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ORIGINAL ARTICLE

Application of two geophysical methods to characterize a former waste disposal site of the Trabzon-Moloz district in Turkey

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Abstract Radionuclide variations, the vertical and lateral extent of a waste mass in the former Trabzon municipal solid waste dumpsite were investigated by combining in situ gamma-ray spectrometric measurements with 2D resistivity imaging methods. In the first step, the natural radioelement concentrations on the surface of dumpsite were measured using a portable gamma-ray spectrometer. The average activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the dumpsite are 42.68, 49.88 and 417 Bq/kg, respectively. In addition, radiation hazard parameters were calculated and compared with the international standard values. As a result of the evaluation of the radiological data, it was found that there are no significant radiologic hazards for humans and the environment. In the subsequent stage, 2D electrical resistivity method, using Wenner array, was carried out in this area. The survey was conducted using a multi-electrode resistivity instrument and the measured resistivity profiles were interpreted using RES2DINV program. Electrical resistivity values were obtained from three parallel lines. Results of the resistivity survey show that the waste masses in the study area reach to depths of about 18 m, with very low resistivity values less than 20 Ωm. According to the 2D inverted resistivity sections, low resistivities (<7 Ωm) at the depth corresponds to areas that may be occupied by leachate or sea water. The high resistivity values (>160 Ωm) in profiles B and C are associated with non-degradable waste materials, medical wastes and buried construction materials. Also, very high resistivity zone (874 and 2636 Ωm) in profile A are interpreted as landfill gases.

Keywords Gamma-ray spectrometer · Electrical resistivity · Radionuclides · Moloz dumpsite · In situ measurement · Hazard index

Introduction

Wastes and the crude disposal techniques have created subtle and yet serious environmental pollution in many developing countries. This has lead to the degradation of abiotic and biotic components of these nations' ecological systems. The dumping of large amount of waste materials in sites without adequate soil protection measures results in soil surface and groundwater pollution (Eikelboom et al. 2001; Namasivayam et al. 2001). In the study area (Moloz dumpsite, Trabzon, Turkey), like most other areas and cities, wastes are generated daily and most of them are discarded in improperly situated and dumping sites that are not engineered. Most of the dumping sites are located within residential areas, markets, farms, roadsides, and other locations (Ekeocha et al. 2012).

One of the most important environmental issues is the existence of municipal waste dump sites where different materials with changing physical and chemical properties are irregularly deposited as wastes. Especially, in today's world, if it is considered that most of the inhabitants are settled in the city centers and its surrounding areas, waste storage in and around these areas it is an extremely important problem to face. Randomly placed waste or formerly stored wastes in such areas will lead to serious environmental risk and problems. Therefore, the selection of a waste storage site is a crucial problem, and particularly

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the geological properties of the selected site have a highly important role to create or avoid environmental problems (Drahor et al. 2006).

In many municipalities, solid wastes are mostly deposited in un-engineered landfills. Municipal solid waste refers to the materials discarded in the urban areas for which municipalities are usually held responsible for collection, transport, and final disposal. They are mainly composed of domestic, co-disposed with industrial, agricultural, building and hospital wastes. Municipal solid waste also contains varying amounts of industrial waste from small industries, as well as dead animals and fecal matter. These wastes may contain toxic substances and as they decompose or are biodegraded, infiltrating water, mixed with organic liquid effluents, produce leachate. Solid waste landfills also constitute local sites where radionuclides are concentrated in the environment.

Due to the soil–solute interaction which could lead to the transport of specific contaminants, such as semi-volatile organic compounds, pesticides, heavy metals, radioactive wastes, chemicals, etc., into groundwater and soil-to-plant transfer processes which results in the accumulation of radionuclides in plants and animals, humans may be exposed to high doses of radiation. Humans incur radiations from waste landfills by external irradiations or by incorporation in the body. Their occurrence and distribution in the soil and groundwater are controlled primarily by the local geology, geochemistry, and specific solubilities of the radionuclides.

In view of this, it is important to monitor terrestrial background radiations and determine the boundaries of contamination, especially around municipal solid waste landfills (Ehirim and Itota 2013). Waste characterization is usually poor and hazardous waste may be co-disposed with non-hazardous waste. Dumping sites are usually uncontrolled, creating considerable health, safety and environmental problems (Pugh 1999).

Landfill monitoring has traditionally relied on direct sampling techniques, such as water samples from wells in and around the landfill and solid sampling from boreholes into the landfill. Not only these techniques are expensive, but also they only provide point source information. It is often necessary to extrapolate between points to interpret the information, a practice that could lead to incorrect or incomplete understanding of the site (Loke 1999; Benson and Mustoe 1998). In contrast, non-invasive geophysical methods provide a fast, effective way to obtain detailed, but sometimes ambiguous, information about landfill sites (Soupios et al. 2007; Saltas et al. 2005; Orlando and Marchesi 2001; Loke 1999; Green et al. 1999).

Successful geophysical studies have delineated landfill boundaries, defined cell boundaries within a landfill, assisted in determining refuse exten t/thickness, and found evidence for the migration of leachate outside landfill borders (Tsourlos et al. 2014; De Carlo et al. 2013; Carpenter et al. 2009; De Iaco et al. 2003; Dawson et al. 2002; Aristodemou and Thomas-Betts 2000; Bernstone et al. 2000; El-Fadel et al. (1997a, b); Cardarelli and Bernabini 1997). Additionally, since some geophysical methods respond to changes in the physical–chemical conditions in the subsurface, useful chemical information may be obtained from repeated or continuous geophysical site monitoring (Meju 2000).

The integrated use of geophysical methods provides an important tool in the evaluation and characterization of contaminants generated by urban residues (domestic and/or industrial) (Soupios et al. 2005, 2006). Among those, electrical methods have been found very suitable for such studies, due to the conductive nature of most contaminants (Jegede et al. 2012).

Two-dimensional geoelectrical imaging has frequently been used in subsurface pollution studies. The method not only maps the distribution of resistivity of subsurface materials but also provides general information on subsurface stratification of buried waste and contaminated soil. Radiological measurement techniques, in recent years, have greatly improved, and provide more detailed measurements of radioactivity at the surface and within the subsurface. Furthermore, by applying the shallow radiometric measurements on a site, natural radionuclide distributions in the solid waste can be inferred.

Landfill-related studies have mainly been carried out using gamma-ray spectrometry and two-dimensional (2D) resistivity imaging techniques by various authors (Iyoha et al. 2013; Ayolabi et al. 2013; Avwiri et al. 2013; Olubosede et al. 2012; Jegede et al. 2012; Ekeocha et al. 2012; Avwiri et al. 2011; Oladunjoye et al. 2011; Drahor et al. 2006; Ehirim et al. 2009; Al-Jundi and Al-Tarazi 2008; Cardarelli and Filippo 2004). 2D resistivity imaging and vertical electrical sounding were used by Samsudin et al. (2006), to identify and delineate the extent of contaminant leachate plumes around landfills. Electrical resistivity tomography (ERT), electromagnetic terrain conductivity (EM) surveys and seismic surveys have all been used to map of the sediments outside the landfill and landfill boundaries (Soupios et al. 2007; Hutchinson and Barta 2000; De Iaco et al. 2003; Doll et al. 2001). Bernstone and Dahlin (1997) used magnetometry, electromagnetic and DC resistivity surveys to assess the location of waste metals at a closed landfill.

Ehirim and Itota (2013) investigated the radiological impact of a municipal solid waste dumpsite on soil and groundwater using 2D resistivity tomography and gamma-ray spectrometry. Oladapo et al. (2012) determined natural radionuclide levels in wasteland (in other words uncultivated land) soils around Olusosun dump site Lagos, Nigeria. Carpenter et al. (1990) used a resistivity technique to map the internal landfill structure, existence of leachate and the thickness of the cover material at the landfill near Chicago in the USA.

Karlık and Kaya (2001) investigated groundwater contamination using electric and electromagnetic methods at an open waste disposal site. As a result of this study, there was found a good correlation between the results of DC resistivity and VLF-EM methods where zones of the contamination are reflected by low resistivity and negative values of electromagnetic fields components.

The management of solid waste landfills has been a major problem in the urban centers in Trabzon, Turkey and similar locations in other worldwide developing economies. In these urban centers, wastes are daily generated and disposed indiscriminately in landfills without precautions for the underground environment, local geology and their proximity to living quarters. Trabzon-Moloz district's old waste dump site, which is now located at the city center and depends mainly on unplanned urbanization of Trabzon City is an un-engineered landfill area where all wastes are randomly stored. Due to the fact that this area is surrounded by inhabitants of Trabzon, it has created large environmental problems for the city. Therefore, the environmental problems associated with this landfill should certainly be revealed and resolved for the population of Trabzon.

The goal of this study is the subsurface exploration and characterization of the former waste dump site of the Trabzon-Moloz district based on the 2D multi-electrode resistivity method combined with radioactivity monitoring. Radionuclides are assessed with 512-channel gamma-ray spectrometer measurements carried out in this area. In addition, other parameters, such as adsorbed dose rate in air, radium equivalent activity, annual effective dose equivalent and external hazard index are calculated and mapped, and then jointly interpreted to delineate radiological hazards.

General features of the study area

This study has examined waste disposal in the area of the coastal city of Trabzon on the Eastern Black Sea Region of Turkey (Fig. 1). Residential waste and rubble has been infilled along the city shore for a distance of 30–50 m from the sea side since the 1970s. This city has, therefore, created an extensive landfill area created seaward from their original shorelines. For almost 40 years (1967–2007), all types of waste has been collected from houses, commercial premises, small scale industries and, health services and transported to a designated site called Moloz, in the city limits, on the shore. Household wastes, industrial wastes and bio-medical wastes are collected separately without any pretreatment (Beyazli and Aydemir 2008).

