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ASSESSMENT OF GEOPHYSICS AS A CHARACTERIZATION AND MONITORING TOOL IN THE DYNAMIC LANDFILL MANAGEMENT (DLM) CONTEXT: OPPORTUNITIES AND CHALLENGES

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ABSTRACT: Advances in geosciences and diverse non-invasive geophysical methods have demonstrated to be useful for landfill exploration, characterization and monitoring. Their use allows to reduce the costs and environmental footprint of conventional characterization surveys, to increase gas production in the case of landfill bioreactors, and to better address and assesss the environmental effects associated with landfills. Geophysical methods can provide valuable decision support tools in applying the concept of Dynamic Landfill Management (DLM), which includes the resource recovery-driven landfill mining to support the transition to a circular low-carbon economy. However, it is important to know beforehand the applicability of the distinct geophysical methods under specific conditions of different landfills and/or DLM projects. In this work, we present an approach to guide the selection of the most suitable combination of geophysical methods considering three aspects of implementation. The first relates to the available historical information of the site, e.g. type, age and morphology of waste deposits, and presence of geomembranes. The second aspect accounts for the current physical structure of the site and its surroundings including the host geology, topography and vegetation. The third aspect covers the most commonly used surface geophysical exploration methods, namely magnetic, electromagnetic (e.g. frequency-domain electromagnetics, ground penetrating radar), electrical (e.g., electrical resistivity tomography), passive and active source seismic methods (e.g. refraction, horizontal to vertical spectral ratio) and the physical properties they target (e.g., electrical conductivity, magnetic susceptibility, elastic moduli, density) which in turn may be translated into parameters of interest (e.g., waste volume, water content, metallic content). The use of this approach can help optimizing the design of geophysical surveys where individual methods can be combined to bring complementary information and achieve a more complete characterization. Finally, we exemplify this approach with two of the landfill sites studied in the RAWFILL project, which are located in Belgium. We expose the motivation to investigate these sites, some geophysical results, their interpretation and following validation through conventional sampling.

Keywords: geophysics landfill characterization RAWFILL

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1. INTRODUCTION

In view of the worldwide growth of waste generation, efforts are been made to develop a broad sustainable vision for the collection of waste and a long-term perspective on management of historic landfills (Jones, Wille, & Krook, 2018). Together with the emerging interest in resource recovery through "mining" the more than 500,000 existing landfills in Europe, this motivated the development of the concepts of enhanced landfill mining (ELFM) and dynamic landfill management (DLM) by the European Enhanced Landfill Mining Consortium (EURELCO). The broader approach of DLM refers to the dynamic - i.e. time variable- view on landfill management, encompassing the ELFM concept which more specifically targets the recovery of materials (Waste-to-Matetial WtM) and energy resources (Waste-to-Energy). Both perspectives support the transition to a resource-efficient, circular, low-carbon economy (Danthurebandara, Van Passel, Vanderreydt, & Van Acker, 2015; Jones et al., 2018).

The characterization stage is essential to evaluate a landfill's potential for WtM or WtE. Conventional methodology for characterization and monitoring of landfill includes borehole drilling and trial pit excavation to obtain information on subsurface structures. However, these are invasive, time-consuming and generally expensive. They can also create new paths for contamination migration. Maybe even most important, the quality of the results depends on the number and spatial distribution of the samples which may be only poorly representative of the true landfill heterogeneity (De Carlo et al., 2013; Jones et al., 2013; Dumont, Robert, Marck, & Nguyen, 2017). Non-invasive geophysical methods and andvances in geosciences, emerge as solutions to reduce the costs and environmental footprint of conventional investigation methods. In addition they can cover a broad range of specific targets going from mapping waste boundaries to advanced hydrodynamics characterization (Nguyen, Ghose, Isunza Manrique, & Dumont, 2018).

In this work we first summarize the capacity of some common surface geophysical methods to address distinct landfill targets. Secondly, we present an approach to select the most suitable combination of methods to support decision-making depending on the objectives of the DLM project. The first aspect relates to all the available historical information of the site, e.g. type of deposits, age, presence of geomembranes, etc. The second aspect is devoted to the current physical structure of the landfill and its surroundings including host geology, topography and vegetation. The third aspect assess the capacity of different surface geophysical methods depending on the first and second aspects. The opportunities and limitations of some geophysical methods are evaluated according to different landfill scenarios and exploration objectives. To illustrate this approach, we use two landfill sites located in Belgium and investigated within the project RAWFILL: supporting a new circular economy for RAW materials recovered from landFILLs. This interdisciplinary project (funded by Interrreg North-West and Wallon Region) provides knowledge to screen landfills and demonstrates the evidence-based, standardized methodology to select profitable landfill mining projects.

2. GEOPHYSICAL METHODS IN THE DLM CONTEXT

2.1 Background

To the best of our knowledge, the earliest geophysical survey conducted on a landfill dealt with contaminant detection (Cartwright & McComas, 1968). Since then, the number of geophysical investigations reported in the literature has significantly increased (Soupios & Ntarlagiannis, 2017; Nguyen et al., 2018). In Europe, several projects with an actual implementation of geophysical methods -mostly at initial stages- can be named. For example, in the Sandform Farm project driven by land redevelopment in UK, 370 tons of scrap metal were recoverd in the period 2013-2016. The MINERVE project, launched in Walloon Region, Belgium, aimed at reducing the waste lifetime cycle and maximizing the generation of alternative energy and materials from a landfill. One of the pilot landfills of SMART GROUND project was a tailing pond located in Finland where geophysical methods were applied together

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with drillings and geochemical analyses (Markovaara-Koivisto et al., 2018). NEW-MINE project aims to transform landfill-excavated material into higher-added-value products, where the advanced landfill exploration comprises a geophysical characterization (Bobe, Van De Vijver, & Van Meirvenne, 2018).

