is about 1.2 km². This landfill serves about 2.5 million inhabitants living in Amman, Zarqa and Ruseifa cities, where the vast majority of solid waste is generated from Amman area and is about 1525 tons/day (Ministry of Municipalities, 2000). The increasing use and expanding of this site will seriously affect the quality of groundwater in the area.

Generally, this work is aimed to investigate the effects of two dumping sites on groundwater by employing an integrated use of VLF-EM, chemical and biochemical methods in order to delineate the spatial leachate plumes and there relation to geological and hydrogeological condition of study area.

The VLF-EM is an electromagnetic method that uses radio signals from worldwide network transmitter stations; it operates in frequency ranges between 5 and 30 kHz. This method is considered as one of the most used among electromagnetic methods and extensively described in the literature (Paterson and Ronka, 1971; Wright, 1988; McNeill and Labson, 1991). The primarily application was mainly used for mineral exploration and related geological structures (Saydam, 1981; Ligas and Palmoba, 2006; Ramesh Babu et al., 2007). Later, it was applied for detecting and mapping water contamination (Nobes, 1996; Benson et al., 1997; Monteiro Santos et al., 2006) and highly fractured silicified limestone and mostly recharged from rainfall of north and northwestern areas. The study area is characterized by dry weather conditions and lack of annual rainfall (150 mm/yr). The groundwater level in the area is shallow and reaches less than 30 m in some places with too many production wells that supply fresh water to thousands of citizens living in Amman and Zarqa cities as well as many farms and factories.

The critical situation of the landfill comes from its location which is placed on the top of the most important ground water aquifer, called Amman/Wadi Sir Aquifer (B2/A7). This aquifer consists mainly of...
well adapted for water exploration related geological structures and sedimentary cover (Sharma and Baranwal, 2005; Oskooi and Pedersen, 2005; Sundararajan et al., 2007).

Fundamentally, VLF methods are classified into two types based on electromagnetic wave measured components, the first type known as VLF-EM or VLF-Z which is applied in this study and only measures the ratio of polarized magnetic field; the second type measures the ratio of both horizontal electric and magnetic field and known as VLF-R method.

At any point of measurements, the total VLF field is given by the sum of primary and secondary magnetic and electric fields; the primary magnetic field is horizontal and oriented at right angle to the line connecting the observation point to the transmitting antenna (Wright, 1988). A review of Paterson and Ronka (1971) concluded that the method is capable of moderate depth of exploration in nonconductive rocks, but it is limited in conductive ground and is not very sensitive to small resistivity changes in a resistive environment (Chouteau et al., 1996). In the presence of conductive bodies, the eddy currents are induced by primary field that in turn will generate secondary field superimposed to the primary one. The horizontal \( (H_x) \) and vertical \( (H_z) \) components of magnetic field are measured by standard VLF instrument; where the real (in-phase) and imaginary (out-phase) parts of vertical magnetic component form a complex component called the tipper \( B \).

The principle of VLF survey is based on the fact that the ratio of the secondary vertical magnetic component to the horizontal primary magnetic field is a measure of conductivity/resistivity contrast since this tipper component is of internal origin of the anomalous body (Chouteau et al., 1996; Gharibi and Pedersen, 1999). Besides, the in-phase response is sensitive to low resistivity bodies whereas the out-phase response is sensitive to the variations of the earth electrical properties (Monteiro Santos et al., 2006).

2. Site description

The Ruseifa landfill is located near Ruseifa city and lies about 15 km to the northeast of Amman (Fig. 1). The landfill receives more than half of the solid waste in Jordan, which accounts for 2200 tons/day (Chopra et al., 2001). The Ruseifa landfill was placed on an abandoned phosphate mine. There is no subsurface drainage system to collect the leachate. Therefore, the leachate goes directly to the groundwater; hence, the depth of water table in the landfill is 30 m. There is also a liquid waste disposal site, which is near the Ruseifa landfill, where the liquid waste comprises untreated industrial wastewater and the cesspools wastewater.

The disposal method practiced at Ruseifa site is known as the sandwich method in which the solid waste is dumped and followed directly by at least 30 cm of compacted earth material (Chopra et al., 2001).