The study area, covering about 3.125 ha area, is easily accessible through roads in the city center (Fig. 2). This site is bordered to the north and west by roads, to the south by buildings, to the east by a car park and the Avrasya bazaar. It is an old and a disused dumpsite of the Trabzon Metropolitan Municipality that has been named as the Moloz waste dumpsite. This site is partially vegetated and has a flat topography. There has not been any landscaping work in the studied area where crabgrass now grows wild, depending mainly on the mineralization of the covered soil.

The Moloz municipal waste dumpsite was arbitrarily created by filling of the sea shore with random wastes. This site was created without any controls or systematic procedures. Household wastes were not pretreated before being transferred to the waste filling site. The elevation of the study area is about 10 m above sea level, which is the level of the Black Sea. Average thickness of the waste landfill is around 25 m, and wastes were covered with about 1.0–1.5 m of excavation and agricultural soils. Average height of solid waste in the studied area is about 15–20 m above sea level. The studied area was formerly part of the sea and now slopes towards to sea [from south (S) to north (N)]. Because of this, groundwater flow direction is from S to N. As a result, leachate is believed to flow seawards, even though no monitoring wells have been emplaced to verify this. Drilling or boreholes are not allowed at the landfill due to the heavy methane gas discharge, explosions or catch fires can occur if not managed carefully, thus drilling could not be carried out in the Moloz municipal waste dumpsite to verify geophysical interpretations (Üçüncü and Angin 2011). There is no information about the saline wedge extent in the dumpsite. Boreholes were not done in this dumpsite which is monolandfill area. For this reason, Darcy test was not done because infiltration rate is different from each point of dumpsite. Figure 3 shows a gas pipe placed in the dumpsite for-venting the methane which is caused by decomposing waste, and the height of landfill from the ground.

The road which is shown in Fig. 3b is about 8 m above mean sea level. Construction–demolition materials, household garbage and medical wastes in the Moloz dump are shown in Figs. 4 and 5.

Data acquisition and processing

Gamma-ray spectrometry

The gamma-ray spectrometry method (GRSM) provides a direct measurement of the spatial distribution of naturally occurring radionuclides (^{40}K, ^{238}U and ^{232}Th). Even

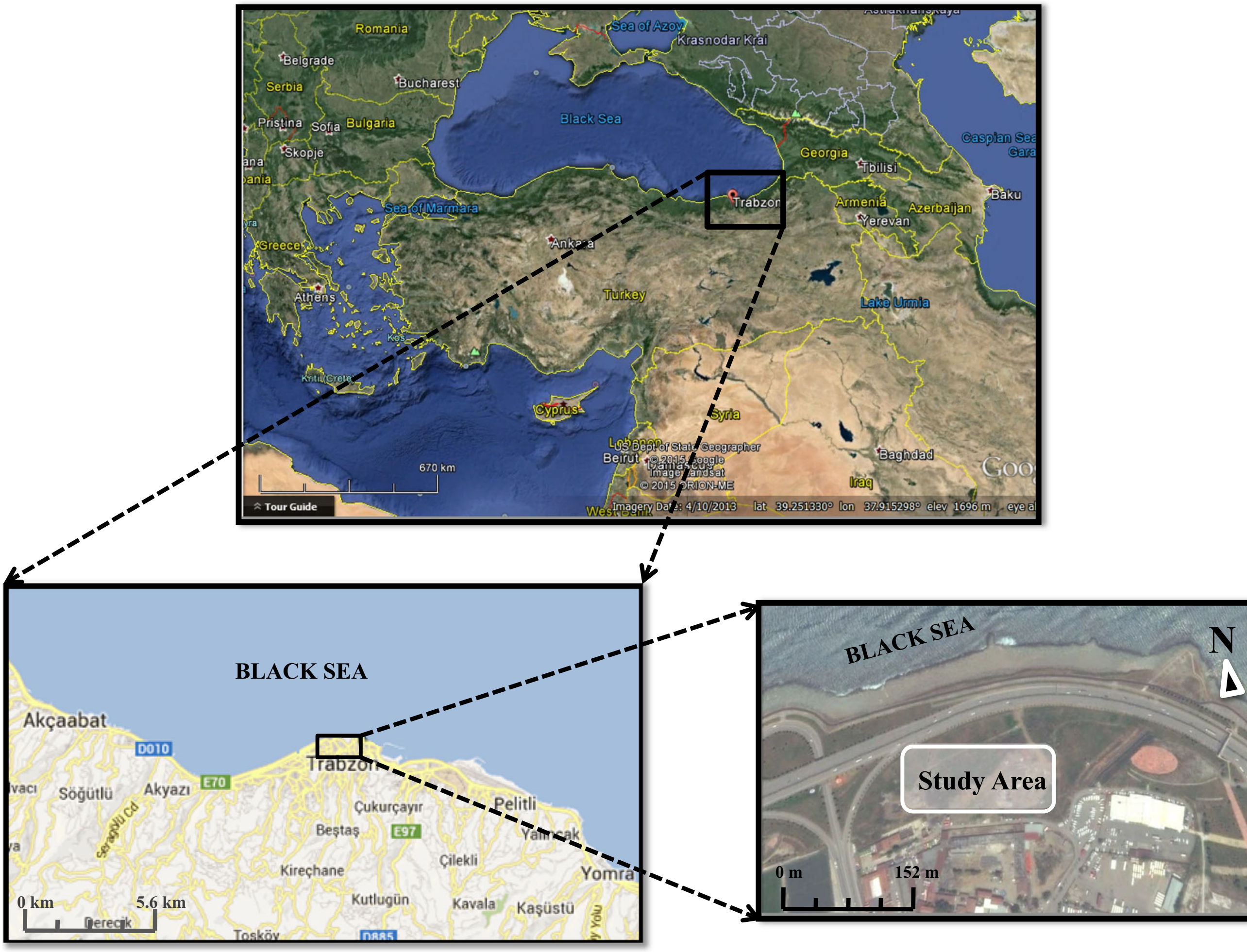

Fig. 1 Location map of Moloz municipal waste dumpsite (modified from Google Earth 2013)

though these are naturally occurring certain types of landfill wastes may concentrate these nuclides. The investigation depth of natural gamma-ray spectrometry method is 50 cm (Hoover et al. 1995). Measured radioelement distribution can reliably be used to map and distinguish the dissimilar geological features depending mainly on variation of radioelement concentrations between different soils and sites (IAEA 1974). On the other hand, because these radioelements have important health effects on humans, determination of the radioactivity level in a habited area should be carried out using in situ radiometric measurements. Furthermore, radioactivity distribution maps created from in situ measurements allow us having a more detailed information about the radiological risk distribution for a habited area.

In this study, a portable gamma-ray spectrometer (GF Instruments, Czech Republic) was used to determine concentration of radioactive substances [equivalent uranium (eU, ppm), equivalent thorium (eTh, ppm) and potassium (K, %), and dose rate (D, nGy/h)] of the studied area. The determinations of uranium and thorium are based on the assumption that the daughter nuclides are in equilibrium with the parent nuclides, that is, none of the intermediate steps in the decay series has been disrupted. Consequently, the deduced amounts of uranium and thorium are equivalent to what would be in equilibrium with the measured radioactivity of the bismuth or thallium isotopes. Therefore, the results of the gamma-ray analyses are expressed as 'equivalent uranium (eU)' and 'equivalent thorium (eTh)' (Killeen and Cameron 1977). The spectrometer was equipped with a thallium activated sodium iodide (NaI(Tl)) scintillation crystal detector and connected to a 512-channels pulse-height analyzer. The calibration of the detector was carried out using the ^{137}Cs isotopic source mounted inside the probe (GF Instruments 2009). Units of radiological parameters and explanations are showed in Table 1.

Gamma-ray spectrometry data were collected on the ground surface (the distance from ground surface is zero.), in a north–south direction, at 231 points along 21 profiles, approximately parallel to each other, where the interval for two measurement points and each profile are 10 m (Fig. 6).

