Interreg North-West Europe
RAWFILL
European Regional Development Fund
EUROPEAN UNION
Co-funded by the Walloon region

WP T3 – Deliverable 2.1 - Cost Benefit Analysis of LF geophysics

June 2021

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SUBJECT: WP T3 – Deliverable 2.1 - Cost Benefit Analysis of LF geophysics				
☐ report	☐ information	☐ consideration	☐ decision	
To: …		From: SPAQuE and ATRASOL		

1. Introduction

This report compares the cost-benefit analysis of two types of landfill characterization methodology: (1) traditional characterization survey by boreholes and trenches and (2) RAWFILL characterization survey (coupling geophysics and targeted waste sampling). It is important to note that it is impossible to achieve the same level of information about the landfill waste content for the two methodologies. The traditional characterization survey is based on drillings and trenches and give detailed local information whereas the second methodology consists of the coupling between geophysical measurements and punctual guided waste samples (drilling and/or trenches), giving less precision but more global information. Geophysics is a powerful tool to assess the 3D geometry of the landfill (lateral and vertical[1] extension), define different geophysical facies[2] as well as lateral variation. When their diameter is large enough, boreholes provide detailed information about the waste content: type of waste materials, water content, precise boundary between two different types of waste deposits as well as the thickness of the waste pile. Trenches give more information than boreholes because they extract more important volumes and exhibit several square meters of waste walls but they are limited in depth (4 to 5 m depth max.). They can sometimes be helpful to define the lateral extent of the landfill. As trenches and boreholes only provides punctual information, identification of lateral variation of the waste deposits can be missing. Moreover, a large number of drilling and trenches are required to cover the entire investigated surface area, which could be very expensive. Therefore combining multi-geophysical measurements with punctual guided waste sampling is the most suitable option to have an accurate landfill characterization suitable for landfill mining purposes.

In the following, we compare the costs of the two methodologies for two RAWFILL pilot sites: Meerhout and Onoz. For that purpose, we used **two approaches**:

[1] The resolution of the geophysics data decreases with depth. For landfill having a thickness thicker than 20 m, the geophysical measurements cannot be sufficient.
[2] Zones with homogeneous, similar geophysical properties. Should all the waste deposit be made of similar waste (domestic waste for instance), geophysical imaging will be used only to find out the landfill boundaries.

- **Approach 1:** First, we calculated the cost of the RAWFILL methodology (geophysical measurements and guided boreholes/trenches) to investigate the landfill. Second, based on the costs obtained with this calculation, we estimated the number of boreholes and trenches that can be done for the same amount of money. Then, we studied the most suitable spatial distribution of the boreholes and trenches on the landfill site and discussed if the number of boreholes/trenches are sufficient to provide accurate data. The cost of equipment mobilization and borehole installation as well as the site restoration is included. This cost varies depending on the presence of a specific capping. It is important to note that for this approach, we do not consider the cost of the works prior to the drilling (e.g., site clearing, historical studies, preliminary meetings, definition of survey plans, etc.).
- **Approach 2:** Based on the surface covered by geophysical surveys, we calculate the price for the traditional characterization survey with a borehole/trench every 250 m^2. With this approach, we also did not include the costs related to work prior the drilling.

For this report, we used the same prices for the two RAWFILL pilot sites. The list of prices can be found in **Appendix 1**. The prices might slightly vary between the different NWE regions. However, to better compare the cost for each site, the prices used here for the calculation were based on the Walloon market price for the last two years. All the expenses presented here are without VAT.

It is important to note that for the RAWFILL pilot sites, most of the time only parts of the landfill were investigated to demonstrate the relevance of the methodology. Therefore, we decided to calculate the costs of the two approaches only for the area investigated by the RAWFILL project partners and not for the entire landfill. To calculate the investigation cost related to the characterization of the entire landfill, please refer to the Deliverable WP T3.3.2 – Business cases.

In the cost/benefit analysis of the RAWFILL methodology vs. the traditional characterization methodology, we consider that for both methodologies, the excavated waste materials were not evacuated off-site or valorized but relandfilled. In addition, the costs prior to sampling (i.e. historical survey, deforestation/clearing, detection of explosive devices, detection of asbestos, research for utilities, safety plan and preliminary meetings) are similar for both methodology and therefore they were not included in the comparison. In the traditional methodology, large number of geochemical and geotechnical analysis are also required which considerably increase the cost of the methodology. With the RAWFILL methodology, these analysis will be performed only if the site present an interest for landfill mining. Therefore, these costs were also not included in the cost benefit analysis as they have to be done for both methodologies but at different steps.

2. Cost benefit analysis for the RAWFILL pilot sites

2.1. Meerhout (Flanders, Belgium)

Based on historical documents, the Meerhout landfill (51°06'11"N, 5°03'00"E) was in operation between 1962 until 1997. In total, more than 1.3 million m^3 of household and industrial (up to 30%) waste materials were deposited on the site. The thickness of the waste deposits varies between 5 m up to 20 m. In the most recent part of the landfill (i.e. in the west and south part of the site), an agricultural foil (1982-1983) and a high-density polyethylene (HDPE) membrane (>1986) were used. Please note that the location of the agricultural foil remains unclear.

In the framework of the RAWFILL project, two areas were investigated (**Fig. 1**). These two areas were chosen because they are representative for the different landfilling activities periods (i.e. 1962-1975, 1982-1983, 1986, 1989, 1993-1997). Additionally, the lack of dense vegetation cover in these areas facilitated detailed geophysical mapping. The investigation area 1 has a surface area of 11,000 m^2. Based on historical documents, the thickness of waste deposits in this area is comprised between 5 and 10 m. The investigation area 2 has a surface area of approximately 6,000 m^2 and an expected thickness up to 20 m.

