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Mapping the Pollution Plume Using the Self-Potential Geophysical Method: Case of Oum Azza Landfill, Rabat, Morocco

Meryem Touzani ^{1,*}, Ismail Mohsine ¹, Jamila Ouardi ², Ilias Kacimi ¹, Moad Morarech ³ , Mohamed Habib El Bahajji ¹, Tarik Bouramtane ¹, Abdessamad Tiouiouine ¹, Suzanne Yameogo ⁴ and Badr El Mahrad ^{1,5,6} 

- ¹ Laboratory of Geoscience, Water and Environment (LG2E-CERNE2D), Department of Earth Sciences, Faculty of Sciences, Mohammed V University of Rabat, Rabat 10999, Morocco; mohsine.ismail@gmail.com (I.M.); iliaskacimi@yahoo.fr (I.K.); mohamed.habib.elbahajji@gmail.com (M.H.E.B.); tarik.bouram@gmail.com (T.B.); tiouiouineas@gmail.com (A.T.); badr.elmahrad@gmail.com (B.E.M.)
- ² Regional Centre for Education and Training Professions, El Jadida 24000, Morocco; jouardi@yahoo.fr
- ³ Laboratory in Applied and Marine Geosciences, Geotechnics and Georisk (LR3G), Faculty of Science Tetouan, Abdelmalek Essaâdi University, Tetouan 93000, Morocco; morarech2000@gmail.com
- ⁴ Earth Sciences Department, University of Ouagadougou, Ouagadougou BP 7021, Burkina Faso; suzanneyameogo@yahoo.fr
- ⁵ Murray Foundation, Brabners LLP, Horton House, Exchange Street, Liverpool L2 3YL, UK
- ⁶ CIMA, FCT-Gambelas Campus, University of Algarve, 8005-139 Faro, Portugal
- * Correspondence: touzani.doc@gmail.com



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Abstract: The main landfill in the city of Rabat (Morocco) is based on sandy material containing the shallow Mio-Pliocene aquifer. The presence of a pollution plume is likely, but its extent is not known. Measurements of spontaneous potential (SP) from the soil surface were cross-referenced with direct measurements of the water table and leachates (pH, redox potential, electrical conductivity) according to the available accesses, as well as with an analysis of the landscape and the water table flows. With a few precautions during data acquisition on this resistive terrain, the results made it possible to separate the electrokinetic (~30%) and electrochemical (~70%) components responsible for the range of potentials observed (70 mV). The plume is detected in the hydrogeological downstream of the discharge, but is captured by the natural drainage network and does not extend further under the hills.

Keywords: self-potential; redox potential; leachate plume; landfill; Rabat (Morocco)

1. Introduction

Landfills exposed to precipitation are expected to create leachate plumes containing complex mixtures of harmful organic and inorganic contaminants [1–4]. The fate of such pollution plumes in a water table depends on many factors [5,6]. In terms of supply, it depends on the flow of polluting compounds towards the water table, which in turn depends on the source of production of the pollutants, their path through the soil, and therefore on functional porosity. In terms of propagation, the main factor is the flow speed of the water table and its possible capture by a drainage network. Finally, the processes of dilution and dispersion usually condition the limits of pollution, as well as biodegradation of the polluting compounds, whose dynamics depend partly on the oxygenation rate of the water table. For all these reasons, the extension and precise delineation of the contour of a pollution plume is delicate [7], especially when the geological structures of the aquifer and aquiclude are complex. Access to the water table and sampling is ideal [8,9], but access points are generally limited and provide punctual information in space. In this context, the use of nonintrusive geophysical techniques [10] and, in

particular, measurements of spontaneous potential (or self-potential, SP) may prove an interesting alternative [11–15]. The method is based on electrical signals related to the different phenomena studied and detectable from the surface. The self-potential may have various origins. It depends on groundwater flow, an electrokinetic contribution generating a streaming potential, due to the displacement of a mass of water with its ionic charges through porous medium [16–18]. The self-potential also depends on redox conditions, an electro-redox contribution generated by the gradient of redox potential in a natural geobattery process [15,19–21] that may prevail near garbage dumps. Several recent studies were based on the sensitivity of spontaneous potential measurements to redox variations [22–25]. Measurements of spontaneous potential can therefore be a passive source of information on the spatial distribution of groundwater parameters and are, *a priori*, particularly suitable for the detection and delineation of pollution plumes.

