Lingreville (France)
Geophysical survey summary

DATE: May 2020

SUBJECT: ...

☒	report	☐	information	☐	consideration	☐	decision

To:	...	From:	University of Liège & British Geological Survey

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Lingreville

Summary of the study area

Site history

The Lingreville landfill is located in Normandy (France) on the edge of the Vanlée estuary in the municipality of Lingreville (*Figure 11*). It lies in the coastal preservation zone, which also corresponds to a natural area of ecological, faunistic and floristic interest (ZNIEFF). The landfill was in operation from 1965 until the 1980s. Mainly household waste was deposited on the site during that period. In the early 1990s, the landfill was covered with sand and soil and its flanks were reinforced with rock riprap. The site covers an area of 4320 m². From the 2010s onwards, due to marine erosion, the waste began to spill into the estuary, requiring urgent rehabilitation actions.

Geology and hydrology

The geological context of the site is composed of Weichselian Pleniglacial wind sands surrounded by pebbles and Eemian sands and Lingreville clay next to recent dunes. The mean altitude of the site is comprised between 8 and 12 m above sea level.

The water level of the Vanlée river is found about 6 m below the bottom part of the landfill.

Summary of landfill characterization activities and remediation

With regards to urgent rehabilitation requirements, an intrusive site investigation was carried out in 2015. This study included several trial pits and its main findings are summarized in the next section.

As part of the RAWFILL project, a geophysical survey was conducted from 3rd to 6th of November 2017 just prior to the site remediation.
The complete excavation and remediation afterwards was completed in 2018 providing information about the recovered waste volumes. Its findings are summarized in the report from BURGEAP (2018).

Summary of available ground truth data

A survey campaign including 11 trial pits was conducted on the site in 2011 (see *Figure 11* and *Table 1*). Its findings are concluded in the report from SERAPIS (2015) and a brief summary is given below.

Waste deposits were mainly composed of plastic, metallic scraps, glass and rubber, as shown in Table 1. Contamination with hydrocarbon and heavy metals (mainly Pb, Cu, Cr) was reported in the samples containing waste. Three main zones were identified within the landfill based on their content:

- Zone 1 including trial pits S4, S5, S6 and S7 where the waste thickness is between 2.5 and 4 m. The waste deposit is not mixed with sand.
- Zone 2 including trial pits S1, S2 and S10 where the waste material is mixed with sand on a thickness of maximum 2.2 m. The waste content is about 30%.
- Zone 3 including trial pits S8 and S9 where almost no waste is present.

Table 1: "Lithology" encountered during the drilling (BURGEAP 2018).

Trial pits	Depth (m)	Depth – Lithology (m)	Content	Waste thickness (m)
S1	4	0 – 0.3	Topsoil with 10% of waste (plastic, scrap metal, glass, rubber and some rubble)	2.2
		0.3 – 2.2	Clayey sand with 20% of waste (plastic, scrap metal, glass, rubber and some rubble)	
		2.2 – 4	Sand	
S2	4	0 – 0.5	Topsoil with 50% of waste (plastic, scrap metal, glass, rubber and some rubble)	2.1
		0.5 – 2.1	Clayey sand with 10% of waste (plastic, scrap metal, glass, rubber and some rubble)	
		2.1 – 4	Sand	
S3	4	0 – 1.2	Topsoil	0.8
		1.2 – 2	Topsoil with 30% of waste (plastic, scrap metal, glass, rubber and some rubble)	
		2 – 4	Sand	
S4	3.5	0 – 2	Topsoil with 80% of waste (plastic, scrap metal, glass, and black waste)	2.5
		2 – 2.5	Topsoil with 30% of waste (plastic, scrap metal, glass, and blackish waste)	
		2.5 – 3.5	Sand	
S5	3.8	0 – 0.4	Topsoil	1.9
		0.4 – 1.8	Clay with 50% of waste (nature not specified)	
		1.8 – 2.3	Sandy clay with some waste (nature unspecified)	
		2.3 – 3.8	Sand	
S6	-	0 – 2.6	100% of waste (nature unspecified)	4
		2.6 – 4	Wet blackish waste with leachate	
		4 - ?	Peat	
S7	-	0 – 0.5	Topsoil	3
		0.5 – 3	Waste (nature unspecified) with hydrocarbon odour	
		3 - ?	Waste drowned in leachate with strong odour	
S8	3	0 – 0.1	Topsoil with some waste (nature unspecified)	0.1
		0.1 – 3	Sand	
S9	3	0 – 0.2	Topsoil	0
		0.2 – 3	Sand	
S10	-	0 – 0.2	Topsoil	1.8
		0.2 – 0.5	Construction waste	
		0.5 – 2	Mixture of clay and peat with 10% of waste (nature unspecified)	
		2 - ?	Sand	

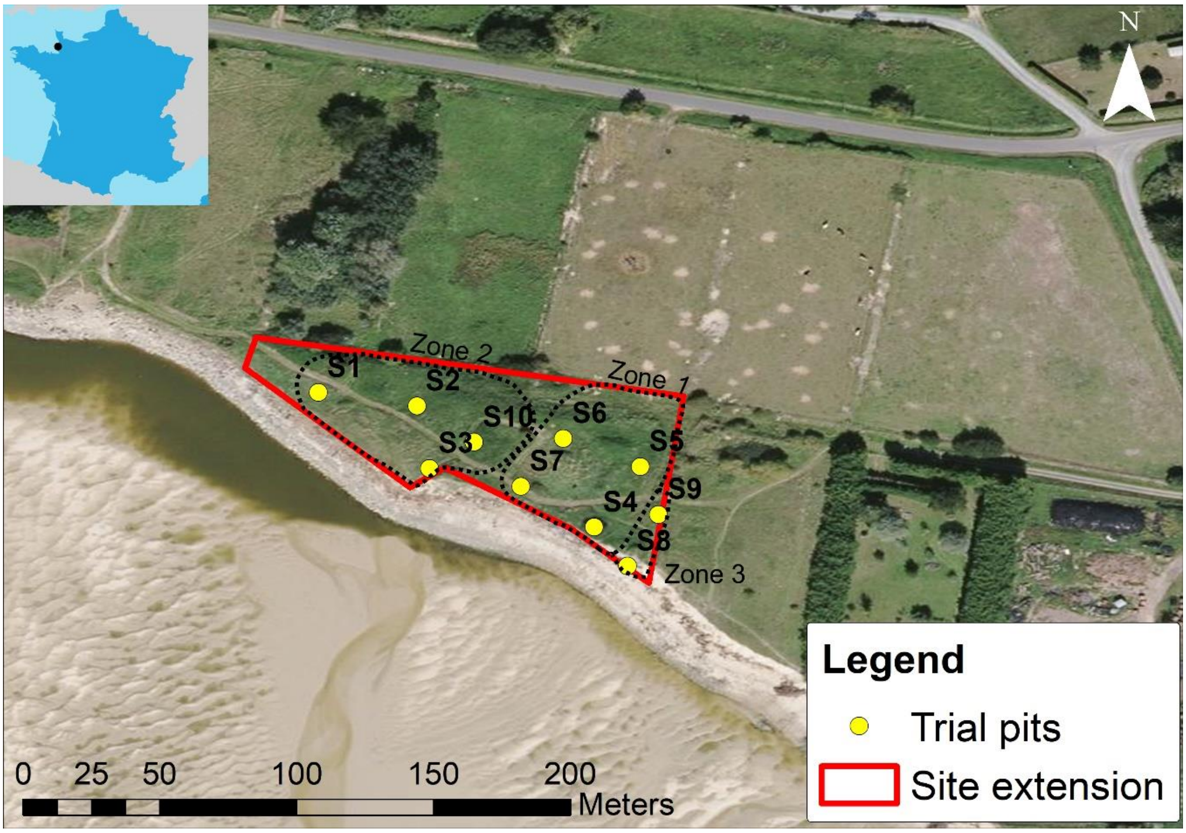

Figure 1: Overview of the Lingreville landfill together with the location of the trial pits conducted in 2011.

