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Geophysical Contribution for the Mapping the Contaminant Plume of Leachate from Rubbish Dumpsite of Hevie, Benin

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Authors' contributions

This work was carried out in collaboration between all authors. Author YN designed the study, performed the analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors LM and AC managed the measurements on the field and analyses of samples. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

In majority of the countries in the process of development like the Benin, the presence of dumpsite of rubbish can cause pollution of the groundwater. Indeed, the leachate resulting from the seepage of rain water into rubbish can infiltrate and pollute the water table. The evaluation of the infiltration of the leachate was carried out by the geophysical methods of frequential electromagnetism in EM34 and Electrical Resistivity Tomography (ERT). The electromagnetic map circumscribed the lateral limits of the leachate diffusion and the electromagnetic surveys showed that it infiltrated with a depth of 20m. The two cross sections of electrical resistivity tomography of NS and SW-NE direction made it possible to map the plume of leachate. These results show that the contact water table - leachate is rather discontinuous, the depths of the feather of leachate varying from few meters to 22m for an average static level of 18m. The leachate infiltration occurs with variable depths and is not everywhere in contact with the water table. This discontinuous pollution has been observed in the water quality of the wells. Indeed, the analyses of water samples of the wells showed a great variation of heavy metal pollution in rather close wells.

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Keywords: Leachate; frequential electromagnetism; electrical resistivity tomography (ERT); dumpsite of rubbish.

1. INTRODUCTION

In African towns, a few kilograms of municipal and domestic waste are produced per day, in each family. This waste is collected and transported from the town to municipal landfills where it is deposited. In the last decade, the increasing public concern with groundwater management problems due to waste disposal has generated significant hydrogeological and geochemical research [1,2]. This research activity concerns, for instance, the mapping of contaminant plume associated with the migration of leachate. The groundwater conductivity indicates its degree of mineralization [3] e.g. elevated concentrations of heavy metals due to the migration of leachate. Mapping the migration of leachate in the field by classical geochemical methods is often difficult because it is cost and time consuming. In addition, the borehole measurements are invasive and can perturb local equilibria. For groundwater sampling in observations wells, the samples are taken after 30 minutes of purging when the geochemical parameters are constant. Moreover, the introduction of a sampling cell into a borehole generates disturbances due to the introduction of oxygen. Establishment of steady state conditions in a borehole can then take from a few hours to a few weeks [4,5].

Driven by the need for a cost-effective and a more continuous characterization of contaminated groundwater, growing interest has emerged very recently in the use of non-intrusive geophysical methods [6,7,8,9,10]. Usually the landfill site investigation is aimed at detecting and determining the extension of the polluted area and for that purpose, several researchers have used resistivity and/or electromagnetic geophysical methods [11]. These studies are possible because both organic and inorganic chemicals can cause a large variation in the electrical resistivity of the earth material [12,6]. The organic-rich contaminated plumes behave like geobatteries. These geobatteries are a source of an electrical field which signature can be recorded at the ground surface [13]. The plume rich in inorganic chemicals is characterized by high values of electrical conductivity of water and chloride concentrations. The geophysical methods in electrical prospection are adequate for the cartography of the mineralization of the groundwater [3]. The Electrical Resistivity Tomography (ERT) and Electromagnetic Methods (EM) are active methods used to image the Direct Current or the frequency-dependent electrical resistivity distribution inside the ground. [1]. Electrical and electromagnetic methods have been successfully used in the detection of groundwater contamination and seepage in many case studies, e.g. [14,15,16,17,18,19], and [20]. Moreover, the uncertainty of geophysical interpretation can be notably reduced when several methods are jointly used [21,22].

In the present study, geophysical methods of Electrical Resistivity Tomography (ERT) and frequential electromagnetism (FEM) have been combined for mapping the contaminant plume associated with the migration of leachate from the dumpsite of rubbish of Hevie in south of Benin. The main objective of the study is to evaluate the extension and possible paths of the groundwater contamination caused by rubbish dumpsite leachate.

2. MATERIALS AND METHODS

2.1 Location and Hydrogeology of Study Site

The study zone is located at the rubbish dumpsite of Hevie on the Allada plate of coastal sedimentary basin of Benin (Fig. 1). The rubbish dumpsite extends on a surface of approximately 7ha. From January to October 2001, the site received 270m^3 not sorted domestic wastes per day [23]. Between 1995 and 2004, the dumpsite received more than 3000m^3 of wastes.