On the other hand, the limits of its application may be linked to the resistivity of the environments studied. The implementation is tricky because of low potential differences, from a few millivolts to a few tens of millivolts. In this context, the methodological aspects play a critical role in the quality of the results obtained. For a few tens of millivolts and a very resistive soil, the currents measured are extremely low, and the signals are impacted by noise variations of the order of 10 mV [26]. These conditions have limited the development and application of the method in arid areas, which are rarely presented in the literature, except in environments where the presence of soluble salts compensates for the resistivity associated with a low water content.

The application of the SP method to the study of pollution generated by household waste landfills shows the existence of hot spots, localized areas in which intense and fleeting fermentative processes occur in the landfill, but the existence of such hot spots is usually not sought outside the landfills. Furthermore, the measurement of spontaneous potential does not allow the water quality of the plume to be characterized, nor the nature of the biogeochemical processes occurring in the plume to be determined. For this purpose, it must be coupled with some direct measurements requiring access points to the water table.

The aim of this work is to highlight the presence of a pollution plume from a landfill site near the city of Rabat (Morocco) by combining geophysical (spontaneous potential), physicochemical and geomorphological approaches. Emphasis will be placed on its downstream limit, and its fate within the Mio-Pliocene water table.

2. Materials and Methods

2.1. Study Area

The study area is located near the city of Oum Azza, about 15 km south from Rabat (Figure 1). The Oum Azza landfill was set between the Sidi Mohamed Ben Abdellah (SMBA) dam reservoir in the east and the Akrech River in the west. The climate was classified as Csa, i.e., hot-summer Mediterranean climate in the Köppen classification. Annual rainfall is around 440 mm, 95% of which occurs in autumn, winter and spring.

In the immediate vicinity of the landfill, the landscape units consist of two hills separated by a thalweg and oriented in the northeast southwest direction (Figure 2). A slight linear depression was detected in the northern hill, corresponding to a former thalweg. It is further referred to as secondary thalweg. Throughout the area, the slopes are gentle, but to the west and northwest, the hydrographic network, which is the outlet of the study area, is incised. The slopes are steep and the land is not cultivated. The water table is about 10 m deep under the hills, and close to the surface at the level of the thalwegs.