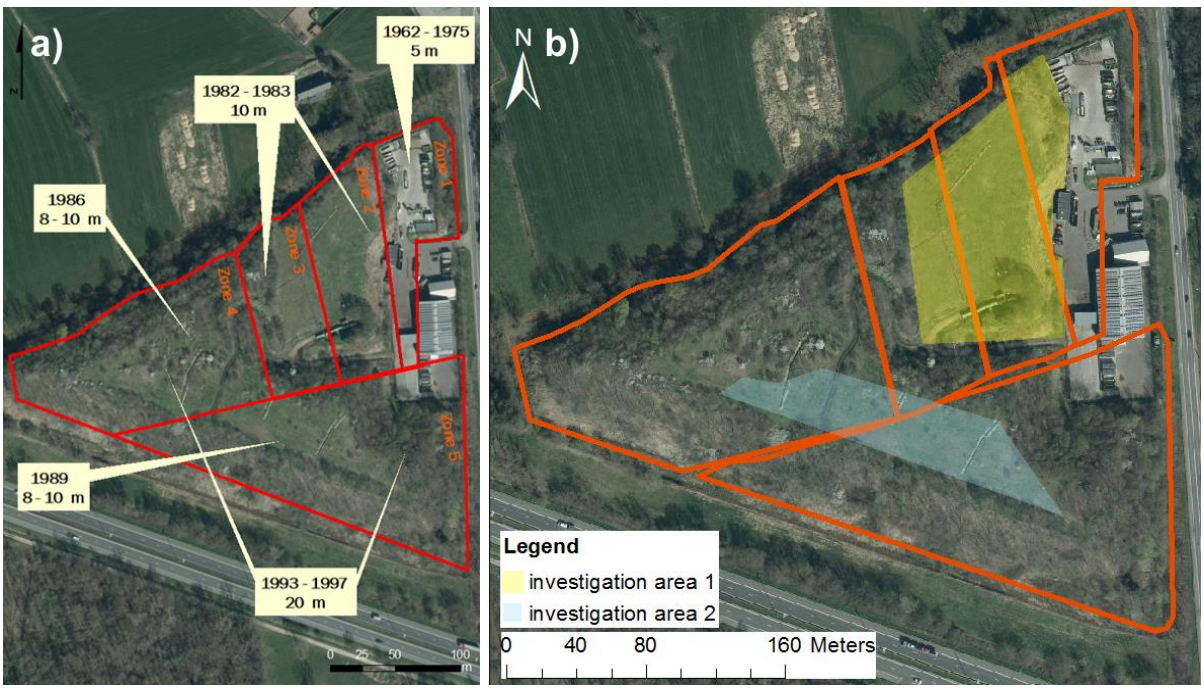

Figure 1 – Presentation of Meerhout landfill site. *The Meerhout Landfill site can be divided into five distinct zones based on the historical landfilling activities (see left figure). The right figure shows the two areas which were investigated during the RAWFILL project.*

a. Approach 1

The detailed cost of the landfill content characterization performed with the RAWFILL methodology are presented in **Table 1**.

LANDFILL CHARACTERIZATION WITH RAWFILL METHODOLOGY				
(1) Geophysics				
Geophysical survey[1]	Unit	Quantity	€/Unit (average price)	**TOTAL**
Electrical resistivity tomography + Induced polarization	Profile[3]	6	2,200.00 €	13,200.00 €
Horizontal to vertical noise spectral ratio	Measurement point	72	30.00 €	2,160.00 €
Multi-channel Analysis of Surface Waves	Profile[4]	7	1,600.00 €	11,200.00 €
Electromagnetic	m^2	19,300	0.06 €	1,080.80 €
Magnetometry	m^2	9,650	0.12 €	1,158.00 €
TOTAL				28,798.80 €
(2) Guided Waste sampling				
Cost of Mobilization equipment To and From the Site	Unit	Quantity	€/Unit	**TOTAL**
Mobilization (boreholes)	Fixed Price	1	975.00 €	975.00 €
Borehole installation, clearing emplacement, levelling and material relocation	Unit	9	235.00 €	2,115.00 €
TOTAL				3,090.00 €
Sampling techniques[3]	Unit	Quantity	€/Unit	**TOTAL**
Drilling Boreholes (180 - 219 mm)				
- Between 0 and 15 m depth	M	97.50	78.00 €	7,605.00 €
- Between 15 and 30 m depth	M	50	78.00 €	3,900.00 €
Trenches	Working day[2]	1	1,240.00 €	1,240.00 €
TOTAL				12,745.00 €
Site restoration	Unit	Quantity	€/unit	**TOTAL**
Capping restoration	m^2	2	1000.00 €	2000.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	m^3	238	8.28 €	1,970.64 €
Borehole closure (boreholes)	Ml	147.40	25.00 €	3,685.00 €

[3] Note that the cost of geochemical and geotechnical analysis were not included in the calculation.

Sowing operations	m^2	81	0.37 €	29.97 €
TOTAL				7685,61 €
TOTAL FOR LANDFILL CONTENT CHARACTERIZATION WITH RAWFILL METHODOLOGY				**52.319,41 €**

Table 1 – Summary of the geophysical data acquired on Meerhout landfill site.
[1]Average price listed in Appendix 1.[2]Eight trenches per working day.[3]Profile length between 69 and 94.5 m. [4]Profile length between 70 and 118 m.

Five geophysical methods (Electrical resistivity tomography/Induced polarization, Horizontal to vertical noise spectral ratio, Multi-channel Analysis of Surface Waves, Electromagnetic, Magnetometry) were used to investigate the Meerhout landfill site. The detailed geophysical investigation can be found in the *deliverables* *WPI1.2.2 - Geophysical imaging pre-sampling report* and *WPI1.2.3. - Geophysical imaging post-sampling report*.

In addition to the geophysical survey, seven trenches and seven boreholes were performed in the investigation area 1. In order to restore the site after sampling, the trenches were refilled with waste materials and soil like fractions. We estimated the volume of the necessary refilled materials around 238 m^3. The average price for relandfilling with onsite material was approximately 8.3 €/m^3. The restoration of the trenches was estimated around 1,970 €. The seven boreholes were filled with clay (bentonite) which approximately cost 2,455 €. In the most recent part of the landfill (Investigation area 2), the site restoration only consisted of refilling the existing two boreholes with clay (bentonite) and restoring the geomembrane that was damaged during the sampling investigations. At the end of the relandfilling, sowing operations should be performed to fully rehabilitate the site. We estimated that 81 m^2 should be sowed for a cost of 30 €. In total, the site restoration cost 7,685 €.