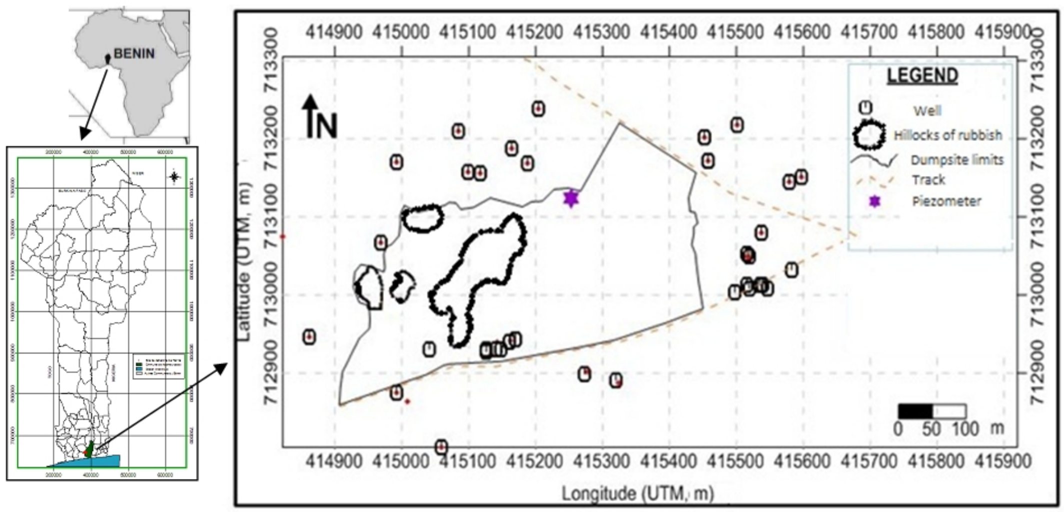

Fig. 1. Localization of hillocks on the rubbish dumpsite of Hevie

In the district of Hevie, the annual average temperature is 25ºC with an annual cumulated pluviometry of 1100mm. The groundwater feeds directly by rainwater with fluctuations of the static level according to the seasons. The evapotranspiration is rather high with a relative humidity of about 90 %. These climatic conditions cause deterioration, degradation and corrosion within waste which produces leachate. The zone of study is located at approximately 15 km of the shore. The shallow aquifer is located under a lateritic layer named “terre de barre”. The unconfined aquifer of Allada plate is dated of Miocene - Pliocene (named Terminal Continental). This aquifer consists of fine sands to coarse, gravels by places and clayey sand. The total porosity calculated starting from the granulometric study of the sandy levels of the plate in the area of Agankomey, lies between 39 and 42%, so an average of 40% [24]. The total porosity of the surface levels of the lateritic formation in this area lies between 34 and 36% [24].

Fig. 2 presents a simplified hydrogeologic section of the Western part of the coastal sedimentary basin of the Benin where is located the site of Hevie. The dumpsite of Hevie is directly on the lateritic formation which is above the aquifer of Terminal Continental.

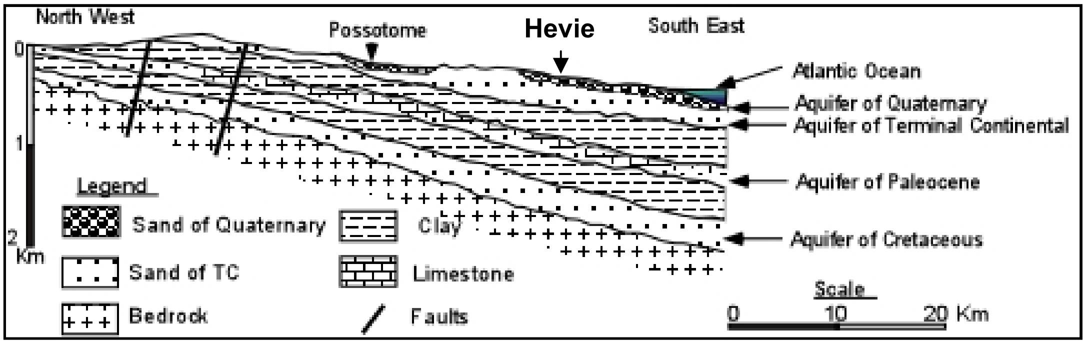

Fig. 2. Hydrogeological section of coastal sedimentary basin of Benin (Source: [25] modified in [3])

The geometry of this aquifer is irregular. In the zone of study, the thickness of the aquifer varies between 25 and 33m. The static level varies between 15 and 20m.

2.2 EM and ERT Principles of Measurement

In this study, an EM-34 (of GEONICS LIMITED) and a fast resistivity-meter were used (SYSCAL KID Switch of IRIS INSTRUMENTS with 24 electrodes equipment). There is a huge scientific literature on near-surface electromagnetic geophysics [26]. The EM-34 transmitter and receiver coils can operate at three separations and frequencies. A spacing of 20m between the coils for the profiling and successively 10, 20 and 40m with respective frequencies of 6400, 1600 and 400 Hz were selected. Coil spacing and height, alternating current frequency, and dipole mode determine instrument sensitivity and exploration depth [27,28]. The ratio of the secondary magnetic field induced by the eddy currents to the primary magnetic field is measured by a receiving coil and can be related to the conductivity of material beneath the instrument [27]. The instrument can be oriented in either the horizontal magnetic-dipole (HMD) or the vertical magnetic-dipole (VMD) mode. Measurements were carried out in mode "vertical dipole" (horizontal coplanar coils). The mode "vertical dipole" was selected for the faster insurance of its coplanarity and its greater depth of investigation [3]. The EM34 provides information to a few tens of meters of depth for the profiling and 20m for the soundings. To predict instrument response over layered-earth models, the forward modeling program PCLOOP was used.

For the resistivimeter, Marescot [29] presents a description of the procedure of commutation of the multi electrode devices. It is about the procedure for obtaining an electric panel of tomography. The Wenner is a robust array that was popularized by the pioneering work carried by the University of Birmingham research group [30,31]. The sensitivity plot of Wenner Alfa array has almost horizontal contours beneath the center of the array. Because of this property, the Wenner array is relatively sensitive to vertical changes in the subsurface resistivity [32]. In general, the Wenner is good in resolving vertical changes like contaminant flow from surface towards the subsurface. The first measurement of the file of acquisition for Wenner alpha will be done using the electrodes 1, 2, 3 and 4 (Fig. 3). Electrodes 1 and 4 will be used for the injection of current (A and B), the 2 and 3 with the measurement of the potential (M and N). The entire device then automatically will be connected to the following position on the line of electrode, at a distance "a" of the first measurement. Electrodes 2 and 5 will then be used as injection from the current and the 3 and 4 for the measurement of the potential. The process is repeated to the electrode 24. One thus has, for the first level of acquisition 21 possibilities (24-3).