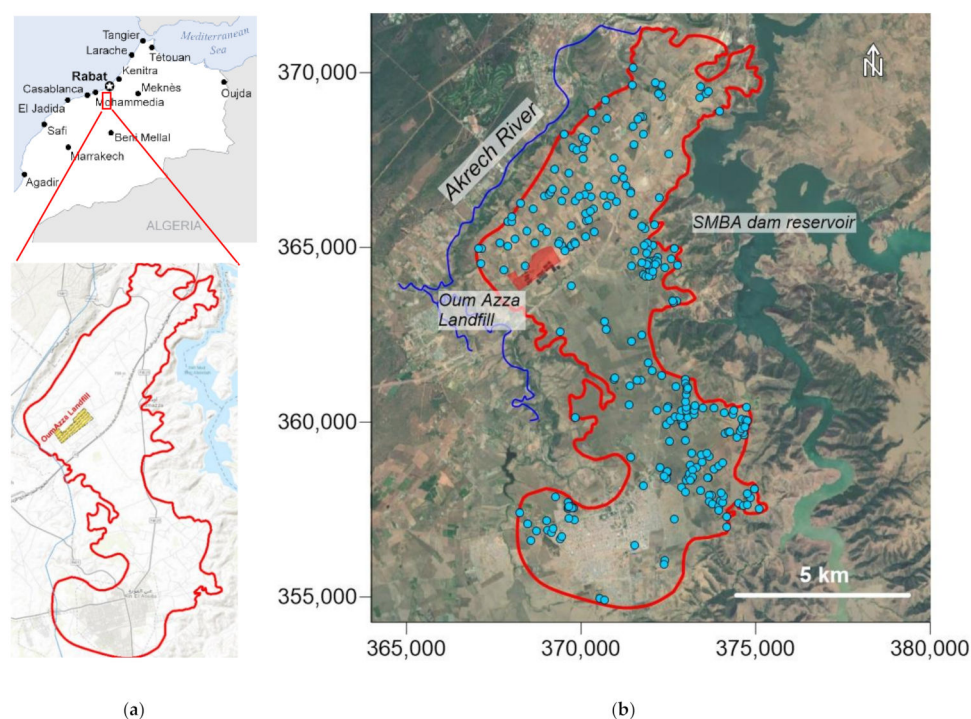


Figure 1. Location of (a) the Oum Azza landfill and (b) the wells (blue dots) used for the regional water level survey. The red line denotes the border of the Mio-Pliocene formations (UTM coordinates in meters using Lambert conical conformal projection).

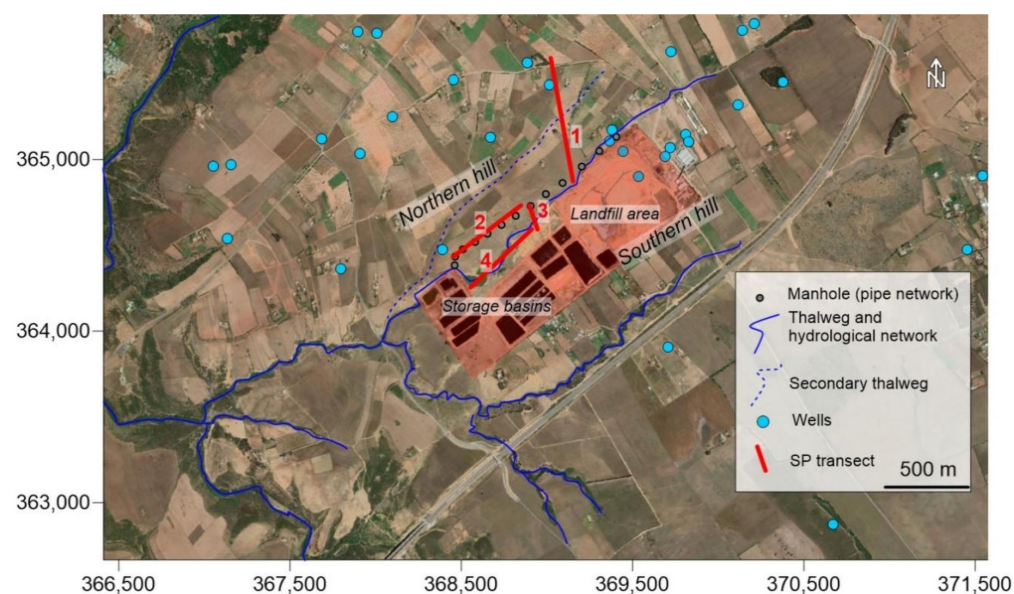


Figure 2. Morphological framework around the landfill, wells and location of the spontaneous potential measurement transects numbered from 1 to 4 (see text).

The soils consist of a sandy horizon with a massive structure over the first 10 cm, then a sandy horizon with lamellar structure, very coherent and dry. The heat and dryness of the summer period strongly limits the development of vegetation. Consequently, the soils are poor in organic matter, which is rapidly mineralized as the sandy texture favors aeration. From 60 to 100 cm deep, a sandy horizon slightly enriched in rubified clays is observed. Despite the ionic charge of the groundwater, soils are very resistive at least to a thickness of about 2 m. A prior survey was performed by low frequency electromagnetic induction using an EM38 device (Geonics Ltd., Toronto, ON, Canada) in the configuration

of vertical dipole, i.e., an investigation of the apparent electrical conductivity (ECa) over a depth of about 1.7 m [27]. The survey revealed a very low range of ECa values from 0 to 3 mS m^{-1} , i.e., a resistive medium that has not made it possible to draw a relevant map of the conductivity variations in space with this equipment. The substratum is composed of very sandy and porous Mio-Pliocene calcarenite that is several tens of meters thick and resting on a bedrock of Visean schistose pelites with almost vertical dipping and much lower permeability.