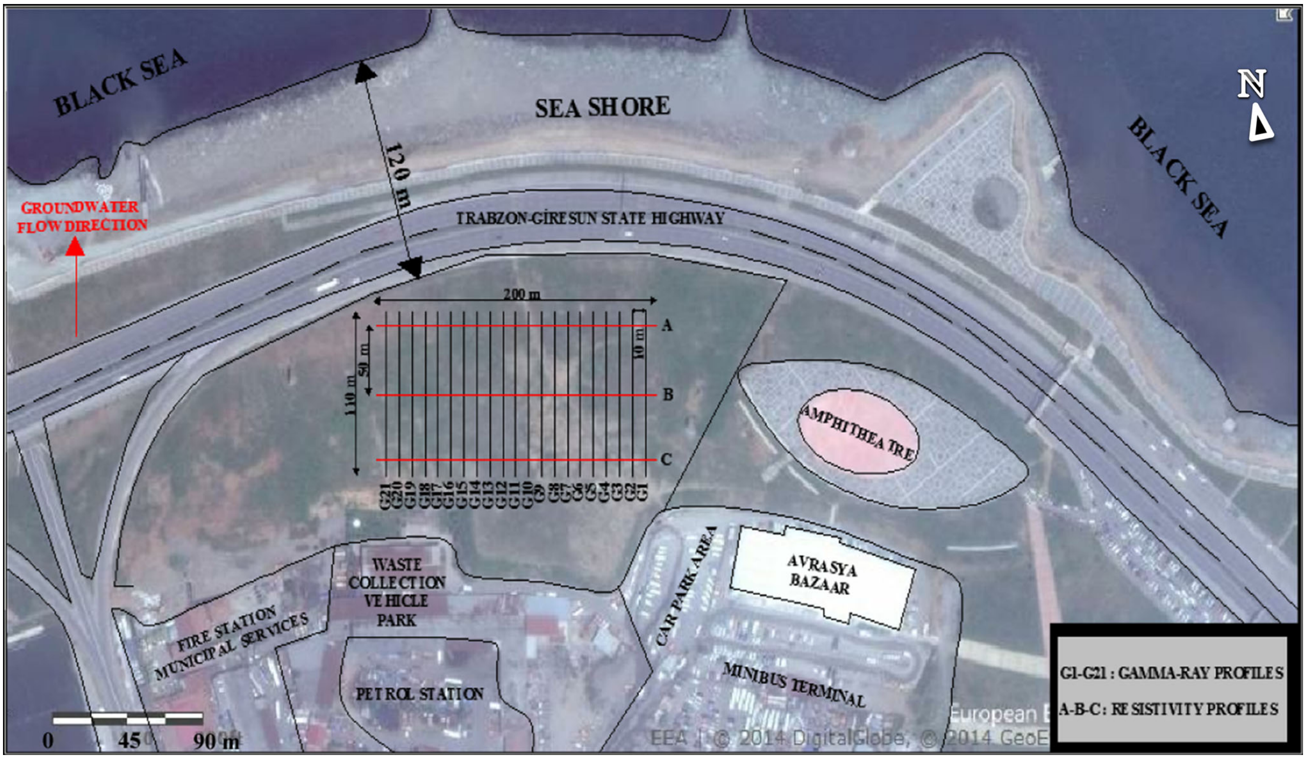

Fig. 2 A schematic sketch showing studied area (resistivity profiles are "*red lines*" and gamma-ray profiles are "*black lines*"). Actual data point locations are shown Fig. 6 (modified from Google Earth 2013)

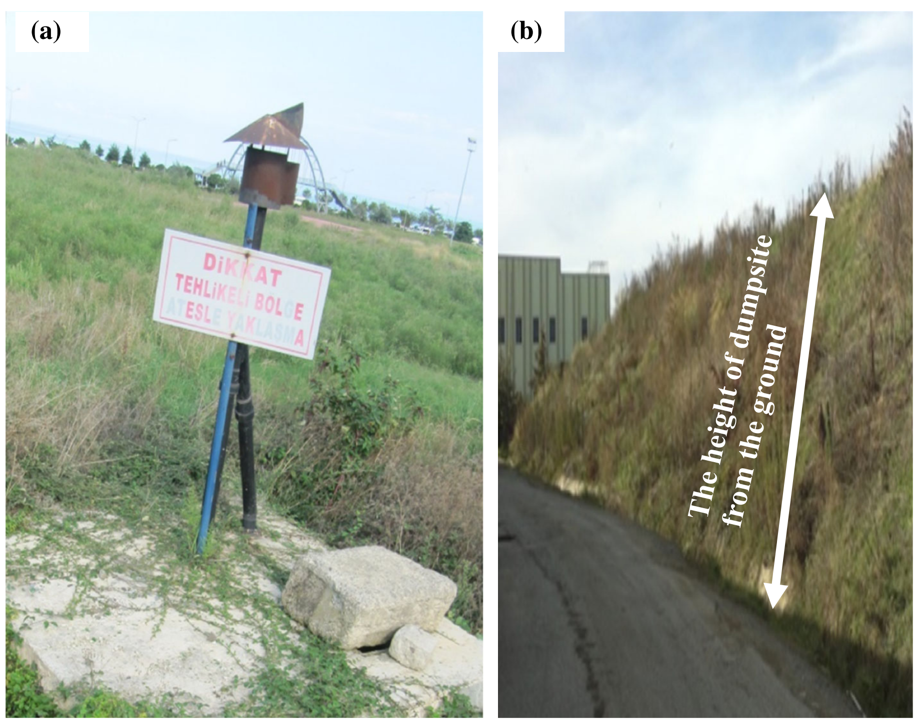

Fig. 3 **a** One of two gas pipes in the landfill (Üçüncü 2013). **b** Height of the landfill from the ground

Each gamma-ray spectrometric measurement took 5 min. Geographical locations of the measurement points were determined using a handheld GPS. After raw radiometric data obtained on the field, measured radionuclide concentrations were converted to the main activity unit (Bq/kg) using an appropriate conversion factor (Table 2).

Fig. 4 Construction and demolition materials and household garbages in the Moloz dumpsite (2013)

Fig. 5 **a** Arbitrarily deposited medical wastes before the site coverage with crabgrass in the Moloz dumpsite (Üçüncü 2013). **b** Construction debris such as gypsum scattered around the area after the site was overgrown with crabgrass

All the converted data were then used to calculate the external hazard index, absorbed dose rate in air, radium equivalent activity, and annual effective dose equivalent. The calculations described below are performed to determine the radiological risk in addition to the measured radionuclide values. As mentioned above, the radioelement

Table 1 Radiation related quantities and explanations (modified from IAEA 2003)

Parameter	Unit	Definition
Dose equivalent	Sievert (Sv)	It is a measure of the health effect of low levels of ionizing radiation on the human body
Activity	Becquerel (Bq)	The rate at which nuclear transformations occur in a radioactive material
Activity concentration	Becquerel per kilogram (Bq/kg)	A measure of activity of a unit mass, expressed in becquerel per kilogram
Dose rate	nanoGray per hour (nGy/h)	The ratio of the dose deposited by radiation in a target to the exposure time

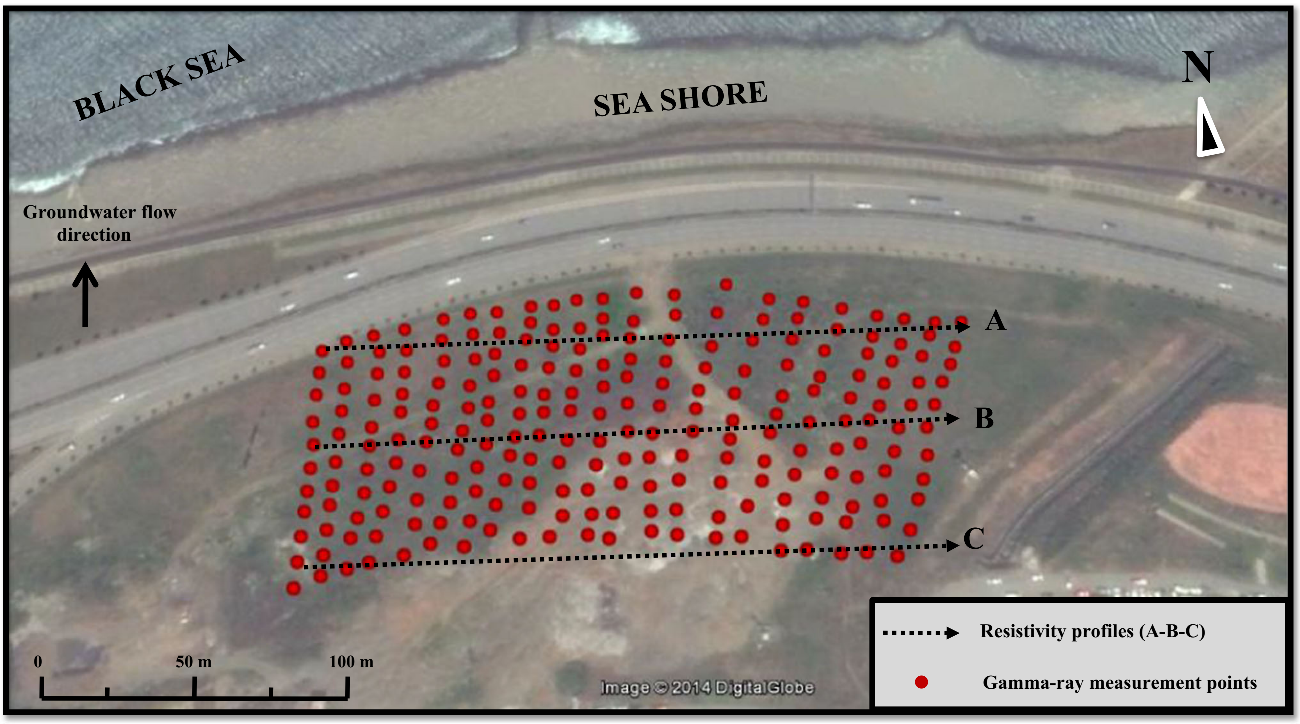

Fig. 6 Gamma-ray measurement points and resistivity profiles locations in studied area (modified from Google Earth 2013)

Table 2 Conversion factors from equivalent concentration (ppm, %) to activity (Bq/kg) (IAEA 1989)

% 1 K	313 Bq/kg	^{40}K
eU (1 ppm)	12.35 Bq/kg	^{238}U or ^{226}Ra
eTh (1 ppm)	4.06 Bq/kg	^{232}Th

concentrations of K (%), eU (ppm), and eTh (ppm) were read from the gamma-ray spectrometer for each point and for calculation of the radiation hazard parameters, measured radionuclide concentrations were expressed in Bq/kg. Finally, all of these parameters were mapped and interpreted to delineate the radiological risk of the studied region, in detail. All radioactivity data are checked using different contouring methods. Consequently, contour maps of K (%), eU (ppm) and eTh (ppm) radionuclide concentrations obtained using the software SURFER through the natural neighbor gridding method. Interpretations described in the text are superimposed in the figures.