To summarize, the cost of the geophysical survey was 28,808 €. This cost increased with the guided samples and the site restoration. In total, the RAWFILL methodology for the Meerhout landfill site cost 50,399 €.
For the same amount of money, we can have 10 boreholes of 12 m depth, 8 boreholes of 24 m depth, and 16 trenches (4m x 4m x 4m). The calculation is detailed in **Table 2** (see below). All the prices used are listed in the **Appendix 1**. The depth of the boreholes was estimated based on the historical documents.

Cost for the RAWFILL methodology	**50,399 €**
Boreholes (312 m in total)	-24,336 €
Trenches (16)	-2,480 €
Mobilization (boreholes)	-975 €
Borehole installation, clearing emplacement and material relocation	-4,230 €

Site restoration after sampling (relandfilling with onsite soil and waste material)	-8,478.72 €
Borehole closure	-7,800 €
Sowing operation	-108.04 €
Borehole installation, clearing emplacement and material relocation	-4,230 €
REMAINDER	**1,671.24 €**

Table 2 – Detailed calculation of the costs of 10 boreholes of 12 m depth, 8 boreholes of 24 m depth, and 16 trenches (4m x 4m x 4m). *[1]Only for the investigation area 2.*

In the investigation area 1, trenches can be done to define the extension of the cells. However, 16 trenches (in total, 64 m length) would probably be not enough to clearly define the boundary of the zones 1, 2, 3 (see **Fig. 2**). As the historical documents revealed that the expected thickness of the waste deposits in the zones 1, 2 and 3 are estimated between 5 m and 10 m, boreholes are essential to define the real thickness of the landfilled waste materials and to analyze the bottom of the landfill (e.g., presence of liner, leachate pollution). Change in waste composition is also expected, as we know, from historical documents that municipal solid waste and industrial waste were landfilled. Based on the budget available, ten boreholes of 12 m depth (to ensure to reach the geological host rock) could be performed in the investigation area 1, which corresponds to approximately one borehole for 1,100 m^2. It will be not sufficient to identify lateral variation.

For the investigation area 2, eight boreholes of 24 m depth are planned to investigate the thickness of the landfill, which corresponds to one borehole for 750 m^2. It would have been interesting to have some trenches to delimit the exact location between the cells 3, 4 and 5.

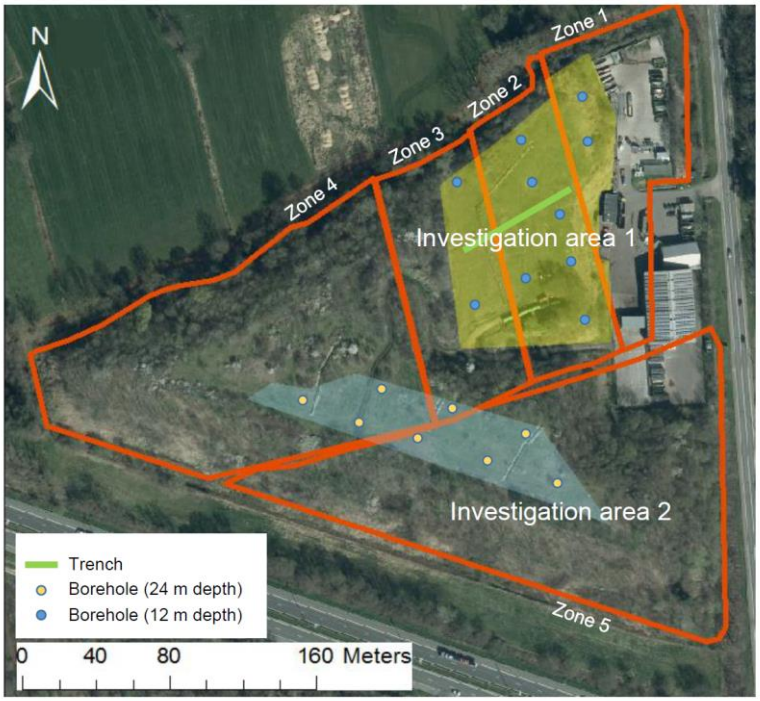

Figure 2 – Waste sampling plan for the same cost than the RAWFILL methodology.

b. Approach 2

To obtain the same level of information as with the RAWFILL methodology, a dense grid of boreholes and trenches is required. Due to the thickness of the waste deposits, trenches only provide valuable information regarding the spatial extension of the cells. In the investigation area 1, boreholes of max. 12 m depth should be performed whereas in investigation area 2, the boreholes should reach the bottom of the landfill (min. 20 m depth). The RAWFILL characterization methodology performed on Meerhout landfill site showed that the waste deposits were thicker in the investigation area 1 than what it is mentioned in the historical documents. Therefore, for this cost-benefit analysis, we will take a standard depth of 24 m for the boreholes performed in the investigation area 2. Extra caution should be taken during the waste sampling to avoid drilling in buried pipes. Geophysics showed that buried pipes were present in the investigation area 1.

We assumed that a borehole or a trench (4 m x 4 m x 4 m) every 250 m^2 on average would be sufficient to provide a similar spatial coverage than with the RAWFILL methodology. A dense coverage would provide more detail about the waste composition. The design sampling plan is displayed in **Figure 3**. In total, 32 trenches (for a total length of 128 m) and 12 boreholes of 12 m depth would be done for the investigation area 1. Regarding the investigation area 2, 16 trenches

(64 m length in total) and 8 boreholes of 24 m depth would be performed (**Fig. 3**).

		Investigation area 1 (11,000 m²)	Investigation area 2 (6,000 m²)
1 borehole/trench	per 25 m²	440	240
	per 50 m²	220	120
	per 100 m²	110	60
	per 250 m²	44	24
	per 350 m²	32	18
	per 500 m²	22	12
	per 1,000 m²	11	6

Table 3 – Calculation of the number of boreholes/trenches needed per square meter for the investigated areas.