The landfill is located on the top of the southern hill. A line of 13 inspection manholes was dug on the slope of the northern hill (Figure 2). These are manholes of a pipe network leading leachates from the active part of the landfill to the storage basins in the southwest. Although they are cemented, these manholes form wells draining the leachates towards the water table. Thus, the water table that accompanies the thalweg between the hills receives both the leachates coming from the landfill on and those infiltrating from the manholes on its northern and southern slopes, respectively. Field observations made along the thalweg suggested a contamination and a pollution plume, which motivated this study. Towards the southwest, the hydrological network drains both surface and deep water, with no indication as to whether or not it drains the entire plume.

2.2. Regional Piezometrical Survey

In order to situate the Oum Azza landfill in the regional context, a study of the regional piezometry was carried out in July–August 2017, based on approximately 400 wells (Figure 1), including 55 wells surrounding the landfill. Prior to this survey, several wells were monitored, showing little temporal variation compared to the spatial variation presented here. The prospected area is approximately 16 km from north to south, and 8 km from east to west. The location of the wells that are close to the landfill is given in Figure 2.

2.3. Self-Potential Measurements

Given the difficulties of measuring self-potential in such an environment, great care was given to the measurement protocol. The electrodes used were wood contact nonpolarizing PM9000 Pb-PbCl₂ NaCl electrodes of PETIAU type (SDEC, Reignac Sur Indre, France) [28]. These electrodes were permanently maintained in a saline NaCl-saturated solution during the period of non-use for resaturation. The reference electrode was installed in sandy soils at the top of the northern hill, north of the secondary thalweg. It was placed in a 7 cm-diameter hand auger hole in the coherent sandy topsoil horizons with lamellar structure. The depth was between 0.2 and 0.3 m. After augering, 250 cm³ of mineralized water at 5 mS cm^{-1} were poured into the hole to moisten and make the bottom and sides of the hole more conductive. The cavity was then filled with a liquid mud consisting of the sandy materials removed during the augering with a 3 to 5 mS cm^{-1} mineralized water. The electric time-drift of these electrodes is very weak. Both the moistening of the lower part of the hole and the use of mineralized mud allowed good electrical contacts between the electrode and the surrounding media. A slight zero correction was applied after measuring the potential with both the fixed reference electrode and moving measurement electrode in the same hole. Then, for each measurement, the moving electrode was installed similarly to the reference electrode. The cables used were multistranded copper wires, 0.5 mm², section, covered with plastic insulation. Special care was given to the quality of the cable-electrode and cable-voltmeter connections, which were optimized by a tin solder. A high precision digital voltmeter with high input impedance ($2.5 \times 10^9 \Omega$) was used (Signstek UNI-T UT71D, Signstek, Wilmington, DE, USA). The high input impedance of the voltmeter was also an essential point for the quality and stability of the measurements in these highly resistive media.

Several self-potential measurement transects have been realized (Figure 2). Measurements were initiated north of the area. The first transect (17 measurements), with a length of about 750 m intersected the upslope portion of the secondary thalweg towards the south to the line of manholes. The second transect followed this line for a distance of about

700 m (12 measurements). A third 250-m long transect joined the line of manholes and the axis of the thalweg at the edge of the landfill (8 measurements). Finally, a last transect accompanied the thalweg to the southwest for a distance of 700 m (9 measurements). During this survey, the distance between successive measurement points was not fixed, but maintained below 70 m.