Geophysical investigations

Geophysical methods and coverage

The geophysical survey, conducted from 3rd to 6th of November 2017, included the following methods: Electromagnetic Induction (EM), Magnetic field mapping (MAG), Electrical Resistivity Tomography (ERT) and Induced Polarization (IP).

In the following, the acquisition parameters and spatial coverage are summarized for each method.

EM data were acquired using a conductivity meter model DUALEM-4 (DUALEM) and a Mini-explorer (GF Instruments). By attaching two antennas of different sizes to the DUALEM-4, it was possible to map electrical properties at four different exploration depths: 0.5 m and 2.3 m with the shortest antenna, and 1.8 m and 5.3 m with the longest antenna. The Mini-explorer allows exploring simultaneously electrical properties at 0.5 m, 1 m and 1.8 m depths. Both quadrature (related to apparent conductivity) and in-phase (related to apparent magnetic susceptibility) components were recorded with each measuring device. In addition, a GPS sensor (without RTK correction) was connected to the system for positioning (see *Figure 12*).

MAG data were acquired with a GSM-19-GW Overhauser-effect gradiometer (GEM-Systems), with sensors located respectively at 2 m and 2.6 m above the ground. The system was used to map the total magnetic field and the magnetic vertical gradient. For positioning, all data were continuously synchronized with a GPS system (without RTK corrections), see *Figure 3*. To identify drifts in the magnetic data, a three-axis fluxgate magnetometer, FGM3D from Sensys, was setup as a base station at a position away from any visible disturbances.

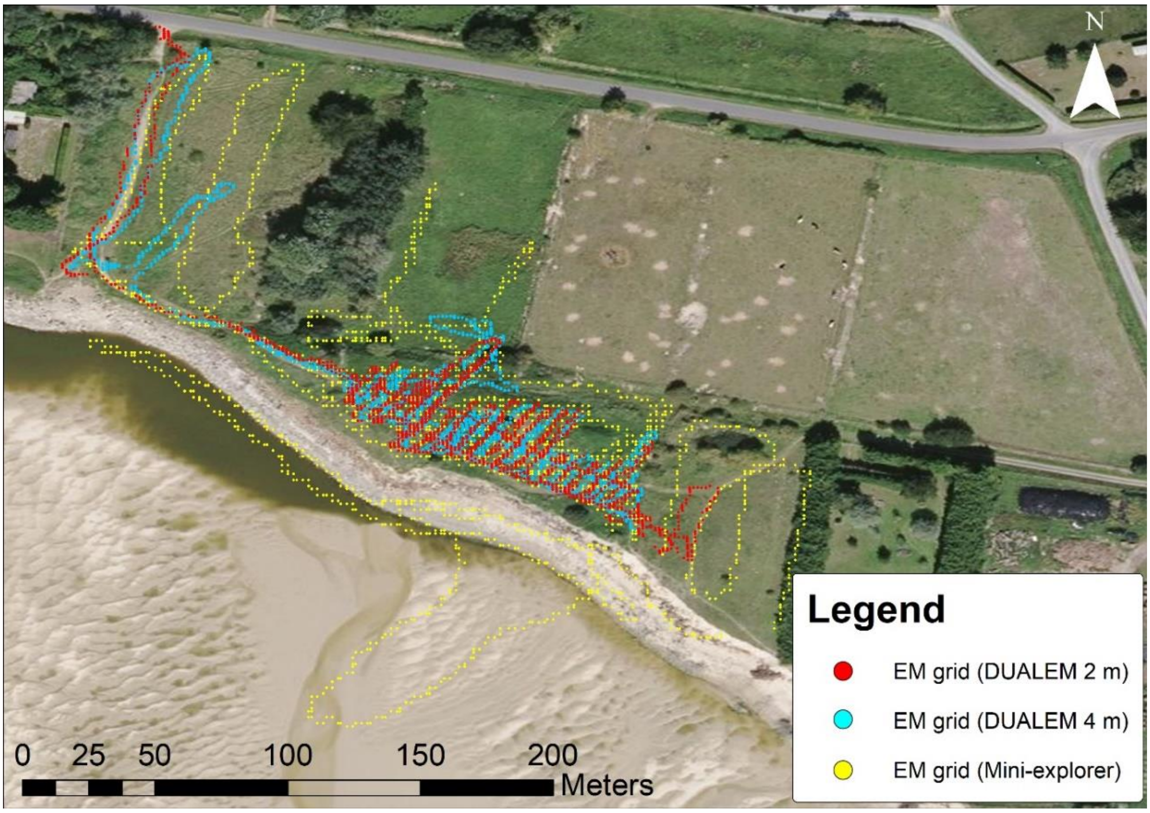

Figure 2: Extent of the EM mapping with the DUALEM 4 m antenna (blue dots), 2 m antenna (red dots) and the Mini-explorer (yellow dots).