The contribution of natural radionuclides to the absorbed dose rate in air (*D*) depends on the radionuclide concentrations in the soil. The greatest part of the gamma radiation comes from terrestrial radionuclides. There is a direct connection between terrestrial gamma radiation and radionuclide concentrations in soil (Beck 1972). If the radionuclide activity in the soil is known, then its exposure dose rate in air at 1 m above the ground can be calculated using the formula proposed by UNSCEAR (1988). The measured specific activity values of ^{238}U, ^{232}Th and ^{40}K are converted into total absorbed dose rate ($D_{absorbed}$) using the following equation (UNSCEAR 1988):

$$D_{absorbed} = (0.462A_U) + (0.604A_{Th}) + (0.0417A_K) \quad (1)$$

where D (nGy/h) is the dose rate at 1 m above the ground and A_U, A_{Th} and A_K are the activity concentrations of ^{238}U, ^{232}Th and ^{40}K (Bq/kg), respectively.

Distribution of ^{238}U, ^{232}Th and ^{40}K in environment is not uniform, so with respect to exposure to radiation, the radioactivity has been defined in terms of radium equivalent activity (Ra_{eq}) in Bq/kg to compare the specific activity of materials containing different amounts of ^{238}U, ^{232}Th and ^{40}K.

An index called the radium equivalent activity (Ra_{eq}) is used to obtain the sum of activities for comparison of the specific radio activities of materials containing different radionuclides like Ra, Th and K. It has been estimated that 370 Bq/kg of ^{226}Ra (^{238}U), 260 Bq/kg of ^{232}Th and 4810 Bq/kg of ^{40}K produce the same gamma-ray dose rate. Thus, the radium equivalent activities (Ra_{eq}) were estimated using the equation (2) of Yang et al. (2005),

$$Ra_{eq} = C_U + 1.43C_{Th} + 0.077C_K \quad (2)$$

where C_U, C_{Th} and C_K are the activity concentration in Bq/kg of ^{238}U, ^{232}Th and ^{40}K, respectively.

In order to estimate the annual effective dose rate from absorbed dose, the conversion coefficient of 0.7 Sv/Gy has been used as suggested by UNSCEAR (2000) The outdoor environment occupancy factor which is about 0.2 is given in the same reference. The annual effective dose equivalent in the outdoor environment ($AEDE_{out.env.}$) is given by the following equation:

$$AEDE_{out.env.}(\mathrm{mSv/year}) = D\ (\mathrm{nGy/h}) \times 8760\ (\mathrm{h/year}) \times 0.2 \times 0.7\ (\mathrm{Sv/Gy}) \times 10^{-6} \quad (3)$$

The external hazard index (H_{ex}) was calculated for the soil samples using the following equation on the basis of the model proposed by Singh et al. (2003):

$$H_{ex} = \left(\frac{A_U}{370}\right) + \left(\frac{A_{Th}}{259}\right) + \left(\frac{A_K}{4810}\right) \leq 1 \quad (4)$$

where A_U, A_{Th} and A_K are the activity concentrations of ^{238}U, ^{232}Th and ^{40}K (Bq/kg), respectively. The value of this index must be less than or equal from unity (<1) in order to keep the radiation hazard to be insignificant. The maximum values of H_{ex} equal to unity corresponds to the upper limit of Ra_{eq} 370 Bq/kg (Mondal et al. 2006).

Electrical resistivity method

Particularly, important problems may arise from old and new waste sites that are sited close to the cities, and the geological properties of the waste site and its environments are also of great importance. The electrical resistivity method is very useful to detect various problems in these sites, and is frequently used in waste and landfill site investigations (Drahor et al. 2006). Resistivity can be a relevant parameter for landfill delineation, since a significant contrast in resistivity occurs between the waste deposits, the top layer and adjacent materials (Aristodemou and Thomas-Betts 2000; Leroux et al. 2007; Clément et al. 2010, 2011). Geophysical surveys are commonly implemented to clarify a variety of problems in wasted sites. Sometimes, the waste electrical resistivity can be altered by saturated fluids through geochemical processes (geochemical processes include dissolution of gases, precipitation/dissolution of solids, redox reactions, hydrolysis and cation exchange.) and therefore a resistivity contrast can be observed between the waste and the surroundings. In addition, leakage from municipal solid waste deposits is generally associated with high ion concentrations and hence very low resistivities. This makes geo-electrical techniques ideal for mapping the vertical and lateral extent of leachate contamination around landfills (Bernstone and Dahlin 1999).

A multi-electrode ABEM Terrameter LS resistivity device was used in this study. It was connected to a total of 41 steel electrodes, which were laid out on a straight line with a constant electrode spacing of 5 m via a multicore cable. Resistivity surveys were conducted across the study area along three profiles, parallel to each other, with a 50 m offset between each profile (Fig. 2). The length of every line is 200 m and approximately oriented west–east. The Wenner electrode array sounding–profiling method was used for this survey because is the most time effective in terms of field work. In this study, variations in both the horizontal and vertical direction were determined by using combined sounding–profiling method. Measurements were made at 5–40 m electrode spacings. A single electrical imaging profile measurement with three stacks took a maximum of about 45 min for the acquisition of 190 apparent resistivity values. The three stacks were used to ensure a reliable average data measurement. The apparent resistivity values were processed using RES2DINV inversion software (Loke 1999). This program automatically subdivides the subsurface into a number of constant resistivity blocks and then uses a least-square inversion to determine the appropriate resistivity values for each block so that the calculated apparent resistivity values agree with the measured apparent resistivity values from the field survey.

Results and discussion

Radionuclide distribution

Highest values of potassium elemental concentrations (^{40}K) were measured in the eastern half of the study area

(Fig. 7). In the western part of the area, potassium concentration exhibits variable values, probably owing to different and mixed type of wastes deposited at the same place of the studied area, such as a mixture of households and harmful industrial wastes. In addition, it is considered that low concentration areas (less than 0.91 %) are associated with decomposed wastes mixed with leachate. Visual inspection suggests that the highest values of potassium-40 concentration are caused by construction demolition materials, clay bricks, decomposed wastes and the lowest ones caused by scattered medical or food wastes. In addition to this, there may be different gases created by the action of microorganisms within wastes (called landfill gas). The high values of potassium radionuclide concentration are associated with asphaltic plates and gypsums (gypsum is a building material and is used in all construction types such as residential, non-residential, new or refurbished.). This conclusion is supported by the field observations as shown in Fig. 5. As the result of field measurements, potassium concentration values vary between 0.37 and 2.25 % with a mean concentration of 1.33 %.

Equivalent uranium elemental concentration (eU) values are measured between 1.9 and 5.5 ppm on the field. Mean eU radionuclide concentration value is 3.45 ppm for the studied area. The eU concentration map (Fig. 8), suggests higher concentration values in the central part of the studied area, along a N–S line, that suggests a channel.

Since the uranium radionuclide is soluble with the liquids, these higher values can be caused by leachate, acidic and/or rain water affecting more radioactive waste. Furthermore, high uranium concentrations are intermittently seen in the studied area owing to asphaltic plates and scattered gypsums. The high concentration areas are associated with decomposed wastes mixed with leachate and household wastes. The low values of uranium concentration may be correlated with construction–demolition materials, decomposed wastes, landfill gases and harmful industrial wastes such as chemical solvents, toxic metals and pesticides. It is suspected that lower values measured in the studied area are caused by precipitation of eU minerals within organic materials existing in wastes or transportation of these minerals into the deeps via groundwater. In addition, the high values of uranium concentration might result from the scattered medical or food wastes from the district which is allowed to mix in the soil.

From the equivalent thorium (eTh) concentration map (Fig. 9), it is clearly seen that higher thorium concentrations (^{232}Th) are measured in the western part of the study area. Here, there are many scattered medical or food wastes (Fig. 5), which cause the increase of thorium concentration. In addition to this, there may be decomposed wastes mixed with leachate and harmful industrial wastes. The two zones are distinguished in the eastern part of the region. One of them is elongated in a NE–SW trend, which has minimum radionuclide concentrations, and the other one is along a NW–SE trend, which has maximum ones.

Maximum values for this region may be caused by construction–demolition materials and metallic wastes. Minimum ones may also be caused by household wastes and landfill gases. The concentration of Thorium is observed comparatively higher than Uranium and Potassium in many measurement points in studied area, and it ranges between 1.20 ppm and 19.43 with an average of 12.28 ppm.