Another example is the RAWFILL project which started in 2017 and focuses on the the region of NW Europe. Its main goal is to develop a standardized framework that allows the public and private sector to make economically informed decisions on landfill mining. Within the project's methodology, the characterization of these sites includes the use of a wide variety of geophysical methods: frequency-domain electromagnetic induction (FDEM), magnetometry, electrical resistivity tomography (ERT), induced polarization (IP), ground penetrating radar (GPR) and different seismic methods, which are the guide to designing conventional sampling surveys. The geophysical methods explored in this project and the experiences while studying different scenarios, are the ones considered for the approach presented here.

2.2 What is the target capacity of geophysical methods in landfill investigations?

Geophysical methods can be useful for a large range of applications in landfills. From a general perspective they can help to identify these sites, delineate the landfill's lateral and vertical boundaries, distinguish different material deposits or resolve heterogeneities within the waste body. In landfill bioreactors, they can be used to monitor and optimize biogas production processes -as a landfill bioreactor is a chemical and biological controlled waste deposit whose primary goal is to accelerate waste stabilization, leading to a biogas production (Imhoff et al., 2007). In the following sections we summarize how some surface geophysical methods suit different targets.

2.2.1 Magnetometry

By measuring variations in the Earth's magnetic field, originating from the landfilled waste, magnetic methods can help to detect large metallic objects (e.g. drums) within the waste body and, therefore, it is often used to identify -usually by qualitative indicatives- valuable metallic objects with respect to mining secondary raw materials. The method has also been used to delineate lateral landfill's boundaries and to detect contamination outside of the landfill limits (Green, Lanz, Maurer, & Boerner, 1999; Yannah, Martens, Van Camp, & Walraevens, 2017; Dumont et al., 2017).

2.2.2 Frequency-domain electromagnetic induction

By inducing electrical currents in the subsurface and analyzing the magnetic field they produce with reference to the primary applied magnetic field, this method is an efficient tool to characterize the boundaries, geometry and sometimes structures of a landfill (Van De Vijver & Van Meirvenne, 2016; White, Day-Lewis, Johnson, & Jr, 2016; Bobe et al., 2018). It has also been used to detect, delineate and monitor leachate contamination (Johnson, White, & Joesten, 2012) and, in a landfill bioreactor, to monitor changes in electrical conductivity due to leachate injection (Clément, Audebert, Loisel, & Moreau, 2018).

Except for inert construction and demolition waste deposits, landfills are often characterized by high conductivities due to the large organic content, metallic content and/or leachate. This may lead to a reduced depth of investigation (DOI) compared to commonly adopted theoretical expectations, which must be considered for the data interpretation. In addition, particularly due to the sensitivity of absolute measurement values to environmental conditions, data calibration and validation is crucial to reliable interpretation, in terms of both physical and waste composition properties targeted. Previous studies illustrate the use of electrical resistivity tomography (ERT) and/or ground truth data, i.e. data from boreholes or trenches for this purpose (von Hebel et al., 2014; Van De Vijver, 2017; Delefortrie et al., 2019).

2.2.3 Ground penetrating radar (GPR)

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The operating principle of GPR is based on the propagation and reflection of high-frequency electromagnetic waves. Under favorable field conditions, the method can be used to characterize subsurface boundaries, identify geological and man-made structural features, e.g. storage tanks, buried utilities, and map contaminat plumes (Soupios & Ntarlagiannis, 2017). It has also been used to monitor leachate recirculation systems in municipal solid waste landfill (MSW) cells (Carpenter & Reddy, 2016). As the signal is rapidly attenuated in highly conductive materials such as household waste, this method is often used for shallow targets in a landfill, including utility and environmental engineering infrastructure embedded in the capping layer (e.g. surface drainage pipes, biogas and leachate collector systems).

2.2.4 Electrical resistivity tomography (ERT)

This method provides the electrical resistivity of the subsurface by injecting electrical current through electrodes “pinned” into the ground surface. It has been used to characterize the geometry of a landfill (e.g. lateral borders, thickness of the waste, waste layer geometry, etc.) in addition to compositional variations. Time-lapse ERT has been widely used to identify and monitor the spatial distribution and dynamics of leachate plumes (Chambers, Kuras, Meldrum, Ogilvy, & Hollands, 2006; Maurya et al., 2017). In landfill bioreactors, important paremeters of waste degradation such as moisture and leachate content have indirectly been assessed using ERT (Dumont et al., 2016; Dumont, Robert, & Nguyen, 2018). However, as the injection of electrical current requires the electrodes to be in contact with the waste mass, the presence of a top geomembrane can limit the method. High-density polyethylene geomembranes are highly resistive with resistivity values of 10^6 ohm-m, thus preventing the electrical current flowing through it (De Carlo et al., 2013).

2.2.5 Induced polarization (IP)

Usually the automatized systems designed for the resistivity measurements allows to record the time-domain induced polarization IP, i.e. chargeability, as well. Typically, landfilled waste – metal scrap, organic material and/or layering of plastic sheets – shows a positive chargeability anomaly as compared to the host formation (Carlson, Mayerle, & Zonge, 1999; Nguyen et al., 2018). IP has succesfully been used for detecting for metallurgical slags (Qi et al., 2018) and monitoring leachate dynamics (Bording, Gianluca, Esben, & Anders Vest, 2018).

2.2.6 Seismic methods

For over than 40 years different seismic techniques have been used to investigate landfills. The methods can help modelling the structure of the subsurface using the propagation of seismic waves traveling at different velocities and generated by an artificial (active) source or by natural fields and noise (passive source). The seismic wavefront is detected at different distances from the source by geophones or seismometers sensing the 3D movement of the soil.