As the characteristic of the Wenner device is to keep a constant distance between all the electrodes, acquisition will thus take, for the following level, a distance equal to 2 x "**a"** making it possible to make circulate the current a little more deeply. The first measurement of the 2nd level will thus imply electrodes 1 and 7 for the injection of the current and 3 and 5 for the measurement of the potential. The process is repeated again to the electrode 24. The second level will include then 18 possibilities (24 (2 x 3)). One thus takes measurements of each level of acquisition with 3 x "**a",** 4 x "**a",** etc... It is obvious that the more the distance between electrodes increases, the more the number of possibilities decreases.

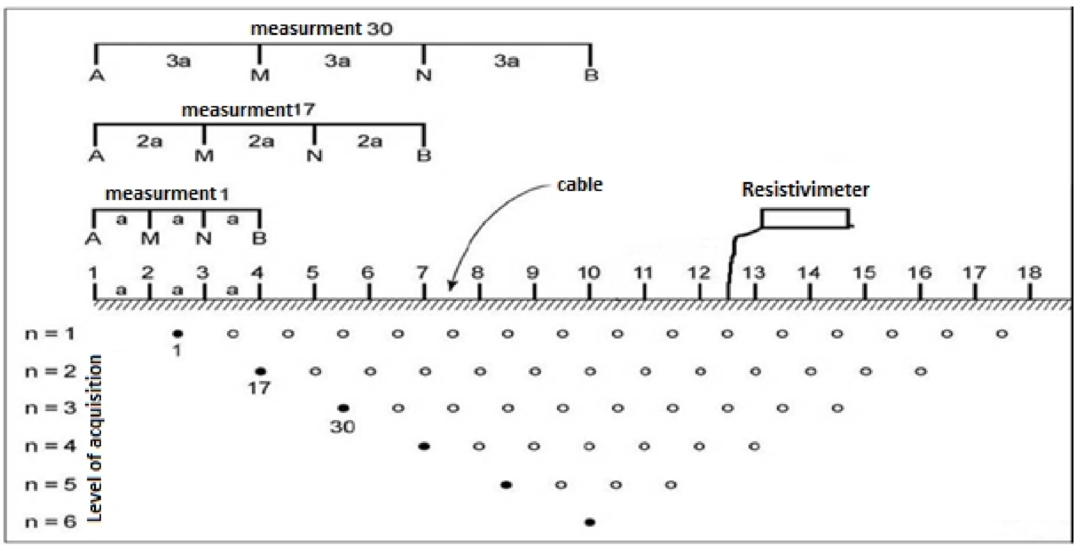

Fig. 3. Arrangement of the electrodes for a 2D acquisition and a sequence of measurement for a Wenner alpha device ([29])

2.3 Geophysical Survey

16 electromagnetic profiles corresponding to 348 measurements were carried out in horizontal configuration according to a North-South direction. This azimuth was selected perpendicularly to recut the hillocks of waste, which was directed according to an East-West direction, in particular the large hillock located at the center of the site (Fig. 1). The steps of measurements are 10 m and the distance from a profile to another is 25m (Fig. 4).

Four (04) electromagnetic surveys, were carried out site on the whole of the site; one in the center of the largest hillock, one between two hillocks, one at the end of the side extension of the leachate and the last one in not polluted zone to be used as outlier (Fig. 5). The data of the surveys were processed and inverted in the FreqEM software.

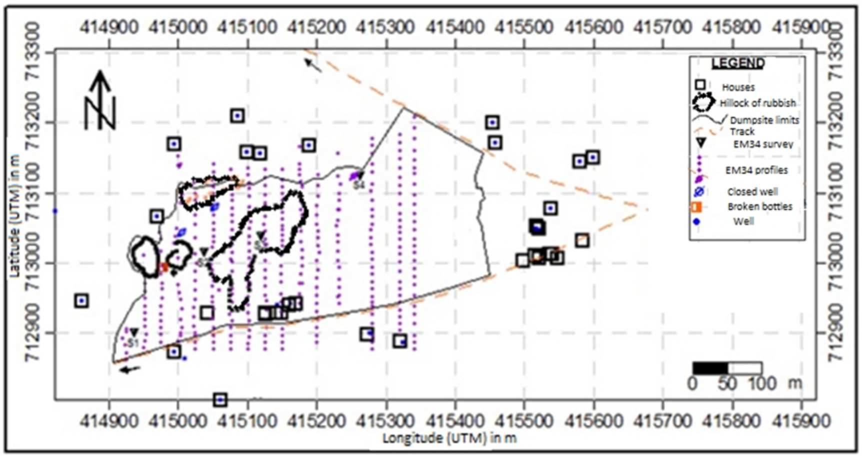

Fig. 4. Chart of the EM34 profiles and electromagnetic surveys distribution on the dumpsite of Hevie

Electrical Resistivity Tomography (ERT) is the measurement of the electrical field associated with the injection of current at the ground surface [33]. Electrical resistivity tomography (ERT) is based on measurement of the potential distribution arising when electrical current is injected into the underground via galvanic or capacitive contact [34]. The method of electrical resistivity tomography was employed in order to obtain a 2D model of the subsoil where the distribution of the resistivity varies vertically and horizontally along the profile. The ERT is a quantitative method which makes it possible to carry out a 2D or 3D imagery of the electrical resistivity variations. It makes it possible to obtain information useful for the construction of a conceptual model of the subsoil [35]. In this study the EM-ERT methods were used to investigate the dispersion of pollution in the dumpsite of Hevie.