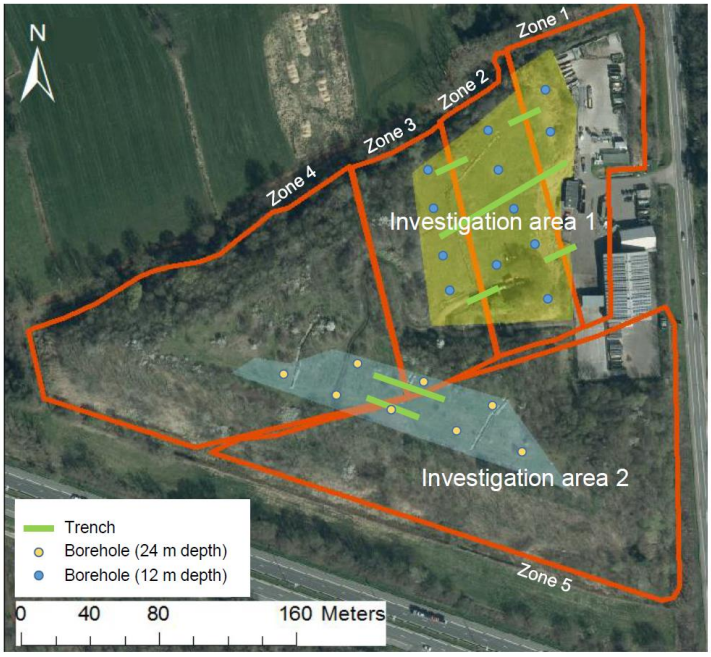

Figure 3 – Waste sampling plan designed for the approach 2.

The calculation of the traditional methodology cost is explained in **Table 4**. Taking only into account, the waste sampling and the site restoration would cost 73,778 €. This price could increase with the geochemical and geotechnical analysis of the waste recovered, building infrastructure on site for the workers and prior investigation study such as the research for utilities. However to facilitate comparison, these costs were not included.

TRADITIONAL LANDFILL CHARACTERIZATION

Cost of Mobilization equipment To and From the Site	Unit	Quantity	€/Unit	**TOTAL**
Mobilization (boreholes)	Fixed Price	1	975.00 €	975.00 €
Borehole installation, clearing emplacement and material relocation	Unit	20	235.00 €	4,700.00 €
TOTAL				5,675.00 €
Sampling techniques	Unit	Quantity	€/Unit	**TOTAL**
Drilling Boreholes (180 - 219 mm)				
- Between 0 and 15 m depth	m	144	78.00 €	11,232.00 €
- Between 15 and 30 m depth	M	192	78.00 €	14,976.00 €
Trenches (including mobilization)	Working day[1]	6	1,240.00 €	7,440.00 €
TOTAL				33,648.00 €
Site restoration	Unit	Quantity	€/unit	**TOTAL**
Capping restoration	m^2	8	1000.00 €	8000.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	m^3	3,072	8.28 €	25,436.16 €
Borehole closure	ml	336	25.00 €	8,400.00 €
Sowing operation	m^2	808	0.37 €	298,96 €
TOTAL				42,135.12 €
TOTAL FOR LANDFILL CONTENT CHARACTERIZATION WITH TRADITIONAL INVESTIGATION METHODOLOGY				81,458.12€

Table 4 – Calculation of the cost for the approach 2. *[1]8 trenches per working day.*

c. Duration

In this section, we calculated the time needed for both methodologies to collect the data on site. For both methodologies, we assume that:

- three persons are simultaneously working on site;
- a working day is equal to 8 hours of work;
- eight trenches can be done in one day;
- On average 50 m of boreholes can be drilled per day.

To simplify our calculation, the displacement of the drilling equipment was not taking into account for both methodologies. Therefore, the working days calculated correspond to a minimum. Note that for the geophysics, the acquisition time strongly depends on the type of equipment used. We calculated the acquisition time based on the geophysical equipment used in the framework of the RAWFILL project. The comparison of the two methodologies is displayed in **Table 5**.

RAWFILL Characterization Methodology						
(1) Geophysics						
	Operator 1	Duration	Operator 2	Duration	Operator 3	Duration
Day 1	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00
	Installation of 1 MASW profile[2]	01:30	Installation of 1 MASW profile[2]	01:30	10 H/V measurements	05:00
		04:30[3]		04:30[3]		08:00
Day 2	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00
	Installation of 2 MASW profiles[2]	03:00	Installation of 2 MASW profiles[2]	03:00	10 H/V measurements	05:00
		06:00[3]		06:00[3]		08:00
Day 3	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00
	Installation of 2 MASW profiles[2]	03:00	Installation of 2 MASW profiles[2]	03:00	10 H/V measurements	05:00
		06:00[3]		06:00[3]		08:00
Day 4	Installation of 2 MASW profiles[2]	03:00	Installation of 2 MASW profiles[2]	03:00	16 H/V measurements	08:00
		03:00[3]		03:00[3]		08:00
Day 5	EM measurement	03:00	MAG measurement	03:00	16 H/V measurements	08:00
		03:00[3]		03:00[3]		08:00
Day 6					10 H/V measurements	05:00
						05:00
TOTAL		5.5 working days				

(2) Waste sampling			
Sampling techniques	Unit	Quantity	Working day
Trench (7)	Piece	15	1
Borehole (9)	ml	146.9	3
TOTAL			4
TOTAL FOR RAWFILL CHARACTERIZATION METHODOLOGY			9.5

TRADITIONAL CHARACTERIZATION METHODOLOGY – ***calculation based on approach 2***			
Sampling techniques	Unit	Quantity	Working day
Trench	Piece	48	6
Borehole			
-12 m depth (12)	ml	144	3
- 24 m depth (8)	ml	192	4

TOTAL FOR TRADITIONAL CHARACTERIZATION METHODOLOGY	13

Table 5 – Comparison between the two characterization methodologies for Meerhout landfill site. *[1]The data acquisition takes on average 2h30. [2]The data acquisition can vary a lot depending on the site conditions. [3]The rest of the time is spent to check the data acquisition.*

For the number of boreholes and trenches required with the traditional methodology, we took the number of boreholes and trenches calculated with the approach n°2. The RAWFILL characterization methodology took around 9.5 working days to acquire data on Meerhout landfill site whereas we can expect 13 working days with the traditional characterization methodology.

d. Benefits

If we compare the total cost between the RAWFILL characterization methodology (50,399 €) and the traditional methodology (81,458 €) for the Meerhout landfill site, we obtain a minimum economic benefit of 31,059 €, which corresponds to **38% of saving costs**. In addition to the financial benefit, the RAWFILL methodology has other advantages in comparison with the traditional landfill characterization methodology (**Table 6**).