For the active source methods, the applications of the refraction tomography include bedrock mapping and subsurface structure characterization. For higher resolution (with correspondingly higher data processing time) seismic reflection can be used; this method allows to accurately determine depth and thickness of geologic strata in complex environments as well as heterogeneities/artifacts within the waste body (Soupios & Ntarlagiannis, 2017). The method of multichannel analysis of surface waves (MASW) gives a general trend of changes inside the landfill (Konstantaki, Ghose, Draganov, Diaferia, & Heimovaara, 2015). The passive source method of horizontal to vertical noise spectral ratio (HVNSR) is a useful technique to estimate and delineate the waste deposit thickness when the velocity of surface waves is known (Dumont et al., 2017).

In practice, the seismic response of MSW landfills is a complex dynamic soil-structure interaction problem (Psarropoulos, Tsompanakis, & Karabatsos, 2007), which often leads to challenging data processing and interpretation. Some complications include scattering, poor transmision of seimic waves due to unconsolidated wastes, source noise, etc. (De Iaco, Green, Maurer, & Horstmeyer, 2003).

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2.3 Towards the development of adaptable geophysical exploration surveys

Due to the heterogeneous nature of the landfills, a multi-methodological geophysical approach has proved to be the most powerful to achieve a general characterization of the landfill and the waste body (Cossu et al., 2005). Combining two or more geophysical methods that target different physical properties can greatly reduce interpretation ambiguities inherent to separate methods (Hellman et al., 2017).

Here, we present a general approach outlining the suitability of different combinations of geophysical methods for distinct landfill scenarios and illustrate this with some results of two test cases performed within the RAWFILL project. We emphasize that this is not a fixed nor a universal approach, as different geophysical methods that those considered here can be included in the geophysical exploration, and new technologies and advances in geosciences may be able to overcome the limitations we currently have.

Figure 1 presents the three-aspect approach to select a suitable combination of surface geophysical methods under a basic landfill scenario. First, we consider gathering all available information of the site such as type of landfill, records of deposition history, knowledge about the layers, presence of geomembrane, etc. Afterwards it is important to assess the current topography, the vegetation of the site, the physical structure and/or infrastructure but also the host geology, e.g. sand, limestone, wetland. Finally, we assess the suitability of different methods for different conditions set by the characteristics and environment of the landill and the exploration targets.

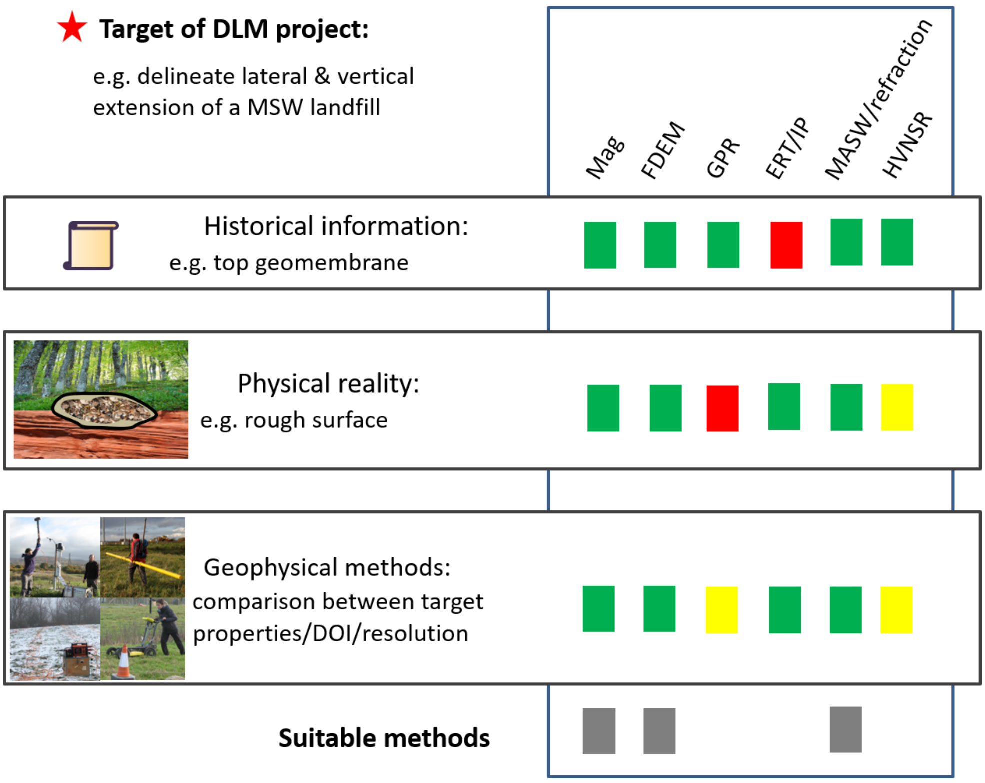

Figure 1. Three aspects approach to select suitable surface geophysical methods under a specific landfill scenario. Through the three aspects we show suitable methods in green, in yellow the methods that might be challenging for data acquisition/processing and in red the methods with the largest limitations. At the end the output is the combination of the most suitable methods.

Optimal use of the accessible landfill survey area – confined by aboveground and/or surface infrastructure - is something we must consider especially for profiling methods such as refraction tomography, MASW, ERT and IP. For practical purposes, the selection of the profile spread length is related to the depth we want to target (although the actual DOI also depends on the physical properties of the medium). For example, in a MSW landfill the acquisition of a 410 m long ERT profile (83 electrodes/5 m spacing), led to a DOI of 15-20 m. In this example, the bottom limit of the waste could not

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be mapped because the profile extension was limited by a road surrounding the site alongside the presence of a geomembrane and the high conductivity of the leachate (Dumont et al., 2016).