The concentration of organic matter is associated with corresponding reduction reactions [4], [36]. Decomposition of organic matter by microorganisms in landfills generates leachate, whose volume is influenced by excess rainwater percolating through the waste layers [37]. In contaminant plumes, the concentrations of organic contaminants and ions increase the conductivity of the groundwater [2]. Therefore, the bulk resistivity of the aquifer polluted by the leachate is expected to be reduced. The value of Terminal Continental aquifer resistivity (340 Ohm.m) was obtained by applying the Archie law and the coefficients of Keller:

$$\boldsymbol{\rho_r = \rho_w a \emptyset^{-n}} \tag{1}$$

with $\emptyset$ = 40% ; a=0,8 ; n =2 for slightly cemented detrital rocks of sand and sandstone aquifer ([38] in [39]).

and $\boldsymbol{\rho_w}$ **=** 110 Ohm.m which was been measured in the piezometer.

The electrical conductivity of solid waste is generally very low [40]. This is in a stark contrast with leachate whose electrical conductivity is high and ranges from 480 to 72500 μScm^{-1}, with a 500 μScm^{-1} average value, i.e. a resistivity of 2 Ohm.m [41]. On the electrical resistivity tomography sections, the electrical resistivities lower than 340 Ohm.m correspond to those of subsurface grounds polluted by the leachate.

3. RESULTS AND DISCUSSIONS

3.1 Results

3.1.1 Lateral extension of the leachate zone

The electromagnetic map charted the resistivity (opposite of conductivity) of the grounds with approximately 10m of depth.

The rubbish zone, characterized by the presence of 4 hillocks, presents a distribution of resistivity varying between 1 and 250 Ohm.m. The lowest resistivities (1 to 100 Ohm.m) are observed on the level of the central hillock which extends on a greater surface. The values from 150 to 250 Ohm.m characterize rubbish of the two hillocks located at the west and the last one located at north.

Basically, the central hillock consists of two clusters. A very conducting central cluster (1 to 50 Ohm.m) and a less conducting second (50 to 100 Ohm.m) surrounding the first one. Contours of these clusters are very well delimited on the chart of the Fig. 5.

A third zone having an intermediate resistivity (250-340 Ohm.m) is highlighted on the chart between the hillocks at the west and the hillocks of rubbish. It is the zone of extension in subsurface of the leachate all around the hillocks of rubbish. The entire zone with a resistivity under 340 Ohm.m delimitates the lateral extension of leachate at a 10m depth.

The electromagnetic map highlighted a resistant zone (400 to 900 Ohm.m) which is the zone where the leachate is missed. This zone forms an external belt around the leachate zone.

3.1.2 Estimate of the leachate depth infiltration

With an aim of estimating the infiltration depth of the leachate, a series of four surveys was carried out in various points of the study zone. The positioning of the surveys has been done on the basis of conductivity chart showing the lateral expansion of the leachate in subsurface. Thus, a third survey (S3) was established at the center of the largest hillock of rubbish. A second survey (S2) was carried out between two hillocks of rubbish, inside the leachate zone. A first survey (S1) was carried out at the end of the leachate zone, approximately 60m from the nearest hillock of rubbish. It is the zone between the polluted subsurface and that not contaminated. Lastly, a fourth survey (S4) was located at the zone not contaminated in subsurface by the leachate. This survey is at 90m from the nearest hillock (Fig. 5).

The logs of survey in frequential electromagnetism show 1D variation of the resistivity of the grounds with the depth. In general, the qualitative inversion of the logs of surveys presents two grounds outside and at the limit of the leachate zone and three grounds inside the leachate zone.