RAWFILL characterization methodology	Traditional methodology
• Vertical extension in the thickest part of the landfill; • Identification of lateral variation; • Detection of buried pipes; • Faster methodology • More safety.	• More details regarding the waste composition. • Possibility to take more samples for laboratory analysis

Table 6 – Comparison between the advantages of the RAWFILL characterization methodology and the traditional methodology.

2.2. Onoz

The landfill site (50°29’23’’ N, 4°40’12’’ E) is located in Onoz, province of Namur, Walloon Region, Belgium. The geology of the site consists of massive carboniferous limestone and dolomite. The site was a former limestone quarry equipped with lime kilns. From 1967 to 1976, the quarry was used as landfill where industrial waste (approximately 185,000 m^3 of lime and fly ash) were illegally dumped, filling progressively the pit. The volume of waste deposits was refined following the RAWFILL investigation up to 210 000 m^3. An aerial photography taken in 1971 showed the spatial distribution of the waste deposits (**Figure 4**).

Due to the topography of the landfill and its vegetation, it was not possible to investigate the entire landfill. Two areas were investigated (**Fig. 4**): the eastern upper part of the landfill (Zone I – 8,000 m²) and the lower part of the landfill (Zone II – 4,000 m²). In total, nine trenches (one in Zone I and eight in Zone II) and five boreholes (two in Zone I and three in Zone II) were performed on site.

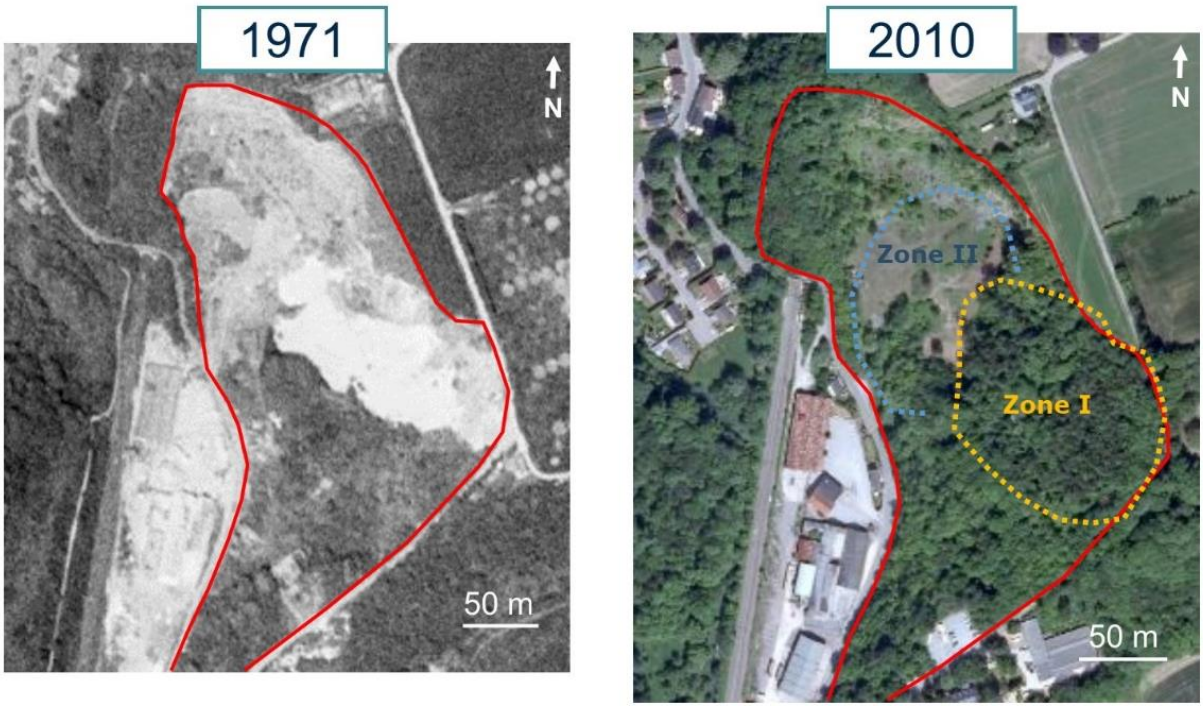

Figure 4 – Onoz site and investigation area (zone I and II).

a. Approach 1

The calculation of the cost of the characterization of Onoz site with the RAWFILL methodology is detailed in **Table 7**.

LANDFILL CHARACTERIZATION WITH RAWFILL METHODOLOGY				
(1) Geophysics				
Geophysical survey[1]	Unit	Quantity	€/Unit (average price)	**TOTAL**
Electrical resistivity tomography + Induced polarization (2D)	Profile[3]	3	2,200.00 €	6,600.00 €
Electrical resistivity tomography + Induced polarization (3D)	Profile[3]	4	2,200.00 €	8,800.00 €
Horizontal to vertical noise spectral ratio	Measurement point	51	30.00 €	1,530.00 €