3. APPLICATIONS: GEOPHYSICAL APPROACH FOR TWO LANDFILL SCENARIOS

In the following sections we describe the motivation to investigate two landfill sites in the RAWFILL project, their geology, infrastructure, etc., and show how the geophysical approach can be applied. We briefly present the most relevant results from the geophysical surveys conducted by British Geological Survey (BGS) and University of Liège and summarize some interpretations validated with boreholes and trenches.

3.1 Meerhout site

This site, owned by the Public Waste Agency of Flanders (OVAM), is a MSW landfill located in the province of Antwerp, Belgium, and was exploited during different periods between 1962 and 1997. A vast amount of historical information was available from which we could derive the approximate thickness of the waste, the general composition (household and industrial waste), the presence of an agricultural foil and a HDPE membrane in different zones of the site and the plan of pipes for gas extraction.

Nowadays, the landfill consists in two main zones with different heights corresponding to different waste thicknesses, and the oldest zone which is now paved with cement and is used as a recycling park. The vegetation and topography did not pose any restrictions on the geophysical surveys. The geology hosting the landfill is composed of very wet alluvial soil.

Part of the motivation to study this site within the RAWFILL project, was to explore the potential of different surface geophysical methods to characterize MSW landfills, i.e. estimate waste thickness, capability of imaging different layers and heterogeneities. Based on the results, BGS and University of Liège designed an optimal sampling survey of boreholes and trenches to validate the interpretation of the geophysical results.

As this was one of the first studied sites, we applied all the methods displayed in Figure 1. First, with the magnetic method and the FDEM we could map the two distincts zones of the site and -some saturated zones and buried pipes were identified, which were also detected with GPR. As the seismic velocities of the alluvial soils can be similar to those from the MSW, it proved to be challenging to estimate the thickness of the waste using these methods, requiring additional data processing. Finally, the ERT/IP methods were conducted on the parts of the site without geomembrane. Figure 2 presents the ERT/IP results of one profile along which 7 shallow trenches were excavated. The models of resistivity, chargeability and their sensitivity (a quantitative measure of the depth of investigation) are displayed together with the location of the trenches and the limits of the 4 to 5 visually observed layers. These five layers were distiguished on the top of the waste body “only” composed of household waste. The first layer, or shallowest one, exists in grass and brown dirt with a depth from 0 to 5 cm (not visible in the figure). The second layer has a variable thickness between 35 and 125 cm and was composed by sand, debris, brick and concrete. The third layer with a thickness of 10-160 cm contains sand, wood, traces of debris, silty sand and some plastics. The fourth layer has a thickness ranging from 90 to195 cm and is composed by silty sand, traces of debris and traces of wood. The final or deepest layer had a variable thickness of around 90 cm, (where its bottom limit was set at the top of the only-household waste body) and is predominantly composed of several plastic foils, metals and few household waste.

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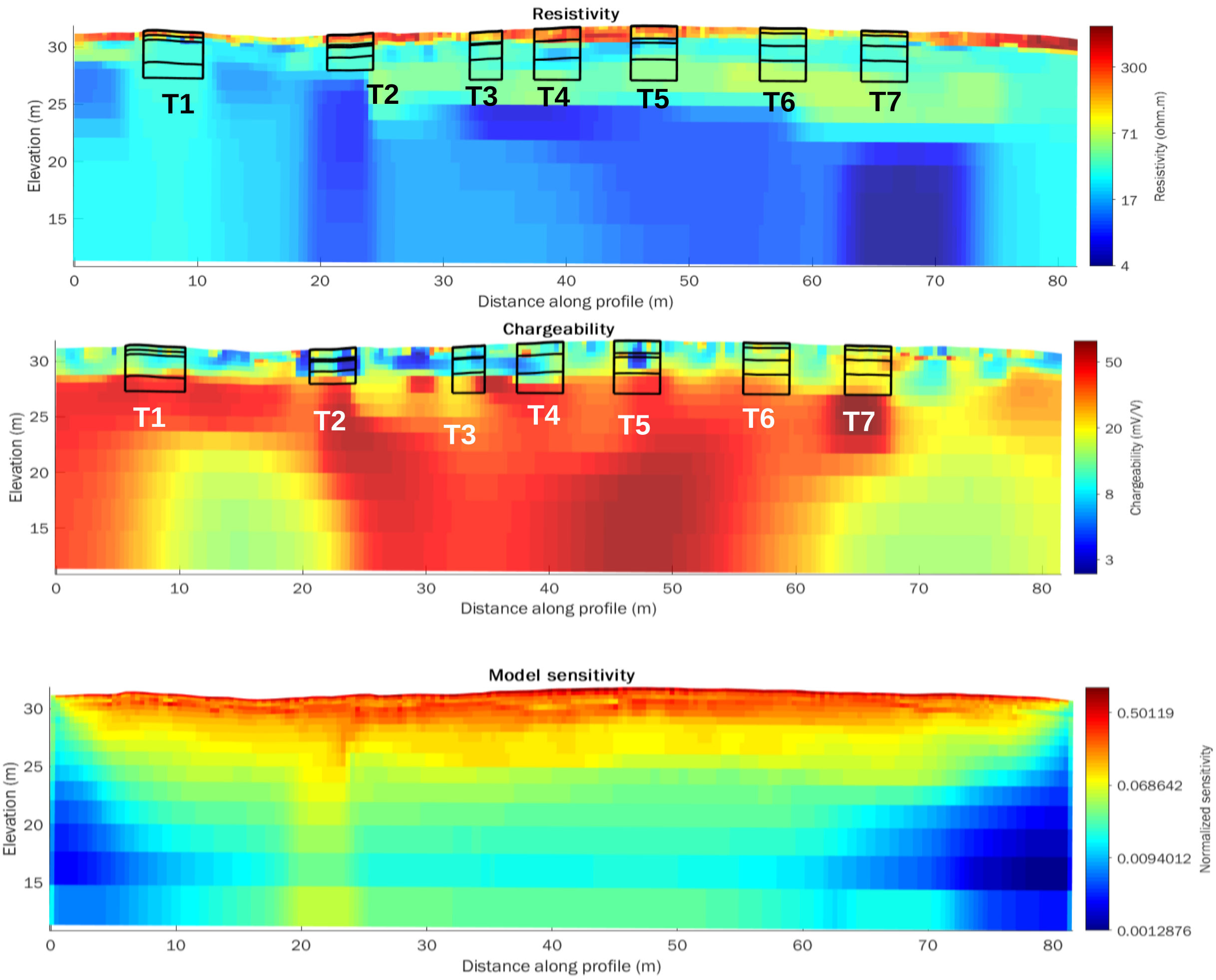