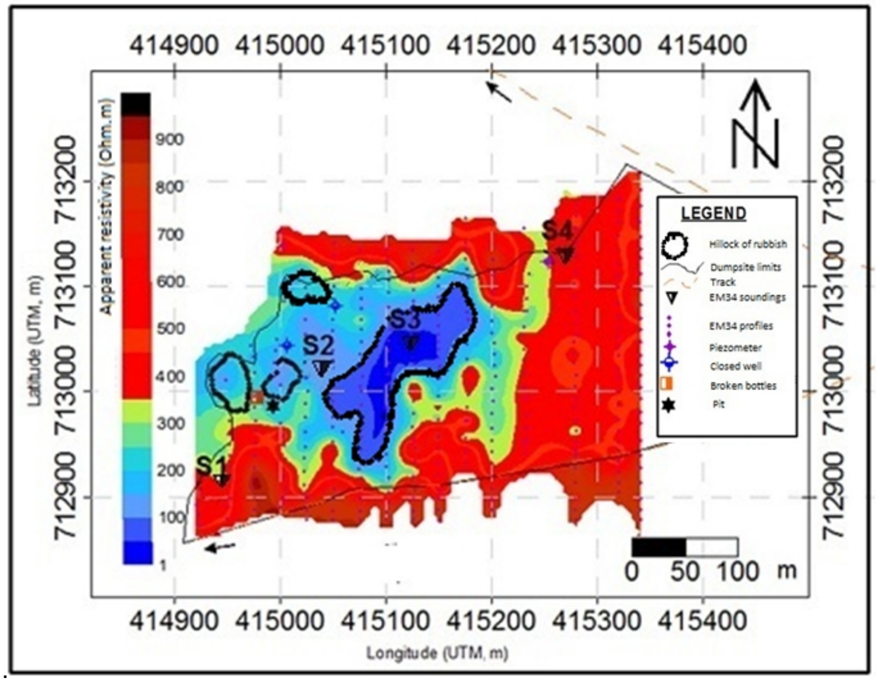

Fig. 5. Map of lateral extension of the leachate at 10m of depth using EM34

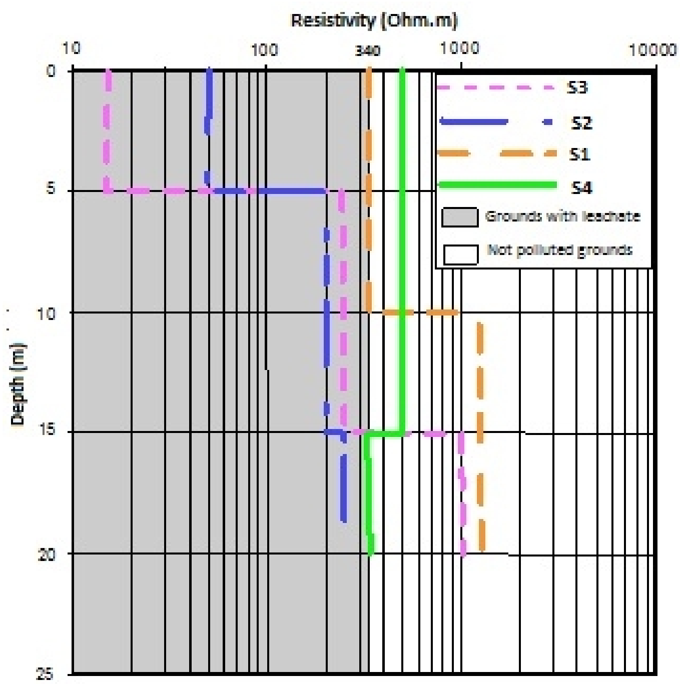

Fig. 6. Logs of surveys EM showing S2-S3 in grounds with leachate plume and S1-S4 in unpolluted grounds

The log of survey S4 presents a first ground of resistivity 500 Ohm.m corresponding to the unsaturated zone with 15m thickness then a second ground of 340 Ohm.m corresponding to the resistivity of the saturated aquifer not polluted by the leachate. It is the pilot log of survey with resistant grounds because it is not polluted by the leachate. Thus, the Fig. 6 shows three grounds in polluted zone (S2 and S3) and two grounds in unpolluted zone (S1 and S4). The log of survey S1 presents a first ground of resistivity 320 Ohm.m of 10m thickness more conducting than the second ground of 1300 Ohm.m. The high resistivity of this second ground shows that it is not polluted by the leachate. On the other hand the first ground more conducting than the first ground of the pilot survey is very slightly polluted by the leachate which penetrates up to a depth of 10m. At the end of the leachate zone, the infiltration of this leachate is only about 10m deep with a very weak concentration.

The log of survey S2 presents a first ground of resistivity 50 Ohm.m on 5m thickness, second ground of 200 Ohm.m on 10m depth, and then a third ground of 260 ohm.m up to 20 m depth. These three grounds of resistivities lower than 340 ohm.m are more conductive than the first pilot ground. These resistivities show that the leachate infiltrated until 20m depth at least and that its concentration decreases with the depth. Between the hillocks of waste inside the leachate zone, the infiltration exceeds the 20m depth.

The log of survey S3 presents a first ground of resistivity 15 Ohm.m on 5m thickness, second ground of 150 Ohm.m, 15m of depth, and then a third ground of 1000 Ohm.m. The first two grounds of resistivities lower than 340 Ohm.m are conductive than the first pilot ground. Knowing that the resistivity of leachate ranges between 0.9 and 5 Ohm.m [42], in [40], these very low resistivities show a high concentration of the leachate whose infiltration limits to 15m depth. Under the hillocks of rubbish, the infiltration of the leachate is limited by the presence of rubbish on the surface which plays a role in retention of rainwater vector of its propagation.

3.1.3 The paths of water table – leachate contact

The choice of the electric tomography profiles was also based on the electromagnetic map of the lateral distribution of the leachate (Fig. 8) in order to cross not only the hillock of rubbish but also the leachate zone in subsurface.