Multi-channel Analysis of Surface Waves	Profile[3]	1	1,600.00 €	1,600.00 €
Electromagnetic Mapping (Dualem 2 m antenna)	m^2	2275	0.06 €	136.50 €
Electromagnetic Mapping (M31 K Geonics)	m^2	21050	0.06 €	1,178.80 €
Magnetometry	m^2	15500	0.12 €	1,860.00 €
TOTAL				21,705.30 €
(2) Guided Waste sampling				
Cost of Mobilization equipment To and From the Site	Unit	Quantity	€/Unit	**TOTAL**
Mobilization (boreholes)	Fixed Price	1	975.00 €	975.00 €
Borehole installation, clearing emplacement and material relocation	Unit	5	235.00 €	1,175.00 €
Sampling techniques	Unit	Quantity	€/Unit	**TOTAL**
Drilling Boreholes (180 - 219 mm)				
- Between 0 and 15 m depth	m	13.5	78.00 €	1,053.00 €
- Between 15 and 30 m depth	m	52	78.00 €	4,056.00 €
Trenches	Working day[2]	1.5	1,240.00 €	1,860.00 €
TOTAL				6,969.00 €
Site restoration	Unit	Quantity	€/Unit	**TOTAL**
Capping restoration	m^2	0	1000.00 €	0.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	m^3	576	8.28 €	4,769.28 €
Borehole closure	ml	65.5	25.00 €	1,637.50 €
Sowing operation	m^2	154	0.37 €	56.98 €
TOTAL				6,463.76 €
TOTAL FOR LANDFILL CONTENT CHARACTERIZATION WITH RAWFILL METHODOLOGY				**37,288.06 €**

Table 7 – Cost for the RAWFILL characterization methodology. *[1]The prices mentioned in the section "geophysical survey" take into account the processing of the data and the reporting. [2]8 trenches per working day. [3]Length profile: 94 m.*

Six geophysical methods were performed on the Onoz landfill site : Electrical resistivity tomography/ Induced polarization (2D and 3D), Horizontal to vertical noise spectral ratio, Multi-channel Analysis of Surface Waves, Electromagnetic Mapping, Magnetometry. The results of the geophysical survey can be found here and in the deliverable *WP T1.3.2. Characterization of multiple sites for benchmarking the SWOT analysis.* The cost of the geophysical survey for the two investigated zones was 21,705 €. In addition to the geophysical measurements,

nine trenches and five boreholes were performed in the two areas. We estimated the price of the waste sampling at 6,969 €. The restoration of the Onoz site after sampling was estimated at 6,463 €. The site restoration consisted of refilled the trenches with soil and waste materials. The boreholes were filled with clay (bentonite) and the sowing operations were performed to fully restore the landfill site after the waste sampling. In the case of Onoz, the absence of geomembrane at the top of the landfill helped to reduce the restoration cost. In total, the RAWFILL characterization methodology on Onoz site cost 37,288 €.

For the same amount of money (37,288€) with the traditional methodology, we can have 6 boreholes of 26 m depth (for the Zone I), 2 boreholes of 5 m depth (for the Zone II), and 24 trenches (4m x 4m x 4m). The calculation is detailed in **Table 8** (see below). All the prices used are listed in the **Appendix 1**. The depth of the boreholes was estimated based on the historical documents and aerial photography.

RAWFILL methodology	**37,288.06 €**
Boreholes (166 m in total)	-12,948.00 €
Trenches (24)	-3,720.00 €
Mobilization (boreholes)	-975.00 €
Capping restoration	0.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	-12,718.08 €
Borehole closure	-4,150.00 €
Sowing operation	-195.36 €
Borehole installation, clearing emplacement and material relocation	-1,880.00 €
REMAINDER	701.62 €

Table 8 – Calculation of the cost for 6 boreholes of 26 m depth (for the zone I), 2 boreholes of 5 m depth (for the zone II), and 24 trenches (4m x 4m x 4m).

The spatial distribution of the boreholes and trenches is presented in **Figure 5**. Six boreholes would not be sufficient to investigate the zone I (i.e. 8,000 m^2 – 1 borehole per 1,333 m^2) in order to assess the lateral variation of the waste deposits as well as the thickness of the waste for the whole area which quite important regarding the economic value of the slaked lime. Regarding the zone II, 24 trenches (96 m length in total) would not be enough to assess the horizontal boundaries of the waste deposits in the two investigated zones. The bottom of the landfill would not be reached in most parts of the zone II as the trenches are limited at a depth of 4 m. Two additional boreholes of 5 m depth (i.e. 1 borehole per 2,000 m^2) would be performed to verify the thickness of the waste deposits in this area but it would not be enough.

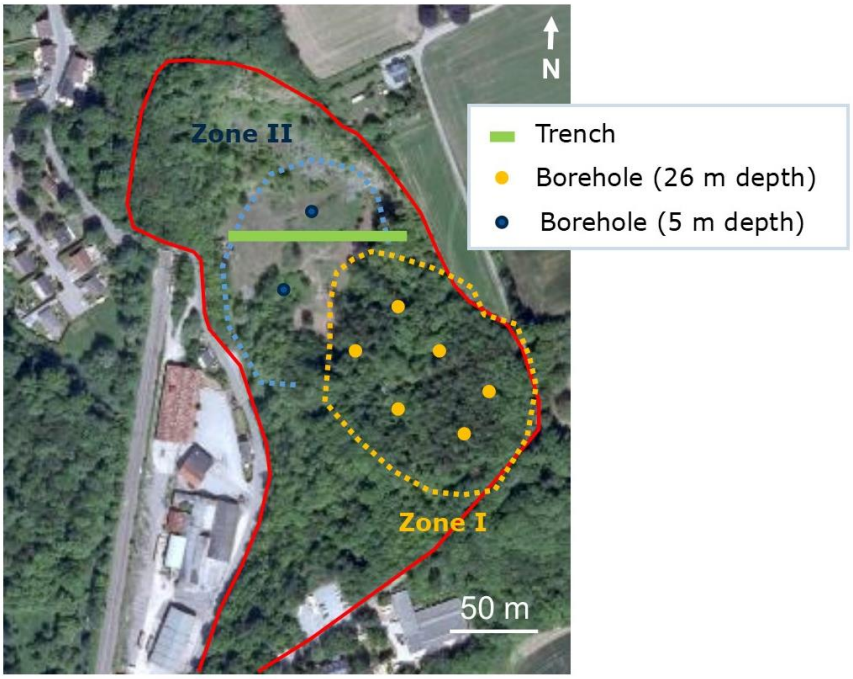

Figure 5 – Waste sampling plan for the approach 1 for the Onoz landfill site.

b. Approach 2

To gain the same level of information as with the RAWFILL methodology, a dense grid of waste samples (boreholes and trenches) is needed. Due to the thickness of the waste deposits in the zone II, trenches only provide valuable information about the horizontal boundaries of the two bodies waste. In some parts of the zone I where the thickness of the waste deposits is below 4 m, the trenches are sufficient to reach the bottom of the landfill. However, additional boreholes (up to 5 - 6 m depth) are necessary to ensure a correct knowledge of the geometry of the waste deposits. In Zone I, the waste deposits are thicker, therefore boreholes of 26 m depth seem more appropriate.