Figure 2. (Top) Inverse resistivity model and (middle) chargeability model with the contour of 7 trench locations (T1 - T7) and the division of 4-5 layers visualized on site during the excavations. Below, the normalized sensitivity model, the higher the sensitivity value, the more reliable is the model resistivity/chargeability value (Loke, 2011).

In the resistivity model of Figure 2, a relevant feature we can notice is a thin high resistivity layer in the shallowest part. We can see how the thickness of this layer decreases towards trenches 6 and 7 and varies in agreement with the thicknesses of the two upper visually detected layers. As we can not resolve the 5 cm thickness of the first layer with this method, the highest resistivity values can be attributed to the inert materials found in the second layer. For the chargeability model, we can see that the upper boundary of the deepest observed layer corresponds to the top part of the highest chargeability values. Thus, we can also conclude that the higher chargeability values (32-58 mV/V) correspond to the predominant deposits of plastic foils, metals and household waste.

In conclusion, the joint interpretation of the data from the two methods together with the information from the excavated trenches, enabled us to extrapolate useful information on the landfill composition. For the Meerhout landfill, the ERT and IP methods demonstrated to deliver complementary information to better characterize the site and to image shallow heterogeneities. For the seismic data, advanced processing is needed.

3.2 Onoz site

The landfill of Onoz lies in a former limestone quarry in the province of Namur, Belgium, and it is owned by a private company from the construction sector. From the vast historical information, it is known that the quarry was exploited from 1932 to 1967. Afterwards, the western part of the site was used for the deposition of ashes and lime until 1976. In the period 1982 – 1987 the site was used as landfill for inert, household and industrial waste. No geomembranes are present.

Nowadays, the landfill zones can still be recognized from a different height; the lower zone is composed of ashes and lime as well as inert, household and industrial waste, while the upper zone has only deposits of ashes and lime. Due to the abundant vegetation, it was necessary to clean the surface along certain paths to conduct the geophysical survey. The topography limited the geophysical acquisiton as a non-accessible steep slope divides the two zones. The local geology consists in stratified limestones containing dolomite beds from the Formations of Onoz and Lives (carboniferous).

The main motivation to study this site was to delineate the lateral and vertical extension of the ashes and lime as these are of interest for material recovery. In addition, we wanted to identify the extension of the (inert, household and industrial) waste deposits of the lower zone and assess possible environmental risks (leachate identification). In this case, the geophysical data could also be compared with information from previous invasive investigations conducted in 1993, 2012 and 2018.

After considering the historical information, the geology, topography and vegetation, BGS and University of Liège conducted a geophysical survey using most of the methods presented in Figure 1 except GPR (too rough surface for good GPR contact). Firsltly, with the magnetic method it was possible to map the waste extension in the lower zone of the site. The FDEM method was useful to map and delineate the lateral extension of the ashes and lime in both the higher and lower zone. Vegetation and topography prevented complete mapping of the terrain. The seismic data coming from the MASW and refraction methods are affected by the quarry structure, the high source attenuation, the strong lateral variations and/or the scatterers in the subsurface, requiring more data processing for meaningful interpretation. Finally, the ERT/IP methods were able to distinguish different zones of the site in the bottom zone, mainly the waste, the bedrock, backfill and the ashes and limes. Data from different trenches and boreholes as well as surface samples of ashes and lime, (whose resistivity was measured in the laboratory) were used for the data interpretation and calibration.

Figure 3 presents an aerial image from 1976 and the conductivity map of the site (FDEM method) where we can see the well delineated high conductivity zone that can be attributed to the ashes and lime deposits.