3. Geological setting

The geological formations outcropping at Ruseifa landfill are of Upper Cretaceous age (Masri, 1963) (Fig. 2); these belong to Ajlun and Balqa Groups except the Wadi fill deposits, which belong to Tertiary age (Table 1). The only formation of the Ajlun group that outcrops on the landfill area is Wadi Sir Formation (A7), which consists mainly of hard crystalline dolomitic limestone, chalky limestone with occasional chert bands and nodules. The thickness of this formation reaches up to 80–100 m (Bender, 1974).

The Balqa Group is represented by the Amman Formation (B2). This formation consists of limestone with chert interbedded with phosphatic layers and marls. It outcrops at the landfill and its
surrounding areas and varies in thickness from 30 m to 150 m (Howard and Humphreys, 1983). The distinguished feature of this formation is its undulations in addition to fracturing and jointing of the chert beds. The Wadi fill deposits overlie the Amman and Wadi Sir formations and consist of sands and gravels with variable thickness from 15 to 20 m (Bender, 1974).

The main structures encountered at the landfill area were the faults which are related to the Amman–Hallabat structure (a set of folding and faulting structure) which extends from southwest of Amman towards the northeast (Mikbel and Zacher, 1986).

4. Hydrogeology of the study area

The Ruseifa landfill is located within the Amman–Zarqa Basin, which is considered the most important groundwater basin in Jordan. Table 1 summarizes the geological and hydrogeological classification of the rock units in Amman–Zarqa basin (Rimawi, 1985). The main aquifers in the Amman–Zarqa basin are the Amman/Wadi Sir (B2/A7), which consists of chert, limestone and phosphate that overlies hard crystalline limestone with chert and dolomite beds. The Hummer (A4) formation, which consists of hard dense limestone and dolomitic limestone. Both aquifers are exposed in the high rainfall region which reaches 400 mm/year. The hydrogeology of the study area is controlled by the prevalent geological conditions in the area. The major aquifer system in the area is (B2/A7), which is known as the Upper Aquifer. These aquifers are well jointed and fissured and on a local scale exhibit solution channels and karstic features. It is believed that the two aquifers are hydraulically connected and in some locations they are separated by an aquiclude (i.e. Ghudran Formation B1), which consists of chalk, marl and marly limestone (Fig. 3). Most of the groundwater wells surrounding the Ruseifa landfill used to extract water from these Aquifers (Fig. 1). The regional groundwater flow in the B2/A7 is influenced by the recharge/discharge areas, topography and the structural characteristics in the region. The main recharge occurs from the south-western side of the area. The rest of the groundwater flows north-eastward down the Amman–Zarqa syncline to recharge the upper aquifer and the rest flows into the desert (Kuisi, 1992). It is obvious that the groundwater flow within the study area is controlled by topographic and structural features of aquifers that are affected by different sets of faults and fold system (Fig. 4). The direction of the groundwater flow in the recent landfill is mainly to the south west, where it is to the north eastern direction in the old landfill.

5. Effect of leachate movement through B2/A7 aquifer

The nature of the host rock of the aquifer is an important control on the nature of the groundwater that is extracted from it. In the case of the B2/A7 aquifer this is shown by the fact that calcium and magnesium are the dominant cations, while bicarbonate is the dominant anion (UNDP/FAO, 1970; Bajjali, 1990). However, some wells showed elevated levels of salinity with a range of 300 to 1000 ppm around Amman (UNDP/FAO, 1970). In these cases sodium...
and chloride become the dominant ions. However, the high concentration of the measured ions from the Amman–Zarqa area is attributed to the extensive industrial activities and the high density of population in the region. In addition to these factors, Bajjali (1990) stated that the third key source for contamination is the burial landfill in the Ruseifa area which is still used to dispose of the municipal refuse of Greater Amman, Zarqa and Ruseifa areas.