We assumed that a borehole or a trench (4 m x 4 m x 4 m) every 250 m^2 on average would be a minimum to provide a similar spatial coverage than with the RAWFILL methodology[4]. A dense coverage would provide more detail about the waste composition than with the RAWFILL methodology. However, incertitude about the waste geometry, the continuity of the waste body and its lateral extension would remain. Traditional investigation methodology would never reach the degree of certainty of the RAWFILL methodology. The design sampling plan is displayed in **Figure 6**. In total, 19 trenches (4 m x 4 m x 4 m) and 13 boreholes

[4] It is important to note that for some NWE regions, the number of sampling locations directly may depend on regional legislation.

of 26 m depth would be performed for the Zone I. Regarding the Zone II, 9 trenches and 7 boreholes of 5 m depth would be done (**Fig. 6**).

		Zone I (8,000 m^2)	Zone II (4,000 m^2)
1 waste sample (borehole/trench)	per 25 m^2	320	160
	per 50 m^2	160	80
	per 100 m^2	80	40
	per 250 m^2	32	16
	per 500 m^2	16	8
	per 1,000 m^2	8	4

Table 9 – Calculation of the number of boreholes/trenches needed per m^2 for the investigated areas.

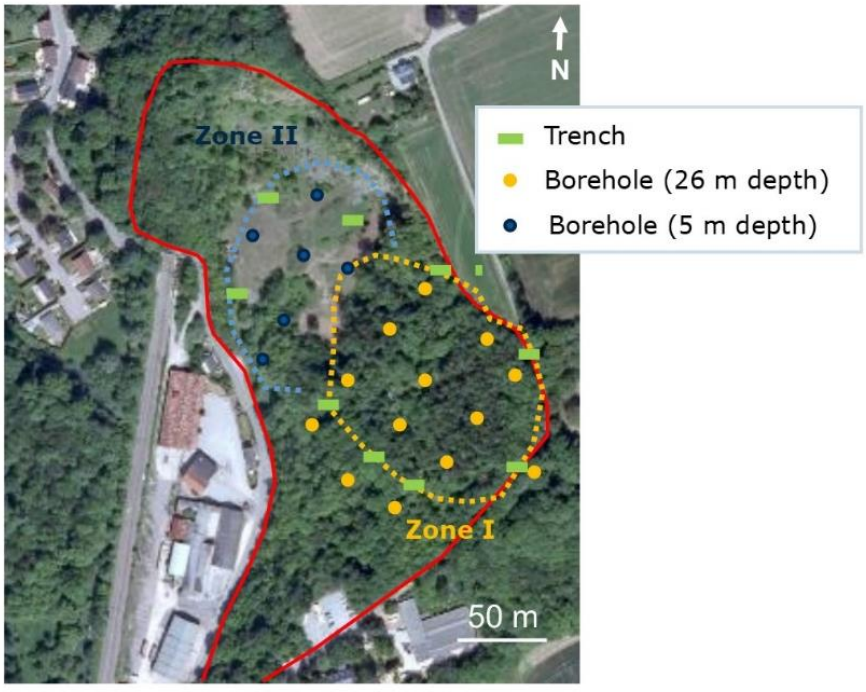

Figure 6 – Waste sampling plan designed for the approach 2 for the Onoz landfill site.

The calculation of the traditional methodology cost is detailed in **Table 9**. The waste sampling and the site restoration would cost 61,592 €. This price could increase with the geochemical and geotechnical analysis of the waste recovered, building infrastructure on site for the workers and prior investigation study such as the research for utilities. However to facilitate the comparison between the two methodologies, these costs were not included.

TRADITIONAL LANDFILL CHARACTERIZATION

Cost of Mobilization equipment To and From the Site	Unit	Quantity	€/Unit	**TOTAL**
Mobilization (boreholes)	Fixed Price	1	975.00 €	975.00 €
Borehole installation, clearing emplacement and material relocation	Unit	20	235.00 €	4,700.00 €
TOTAL				5,675.00 €
Sampling techniques	Unit	Quantity	€/Unit	**TOTAL**
Drilling Boreholes (180 - 219 mm)				
- Between 0 and 15 m depth	m	35	78.00 €	2,730.00 €
- Between 15 and 30 m depth	m	338	78.00 €	26,364.00 €
Trenches	Working day[1]	2	1,240.00 €	2,480.00 €
TOTAL				31,574.00 €
Site restoration	Unit	Quantity	€/unit	**TOTAL**
Capping restoration	m^2	0	1000.00 €	0.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	m^3	1792	8.28 €	14,837.76 €
Borehole closure	ml	373	25.00 €	9,325.00 €
Sowing operations	m^2	488	0.37 €	180.56 €
TOTAL				24,343.32 €
TOTAL FOR LANDFILL CONTENT CHARACTERIZATION WITH TRADITIONAL INVESTIGATION METHODOLOGY				61,592.32 €

Table 10 – Calculation of the cost for the approach 2. *[1]8 trenches per working day.*

c. Duration

We calculated the time needed for both characterization methodologies (i.e. RAWFILL characterization methodology vs. Traditional characterization methodology) to acquire data on site. For both methodologies, we assume that:

- three persons are simultaneously working on site;
- a working day is equal to 8 hours of work.
- Eight trenches can be done per day;
- 50 m of boreholes can be drilled per day.

The displacement of the sampling equipment was not taking into account for both methodologies. Note that for the geophysics, the acquisition time depends on the

type of equipment used. We calculated the acquisition time based on the geophysical equipment used in the framework of the RAWFILL project. The comparison of the two methodologies is presented in **Table 11**.