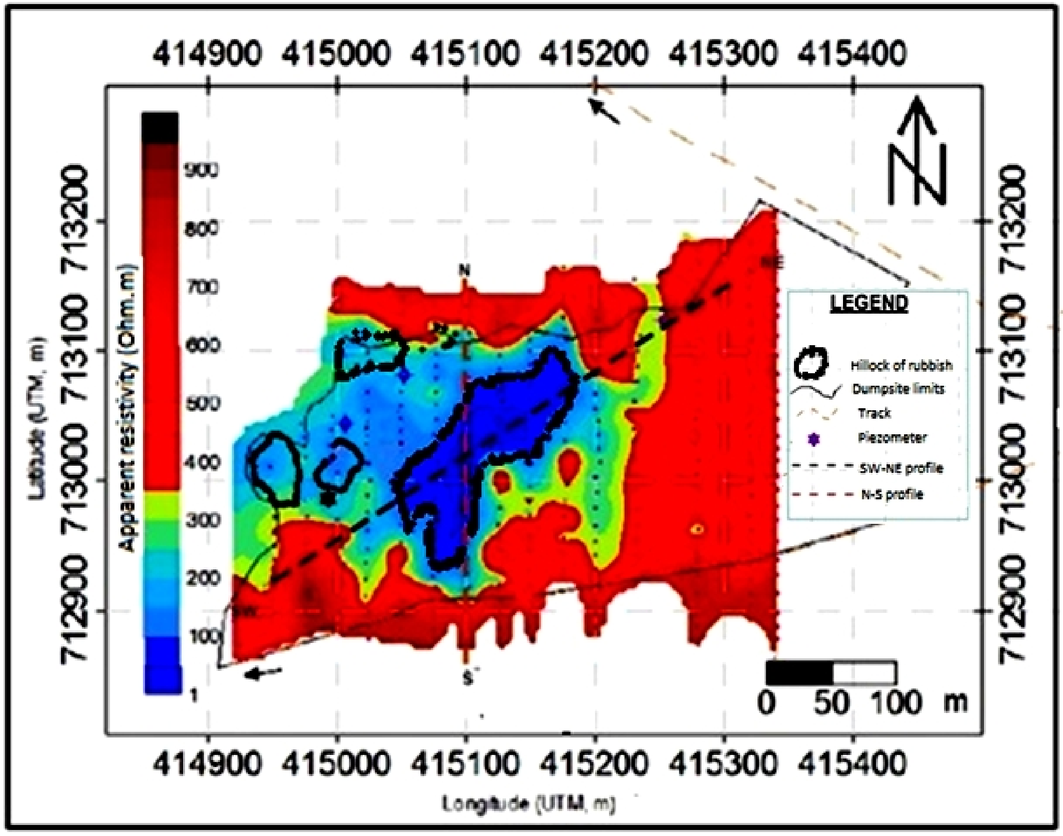

Fig. 7. Localization of the ERT profiles on the electromagnetic map

The pseudo-sections of electric tomography show the 2D variation of the true resistivity of the grounds according to the depth. The lowest values of resistivity are concentrated on the level of the hillocks of rubbish and also below these but until an average depth of 5m. Rubbish not having been buried, these low values of resistivity is due to the infiltration of leachate of rubbish

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The low resistivity domains detected can be interpreted by the significant accumulation of a low resistivity fluid [11]. Using Archie's law, the calculated resistivity of not polluted Terminal Continental aquifer equal 340 Ohm.m. Knowing that the leachate average resistivity equal 2 Ohm.m [41], the layers with low resistivities (under 340 Ohm.m) are supposed been polluted by the leachate and represent the in-depth plume of leachate. The layers with true resistivities higher than 340 Ohm.m are not supposed to be polluted by the plume of leachate. The limit of this plume marks the contact between the zone polluted by the leachate plume and the unpolluted zone.

The two cross profiles in general present the same variations of resistivity at the difference that the conducting zone is broader on the pseudo-section of South West-North East (SW-NE) profile than on that of the North South (NS) profile. That is also illustrated by the electromagnetic chart where it is noted that SW-NE profile crosses a conducting zone over all its length while the second profile crosses this same zone at a more reduced distance (Fig. 7). The bottom marking the lower limit of the plume of leachate is not linear. Under the hillocks of rubbish it oscillates between 11 and 14m, around the hillocks of rubbish it deepens by places until 18m on the NS section and 22m on SW-NE section. In general the plume of leachate goes down more deeply around hillocks of rubbish than under the hillocks of rubbish. The deeper interface of the plume of leachate presents undulations. Considering that the average static level of the Terminal Continental aquifer is around 18m, one can conclude that the water table is not in any point of its surface in contact with the plume of leachate. Only the zones of the plume with a depth higher than 18m are in contact with the water table (Fig. 8a and 8b). The absolute error of 12.3% and 7.7% explains the difference between the measured and inversed data. These values of absolute errors have been influenced by the electrical noise of rubbish. The very low resistivities can be explained by the presence of leachate which resistivity ranges from 0.9 to 5 Ohm.m [42].