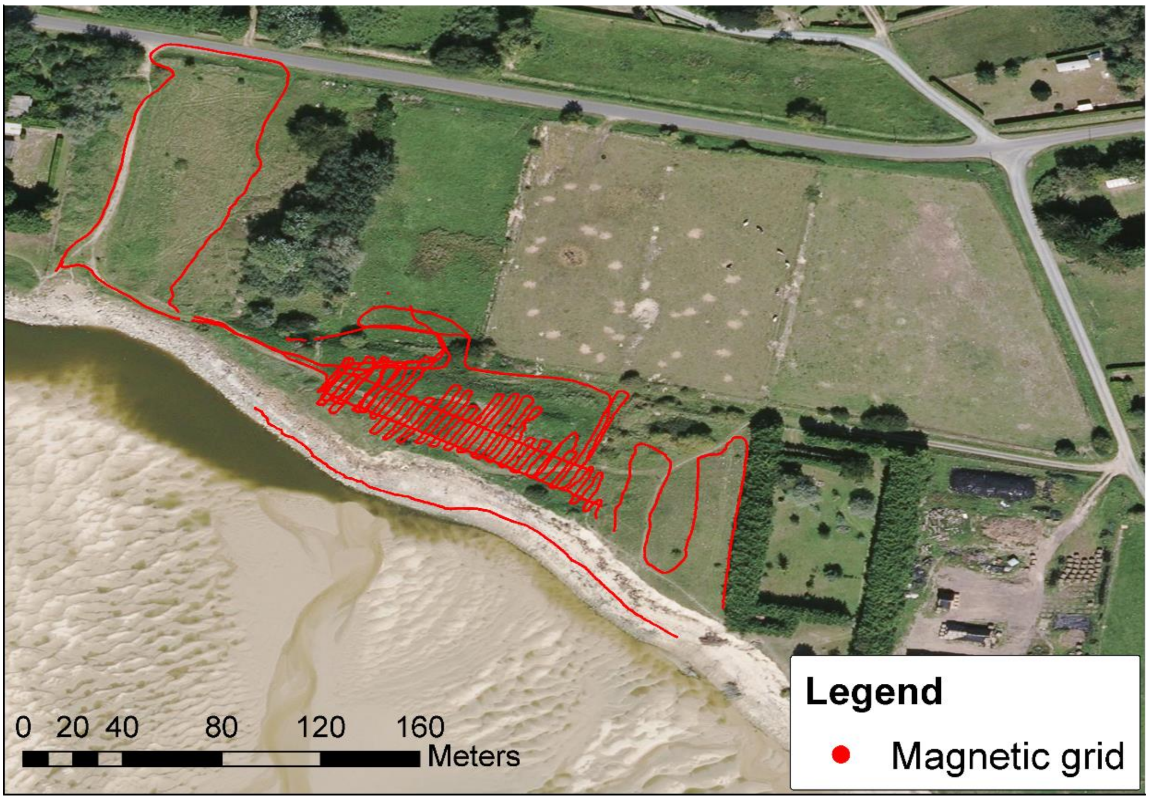

Figure 3: Extent of the magnetic mapping

ERT and IP data were acquired with an ABEM Terrameter LS system. Three profiles (P1, P2 and P3) perpendicular to the coastline were deployed across the landfill (*Figure 14*) using separately cables for electrical current injection and potential measurements. The lengths of P1, P2 and P3 are 57 m, 48 m and 51 m, respectively. For each profile, the electrode spacing was 1 m. For the data acquisition, a gradient array with a 's' factor equals to 6 (Dahlin and Zhou, 2006) was used. Electrical current injection was setup to 2 s and voltage drop was measured for 2.1 s after the current was switched off. The measurements were repeated twice to estimate the repetition error.

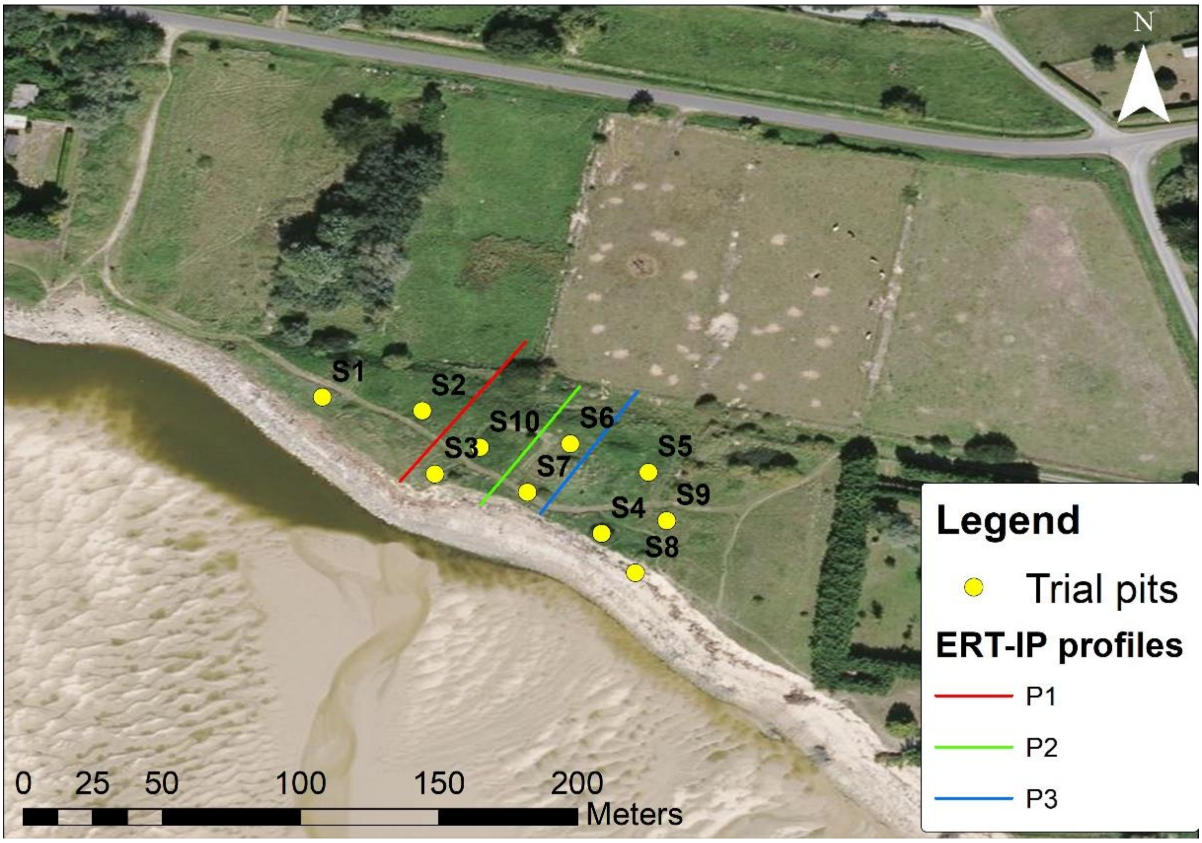

Figure 4: Location of ERT and IP profiles together with the position of the trial pits conducted in 2011 by SERAPIS (2015).

Geophysical processing and results

Data processing and results of each geophysical method are described and discussed in the following section.

EM results

The electrical conductivity and magnetic susceptibility maps at 5 different depths are shown in *Figure 15* (DUALEM antenna) and 6 (Mini-Explorer antenna). The extent of the landfill is clearly visible in *Figure 16A*. Indeed, the electrical conductivity observed in the landfill at 0.5 m depth presents a strong contrast with the surrounding areas (sand) characterized by low electrical conductivity. The measured values (≥ 50 ms/m) are in the range of those observed along the shoreline where the presence of salt water induces very high electrical conductivity. These values are likely related to the presence of waste deposits and leachate. Overall, conductivity tends to decrease with depth. For example, at 2.3 m depth (*Figure 15*), only the eastern part of the landfill (corresponding to Zone 1 in Figure 11) still shows a strong contrast in electrical conductivity with the surrounding environment. At a depth of 5.3 m (*Figure 15C*), the contrast is strongly attenuated. The susceptibility maps show anomalies that are mostly located within the landfill. They are particularly visible at 1 m (*Figure 16B*), 1.8 m (*Figure 16D*) and 5.3 m (*Figure 15D*). These anomalies are induced by buried metal objects. It should nevertheless be mentioned that the depths of investigation presented in the EM maps are only theoretical and are likely to vary with the electrical properties of the investigated environment.