The overall gamma dose rates in the dumpsite due to the combined activities of these eU and eTh elements series and K were also measured. Gamma dose rate values range from 44.3 to 89.2 nGy/h with an average of 67.91 nGy/h. The measured gamma dose rate distribution for study area

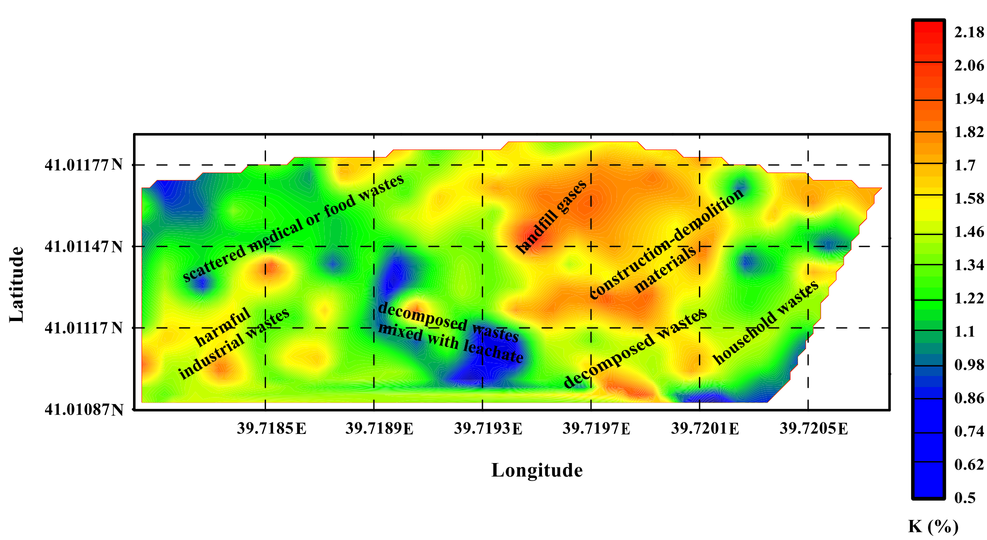

Fig. 7 Interpreted ^{40}K (%) concentration map of the studied area

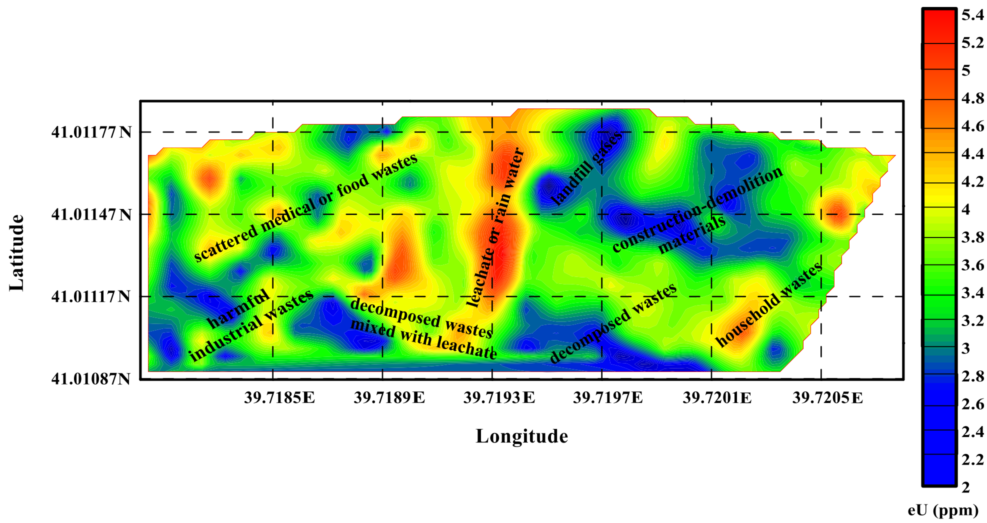

Fig. 8 Interpreted eU (ppm) concentration map of the studied area

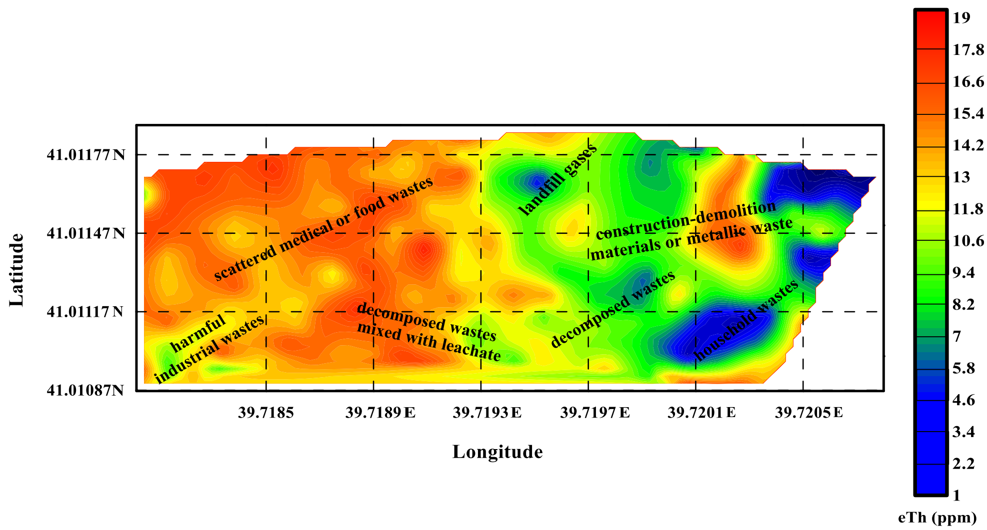

Fig. 9 Interpreted eTh (ppm) concentration map of the studied area

is shown in Fig. 10. As can be seen from Fig. 10, the highest gamma dose rate values are in the western half of the study area where are located scattered medical or food wastes, harmful industrial wastes and decomposed wastes mixed with leachate, and the lowest values are observed area where exist decomposed and household wastes.

In UNSCEAR (2000), it is reported that median values of ^{238}U, ^{232}Th, ^{40}K activities, and gamma dose rates of 35, 30, 400 Bq/kg, and 60 Gy/h, respectively. In this study, the calculated mean radionuclide activity concentrations and mean dose rate value were found to be a little higher than given values in UNSCEAR (2000). Table 3 shows the minimum, maximum and mean values of the ^{238}U, ^{232}Th, ^{40}K activity concentrations, calculated absorbed dose in air (D_{absorbed}), radium equivalent activity ($\mathrm{Ra}_{\mathrm{eq}}$), external hazard index (H_{ex}) and annual effective dose equivalent for outdoor environment ($\mathrm{AEDE}_{\mathrm{out.env.}}$) of the study area.

The absorbed dose rate is calculated from the activity concentration of ^{238}U, ^{232}Th and ^{40}K (Eq. 1), ranges from 43.20 to 91.01 nGy/h with an average value of 69.30 nGy/h. The corresponding annual effective dose equivalent for the outdoor environment range from 0.053 to 0.112 mSv with a mean value of 0.085 while its acceptable value is approximately 2.4 mSv (IAEA 2003). Generally similar trend are observed in all the measurement points. Our results for the average annual effective dose are in accordance with the range of worldwide acceptable value.

The calculated external hazard index values for the dumpsite range from 0.24 to 0.52, with a mean value of 0.39 (Table 3). Obtained mean value for the studied area is less than the acceptable value ($\leq$1). The external hazard

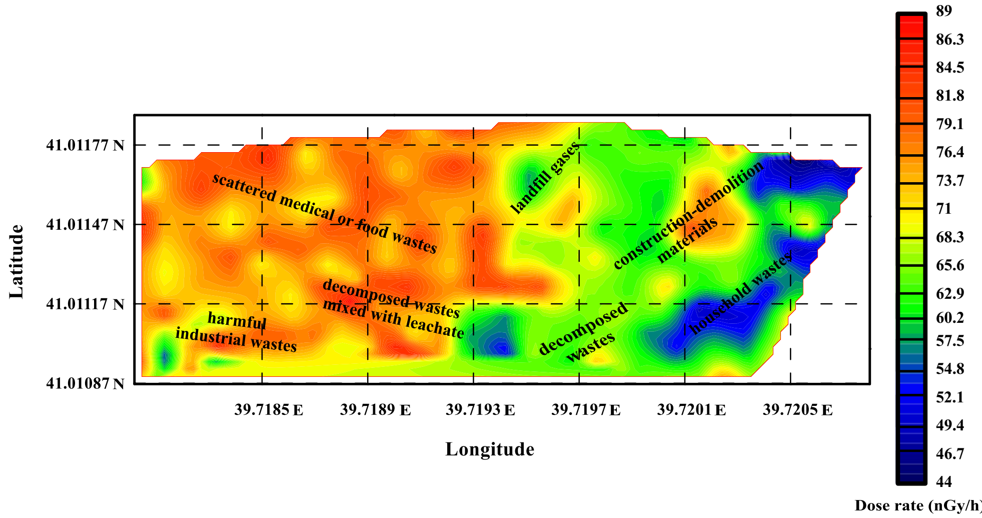

Fig. 10 Interpreted dose rate (nGy/h) distribution map of the studied area

Table 3 Minimum, maximum and average values for the radionuclide activity concentrations (columns 1, 2 and 3) and the gamma radiation hazard indices (columns 4, 5, 6, 7 and 8) of the study area

	^{40}K (Bq/kg)	^{232}Th (Bq/kg)	^{238}U (Bq/kg)	$D_{measured}$ (nGy/h)	$D_{absorbed}$ (nGy/h)	Ra_{eq} (Bq/kg)	H_{ex}	$AEDE_{out.env}$ (mSv/year)
Min.	115.81	4.87	23.46	44.3	43.2	88.25	0.24	0.053
Max.	704.25	78.89	67.92	89.2	91.01	193.22	0.52	0.112
Average	417	49.88	42.68	67.91	69.3	146.19	0.39	0.085

index is less than 1, which means it is safe for human to carry out their activities in the area. According to all calculated radiometric parameters, we concluded no radiological hazards exist for people living in the studied region. Using Eq. 2, the Ra_{eq} found in the measurement points is shown in Table 3. The Ra_{eq} calculated for all the studied area, varies from 88.25 to 193.22 Bq/kg with a mean value of 146.19 Bq/kg. It is inferred for all the measurement points that the mean radium equivalent activity value is well within and less than the permissible limits of 370 Bq/kg (Singh et al. 2003).