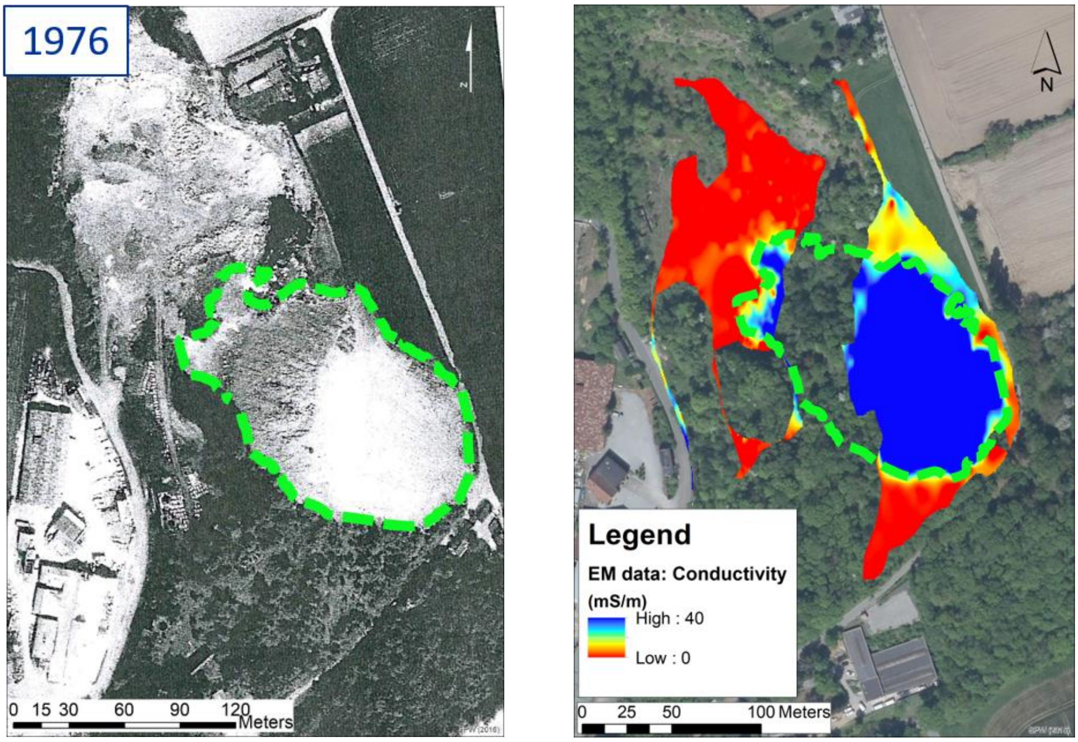

Figure 3. Aerial view from 1976 (left) and conductivity map of Onoz site displayed with the recent aerial view (source: Public Service of Wallon, 2017). The green line delineates the high conductivity extension interpreted as the deposits of ashes and lime.

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Figure 4 shows the resistivity model of one profile located in the bottom part of the site with a South-North orientation. From this model we can see that the highest resistivity values correspond to the bedrock or limestone from the quarry. The lime and ashes have very low resistivity values (as shown in Figure 3 with the inverse physical property of conductivity) and their location is well defined in the model. We can see that the waste is characterized by intermediate resistivity values and lies on the lime and ashes with a very small thickness. Due to the low sensitivity of the method at the edges and deeper zones in the middle of the profile, some structural features of the quarry and the lime/ashes extension are not well resolved. A more complete interpretation might be achieved by using other datasets such as seismic.

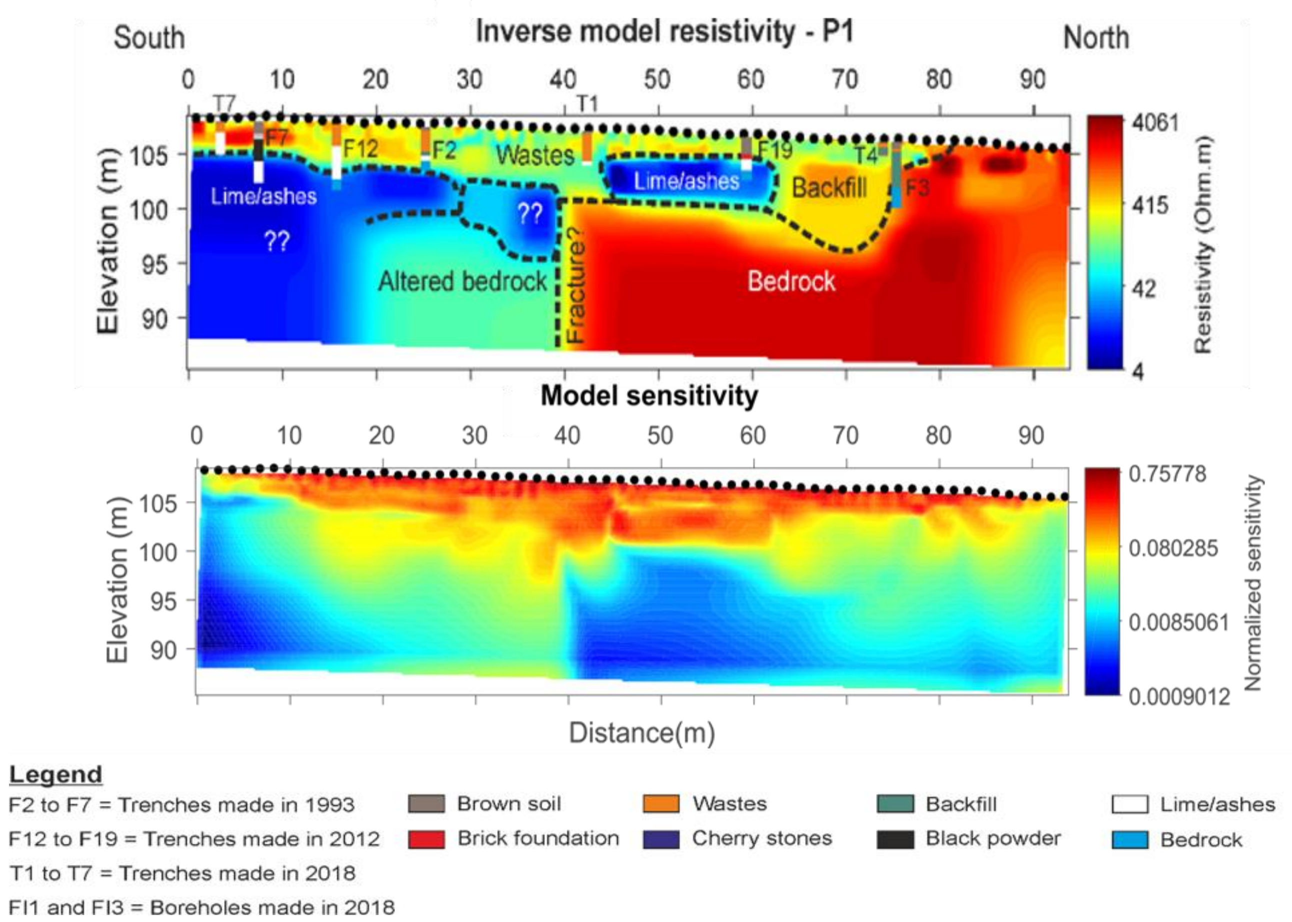

Figure 4. Inverse model resistivity and model sensitivity for one of the profiles. On the top of the resistivity the trenches/boreholes are overlapped and below the labels for the distinct materials are shown.