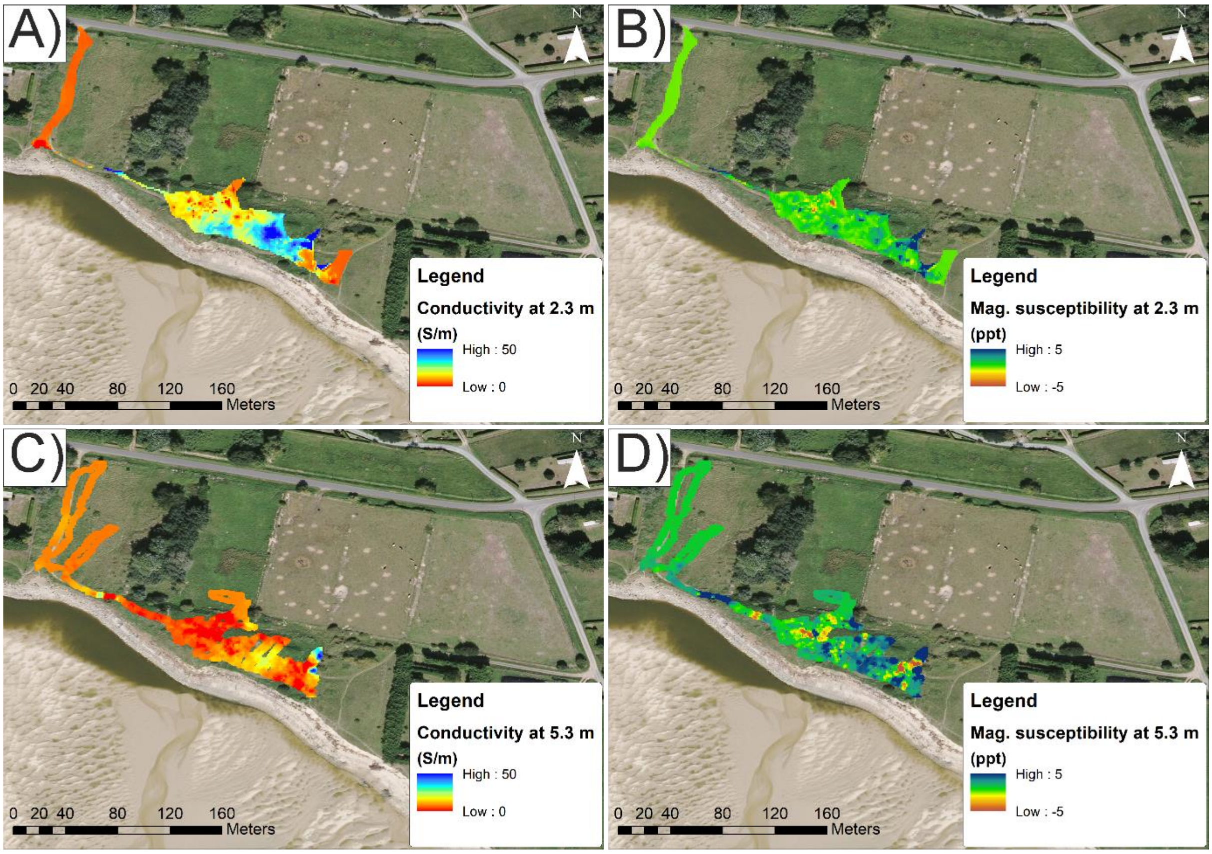

Figure 5: Electrical-conductivity maps derived from the quadrature-phase data (A and C) and magnetic susceptibility maps derived from the in-phase data (B and D) measured with the DUALEM-4 antennas. Investigation depth is from top to bottom: 2.3 m and 5.3 m, respectively.

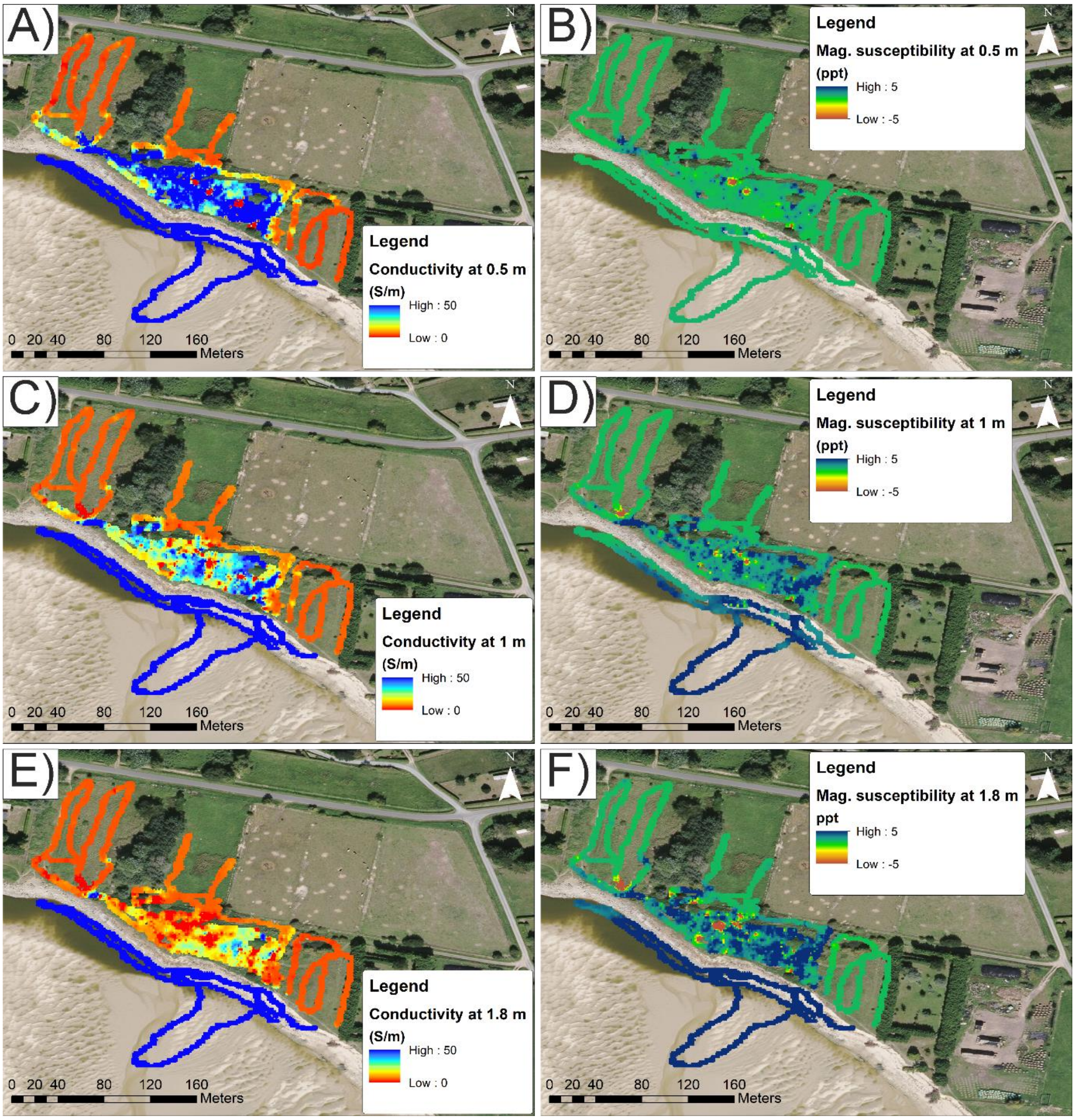

Figure 6: Electrical-conductivity maps derived from the quadrature-phase data (A, C and D) and magnetic susceptibility maps derived from the in-phase data (B, D and F) measured with the Mini-explorer antenna. Investigation depth is from top to bottom: 0.5 m, 1 m and 1.8 m, respectively.