2.4. Groundwater and Leachates Physico-Chemical Characteristics

To check the consistency of the self-potential measurements in the landscape, concomitant measurements of the redox potential (Eh), pH and electrical conductivity (EC) of the water were carried out. Daily calibration was performed for pH-meter (3 points calibration, 4, 7 and 10) and Redox potential (ZoBell solution). For this, all access to water was valued. The local population is supplied with water from the water table through individual pumps usually installed in each household. During the field campaign, we had access to 28 points for the measurement of physicochemical parameters, within a radius of 1000 m around the landfill. These points included 18 from the water table near the thalweg, and 10 from the water table in the northern hill. Two additional measurement points were leachates from the landfill. The redox measurements have been corrected for the temperature-dependent potential of the platinum electrode. Between two measurements, the electrode was kept out of direct sunlight and in a solution whose characteristics were close enough to those to be measured to reduce the stabilization time.

3. Results

3.1. Regional Watertable Flow

The plot of the regional piezometric map of the Mio-Pliocene aquifer is shown in Figure 3a. The region is crossed from the southwest to the northeast by a main groundwater divide, consisting of a piezometric dome rising to an altitude of 300 m and located in the outcrop zone of the Pliocene terrains. From this dome the water table flows southeast and northwest in the direction of the Akrech River. Hydraulic gradients vary between 0.8 near the divide, but can reach 6.6‰ at the extreme north of the map, near the Akrech River. The Oum Azza landfill is located in the northwestern flow area.

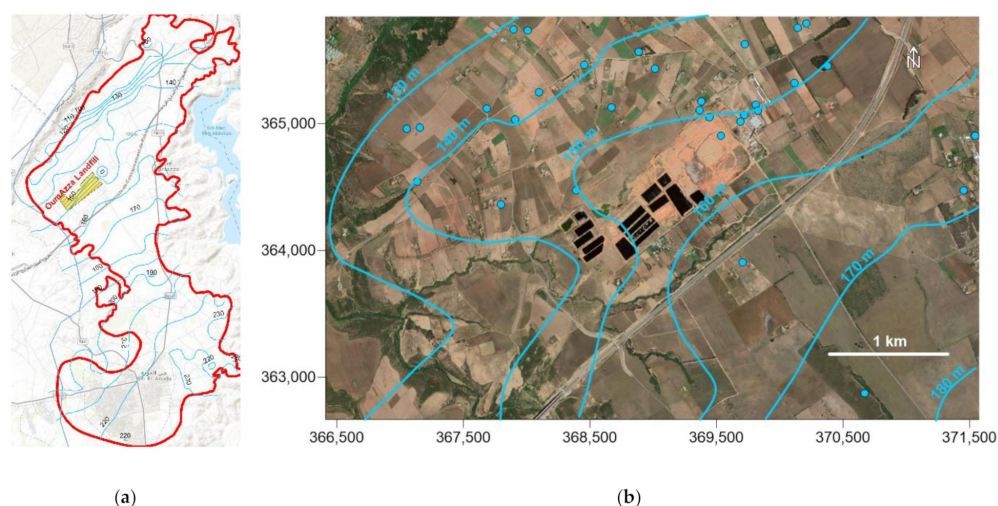


Figure 3. Regional (a) and local (b) groundwater level around Oum Azza landfill. Blue dots denote wells. UTM coordinates in meters using Lambert conical conformal projection.

3.2. Physico-Chemical Parameters

The mean values of the physicochemical parameters measurements (pH, Eh and EC) of the waters of the hills, thalwegs and leachate are shown in Table 1. The pH was close to neutral and slightly alkaline for leachates. Groundwater had a high regional conductivity of around 5.5 mS cm^{-1} , while the conductivity of leachates was lower, around 3 mS cm^{-1} .

The lower conductivity of the leachates reflects their dilution by rainwater mainly during autumn, winter and spring. The redox conditions in the water table were generally very oxidizing to the north, east and south of the landfill with an average Eh value of +310 mV. The water table accompanying the thalweg showed oxidizing conditions upstream of the discharge with Eh values ranging from 10 to 170 mV, but the conditions shifted to very reducing from the landfill toward downstream with much lower values from −18 to −276 mV (Figure 4). There was also a noticeable change in the color of the water, which became much darker, indicating an increase (not quantified) in organic matter content. It should be noted, however, that in the immediate vicinity of the landfill to the south, redox conditions were also more reductive.