RAWFILL Characterization Methodology						
(1) Geophysics						
	Operator 1	Duration	Operator 2	Duration	Operator 3	Duration
Day 1	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00	Installation of 2 ERT/IP profiles[1]	03:00
	Installation of 1 MASW profile[2]	01:30	Installation of 1 MASW profile[2]	01:30	10 H/V measurements	05:00
		04:30[4]		04:30[4]		08:00[4]
Day 2	Installation of 1 ERT/IP profile (2D) [1]	01:30	Installation of 1 ERT/IP profile (2D) [1]	01:30	Installation of 1 ERT/IP profile[1]	01:30
	Installation of 1 ERT/IP profile (3D)[3]	01:30	Installation of 1 ERT/IP profile (3D)[3]	01:30	13 H/V measurements	06:30
		03:00[4]		03:00[4]		08:00[4]
Day 3	Installation of 1 ERT/IP profile (3D)[3]	01:30	Installation of 1 ERT/IP profile (3D)[3]	01:30	16 H/V measurements	08:00
	EM Measurement	05:30	MAG measurement	04:00		
		07:00[4]		05:30[4]		08:00[4]
Day 4	Installation of 1 ERT/IP profile (3D)[3]	01:30	Installation of 1 ERT/IP profile (3D)[3]	01:30	12 H/V measurements	06:00
		01:30[4]		01:30[4]		06:00[4]
Day 5	Installation of 1 ERT/IP profile (3D)[3]	01:30	Installation of 1 ERT/IP profile (3D)[3]	01:30	Installation of 1 ERT/IP profile (3D)[3]	01:30
		01:30[4]		01:30[4]		01:30[4]
TOTAL		5 working days				

(2) Waste sampling			
Sampling techniques	Unit	Quantity	Working day
Trench	Piece	15	2
Borehole			
Lower part	Ml	13.5	05
Upper part	Ml	52	2
TOTAL			4.5
TOTAL FOR RAWFILL CHARACTERIZATION METHODOLOGY			9.5

TRADITIONAL CHARACTERIZATION METHODOLOGY – *calculation based on approach 2*			
Sampling techniques	Unit	Quantity	Working day
Trench	Piece	28	3.5
Borehole			
-5 m depth (7)	ml	84	2
- 26 m depth (13)	ml	338	7
TOTAL FOR TRADITIONAL CHARACTERIZATION METHODOLOGY			12.5

Table 10 – Comparison between the two characterization methodologies. *[1]The data acquisition takes on average 2h30. [2]The data acquisition can vary a lot depending on the site conditions. [3]The data acquisition takes on average 4h30. [4]The rest of the time is spent to check the data acquisition.*

For the number of boreholes and trenches required with the traditional methodology, we took the number of boreholes and trenches calculated with the approach n°2. The RAWFILL characterization methodology took around 9.5 working days to acquire data on Onoz landfill site whereas we can expect 12.5 working days with the traditional characterization methodology.

c. Benefits

If we compare the total cost between the RAWFILL characterization methodology (37,288€) and the traditional methodology (61,592 €) for the Onoz landfill site, we obtain a minimum economic benefit of 24,304 €, which corresponds to a minimum of **39% of saving costs**. In addition to the financial benefit, the RAWFILL methodology has other advantages in comparison with the traditional landfill characterization methodology **(Table 12)**.

RAWFILL methodology	Traditional methodology
• Definition of the landfill vertical and lateral extension • Refine the volume of landfill waste material deposits (210,000 m^3 instead of 185,000 m^3 of lime and fly ash) • Faster • More safety • Non-destructive methods	• Identification of the water table • Thickness of the waste deposits in the thickest part of the landfill • More details regarding the waste composition (Zone II – municipal solid waste) • Possibility to analyze more samples • More destructive

Table 12 - Comparison between the advantages of the RAWFILL characterization methodology and the traditional methodology.

3. Conclusions

Two approaches were used to compare the RAWFILL methodology versus the traditional methodology to characterize the landfill content of two RAWFILL pilot

sites: Meerhout and Onoz (**Table 12**). The RAWFILL methodology was always the cheapest option. In addition, it provides more information regarding the landfill geometry and waste content. For the Meerhout landfill site, the RAWFILL methodology helps to reduce the cost of the landfill characterization by a minimum of 32% (compared to the traditional investigation method). Similar results were obtained for the Onoz landfill site (at least 39% of saving costs). Based on these two examples, we demonstrate the pertinence of using the RAWFILL methodology to characterize landfill content.

	Meerhout		Onoz	
	Trad.	**RAWFILL**	**Trad.**	**RAWFILL**
Approach 1				
Approach 2				

Table 13 – Comparison between the two approaches used. *The most favorable option is shown in green in the table.*

Appendix 1 – List of prices

Geophysics

	€/profile	€/ point	€/m^2
Electrical resistivity tomography	1,650 -2,100		
Electrical resistivity tomography + Induced polarization	1,900 – 2,500		
Horizontal to vertical noise spectral ratio		20 - 40	
Multi-channel Analysis of Surface Waves	1,200 – 2,000		
Electromagnetic			0.013-0.1
Magnetometry			0.07-0.17
Self Potential	400 - 830		
Ground Penetrating Radar			0.026-0.4

Trench

Price per day 1	**Price per day 2**	**Average**
1,340 €	1,140 €	**1,240 €**

Boreholes

Drilling Boreholes (180 - 219 mm)	€/m
- Between 0 and 15 m depth	78
- Between 15 and 30 m depth	78

Cost of mobilization equipment to and from the Site

	Unit	€/Unit
Mobilization (boreholes)	Fixed Price	975.00 €
Borehole installation, clearing emplacement and material relocation	Unit	235.00 €

Site restoration

	Unit	€/Unit
Capping restoration	m^2	1000.00 €
Site restoration after sampling (relandfilling with onsite soil and waste material)	m^3	8.28 €
Borehole closure	Ml	25.00 €
Sowing operations	m^2	0.37 €

Contact

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