MAG results

The first step in processing magnetic data is to check temporal variations of the magnetic field. Thanks to a base station installed outside the waste disposal area, these variations could be monitored throughout the magnetic mapping. The mean magnetic field measured by the base station is 48,025 nT. Variations observed during the whole acquisition did not exceed 14 nT around the mean value. These low variations do not affect the magnetic mapping results and are therefore not taken into account in the following.

The total magnetic field and the vertical magnetic gradient measured along the path followed by the operator are provided in *Figure 17A* and *B*, respectively. It is evident that the total and vertical magnetic variations are almost exclusively observed in the landfill area. This becomes clear when comparing the data measured in the central part of the area covered (= landfill area) with the data measured in the eastern and western parts which are free of waste. In general, the reported anomalies are strongest in Zone 1, where the waste thickness is the highest. However, it should be noted that the strong positive anomaly in the western part of the landfill is due to the metal fences that limit the site. The vertical magnetic gradient map highlights metallic objects that are close to the surface. As can be seen in *Figure 17B*, there are many points where the value of the vertical magnetic gradient is high, suggesting that such objects are present at shallow depths in the different zones of the landfill. Finally, the vertical magnetic map reveals that they are also present along the shoreline. They may be related to the waste that reached the beach after the dike was eroded.

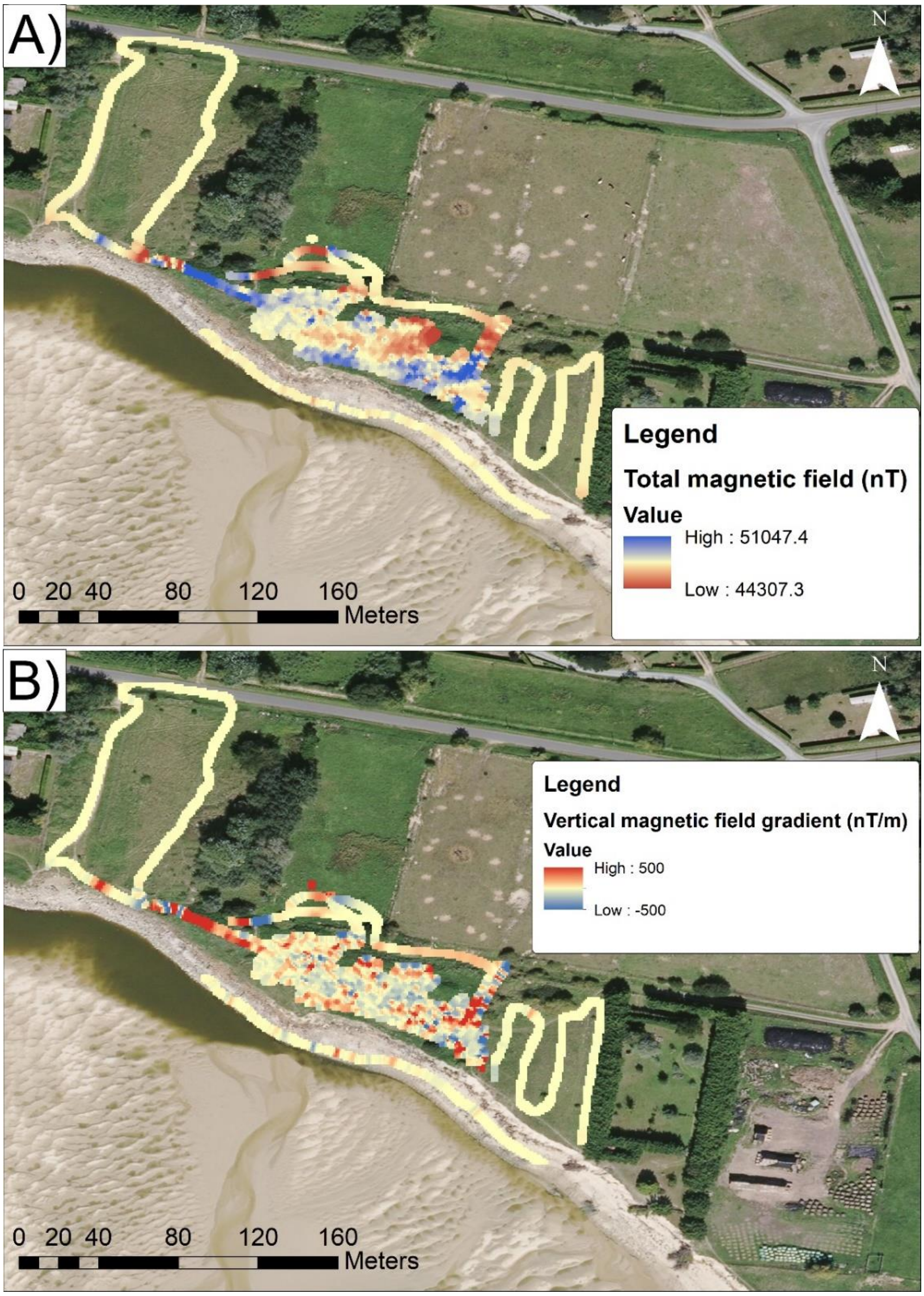

Figure 7: Maps of total magnetic field (A) and vertical magnetic gradient (B).

ERT and IP results

Data collected were first filtered by removing all measurements characterized by a repetition error on the measured resistance larger than 5%. The data were then inverted with BERT (Günther et al. 2006) using a robust constraint on the data and a blocky constraint on the model. The 2D models obtained with BERT satisfy the error weighted chi-square, $\chi^2 = 1$, meaning that the data are fitted to their estimated error level. *Figure 18* to *Figure 20* show the resistivity, chargeability, and sensitivity models for the ERT/IP profiles P1, P2 and P3, respectively. The trial pits closest to the profiles are also shown along with an interpretation of the results. In all profiles, the landfill area corresponds to the heap. As previously revealed by the EM mapping, the electrical resistivity of the natural ground is high (>400 Ohm.m) which is expected given its sandy nature. Within the landfill area, electrical resistivity generally shows very different values. Typically, a layer of medium resistivity is observed close to the soil surface and coincides with low chargeability values. It likely represents the cover material (composed of sand and topsoil) that was placed over the waste in the early 1990s. Its thickness varies from one profile to the other as also observed during trial pitting (see Table 1). Below the cover layer, low (P1) to very low (P2 and P3) electrical resistivity is observed. This electrical signature can be attributed to the presence of household waste containing metals and leachate. In their upper part, these low electrical resistivity areas correspond to high chargeability values. As the chargeability is sensitive to metal, plastic and organic content, it allows a good delineation of the base of the landfill as illustrated in *Figure 20B* where the trial pit (S6) shows a transition from waste to natural ground at the location of the transition from high to low chargeability. Areas of low electrical resistivity, assumed to arise from the household waste, extent beyond the high chargeability zones indicating the presence of leachate below the physical limit of the landfill as also reported during the sampling survey (SERAPIS, 2015). Finally, the resistivity and chargeability contrast within the landfill area increases from West (P1) to East (P3) suggesting a higher waste content as we move eastwards which was also highlighted by the first characterization study.