Table 1. Mean values for pH, Eh and electrical conductivity for the water table around the landfill in the thalweg and for the leachates.

| | pH | Eh (mV) | EC ($\mu\text{s cm}^{-1}$) |
|------------------------------------|------|---------|------------------------------|
| Groundwater around the landfill | 7.27 | +128 | 5662 |
| Groundwater in the thalweg (plume) | 7.09 | +36 | 5399 |
| Leachates | 8.01 | −320 | 2950 |

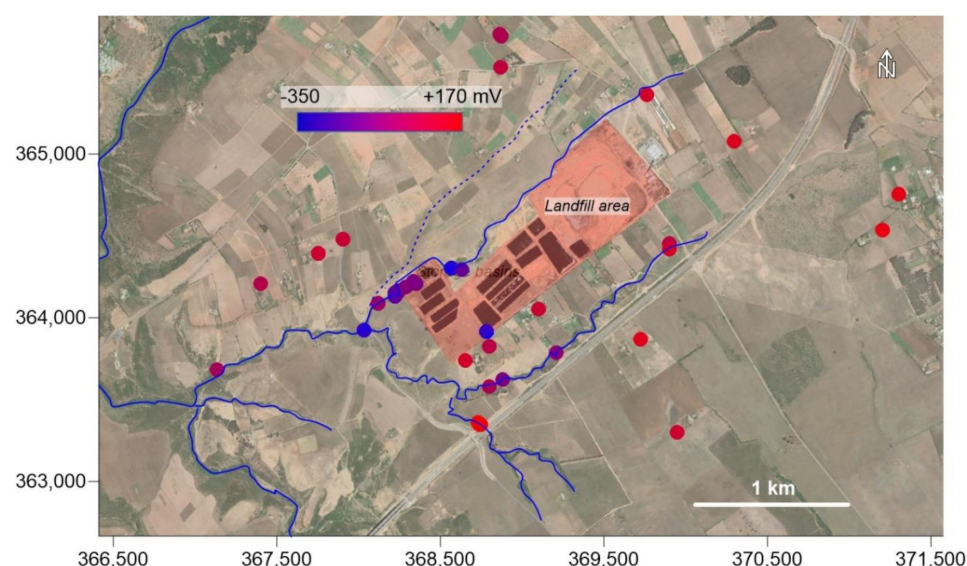


Figure 4. Distribution of the redox potential values in watertable around the landfill (UTM coordinates in meters).

3.3. Self-Potential Measurements

The values were quite stable during the acquisition, and they locally highlighted strong contrasts over short distances. They varied in a range from −25 to +45 mV. The position of the measurement points and the measured self-potential are shown in Figure 4 using a color scale. The reference electrode was placed close to the top of the northern hill. On transect 1, the self-potential values were slightly positive in the north, then became slightly negative (−8 to −14 mV) while crossing the secondary thalweg. Continuing southwards, the self-potential was positive in the sandy soils down the slope until the thalweg. On the second transect along the manholes line, the values were higher and clearly positive, between +10 and +45 mV. Approaching the confluence between the thalweg with the secondary one, the last three values were a little lower and slightly negative, close to zero. On the third transect towards the south, the values were generally positive (0 to 20 mV), but became abruptly negative (−20 mV) at the immediate approach of the thalweg axis. Finally, the values were very negative on the last transect throughout the thalweg axis near the landfill edge. They oscillated in a range from −15 to −20 mV in the upstream part,

then close to -10 mV downstream. At this level, the contrast was very strong with the values measured just upslope along transect 2 (about 60 to 70 mV).