The leachate composition affects the chemistry of groundwater, as it percolates through the soil horizon reaching the subsurface groundwater aquifers. Therefore, four monitoring wells have been selected (Phosphate Mine No.7 (AL 1345), Phosphate Mine No.10 (AL 1350), Ruseifa landfill monitoring well No.2 (AL 3385) and Waste Disposal monitoring well AL 2720) to show the effect of the leachate contamination on the quality of groundwater, these wells are close enough to differentiate between two landfill sites basis on chemical and biochemical analysis of groundwater samples. (Fig. 1). Another seven wells lacated to the north and east directions of both sites have been used to extract average background values of two unique dependant parameters; the electrical conductivity (EC) and chloride concentrations (Cl), both values are significant indicator of ground water pollution due to a wide domain difference and good correlation through time with respect to leachate halo movements. It should be mentioned that further measurements were taken on 2006 to update the previous values for conductivity and chloride concentration.

Comparing the results of chemical constituents of the Ruseifa landfill monitoring well (AL 3385) between 1992 and 2006 (Fig. 5) it is apparent that there is an increase in salinity from 650 to 788 mg/l and an increase in the other inorganic constituents; the concentration of Cl has increased from 4.8 to 332 mg/l; and SO4 increased from 0.59 to 36 mg/l. Also the Fe concentration reaches 0.3 mg/l. Furthermore, at AL 1350 (Fig. 5) the chemistry of the groundwater is affected by the landfill and showed increasing concentration of different constituents including Ca, Mg, Na, Cl, SO4, and NO3. The concentration of Cl increased from 40 mg/l to around 70 mg/l; the concentration of SO4 increased from 17 mg/l to 31 mg/l.

At well AL 1345 (Fig. 5), there is an increase in the concentration of different cations and anions; for example, the Cl concentration increased from 35.5 mg/l in 1991 to 280.9 mg/l in 2006; the SO4 concentration slightly increased from 30.7 mg/l to 38.4 mg/l; and the Na concentration increased from 20.7 mg/l to 137.1 mg/l. Therefore, the increase of inorganic constituents such as Cl, Na, SO4, and HCO3 occurred along the groundwater flow which is outlined in Fig. 4.

Other indication of the deterioration of groundwater near the landfill is the presence of fecal and total coliform bacteria in the groundwater; hence, the total coliform and or fecal coliform numbers should be less than 1.1 MPN/100 ml for drinking water. For example the phosphate mine well (AL 1350), showed increasing values in total coliform from 5.1 MPN (Most Probable Number) to 300 MPN which indicated pollution of the groundwater (Tadros, 2000). In addition, the measured total coliform increased from 162 MPN/100 ml at monitoring well (AL 3385). Also, the bacteriological analysis of the monitoring well (AL 2720) indicates that the measured total coliform and fecal coliform were 2400 MPN/100 ml and 150 MPN/100 ml at monitoring well (AL 3385). Also, the bacteriological analysis of the monitoring well (AL 2720) indicates that the measured total coliform and fecal coliform were 2400 MPN/100 ml and 150 MPN/100 ml, respectively. It can be concluded from these analyses that the landfill is polluting directly the upper part of the aquifer.

6. VLF-EM measurements

The VLF-EM measurements conducted in the landfill area were made with a Geonics EM 16 unit. Of the several radio stations transmit in the VLF-EM bands, the transmission from the Russian station (UMS) with a 17.1 kHz and 1 MW power, was strong enough for reliable VLF

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**Table 1**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Age</th>
<th>Group</th>
<th>Formation Symbol</th>
<th>Rock type</th>
<th>Thickness (m)</th>
<th>Aquifer potentiality</th>
<th>Permeability (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Holocene</td>
<td>Balqa</td>
<td>Wadi fill S</td>
<td>Soil, sand and gravel</td>
<td>10–40</td>
<td>Good</td>
<td>$2.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Basalt V</td>
<td>Basalt. Clay</td>
<td></td>
<td></td>
<td>0–50</td>
<td>Good</td>
<td>–</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Maestrichtain</td>
<td>Muwaqqar B3</td>
<td>Chalk, marl and chalky limestone</td>
<td>60–70</td>
<td>Poor</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Campanian</td>
<td>Amman B2</td>
<td>Chert, limestone with phosphate</td>
<td>30–120</td>
<td>Excellent</td>
<td>$10^{-3} \cdot 3 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santonian</td>
<td>Ghudran B1</td>
<td>Chalk, marl and marly limestone</td>
<td>15–20</td>
<td>Poor</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turonian</td>
<td>Ajlun A7</td>
<td>Hard Crystalline Limestone, Dolomitic and some chert</td>
<td>90–110</td>
<td>Excellent</td>
<td>$1 \times 10^{-7} \cdot 1 \times 10^{-4}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
measurements. A total of 18 profiles with 25 m station to station distance were conducted making 50° to 80° for profiles from V1 to V10 (minimum angle between transmitter direction and profiles direction) and reaches almost 90° maximum for profiles from V11 to V18. The length of these profiles varied between 250 and 1500 m. Fig. 1 shows the location of the VLF-EM profiles taken in the study area. Ten of these profiles were conducted fairly inside the boundaries of the both landfills. The rest of these profiles were conducted outside the landfill boundaries to the south west direction of the study area.