In this case, the FDEM mapping was useful to delineate the lateral extension of the ashes and lime. The ERT method together with the excavated trenches could also estimate the thickness of the waste and the lime/ashes in some zones as well as the depth to the top bedrock. However, neither of these methods could differentiate the ashes from the lime deposits as the conductivity (or resistivity) values are very close. Further processing of seismic data might help to better resolve and interpret the structure of the bedrock, the lime and ashes distribution.

4. DISCUSSIONS AND CONCLUSION

In this contribution, we first presented a brief overview on how different surface geophysical methods can be used for different landfill applications. Afterwards, based on the methods we have used in different scenarios within the RAWFILL project we proposed an adjustable approach to select the most suitable combination of geophysical methods that could support decision-making according to the objectives of a DLM project. In this approach, as a first stage we consider the gathering and the analysis of historical (available) information. Sencondly, we assess both the host geology of the site as well as the physical status of the site on surface, i.e. vegetation, topography, surface roughness, etc. By evaluating the geophysical methods, the properties they target, the field conditions needed for the data acquisition, etc., we suggested most convenient combination of methods under distinct landfill scenarios. Finally, we presented two examples were this approach was followed and summarize the most relevant results.

We conclude that multi-geophysical methodologies can be useful for a wide variety of landfill investigations, as each method target different physical properties and their complementary use might takle uncertainties of each separate method. Nevertheless, in such heterogeneous and complex sites, gorund truth data coming from excavations is always required to validate the geophysical data and achieve a more reliable interpretation.

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REFERENCES

Bobe, C., Van De Vijver, E., & Van Meirvenne, M. (2018). Exploring the potential of electromagnetic surface measurements for the characterisation of industrial landfills. *Proceedings of the 4th International Symposium on Enhanced Landfill Mining*, 45–50. Retrieved from http://hdl.handle.net/1854/LU-8551569

Bording, T. S., Gianluca, F., Esben, A., & Anders Vest, C. (2018). *Monitoring seasonal variations of leaching from a landfill through time-domain induced polarization*.

Carlson, N., Mayerle, C., & Zonge, K. (1999). Extremely fast IP used to delineate buried landfills. *Proceedings of the 5 Th Meeting of the Environmental and Engineering Geophysical Society European Section*. Presented at the Budapest (Hungary). Budapest (Hungary).

Carpenter, P. J., & Reddy, K. R. (2016). Ground-Penetrating Radar (GPR) Surveys and Geophysical Well Logs at a Leachate-Recirculation Landfill, Northern Illinois. *Geo-Chicago 2016*. https://doi.org/10.1061/9780784480144.016

Cartwright, K., & McComas, M. R. (1968). Geophysical Surveys in the Vicinity of Sanitary Landfills in Northeastern Illinoisa. *Groundwater*, *6*(5), 23–30. https://doi.org/10.1111/j.1745-6584.1968.tb01661.x

Chambers, J., Kuras, O., Meldrum, P., Ogilvy, R., & Hollands, J. (2006). Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. *GEOPHYSICS*, *71*(6), B231–B239. https://doi.org/10.1190/1.2360184

Clément, R., Audebert, M., Loisel, S., & Moreau, S. (2018). Straightforward assessment of horizontal leachate injection system using frequency domain electromagnetic induction method. *Environmental Research*, *1*, 6.

Cossu, R., Di Maio, R., Fais, S., Fraghí, A., Ligas, P., & Menghini, A. (2005). Physical and structural characterisation of an old landfill site by a multimethodological geophysical approach. *Institute of Geology Environmental and Engineering*, 1–7.

Danthurebandara, M., Van Passel, S., Vanderreydt, I., & Van Acker, K. (2015). Assessment of environmental and economic feasibility of Enhanced Landfill Mining. *Waste Management*, *45*, 434–447. https://doi.org/10.1016/j.wasman.2015.01.041

De Carlo, L., Perri, M. T., Caputo, M. C., Deiana, R., Vurro, M., & Cassiani, G. (2013). Characterization of a dismissed landfill via electrical resistivity tomography and mise-à-la-masse method. *Journal of Applied Geophysics*, *98*, 1–10. https://doi.org/10.1016/j.jappgeo.2013.07.010

De Iaco, R., Green, A. G., Maurer, H.-R., & Horstmeyer, H. (2003). A combined seismic reflection and refraction study of a landfill and its host sediments. *Journal of Applied Geophysics*, *52*(4), 139–156. https://doi.org/10.1016/S0926-9851(02)00255-0

Delefortrie, S., Hanssens, D., Saey, T., Van De Vijver, E., Smetryns, M., Bobe, C., & De Smedt, P. (2019). Validating land-based FDEM data and derived conductivity maps: Assessment of signal calibration, signal attenuation