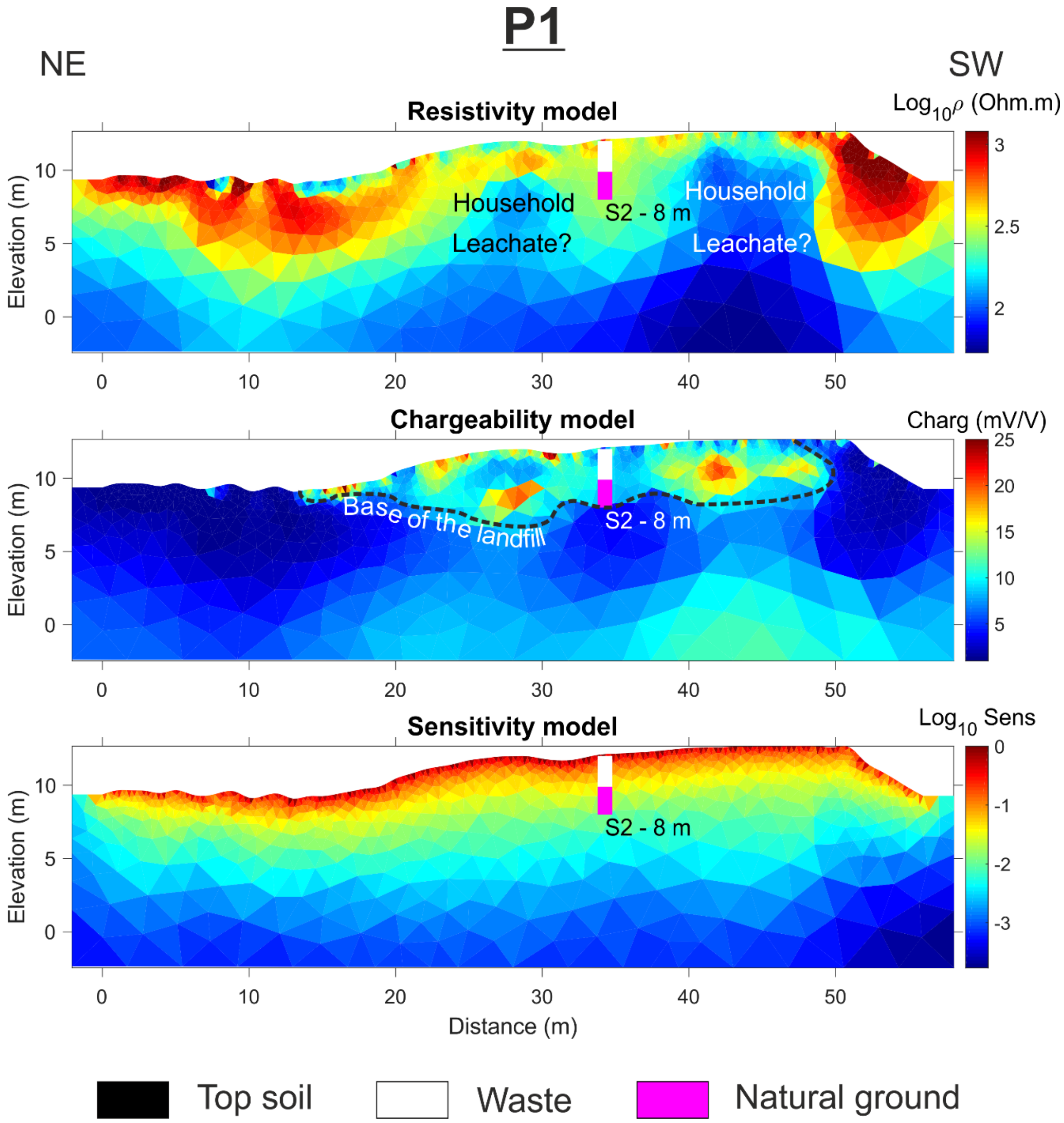

Figure 8: Electrical resistivity (top), chargeability (middle) and sensitivity (bottom) models obtained in P1. To make the interpretation easier, the "lithological" log of the closest trial pit (S2 located at a distance of 8 m) is displayed.

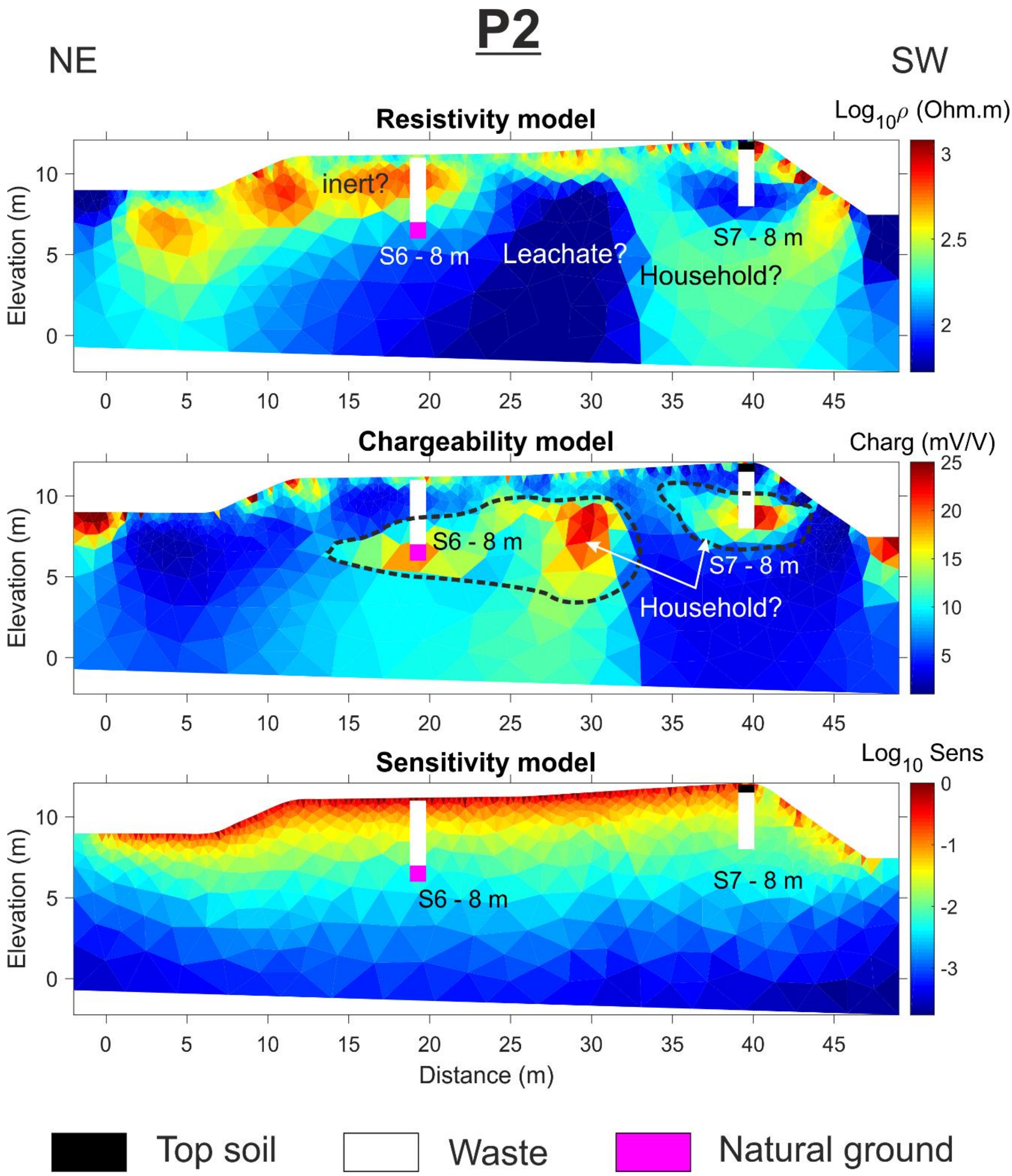

Figure 9: Electrical resistivity (top), chargeability (middle) and sensitivity (bottom) models obtained in P2. To make the interpretation easier, the "lithological" logs of the closest trial pits (S6 and S7 both located at 8 m) are displayed.