The VLF-EM profiles were set in order to ensure adequate conductor coupling. Apparently the leachate body deduced to be elongated in nearly perpendicular direction to the primary magnetic field (apparently deduced to be striking to the north-northeast direction for old and recent landfills (Al-Tarazi et al., 2006), the VLF-EM profiles are laid approximately parallel to incident magnetic field and at right angles to the strike of conductors in both old and recent landfills, technically, at each point of measurement, the EM 16 unit was set where the horizontal primary magnetic field is perpendicular to the line facing transmitter station (Fig. 1). Both the in-phase and the out-phase components of the EM field have been measured; however, and due to high levels of noise encountered in certain parts of the area, it was not always possible to receive a good out-phase component with an acceptable quality, this kind of noise is because of that the secondary field is always much weaker than the primary field, the out-phase data are comparatively unreliable, except for high conductivity targets (Jeng et al., 2007). Generally, the main sources of noise in the area are metal fences, power lines, biogas station and the landfill architecture topography.

6.1. VLF-EM data linear filtering and qualitative interpretation

The acquired VLF-EM data were processed using Matlab code (VLFPROS) (Sundararajan et al., 2006). Processing is mainly achieved by applying two types of filters, these are: the Fraser filter and the Hjelt filter. The Fraser filter (Fraser, 1969) converts crossover points into peak responses by 90° phase shifting. This process removes direct
current bias that reduces the random noise between consecutive stations resulting from very low frequency component of sharp irregular responses; it also removes Nyquist frequency related noise and the long spatial wavelengths in order to improve the resolution of local anomalies. The Hjelt filter (Karous and Hjelt, 1983) uses the linear fit theory to solve the integral equation for the current density, assumed to be located in a thin horizontal sheet of varying apparent current density, situated everywhere at a depth equal to the distance between measurement stations. It is essential to emphasize some considerations regarding the depth of penetration of the VLF-EM technique. The tendency of the VLF-EM fields to diminish as they penetrate the earth is calculated by a parameter called the skin effect \(\delta\) which can be defined as the depth at which the wave amplitude drops to 37.0% and phase changes by 1 rad (McNeill and Labson, 1991).

The expected exploration depth in the study area is 54 m (considering a range of half space resistivity of 150 \(\Omega\) m and an average thickness of wastes reaches to 2–20 m (Al-Tarazi et al., 2006)). This value implies that major anomalies have been originated from the waste materials and/or from the leachate body developed in the landfill area.

6.2. Fraser filtered map

The Fraser filtered map of in-phase component (Fig. 6) revealed the presence of several anomalies; most of the anomalies with positive values (0–40%) are developed within the old and the recent landfills. A major one is centered at a location that corresponds to the old landfill and has irregular shape; this anomaly indicates, most probably, the presence of a conductive body that is developed inside the dumping area. Another anomaly can be noticed at the recent landfill which represents another conductive body that is related to this part of the dumping area; it can be traced out at the eastern side of the landfill body. The Fraser filtered map may provide indication on the connectivity between these two conductive bodies. Another imprint from Fraser map is the presence of moderately resistive fault (anomaly with negative Fraser values; more than −20% and form linear features) in NW–SE direction. This direction is coinciding with the main fault found in the geological map (Fig. 2).