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and the impact of heterogeneity. *Journal of Applied Geophysics*, *164*, 179–190. https://doi.org/10.1016/j.jappgeo.2019.03.001
Dumont, G., Pilawski, T., Dzaomuho-Lenieregue, P., Hiligsmann, S., Delvigne, F., Thonart, P., … Hermans, T. (2016). Gravimetric water distribution assessment from geoelectrical methods (ERT and EMI) in municipal solid waste landfill. *Waste Management*, *55*, 129–140. https://doi.org/10.1016/j.wasman.2016.02.013
Dumont, G., Robert, T., Marck, N., & Nguyen, F. (2017). Assessment of multiple geophysical techniques for the characterization of municipal waste deposit sites. *Journal of Applied Geophysics*, *145*, 74–83. https://doi.org/10.1016/j.jappgeo.2017.07.013
Dumont, G., Robert, T., & Nguyen, F. (2018). Electrical resistivity tomography and distributed temperature sensing monitoring to assess the efficiency of horizontal recirculation drains on retrofit bioreactor landfills. *GEOPHYSICS*, *83*(2), B13–B23. https://doi.org/10.1190/geo2016-0622.1
Green, A., Lanz, E., Maurer, H., & Boerner, D. (1999). A template for geophysical investigations of small landfills. *The Leading Edge*, *18*(2), 248–254. https://doi.org/10.1190/1.1438264
Hellman, K., Roncza, M., Günther, T., Wennermark, M., Rücker, C., & Dahlin, T. (2017). *Structurally coupled inversion of ERT and refraction seismic data combined with cluster-based model integration*. *143*, 169–181. https://doi.org/10.1016/j.jappgeo.2017.06.008
Imhoff, P. T., Reinhart, D. R., Englund, M., Guérin, R., Gawande, N., Han, B., … Yazdani, R. (2007). Review of state of the art methods for measuring water in landfills. *Waste Management*, *27*(6), 729–745. https://doi.org/10.1016/j.wasman.2006.03.024
Johnson, C. D., White, E. A., & Joesten, P. K. (2012). *Use of electromagnetic induction methods to monitor remediation at the University of Connecticut landfill: 2004–2011*. 36–56. https://doi.org/10.4133/1.4721692
Jones, P. T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., … Hoekstra, N. (2013). Enhanced Landfill Mining in view of multiple resource recovery: a critical review. *Journal of Cleaner Production*, *55*, 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021
Jones, P. T., Wille, E., & Krook, J. (2018). *2nd ELFM Seminar in the European Parliament: 5 Lessons Learned*. 12.
Konstantaki, L. A., Ghose, R., Draganov, D., Diaferia, G., & Heimovaara, T. (2015). Characterization of a heterogeneous landfill using seismic and electrical resistivity data. *GEOPHYSICS*, *80*(1), EN13–EN25. https://doi.org/10.1190/geo2014-0263.1
Loke, M. H. (2011). *Tutorial: 2-D and 3-D electrical imaging surveys*.
Markovaara-Koivisto, M., Valjus, T., Tarvainen, T., Huotari, T., Lerssi, J., & Eklund, M. (2018). Preliminary volume and concentration estimation of the Aijala tailings pond – Evaluation of geophysical methods. *Resources Policy*. https://doi.org/10.1016/j.resourpol.2018.08.016
Maurya, P. K., Rønde, V. K., Fiandaca, G., Balarini, N., Auken, E., Bjerg, P. L., & Christiansen, A. V. (2017). Detailed landfill leachate plume mapping using 2D and 3D electrical resistivity tomography - with correlation to ionic strength measured in screens. *Journal of Applied Geophysics*, *138*, 1–8. https://doi.org/10.1016/j.jappgeo.2017.01.019
Nguyen, F., Ghose, R., Isunza Manrique, I., & Dumont, G. (2018). *4TH INTERNATIONAL SYMPOSIUM ON ENHANCED LANDFILL MINING - MANAGING PAST LANDFILLS FOR FUTURE SITE DEVELOPMENT: A REVIEW OF THE CONTRIBUTION OF GEOPHYSICAL METHODS*. 12.
Psarropoulos, P. N., Tsompanakis, Y., & Karabatsos, Y. (2007). Effects of local site conditions on the seismic response of municipal solid waste landfills. *Soil Dynamics and Earthquake Engineering*, *27*(6), 553–563. https://doi.org/10.1016/j.soildyn.2006.10.004
Qi, Y., Soueid Ahmed, A., Revil, A., Ghorbani, A., Abdulsamad, F., Florsch, N., & Bonnenfant, J. (2018). Induced polarization response of porous media with metallic particles — Part 7: Detection and quantification of buried slag heaps. *GEOPHYSICS*, *83*(5), E277–E291. https://doi.org/10.1190/geo2017-0760.1
Soupios, P., & Ntarlagiannis, D. (2017). Characterization and Monitoring of Solid Waste Disposal Sites Using Geophysical Methods: Current Applications and Novel Trends. In *Modelling trends in solid and hazardous waste management*.
Van De Vijver, E. (2017). *Proximal soil sensing in the context of urban (re)development : an evaluation of multi-receiver electromagnetic induction and stepped-frequency ground penetrating radar at landfills and industrial sites* (Dissertation, Ghent University). Retrieved from http://hdl.handle.net/1854/LU-8531702
Van De Vijver, E., & Van Meirvenne, M. (2016). Delving into the potential of multi-receiver electromagnetic induction surveying for enhanced landfill exploration in view of ELFM. *Proceedings of the Third International Symposium on Enhanced Landfill Mining*, 175–187. Retrieved from http://hdl.handle.net/1854/LU-8058652
von Hebel, C., Rudolph, S., Mester, A., Huisman, J. A., Kumbhar, P., Vereecken, H., & Kruk, J. van der. (2014). Three-dimensional imaging of subsurface structural patterns using quantitative large-scale multiconfiguration electromagnetic induction data. *Water Resources Research*, *50*(3), 2732–2748. https://doi.org/10.1002/2013WR014864
White, E. A., Day-Lewis, F. D., Johnson, C. D., & Jr, J. W. L. (2016). *Application of frequency- and time-domain electromagnetic surveys to characterize hydrostratigraphy and landfill construction at the Amargosa Desert Research Site, Beatty, Nevada*. 119–125. https://doi.org/10.4133/SAGEEP.29-024
Yannah, M., Martens, K., Van Camp, M., & Walraevens, K. (2017). Geophysical exploration of an old dumpsite in the perspective of enhanced landfill mining in Kermt area, Belgium. *Bulletin of Engineering Geology and the Environment*. https://doi.org/10.1007/s10064-017-1169-2