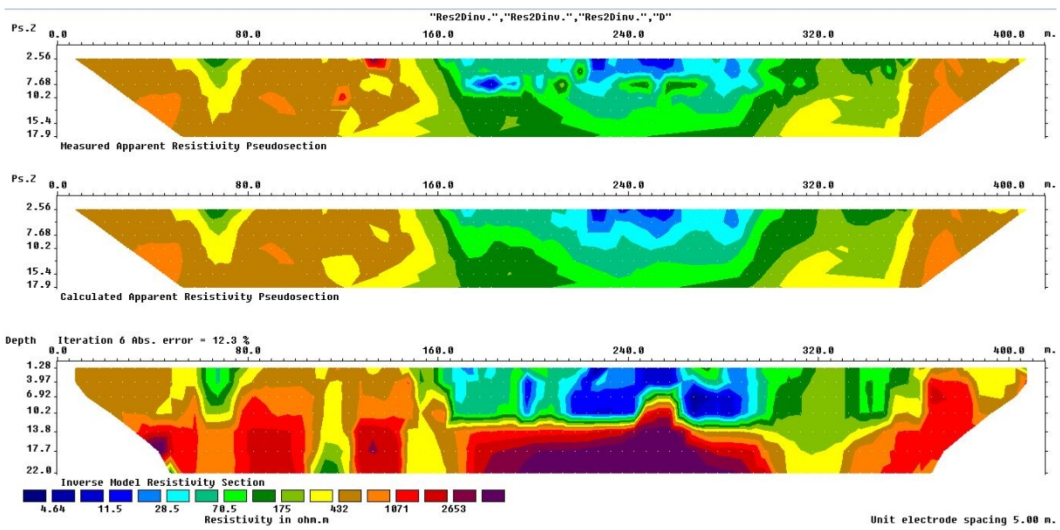

Fig. 8(a). Interpreted ERT section according to the N-S profile

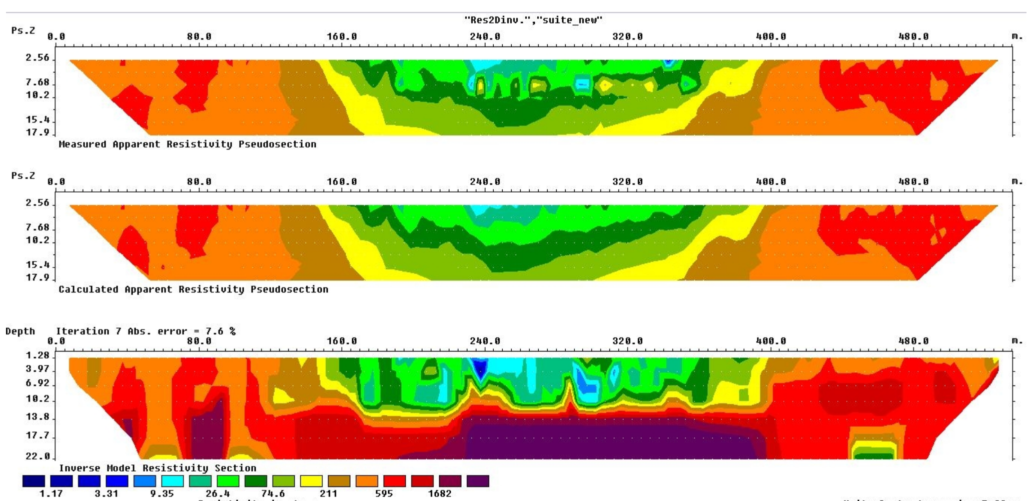

Fig. 8(b). Interpreted ERT section according to the SW-NE profile

4. DISCUSSION

The 1D logs of survey in frequential electromagnetism showed that the leachate has polluted the aquifer until 20m under and around the hillocks of rubbish. This result could be accepted only with the assumption of the tabularity of grounds. Basically, two logs of survey (S2 and S3) are located in the low resistivity domain (Fig. 7). It is the domain of leachate plume. The low resistivity domains detected can be interpreted by the significant accumulation of a low resistivity fluid [11]. The lateral extension of leachate plume was delimitated on the electromagnetic map. The lateral extension of leachate plume has been located around the hillocks of rubbish. The low resistivities detected in the EM profiles are originated by grounds and groundwater contamination resulting from leachate intrusion. Thus, the electromagnetic techniques have the advantage to get a fast response to leachate front arrival [34]. In rainy season, period of the realization of the study, the level of the groundwater in the Terminal Continental is on its higher level. This is oscillating between 15 and 18m from the surface of the ground. The leachate plume was found to be in contact with the water table at certain places from a depth of few meters to 22m in all the zone of study (Fig. 9a, Fig. 9b). The 2D pseudo-sections in electric resistivity tomography respectively showed that the infiltration of the leachate varies from one point to another. This means that a fairly continuous leachate leak from the dumpsite is being dispersed at distinct depths. That is in conformity with the results of Monteiro et al. The electrical resistivity tomography has the advantage to obtain a two-dimensional evolution of leachate plume [34]. Thus, the degree of pollution of the water table is not the same one on its entire surface. In landfills without liners there might be migration of different organic and inorganic chemical compounds to the unsaturated zone of soil which may reach the saturated zone [43]. Wells relatively close to each other will not inevitably have the same degree of pollution. This abrupt variation of the degree of pollution of the water table is highlighted by the physicochemical analysis of the water samples of the wells present in the zone of study. The relationship between fluid conductivity, measured in monitoring wells and electrical conductivity from ERT in the saturated zone can be made for co-located data, assuming some equivalence in scale [2]. Fig. 10 presents a chart of recording of water electric conductivities in the wells of the study zone, obtained following the measurements taken in wells present on the dumpsite of rubbish. All wells are a total depth ranging between 17 and 24m. At these depths the aquifer consists of fine sands to coarse gravels by places and clayey sand. This chart confirms that the leachate plume dispersed at distinct depths so it has a discontinuous contact with the water table surface. Moreover, knowing that the aquifer consists of fine sands and clayey sand, small clay lenses inside sandy clay can constitute small local barriers on the paths of the leachate infiltration. The presence of clay lens in the part of a landfill also affects the flow path there [2]. It is also important to notice that the thickness of lateritic layer above the aquifer varies from 8 to 15m. Thus, geological heterogeneity of the aquifer can also contribute to the discontinuous contact between the leachate plume and the water table.