6.3. Karous–Hjelt apparent current density cross-sections

Apparent current density cross-sections have been constructed for specific and distinctive profiles to show the variation of apparent current density, and consequently to derive the change of conductivity with depth. Qualitatively, it is possible to discriminate between conductive and resistive structures using apparent current density cross-section, where, a high positive value corresponds to conductive subsurface structure and low negative values are related to resistive one (Benson et al., 1997; Sharma and Baranwal, 2005). The apparent current density cross-section of profile V2 (Fig. 7) reveals the presence of a major anomaly that is extended laterally from 900 m to about 1100 m, and could be traced in terms of one skin depth. Qualitatively it is hard sometimes to discriminate between deep and shallow sources (Sharma and Baranwal, 2005). It can be noticed, however, that this anomaly has a structural origin since the northern part of the study area has an immense structural strain deformations (Mikbel and Zacher, 1986). Consequently, this may provide a seepage path for leachate plume to spread out in that direction. The apparent current density cross-section of V6 (Fig. 7) actually discloses the combination effect of both landfills (Fig. 1); it shows a major wide anomaly between 220 m and 920 m. The representative apparent current cross-sections of V7 and V9 (Fig. 7) reflect the effect of active landfill. Particularly, the main conductive anomaly that appears in V7 is wide and starts to get narrow in V9. Generally, the developments of conductive bodies of high apparent current positive values show relatively a wide width in V5, V6, V7 and V8. On the other hand, these anomalies become relatively narrow and sharp in V1, V2, V3, V4, V9 and V10 (Fig. 7).

6.4. 2-D inversion of VLF-EM tipper data

In the last decades, literatures dealing with inversion approaches of 1D and 2D EM plane wave have been developed by many researchers (such as Chouteau et al., 1996; Kaikkonen and Sharma, 1998; Sriprunvaraporn and Egbert, 2000; Beamish, 2000; Monteiro Santos et al., 2006). Of these, Monteiro Santos et al. (2006) worked extensively on the quantitative interpretation of single frequency of VLF-EM and data quality efficiency, it based on considering a 2-D...
subsurface resistivity distribution at different point of measurement sites with strike direction along the x-axis and pointing toward VLF-EM transmitter station. At each point, one can define a linear function $H_z = AH_x + BH_y$, where $H_z$ is the vertical induced magnetic field and $H_y$ is the primary magnetic field; the scalar tipper $A$ is identically equal to zero which is assumed to be directed along the transmitter station. Consequently, the scalar tipper $B$ given by $H_z = BH_y$ that varies along profile direction. At this case one can interpret scalar VLF-EM measurements with 2D model (Oskooi and Pedersen, 2006). The tipper $B$ quantity exists only over inhomogeneous layered earth and originated by the time lag between horizontal and vertical components of the magnetic field as a result of electromagnetic induction. The code structure is based on forward solution using the finite-element method. It is the initial parametrization of the model that depends on the following parameters: the number of input data, background resistivity and on the single frequency value. The 2D regularized inversion is done, to generate resistivity model that fit the tipper data with acceptable RMS (%) or global misfit (%).

The previous DC resistivity study of the same area by Al-Tarazi et al. (2006) gives a reasonable estimation of half space resistivity of rock far away from resistive or conductive anomaly, which was determined to be equal to 150 $\Omega$ m as an initial model for inversion processing, this resistivity value is considered as a reasonable back ground value for all profile data inversion, fundamentally, that led to resolve a better high conductive anomalous zone up to 50 m depth.