Interpretation of 2D electrical resistivity sections

At this landfill site, the resistivity imaging sections clearly outline a large variation in the electrical properties of disposed wastes. Between 42.5 and 65.0 m, we found a trend of increasing resistivity from the surface down to a depth of 13.8 m in the profile A. A similar trend can also be seen between 92.5 and 120.0 m. The 2D inverted resistivity section obtained from the field measurement is shown in Fig. 11. In this section, shallow high resistivity zones (200 and 874 Ωm) are interpreted as scattered medical and food wastes, construction–demolition wastes or municipal waste.

High resistivity areas (874 and 2636 Ωm) are suspected to be landfill gases (ammonia, methane, etc.), generated from the result of the anaerobic decomposition of the landfill organic wastes. For example, Ehirim et al. (2009), Iyoha et al. (2013) and Tsourlos et al. (2014) interpreted zones of high resistivity as landfill gases. After that, hydrostatic pressure reduces the aspect ratio of cracks, induce variations in pore geometry and thereby change both, the overall electrical (bulk)-conductivity by closing and opening of conduction path, and thus cause a decrease of permeability and electrical bulk conductivity (Heikamp and Nover 2003). Therefore, electrical resistivity increases with increasing hydrostatic pressure. Also, increasing hydrostatic pressure causes to degassing of landfill gases. Thus, observed very high resistivities, in this study, on surface-near layer can actually be attributed to degassing of these gases.

However, between the 70.0 and 92.5 m, a low resistivity zone exists from the surface to depths ranging from 1.28 to 38.0 m because of the presence of a water retention material which has the resistivity ranging from about 1–30 Ωm (Fig. 11). The dark-blue zone of low resistivity in Fig. 11 is interpreted as decomposed wastes, or leachates.

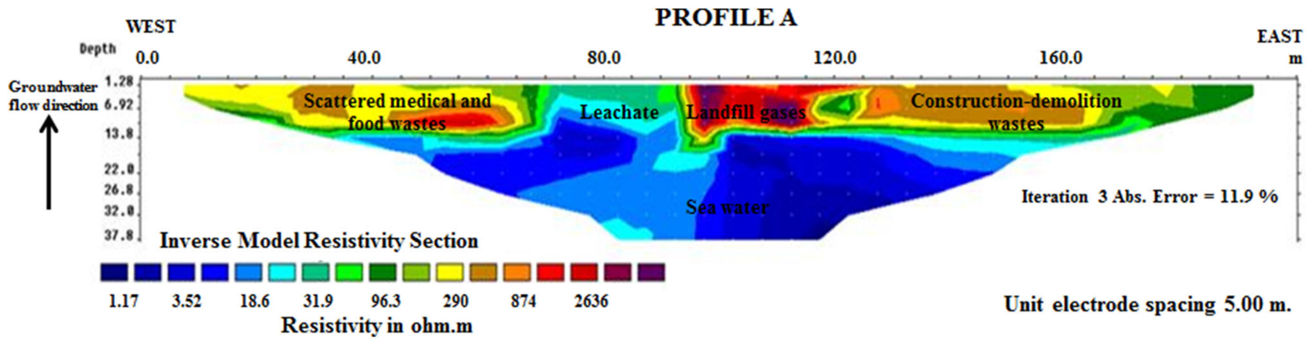

Fig. 11 Inverted resistivity sections of profile A and interpretation

These areas likely contain materials that are highly porous and permeable. Consequently, the low resistivity regions are attributable to leachates in the subsurface, whereas isolated relatively high resistivity regions might be due to the affect of non-degraded solid waste within the dumpsite.

Figure 12 corresponds to the profile in the middle of the dumpsite. The electrode spacing chosen is 5.0 m, which gives a total length of 200.0 m, and this allows a depth of investigation down to almost 38.0 m. In profile B, at positions 20.0–65.0, 105.0–120.0 and 135.0–192.5 m there are indications of resistant zones represented by high resistivity (77.4–348.0 Ωm), starting at the ground surface down to 18.0 m depth, 13.8 m depth and 16.0 m depth, respectively. In this profile, the dark reddish to yellowish zones at the near surface are associated with non-degradable waste materials, medical wastes and buried construction materials as shown in Fig. 12. This conclusion is clearly supported by the field observations (Fig. 4).

Underlying this high resistivity zone, there is a channel-shaped very low resistivity zone (1.8–17.2 Ωm) between 70.0 and 90.0 m with depth approximately 38.0 m. A similar structure is also observed in profile A. This channel-shaped structure plunges into the soil towards the middle of the section. As mentioned in Sect. 2, this waste dumpsite was formed by filling the sea with waste. For this reason, low resistivity region is thought to be sea water. Hence, this conductive region creating the bottom of the site which is shown in inverse resistivity section may be interpreted as sea water underlying the dumpsite. The low resistivity section between the mass of wastes (between approximately 70.0 and 90.0 m) near the surface can also be interpreted as either accumulated garbage or rain waters.

Profile C (Fig. 13) exhibits resistivity variations such as profiles A and B. These variations between upper and lower parts of the profile are strongly attributed to the degree of waste decomposition, which in turn, reflects the type of wastes (conductive or resistant wastes).

The inversion section depicts two outstanding anomalous regions referred to here as upper and lower zones. The high resistivity zone is seen at the upper part of the entire section. This part has resistivity values varying from 95.2 to 368.0 Ωm and depth varying between 10.0 and 18.0 m, and is interpreted to be same high resistivity materials as in the other profiles: gravels, asphalt, plastic and household wastes, construction and industrial wastes, as delineated in the two previous profiles. This interpretation is supported by visual observation on the field during the survey. Also, it is suspected that between the 110.0 and 135.0 m, a high resistivity anomaly exists from the surface through depth ranging from 1.28 to 18.0 m because of the presence of decomposed waste which has the resistivity ranging from

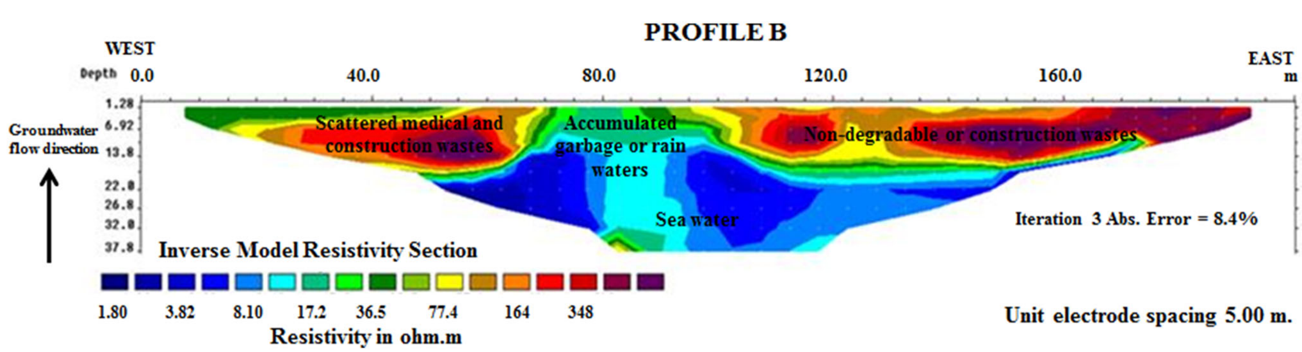

Fig. 12 Inverted resistivity sections of profile B and interpretation

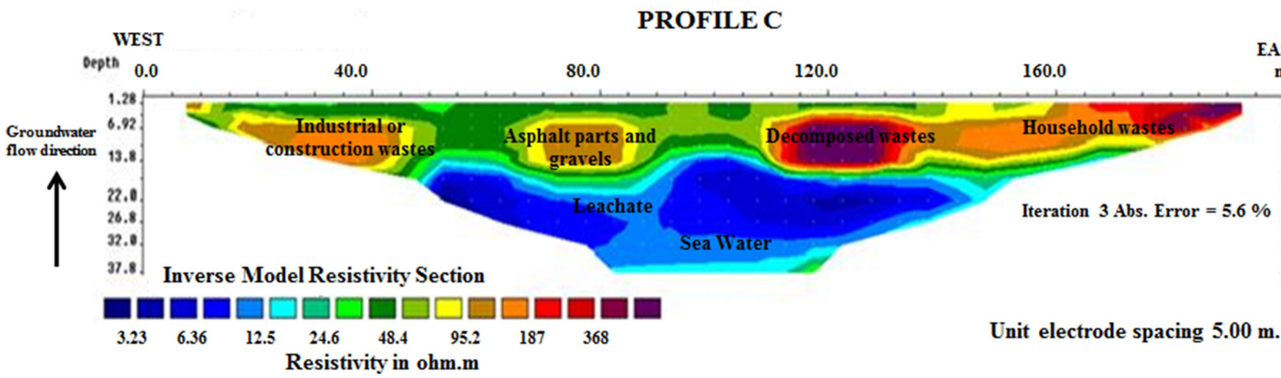

Fig. 13 Inverted resistivity sections of profile C and interpretation

187–368 Ωm (Fig. 13). A channel-shaped area, observed in the first and second profiles, has been replaced by a new mass of waste at surface points between 65.0 and 85.0 m in the third profile. Beneath this zone, a very low resistivity zone (3.23–12.5 Ωm) exist with depth ranges from 18.0 to 37.8 m. This zone corresponds to mixed materials such as sea water, leachate, and rain water that seeped from the surface.