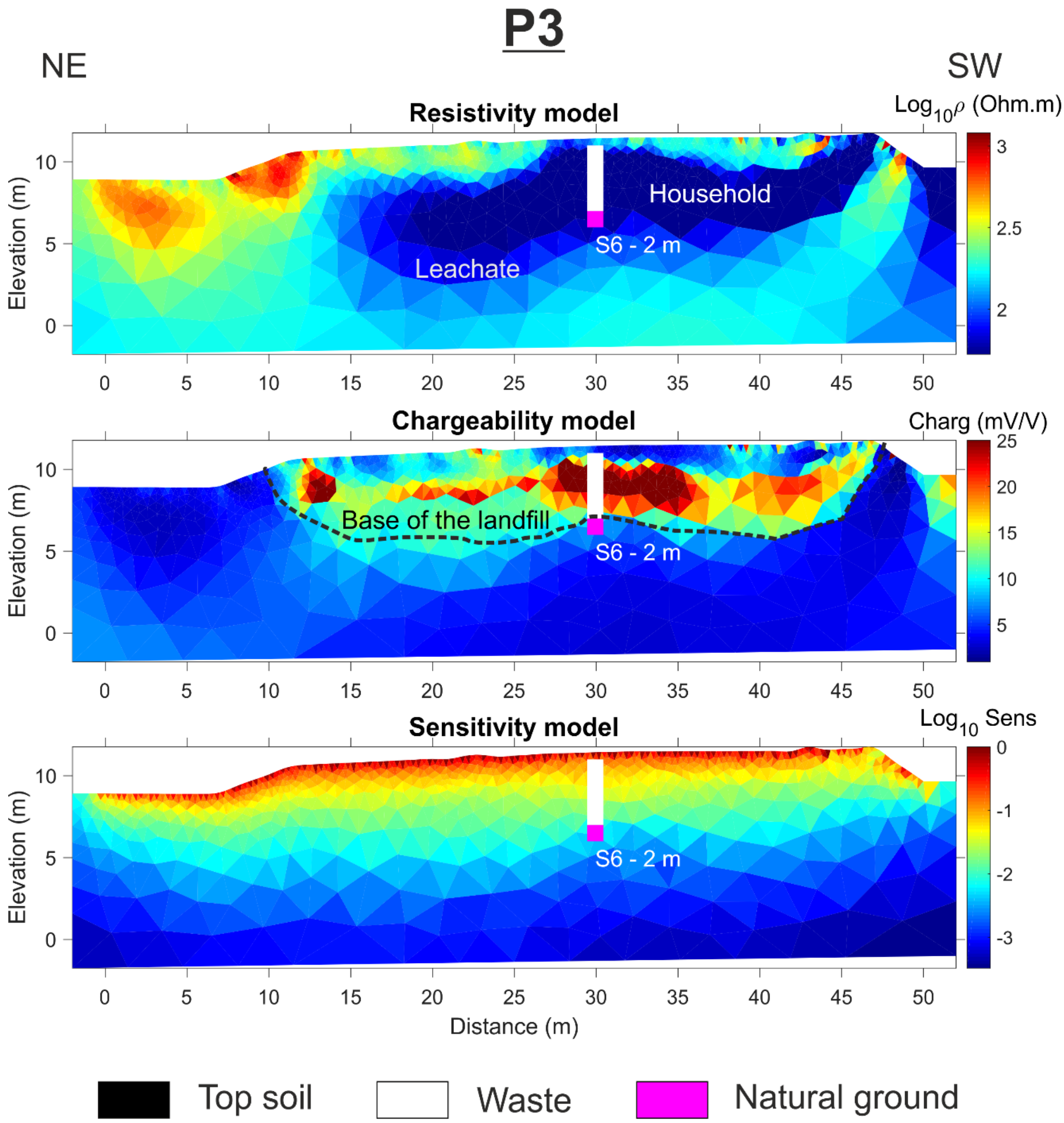

Figure 10: Electrical resistivity (top), chargeability (middle) and sensitivity (bottom) models obtained in P3. To make the interpretation easier, the "lithological" log of the closest trial pit (S6 located at 2 m) is displayed.

Summary of geophysical findings

EM mapping and magnetic mapping provided a quick overview of the extent of the landfill. The EM even showed an increase in the thickness of the waste towards the west which was observed during the intrusive characterization. Household waste appears to be characterised by high chargeability and low electrical resistivity, which allows it to be detected and imaged with ERT and IP.

Resource Distribution Model

The following data sources were used in order to build the resource distribution model: the rehabilitation project (SERAPIS, 2015), the geophysical results, the site remediation completion report (BURGEAP 2018) and geographical data (including the digital elevation model).

According to the rehabilitation project report (SERAPIS, 2015), the surface area of the landfill was 4,320 m². Using EM and MAG data, similar estimation (4,420 m²) was obtained. A map of the landfill extent based on the geophysical mapping is shown in *Figure 21*.

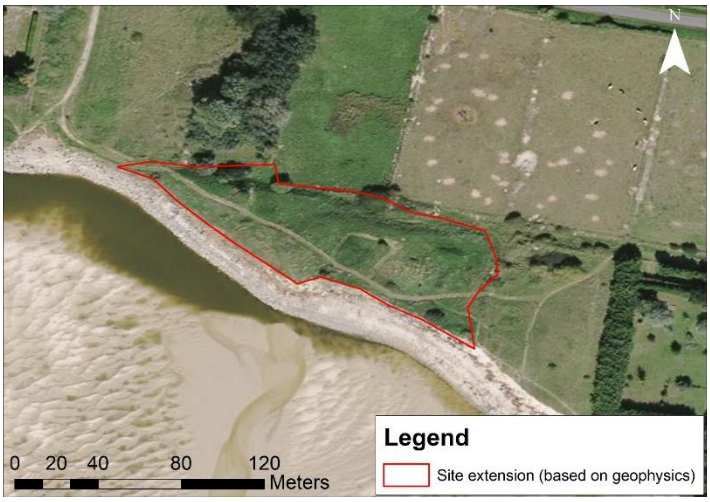

Figure 11: Landfill extent obtained with the geophysical mapping methods.

Unfortunately, the lack of ground truth data along the ERT/IP profiles does not allow to validate nor calibrate the models obtained. It also impedes the use of supervised machine learning tools to build the resource distribution model. Therefore, to estimate the volumes of waste, we first rely only on data collected during sampling in 2011 (see *Table 1*). With this approach, the volume of waste in the Lingreville landfill was estimated at 5,185 m³ (*Figure 22A*). For comparison, in the rehabilitation project report (SERAPIS, 2015), the volume of waste was estimated at 4,300 m³ with the same data. The discrepancy can presumably be explained by a difference in the interpolation method used (we applied the nearest neighbour method).