6.4.1. Evaluation of data inversion

All the VLF-EM inverted profiles were tested for inversion sensitivity and ambiguity results, i.e. the sensitivity model block-division represents 2D subsurface structures with various resistivity variation in which the grid of rectangular blocks get coarser towards greater depths and appear smoother and remain unchanged in the first 30 m depth. As a result, the plus sign (Fig. 8b) shows high sensitive values and relatively close to apparently high conductivity zones. The input parameters for forward modeling, such as lagrange (not less than 0.03), number of iteration (best only achieved between 20 and 23) and initial background resistivity (150 $\Omega$ m), is found suitable to start the inversion. This demonstrates the importance of selecting adequate priori background resistivity information for getting the real subsurface resistivity distribution. These parameters

Fig. 7. Apparent current density cross-sections of V2, V4, V6, V7 and V9 VLF-EM profiles, that show different conductive anomaly structures of old and recent landfills.
facilitate the process of obtaining a reasonable output model with moderate RMS values. The average RMS of all inverted profiles is equal to 6.2% where

\[
\text{RMS}\% \text{(misfit)} = \left[ \frac{\sum_{i=1}^{n} (X_{\text{obs}} - X_{\text{cal}})^2}{N_{\text{obs}}} \right]^{\frac{1}{2}}
\]

where,

- \(N_{\text{obs}}\): Total number of observed data.
- \(X_{\text{obs}}\): Observed in-phase and out-phase data.
- \(X_{\text{cal}}\): Calculated in-phase and out-phase data.

However, the model with lowest possible RMS error and high number of iterations can sometimes show large and inaccurate in the model resistivity values and might not always be the best model when compared with priori information.

The V5 survey profile has been chosen to be used for assessment of raw data quality (Fig. 1) since it cuts across both damping sites and may reflect a variation of leachate developing plumes. The inversion results of the in-phase and out-phase data sets for this profile show a good correlation between measured and calculated values (Fig. 8a and b), the coefficient of determination \(R^2\) obtained from scatter plot of measured-computed in-phase and out-phase values reaches around 0.70 (Fig. 9) which is statistically significant for VLF-EM data that have major noise contributions from various complicating factors, such that; the VLF-EM data contains more than one oscillatory mode as a result of wave dispersion and harmonic distortion of nonlinear–nonstationary natural systems (Jeng et al., 2007). The inversion of the V5 profile demonstrates the presence of low resistivity values below 110 \(\Omega\) m which extend to 50 m depth; this coincides with the landfill structure boundaries between 400 m and 800 m and from 900 m to 1200 m. These anomalies correspond to old and recent landfill areas respectively (Fig. 8b). The generated leachate body can be recognized also in both sites with lowest resistivity values of less than 20 \(\Omega\) m and varies in depth from surface to 30 m depth in both sites; this coincides with the same results obtained by previous DC study conducted in the same area (Al-Tarazi et al., 2006). The apparent current density values for V5 profile (Fig. 8c) show the presence of a large conductive structure close to recent landfill boundary. This result demonstrates the consistency between qualitative and quantitative interpretation;
in terms of relative disposition of the discrete conductors, frequency and influence of different anomalies size and depth.

6.4.2. 2D resistivity models of old and recent landfill sites

The inverted VLF-EM profiles into 2D resistivity models (Fig. 10) was classified and sampled based on similarity of anomalies development, shape, position and location.

Resistivity model sections for the profiles V1, V2 and V3 (Fig. 10) follow same sense and mainly shows a separated batches of different heterogeneous structure of low resistivity zones at different depth levels. Basically, these profiles (Figs. 1 and 10) reflect inhomogeneities in resistivity distribution inside the folded and fractured B2/A7 formations. Furthermore, these profiles were laid down on northern bank of the old landfill area and may consider as seepage path for leachate transfer to this direction. Consequently, leachate will flow to a direction wherever it finds joints and cracks in the rocks. The zone of low resistivity leachate body (~20 Ωm) which starts to develop in both old and recent one, can be seen in profiles V4, V5 and V6 (Figs. 8 and 10), it differentiates two zones. The shallow conductive body that reached the surface and addressed in the field as a small pool body. Basically this surface liquid body starts to move up through fractured waste cover as a result of hydrostatic pressure of refuse weight on leachate body. The second deep conductive body is also recognized at depth less than 50 m.

It has been observed that the eastern part of the landfill area is bounded by fault structure trending NW–SE direction (Figs. 1 and 6), this fault may control the leachate movement; in such way that it may has have the capability to drive it toward fractured directions. This case is clear at the eastern part of V4 and V5 resistivity model sections (Figs. 8b and 10). Resistivity model of V6 (Fig. 10) reveals shallow and deeper conductive bodies as most resistivity model sections that cut through landfill waste bodies. The resistivity models for profiles through V7 to V10 outline only the conductive body zone that developed in recent landfill area (Fig. 10).