4. Discussion

4.1. Mio-Pliocene Watertable

The flow lines of the water table, perpendicular to the isohypses shown in Figure 3a, converge towards the major drainage axes for surface water, and in particular the Akrech River, which are preferred directions for underground flows. On a more local scale (Figure 3b), the water table emerges in the lower part of the thalwegs, confirming that the river network, although with temporary flow, drains both surface water in the rainy season and the water table throughout the year.

The groundwater in the hills and at the hydrogeological upstream of the landfill site is clearly oxidizing, which may be explained by the characteristics of the environment. On the one hand, sandy formations develop a coarse porosity, allowing exchanges with the atmosphere. This context is favorable to water aeration. On the other hand, the position in the landscape and the slopes are favorable elements for a fairly rapid water flow. Finally, the low humus in the soils and the associated low biological activity favor high oxygen content in the groundwater.

4.2. Reliability of the Self-Potential Data

An important aspect of this study site is the high electrical conductivity of groundwater on a regional scale. As the leachate has an EC of the same order of magnitude as the water table, the pollution plume would probably not have been detected by other geophysical methods based on conductivity contrasts [25]. In such a resistive media, the good stability of the self-potential measurements and the observed range highlight the reliability of the values obtained. This stability is largely due to the care taken in the implantation of the electrodes, the choice of the voltmeter and the quality of the electrical contacts. In addition, the results evolve in a relatively large value range of the order of 70 mV. These variations are significant. The standard deviations reported by several authors are generally of the order from 5 to 10 mV [16,29,30]. On the studied area, the sedimentary geology and consequently the absence of metal veins and the shallow aquifer (from 0 to 10 m deep) favor the detection of self-potential variations induced by the studied processes, namely the streaming and electrochemical potential. Crossing these variations with, on the one hand, the morphology of the landscape and, on the other hand, measurements of redox conditions makes it possible to better specify the process involved in the SP values detected at the topsoil.

4.3. Self-Potential Variations in the Landscape

The variations appeared correlated with the functional units of the landscape, positive in higher zones and upslope, negative at crossing the secondary thalweg and frankly negative near the landfill at the level of the thalweg separating the two hills (-15 to -20 mV). Variation in the self-potential values appeared on transect 1 while crossing the secondary thalweg with a decrease in the SP values of the order of 15 mV. This must be attributed to a concentration of underground flow lines and the creation of a streaming potential. Such streaming potential, or electrofiltration, cause self-potential anomalies and are commonly correlated with relief at the topsoil [18]. Several authors have shown that streaming potential depends on the ionic charge of the flows [31]. Analysis of the nearest wells revealed electrical conductivity of around 1.5 mS cm^{-1} . This is less than the regional average presented in Table 1, but it is nevertheless mineralized water that may promote the appearance of a streaming potential detected in the decrease of self-potential values. Thus, the results were spatially structured. The measured values correlate strongly with the functional units of this environment. The results of spontaneous potential measurements were spatially meaningful.

A streaming potential may also impact the measurements made along the axis of the thalweg (Transect 4), but it cannot be sufficient to explain the drastic and abrupt difference in SP value between upstream and downstream of the discharge, nor the contrast of SP values along the slope, between transect 2 and 4. These self-potential values are necessarily also influenced by the gradient in the redox conditions. The water chemistry, the redox potential values and the very negative SP values measured in the axis of the main thalweg attest for the presence of a plume of water rich in dissolved organic carbon, as attested by the darker color, with strong ongoing biological activity that leads to low redox conditions. Various authors have pointed out a link between the measured potential and the intensity and nature of the oxidation–reduction processes produced by biological activity directly in the vertical below the potential measurements [32]. Over the observed range of values, if we consider that a drop of about 15 to 20 mV can be attributed to electrofiltration, 40 to 50 mV must be attributed to electrochemical potential. These are orders of magnitude similar to those pointed from other pollution plumes [33].