In a second approach to estimate the volume of waste, we combined sampling data and the vertical extent of the landfill identified in the ERT/IP profiles. The resulting volume of waste was significantly increased to 7,930 m³ (*Figure 22B*). The volumes presented above do not take into account the sand under the landfill that has been contaminated by leachate. It should also be noted that in the calculation of the waste volume, topsoil or sand mixed with waste (regardless of the waste content) was considered as waste materials. *Figure 22* shows 3D views of the landfill divided into two types of materials: topsoil and waste using the two approaches described above.

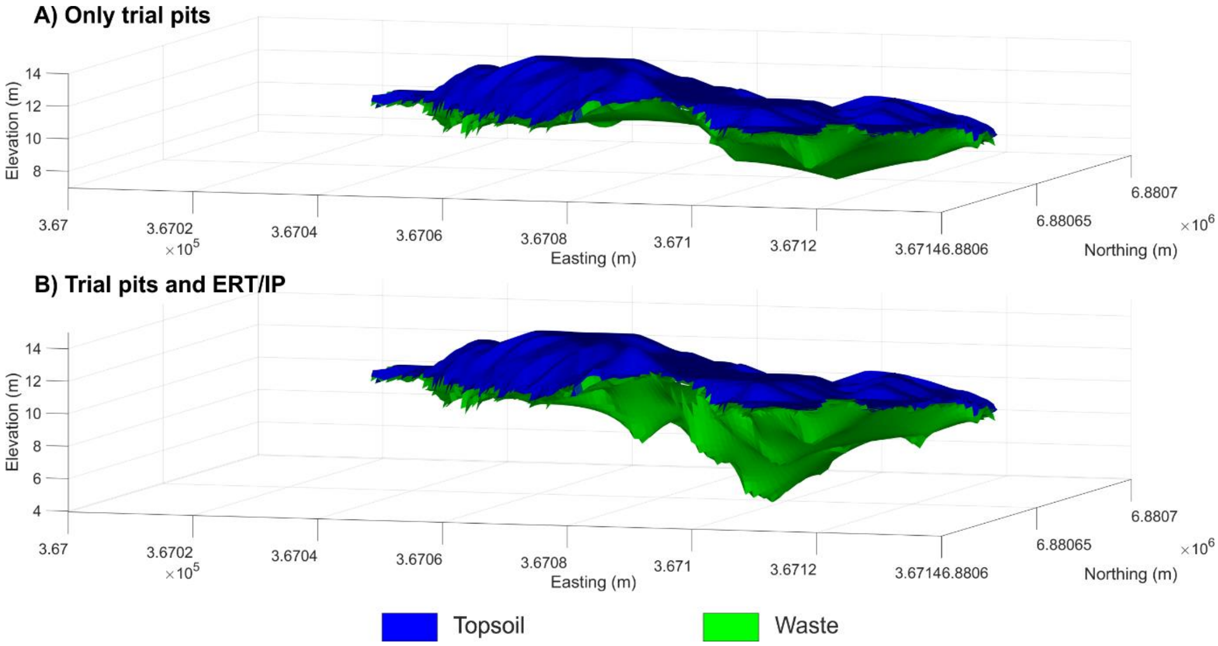

Figure 12: 3D view of the waste deposits showing a thicker layer of waste in the eastern part of the landfill.

At the end of the remediation activities (BURGEAP, 2018), 11,925 m³ were excavated and sorted. The volume of sand and waste was 8,097 m³, which is much closer to the value provided by combining geophysics and sampling data than using sampling data alone. The tonnages of sand, waste and riprap removed are distributed as follows:

Table 2: Tonnages of sand and waste landfill mined (BURGEAP 2018).

	Tonnes
Waste + sand	12,493
Metal scraps	87.18
Asbestos	0.22
Inert sand and rubble	1,131.8
Rock riprap	1,300

The landfill has been remodelled with the 3,586 m³ of screened sands. An aerial view before and after the remediation activities is shown in *Figure 23*.

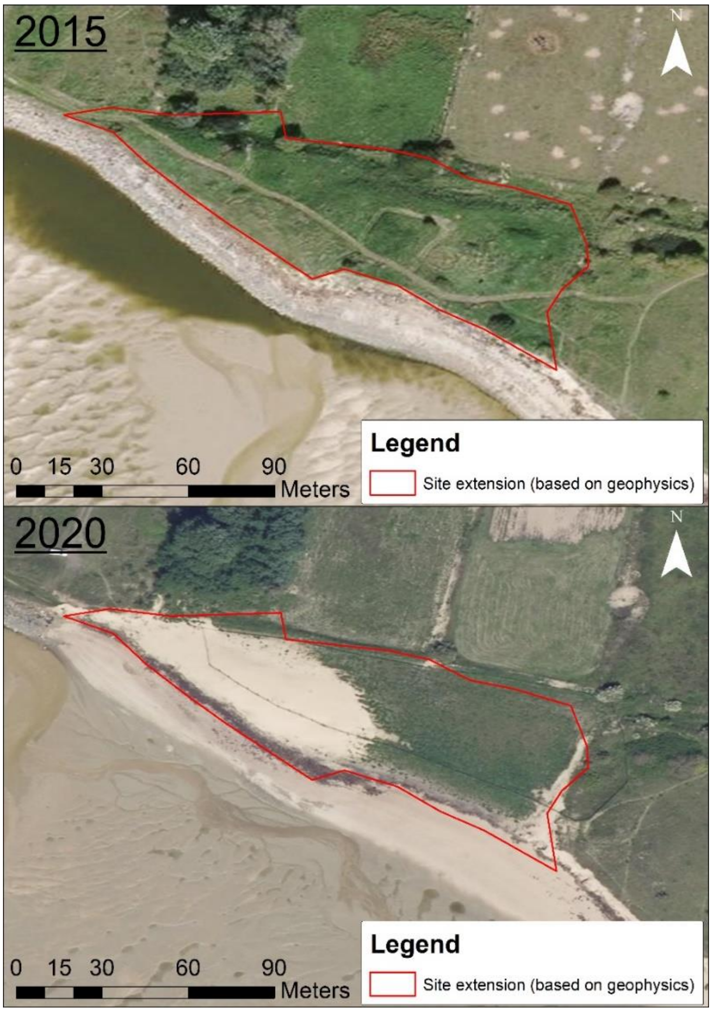

Figure 13: Aerial views of the Lingreville site before (top) and after (bottom) remediation actions.

Conclusion

The geophysical survey carried out in the landfill of Lingreville just before its rehabilitation allowed to:

(1) clearly identify the lateral extent of the landfill (EM and magnetic mapping);
(2) reveal a zonation of the landfill (all methods combined);
(3) get information about the vertical extent of the waste deposits (ERT and IP);
(4) detect zones impacted by leachate infiltration (ERT).

Overall, geophysical results are consistent with the findings of a previous study using traditional characterization techniques.

The Lingreville site has the particularity to have been landfill mined just after the geophysical survey. Geophysical mapping clearly identified the lateral extent of the landfill whereas profiling methods provided information on its vertical extent. Combining sampling and geophysical data allowed to significantly improve the waste volume estimation. Unfortunately, the lack of spatialized data collected during landfill mining operations impeded the refinement of the model obtained (i.e. estimation of the different waste streams).

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