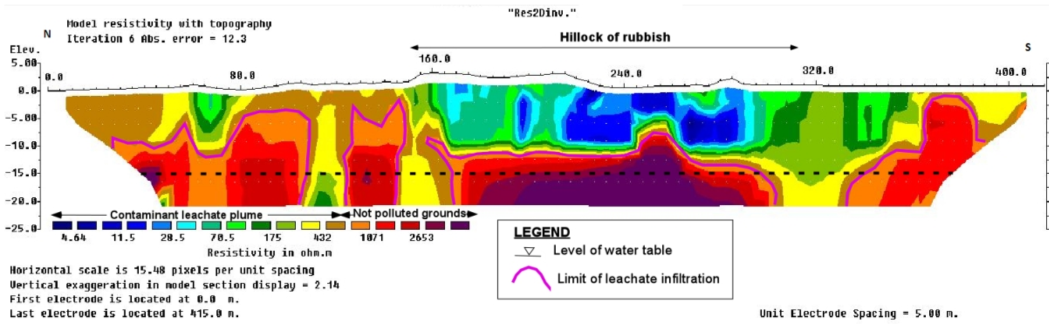

Fig. 9a. ERT N-S section showing the water table – leachate plume contact

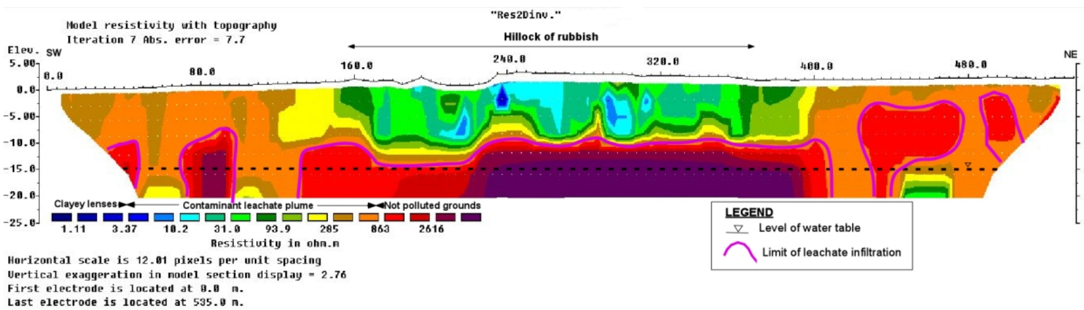

Fig. 9b. ERT SW-NE section showing the water table – leachate plume contact

Moreover, work of Mama et al. [23] revealed that the impact of the leachate of rubbish at dumpsite of Hevie on the environment is primarily related to a pollution of the water table by the organic matter and heavy metals like lead and cadmium. The lead concentration in certain wells of Hevie reached 0.18 mg/l [44]. Thus, the chemical nature of the plume of leachate on the dumpsite of rubbish of Hevie can explain the variation of the degree of pollution in the water table according to its contact with the leachate.

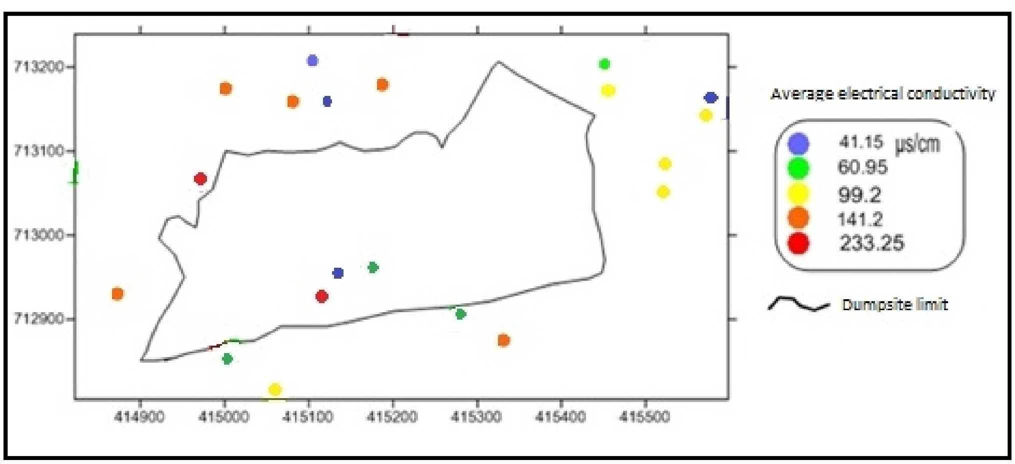

Fig. 10. Map of Electrical conductivity of well water samples on the Hevie dumpsite

5. CONCLUSION

The evaluation of the Terminal Continental groundwater contamination was carried out by frequential electromagnetic map, the log of electromagnetic surveys and the panels of electrical resistivity tomography. The electromagnetic map showed that the leachate is laterally extended in subsurface around the hillocks of rubbish. The electromagnetic logs of surveys made it possible to estimate in the 1D depth infiltration of the leachate. This infiltration is more significant around the hillocks of rubbish than under the hillocks of rubbish. The 2D electric resistivity tomography sections showed the in-depth leachate plume and made it possible to deduce that the contact between the leachate plume and the top of the water table is rather discontinuous. Basically, the leachate plume is not in continuous contact with the water table surface because it is leaking at distinct depths. Because of the strong lead concentration of the leachate, this discontinuity implies heterogeneity of the degree of pollution on the surface of the water table as shown from results of well water samples analyses. The conductivity of groundwater indicates its ionic strength and its degree of ionic mineralization e.g. elevated of heavy metals [2]. The use of the geophysical methods in frequential electromagnetism and electrical resistivity tomography have contributed for the mapping the lateral extension and the local flow path heterogeneities of the leachate contaminant plume infiltration from rubbish dumpsite of Hevie.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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