7. Discussion and conclusion

This study presents the results of the combined use of VLF-EM method, hydrochemical and biochemical analysis of wells in drawing the spatial distribution of leachate plume and its migration at two sites of dumping of domestic waste materials; the first one is closed since 1994 while the other one is still in use. The complexity to conduct VLF-EM survey in this area arises due to the interactions of a) apparently two different leachate strikes for investigated landfill sites b) two different conductive zones maturity c) different sets of fault structure and local groundwater movement and d) 3D leachate plume structure effects in case of interpreting VLF-EM scalar data using one transmitter station.

Qualitative interpretation of VLF-EM profiles using different linear filtering such as Fraser and Karous–Hjelt filters (Figs. 6 and 7), shows that the two sites have developed a subsurface low resistivity zones within and outside the landfill boundaries. The interpreted apparent current density cross-sections provide a subsurface image of narrow vertical to subvertical conductors in the northern part (Fig. 7). Furthermore, the available geological mark a weakness zones that are effected by folded and fractured rocks. This was supported by Fraser and geological maps (Figs. 2 and 6) which show two sets of fault direction: NW–SE and NE–SW. Furthermore, these play a major role in groundwater movement (Fig. 4) by providing access to leachate plume to reach A7/B2 aquifer.

The quantitative interpretation of VLF-EM tipper data was resolved by 2D resistivity models which have been calculated for all the profiles (Fig. 10). The quantitative interpretation of VLF-EM profiles, hydrochemical and biological analysis of wells imply three scenarios that try to explain the access of the leachate plume (with typical resistivity <20 Ωm) to the groundwater. The first one is through the northern boundary of old landfill where the plume has penetrated into fractured rocks and driven by groundwater flow to north direction (Fig. 4) since the groundwater depth is about 30 m (Figs. 3 and 10). This movement is supported by folded increases of measured organic and inorganic parameters in AL 1345 and AL 3385 (Fig. 5). The second access possibility could be through the bottom base of the two landfill sites. In most of the resistivity model sections (V4 to V10), it can be seen that the plume had touched the groundwater surface (Fig. 10); this is also observed from monitoring well AL 2720 within landfill areas where the biochemical analysis shows an extremely high organic pollution of coliform content in that well compared to other selected wells. The third way is based on the role of the major fault that influences the leachate movement to the west and southwest directions. This fault was recognized by a Fraser and inverted 2D resistivity cross-section in V4 and V5 (Figs. 1, 8 and 10). The fault and direction of groundwater movement (Fig. 4) may control the plume movements to take a slight effect to the east direction. This was supported by chemical analysis. Remarkably, the gradual increase of Cl concentration in well AL 1350 to east direction of recent landfill and fault shows slight changes and lies within the background value (Fig. 5); this implies that either fault and or groundwater movement have a potential role governing leachate movements. The 3D perspective resistivity view (Fig. 11) shows the development of different anomalous zones within study area and its surrounding.
Fig. 10. 2D resistivity models in $\Omega$ m, that are obtained by the inversion of the VLF-EM data for some profiles located in the old and the recent landfills (V2, V4, V6, V7 and V9 profiles).

Fig. 11. 3D perspective resistivity view in $\Omega$ m, obtained by the stacking of the inverted VLF-EM data of all profiles from V1 to V18.
The leachate plume of resistivity <20 Ω m can be recognized at the surface and at a depth of more than 30 m. The high resistivity values reflect the waste cover at the surface. The anomalies of high resistivity values may indicate also the presence of an elongated subvertical structures that represent fractures and faults in the east direction of the study area. In addition, a resistivity contrast can be noticed between the west and east directions. It can be concluded that the pollution of the water in the wells in the landfill area is attributed to the leachate plume which flows through the upper part of the A7 or B2/A7 aquifer which is highly jointed and fractured. Due to the increasing efforts made by the civil community and researchers, the government started to take serious steps to close this site permanently and to transport the solid wastes to a new better-managed landfill.

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