The oxidizing conditions observed in the hills contrast with the much more reductive conditions on the immediate periphery of the landfill and within the thalweg, i.e., in its hydrogeological downstream. Although located upstream, the waters near and south of the landfill seem to be slightly impacted by the pollution. This can be explained by the presence of a slight dome of the water table under the landfill, which corresponds to a more important recharge area because of rainwater retention in the basins, mainly during autumn, winter and spring. Thus, the induced pollution radiates slightly a few tens of meters in other directions, and not only towards the thalweg. From these observations, it is possible to propose a probable distribution of the pollution plume induced by the landfill (Figure 5). The pollution does not propagate towards the northwest according to the regional hydrogeological flow. It is captured by the drainage network that runs alongside the landfill to the north and northwest, and is directed to the west where the contaminated water will join the Akrech river system.

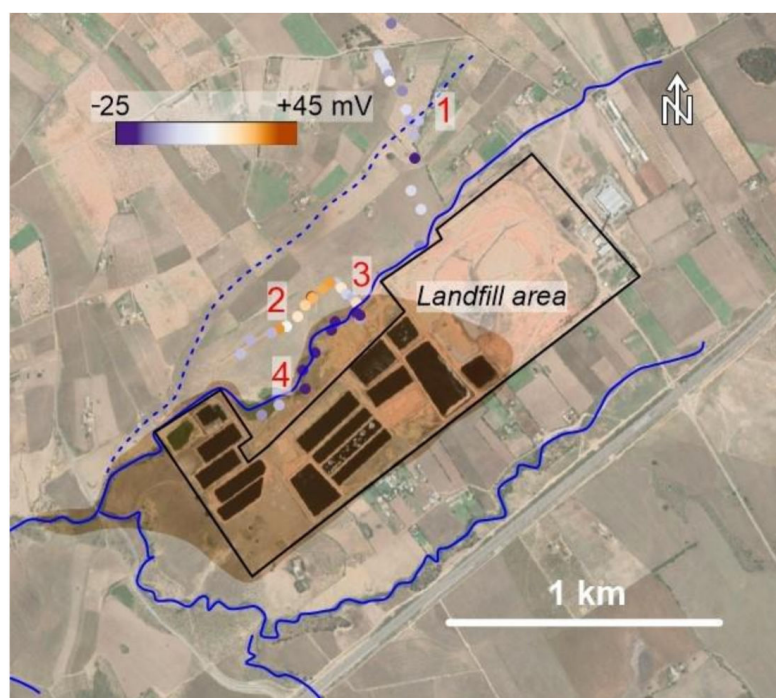


Figure 5. Distribution of the self-potential values along the four prospected transects (numbers 1 to 4) and probable delineation of the pollution plume captured by the drainage network (brown patch).

5. Conclusions

Our study confirms that the Oum Azza landfill near the capital Rabat causes a plume of strongly reducing water rich in dissolved organic carbon in the Mio-Pliocene aquifer.

On the one hand, the dry, sandy and therefore resistive environment is not propitious for the implementation of spontaneous polarization measures for the detection of such a plume, and a certain number of precautions had to be taken during data acquisition. On the other hand, the low conductivity contrast between groundwater and leachate is not conducive to identifying the pollution plume on the basis of other geophysical methods such as, for example, electromagnetic induction. In this context, stable data and a self-potential range of the order of 70 mV were obtained, consistent with the functional units of the landscape. Approximately 30% of this variation can be attributed to a significant electrokinetic component due to the shallow depth of the aquifer and its high ionic charge. The remaining 70% is attributed to an electrochemical component due to the gradients of redox conditions towards the pollution plume. The results, which showed locally significant contrasts, indicated that the plume does not propagate under the hills towards the downstream hydrogeological part of the landfill, but is captured and drained by the river system, in this case by a thalweg bordering its northwestern limit. The nearby dwellings are located to the south, i.e., upstream, and therefore the health risk is limited. This study shows that cross-referencing spontaneous potential data with landscape analysis and punctual measurements at the access points to the aquifer can help in the detection and therefore in the management of the pollution. Thus, even in an arid environment and on sandy terrain, the method used is very sensitive and must allow a fine mapping of pollution plumes, which is generally limited by the low number of access points to the water table.

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