A block representing the 3D resistivity model was created by 3D inversion of 2D resistivity data obtained from three parallel lines on the field. The DC3DInvRes program (Günter 2004) is used to create the 3D model. The 3D resistivity model and 2D dose rate maps are compared and interpreted together in Fig. 14. This figure clearly shows the lateral and vertical extent of the waste masses existed in the dumpsite. Owing to the fact that the radioactivity measurements cannot give depth-related information, these two maps can only be used for comparison of the superficial changes throughout the area. Furthermore, radioactivity maps provide important information in terms of environmental hazards of the studied area.

The electrical resistivity and gamma-ray spectrometry results show good agreement, which is supported by visual inspection in the studied area. From the 3D resistivity model and 2D dose rate map (Fig. 14), it is clearly seen that higher electrical resistivity and dose rate values correspond to several dumps such as scattered medical, industrial and construction–demolition waste materials. Furthermore, there are some low resistivity and dose rate values seen in Fig. 14a, b, which is being suspected to be household and decomposed wastes.

Conclusions

The 2D resistivity imaging technique and gamma-ray spectrometry measurements were combined to investigate the lateral and vertical extent of leachate contamination and location of waste masses, and to determine the activity concentrations, and dose rates of radionuclides at the municipal solid waste dumpsite of the Trabzon-Moloz district. The electrical resistivity and gamma-ray spectrometry results show good agreement, which is supported by visual inspection in the studied area. Electrical resistivity survey results indicate that the waste in the dumpsite was buried to as much as 18.0 m depth. This may portend a great danger for sea creatures, due to diseases caused by micro-organisms, radiological impacts and heavy-metal poisoning. While the higher electrical resistivity values correspond to several dumps such as scattered medical, industrial and construction–demolition waste materials, there are some low resistivity values seen in the 2D inverted resistivity sections which is being suspected to be leachate and sea water. In our study, variation of very high resistivity is seen from 2D inverted resistivity section in the profile A. Unfortunately, we can not proof landfill gas because there is no sample work. We do not have any wells to show sea-water intrusion. All our interpretations which is about sea-water intrusion and landfill gases is our predicted ideas.

Although radionuclide activity concentrations (^{40}K, ^{238}U, and ^{232}Th) in the landfill area are higher than the median values given in the literature, it is concluded that radionuclide levels in the region are not harmful for human health and environment. Despite the fact that radiological risk values (D_{absorbed}, $\mathrm{AEDE}_{\mathrm{out.env.}}$, $\mathrm{Ra}_{\mathrm{eq}}$, and H_{ex}) of the dumpsite are consistent with the median values in the literature, the activity values of radionuclides show the existence of low level activity in the dumpsite. However, an increase in the activity concentration and dose rates of these radionuclides may lead to adverse effects on humans in their lifetime. As it is well known that high dose of radioactivity is a main source of cancer. In order to beware of this risk, more research should certainly be needed to assess the potential impact

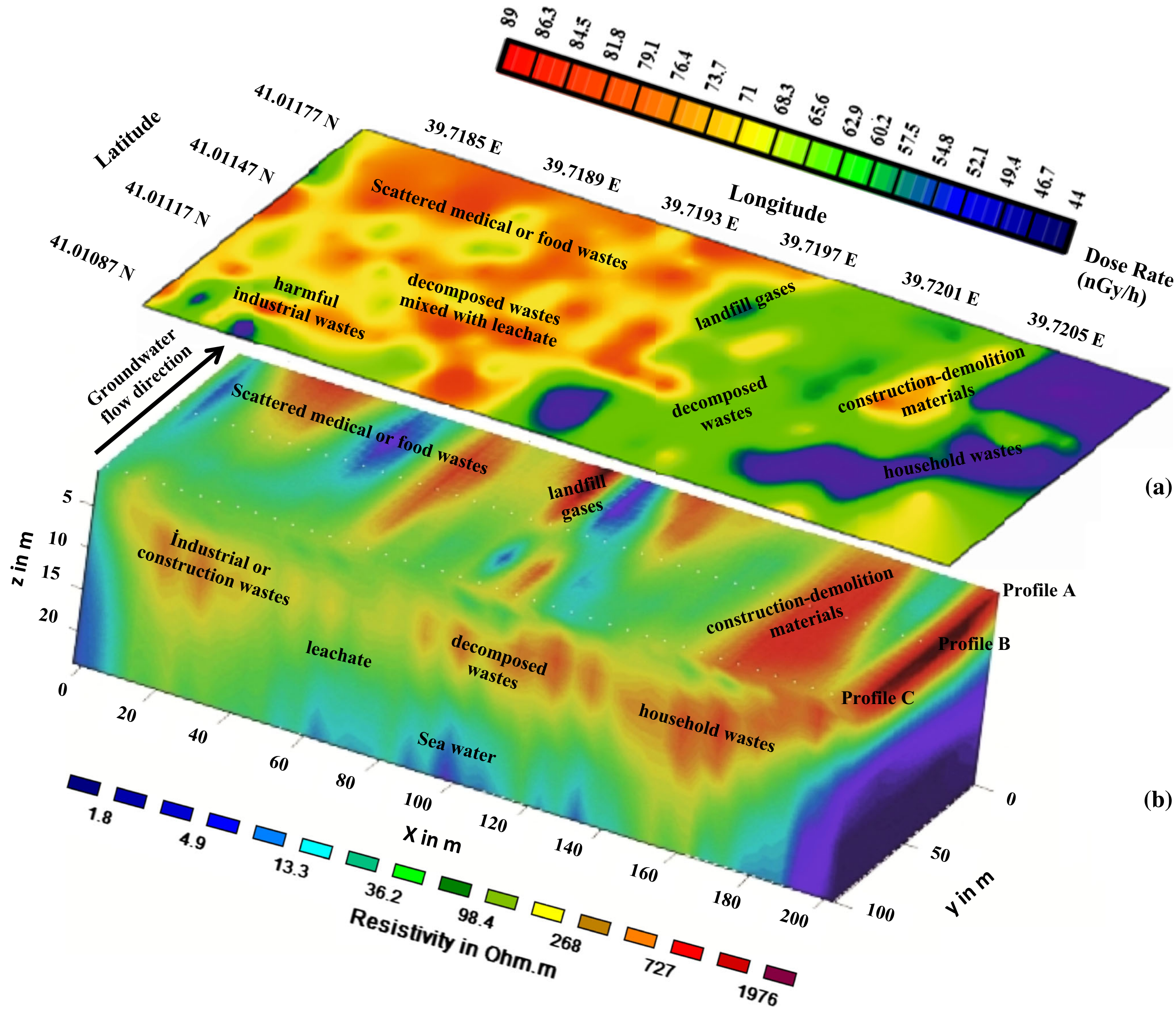

Fig. 14 Comparing 3D block model of electrical resistivity inversion results (**a**) and 2D dose rate map (**b**)

of radiological emission on human life in the studied area. In addition this, the biological and chemical constituents of these wastes are unknown and should be investigated using more detailed methods. Consequently, the complexity of subsurface conditions beneath contaminated lands requires a multidisciplinary approach, combining the systematic and careful application of hydrogeological, chemical and environmental geophysical techniques.

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References

Al-Jundi J, Al-Tarazi E (2008) Radioactivity and elemental analysis in the Ruseifa municipal landfill, Jordan. J Environ Radioact 99:190–198

Aristodemou E, Thomas-Betts A (2000) DC resistivity and induced polarisation investigations at a waste disposal site and its environments. J Appl Geophys 44:275–302

Avwiri GO, Nte FU, Olanrevaju AI (2011) Determination of radionuclide concentration of landfill at Eliozu, Port Harcourt, Rivers State. Sci Afr 10(1):46–57

Avwiri GO, Egieya JM, Ononugbo CP (2013) Radiometric survey of Aluu landfill, in River State, Nigeria. Adv Phys Theor Appl 22:24–29

Ayolabi EA, Folorunso AF, Kayode OT (2013) Integrated geophysical and geochemical methods for environmental assessment of municipal dumpsite system. Int J Geosci 4:850–862

Beck HL (1972) The physics of environmental radiation fields. Natural radiation environment II, CONF-720805 P2. In:

Proceedings of the second international symposium on the natural radiation environment
Benson AK, Mustoe NB (1998) Integration of electrical resistivity, ground penetrating radar, and very low frequency electromagnetic induction surveys to help map groundwater contamination produced by hydrocarbons leaking from underground storage tanks. Environ Geosci 5:61–68
Bernstone C, Dahlin T (1997) DC resistivity mapping of old landfills: two case studies. Eur J Eng Environ Geophys 2:121–136
Bernstone C, Dahlin T (1999) Assessment of two automated DC resistivity data acquisition systems for landfill location surveys: two case studies. J Environ Eng Geophys 4(2):113–121
Bernstone C, Dahlin T, Ohlsson T, Hogland H (2000) DC resistivity mapping of internal landfill structures: two pre-excavation surveys. Environ Geol 39:360–371
Beyazli D, Aydemir S (2008) Black Sea region of Turkey landfilling with mixed wastes: environmental effects of wastes and their management in the Eastern. Indoor Built Environ 17:92–102
Cardarelli E, Bernabini M (1997) Two case studies of the determination of parameters waste dumps. J Appl Geophys 36:167–174
Cardarelli E, Filippo GD (2004) Integrated geophysical surveys on waste dumps: evaluation of physical parameters to characterize an urban waste dump (four case studies in Italy). Waste Manag Res 22:390–402
Carpenter PJ, Kaufmann RS, Price E (1990) Use of resistivity soundings to determine landfill structure. Ground Water 28:569–575
Carpenter PJ, Aizhong D, Lirong C, Puxin L, Fulu C (2009) Apparent formation factor for leachate-saturated waste and sediments: examples from the USA and China. J Earth Sci 20:606–617
Clément R, Descloitres M, Günther T, Oxarango L, Morra C, Lauren JP, Gourc JP (2010) Improvement of electrical resistivity tomography for leachate injection monitoring. Waste Manag 30:452–464
Clément R, Oxarango L, Descloitres M (2011) Contribution of 3-D time-lapse ERT to the study of leachate recirculation in a landfill. Waste Manag 31:457–467
Dawson CB, Lane JW, White EA, Belaval M (2002) Integrated geophysical characterization of the Winthrop, Maine. In: Symposium on the application of geophysics to engineering and environmental problems, Las Vegas
De Carlo L, Perri MT, Caputo MC, Deiana R, Vurro M, Cassiani G (2013) Characterization of a dismissed landfill via electrical resistivity tomography and mise-à-la-masse method. J Appl Geophys 98:1–10
De Iaco R, Maurer H, Horstmeyer H (2003) A combined seismic reflection and refraction study of a landfill and its host sediments. J Appl Geophys 52:139–156
Doll WE, Gamey TJ, Nyquist J E, Mandell W, Groom D, Rohdewald S (2001) Evaluation of new geophysical tools for investigation of a landfill, Camp Roberts, California. In: Symposium on the application of geophysics to engineering and environmental problems, pp LWS4. doi:10.4133/1.2922927
Drahor MG, Berge MA, Kurtulmuş TÖ (2006) Resistivity inverse modelling in landfill sites and its application in an old waste landfill site. J Earth Sci Appl Res Centre Hacettepe Univ 27(3):195–209
Ehirim CN, Itota GO (2013) Radiological impact of a municipal solid waste dumpsite on soil and groundwater using 2-D resistivity tomography and gamma ray spectroscopy. IOSR J Environ Sci Toxicol Food Technol 2(5):35–42
Ehirim CN, Ebeniro JO, Olanegan OP (2009) A geophysical investigation of solid waste landfill using 2-D resistivity imaging and vertical electrical sounding methods in Port Harcourt Municipality, River State, Nigeria. Pac J Sci Technol 10(2):604–613
Eikelboom RT, Ruwiel E, Goumans JJJM (2001) The building materials decree: an example of a Dutch regulation based on the potential impact of materials on the environment. Waste Manag 21:295–302
Ekeocha NA, Okereke ID, Okonkwo SE (2012) Electrical resistivity investigation of solid waste dumpsite at Rumuekpolu in Obio Akpor L.G.A., Rivers State, Nigeria. Int J Sci Technol 1(11):631–637
El-Fadel M, Findikakis AN, Leckie JO (1997a) Modeling leachate generation and transport in solid waste landfills. Environ Technol 18:669–686
El-Fadel M, Findikakis AN, Leckie JO (1997b) Environmental impacts of solid waste landfilling. J Environ Manag 50:1–25
Google Earth (2013) Google Earth 7.1.2.2041. Google Inc, Satellite view
Green A, Lanz E, Maurer H, Boerner D (1999) A template for geophysical investigations of small landfills. Lead Edge 18:248–254
Günter T (2004) Inversion methods and resolution analysis for the 2D/3D reconstruction of resistivity structures from dc measurements. http://www.resistivity.net
Heikamp S, Nover G (2003) An integrated study on physical properties of a KTB gneiss sample and marble from Portugal: pressure dependence of the permeability and frequency dependence of the complex electrical impedance. Pure Appl Geophys 160:929–936
Hoover DB, Klein DP, Campbell DC (1995) Geophysical methods in exploration and mineral environmental investigations. In: DuBray E (ed) Preliminary compilation of descriptive geoenvironmental mineral deposit models. U.S. Geological Survey Open-File Report 95–831,19–27
Hutchinson PJ, Barta LS (2000) Geophysical applications to solid waste analysis. In: The 16th international conference on solid waste technology and management, Philadelphia, pp 2–68
IAEA (1974) Instrumentation for uranium and thorium exploration. Technical reports series no. 158, Vienna
IAEA (1989) Construction and use of calibration facilities for radiometric field equipment. In: Proceedings of IAEA technical reports series, vol 309. International Atomic Energy Agency, Vienna
IAEA (2003) Guidelines for radioelement mapping using gamma ray spectrometry data. IAEA Technical Reports Series, vol 1363. International Atomic Energy Agency, Vienna
GF Instruments (2009) Gamma Surveyor User Guide v1.3
Iyoha A, Akhirevbulu OE, Amadasun CVO, Evboumwan IA (2013) 2D Resistivity imaging investigation of solid waste landfill sites in Ikhueniro Municipality, Ikpoba Okha Local Government Area, Edo State, Nigeria. J Resour Dev Manag 1:65–69
Jegede SI, Ujuanbi O, Abdullahi NK, Iserhien-Emekeme RE (2012) Mapping and monitoring of leachate plume migration at an open waste disposal site using non-invasive methods. Res J Environ Earth Sci 4(1):26–33
Karlık G, Kaya MA (2001) Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey. Environ Geol 40(6):725–731
Killeen PG, Cameron GW (1977) Computation of in situ potassium, uranium and thorium concentrations from portable gamma-ray spectrometer data. In: Report of activities, part A, Geological Survey of Canada, paper no 77-1A, pp 91–92
Leroux V, Dahlin T, Svensson M (2007) Dense resistivity and induced polarization profiling for a landfill restoration project at Härlöv, Southern Sweden. Waste Manag Res 25:49–60
Loke MH (1999) Electrical imaging surveys for environmental and engineering studies—a practical guide to 2D and 3D surveys. http://www.abem.se
Meju MA (2000) Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach. J Appl Geophys 44:115–150

Mondal T, Sengupta D, Mandal A (2006) Natural radioactivity of ash and coal in major thermal power plants of West Bengal, India. Curr Sci

Namasivayam C, Radhika R, Suba S (2001) Uptake of dyes by a promising available agricultural solid waste: coir pith. Waste Manag 21:381–387. doi:10.1016/S0956-053X(00)00081-7

Oladapo OO, Oni EA, Olawoyin AA, Akerele OO, Tijani SA (2012) Assessment of natural radionuclides level in wasteland soils around Olusosun Dumpsite Lagos, Nigeria. J Appl Phys 2(3):38–43

Oladunjoye MA, Olayinka AI, Amidu SA (2011) Geoelectrical imaging at an abandoned waste dump site in Ibadan, Southwestern Nigeria. J Appl Sci 11(22):3755–3764

Olubosede O, Akinnagbe OB, Adekoya O (2012) Assessment of radiation emission from waste dumpsites in Lagos State of Nigeria. Int J Comput Eng Res 2(3):806–811

Orlando L, Marchesi E (2001) Georadar as a tool to identify and characterize solid waste dump deposits. J Appl Geophys 48:163–174

Pugh M (1999) The path to affordable landfills. J Waste Manag 58–59

Saltas V, Vallianatos F, Soupios PM, Makris JP, Triantis D (2005) Application of dielectric spectroscopy to the detection of contamination in sandstone. In: Proceedings of the international workshop in geoenvironment and geotechnics (GEOENV 200), Milos, p 269

Samsudin AR, Rahim BE, Yaacob WZW, Hamzah U (2006) Mapping of contamination plumes at municipal solid waste disposal sites using geoelectric imaging technique: case studies in Malaysia. J Spatial Hydrol 6(2):13–22

Singh S, Singh B, Kumar A (2003) Natural radioactivity measurements in soil samples from Hamirpur district. Radiat Meas 36:547–549

Soupios P, Manios T, Sarris A, Vallianatos F, Maniadakis K, Papadopoulos N, Makris JP, Kouli M, Gidarakos E, Saltas V, Kourgialas N (2005) Integrated environmental investigation of a municipal landfill using modern techniques. In: Proceedings of the international workshop in geoenvironment and geotechnics, Milos Island, pp 75–82

Soupios P, Papadopoulos N, Kouli M, Georgaki I, Vallianatos F, Kokkinou E (2006) Investigation of waste disposal areas using electrical methods: a case study from Chania, Crete, Greece. Environ Geol. doi:10.1007/00254-006-0418-7

Soupios P, Papadopoulos I, Kouli M, Georgaki I, Vallianatos F, Kokkinou E (2007) Investigation of waste disposal areas using electrical methods: a case study from Chania, Crete, Greece. Environ Geol 51:1249–1261

Tsourlos P, Vargemezis GN, Fikos I, Tsokas GN (2014) DC geoelectrical methods applied to landfill investigation: case studies from Greece. Near Surf Geosci 32:81–89

Üçüncü O (2013) Personal photograph archive of Dr. Üçüncü about Moloz waste dumpsite

Üçüncü O, Angin Z (2011) Engineering geological assessment of the Trabzon ad Rize Cities solid waste landfill site (NE Turkey). In: Second international conference on solid waste management in developing countries

UNSCEAR (1988) United Nations sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General Assembly, with scientific annexes. United Nations sales publication E.88.IX.7. United Nations, New York

UNSCEAR (2000) United Nations sources and effects of ionizing radiation, vol I: Sources; vol II: Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 2000 Report to the General Assembly, with scientific annexes. United Nations sales publications E.00.IX.3 and E.00.IX.4. United Nations, New York

Yang Y, Wu X, Jiang Z, Wang W, Lu J, Lin J, Wang LM, Hsia Y (2005) Radioactivity concentration in soil of the Xiazhuang granite area. China Appl Isot Radiat 63:255–259