detritus
Multidisciplinary
Journal for Waste
Resources & Residues

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SPATIAL VARIABILITY OF LEACHATE TABLES, LEACHATE COMPOSITION AND HYDRAULIC CONDUCTIVITY IN A LANDFILL STABILIZED BY IN-SITU AERATION

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Article Info:
Received:
18 January 2022
Revised:
7 May 2022
Accepted:
12 May 2022
Available online:
22 June 2022

Keywords:
Emission potential
Waste hydrology
Leachate tables
Hydraulic conductivity
Leachate composition

ABSTRACT

Within the framework of the Dutch sustainable landfill project iDS, four compartments of the Dutch landfill Braambergen have been treated by in-situ aeration since 2017. The aeration infrastructure comprises 230 wells with a spacing of 15 to 20 m, distributed over an area of around 10 ha, intercepting a waste body of 1.2 × 10^6 t of contaminated soils, soil treatment residues, bottom ashes and construction and demolition waste. The wells, used in an alternating fashion for air injection and gas extraction, can also be used to monitor water tables within the waste body. In order to describe the spatial variability of waste hydraulics, design a larger scale leachate pumping test and, eventually, support model predictions of the site's water balance and emission potential, analyses of leachate composition and pumping tests on individual wells have been conducted. The spatial variability of leachate quality and water tables is very high with no geospatial relationship between the sampling points. Each sampling point is representative of itself only. Large differences prevail not only between and across the compartments, but also between directly neighbouring wells. Both the small scale differences in leachate tables as well as in leachate quality indicate a spatial pattern of zones with low horizontal connectivity within the waste body. Recovery rates of drawdown in the wells yielded preliminary estimates of horizontal waste hydraulic conductivity in the order of 1×10^{-7} to 6×10^{-4} m/s.

1. INTRODUCTION

A novel approach to landfill after-care has seen a focus on the accelerated stabilization of wastes under controlled conditions within in the time frame of current liability using in-situ techniques such as aeration and/or (re-)infiltration of water or leachate. Both techniques aim to decrease a landfill's emission potential by accelerating the decay of reactive organic matter to expedite the attainment of stable conditions in the waste (Kosson et al., 2002; Scharff et al., 2011; van der Sloot et al. 2017) and environmentally acceptable residual emissions (Brandstätter et al., 2015a,b, Heyer et al., 2005; Oonk et al., 2013; Reinhart et al., 1996, 2002; Ritzkowkski et al., 2006). These are reached when the water leaving the landfill complies with soil and groundwater quality criteria and can therefore be safely received by soil, ground- and surface waters. Heterogeneity and anisotropy of waste properties challenge the desired homogeneity of aeration (Ritzkowksi & Stegmann, 2012). The extent of the (preferably homogeneous) spatial outreach of air flow depends on well spacing, aeration/extraction pressure, waste permeability (Xu et al., 2020) and the amount of water in the waste, obstructing air and gas flow (Hrad et al., 2013). The typical, construction-related layered structure in waste bodies, the differential response of the heterogeneous waste inventory to vertical overburden, impermeable waste constituents such as plastic sheets, and entrapped landfill gas (Woodman et al., 2014) can lead to the development of perched water tables and preferential flow paths for water and gas. In such a system, significant volumes of the contaminated material are isolated from water flow, so that transport of contaminants can only take place through (slow) diffusion rather than (fast) advection (Bendz et al., 1998; Rosqvist & Bendz, 1999; Rosqvist et al., 2005). Preferential flow paths therefore pose a major rate-limiting constraint on both in-situ treatment and emissions.

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Detritus / Volume 19 - 2022 / pages 114-120
https://doi.org/10.31025/2611-4135/2022.15189

Within the framework of the Dutch sustainable landfill project iDS (https://duurzaamstortbeheer.nl), two landfills have been treated by in-situ aeration since 2017 (Lammen et al., 2019, 2021; Cruz Osorio et al., 2021). In some of the four aerated compartments of the landfill Braambergen, high leachate tables are observed. It is hypothesized that these are responsible for reducing the efficacy of in-situ stabilization. The aeration infrastructure can also be used to monitor and sample leachate tables and provided a unique opportunity to study the variability in hydraulic behavior and leachate properties within the waste body. In order to design a larger scale leachate pumping test and, eventually, support model predictions of the site's water balance and emission potential, analyses of leachate levels, composition and pumping tests on individual wells were conducted.

2. DESCRIPTION OF SITE AND AERATION SYSTEM

Braambergen landfill is located near the city of Almere in the northern part of the Netherlands, with four pilot compartments 11N/Z and 12O/W in operation from 1999 to 2008 with a surface area of approximately 10 ha. The pilot compartments contain around 1,200,000 tons of waste, mainly composed of contaminated soils, soil residues, bottom ashes, and construction and demolition waste (Lammen et al., 2019) and are covered with at least one meter of soil of varying origin. In-situ aeration is carried out since September 2017. A network of 230 wells spaced at 15 to 20 m distance over the four compartments can be operated in an over-extraction (until October 2019) or low-pressure aeration mode (combi-aeration, since November 2019) (Figure 1). All wells are deep filtered with the filter screen over a height of 1.8 m from the bottom of the well, which have been inserted to a total depth of approximately 2 m below Amsterdam ordnance datum (NAP, Normal Amsterdams Peil) into the waste body, equivalent to a depth of 10 to 12 m from the surface, depending on the specific location. The total extracted flow from the four compartments since three months after the beginning of aeration in 2017 varies between 200 and 400 Nm³/h, with CH_4 concentrations between 5 and 15% and CO_2 concentrations between 15 and 22% (Cruz-Osorio et al., 2021).

3. METHODS

3.1 Leachate tables and leachate composition

Water levels in the 230 wells of the complete aeration/injection network of all four compartments were measured in March 2020 with a dip meter and, in the 132 wells of compartment 11Z, additionally with CTD Divers (Model DI271) in combination with a Baro Diver (Model DI500, both van Essen instruments). The CTD divers also delivered data on electrical conductivity (EC) of the leachate. In compartment 11Z (132 wells), leachate was also sampled for standard parameters in December 2020 using manually operated inertial pumps (Type SKU, In-Situ). These included pH, EC, redox potential, concentration of NH_4^+ (LCK303 ammonia cuvette test kit, Hach-Lange DR6000 UV-VIS spectrophotometer), dissolved organic carbon (DOC), measured as absorbance at 254 nm on a Hach-Lange DR6000 UV-VIS spectrophotometer and translation to DOC using a calibration function established for landfill leachate.

3.2 Pumping tests

Pumping tests were carried out in compartment 11Z using inertial pumps in combination with the CTD and Baro

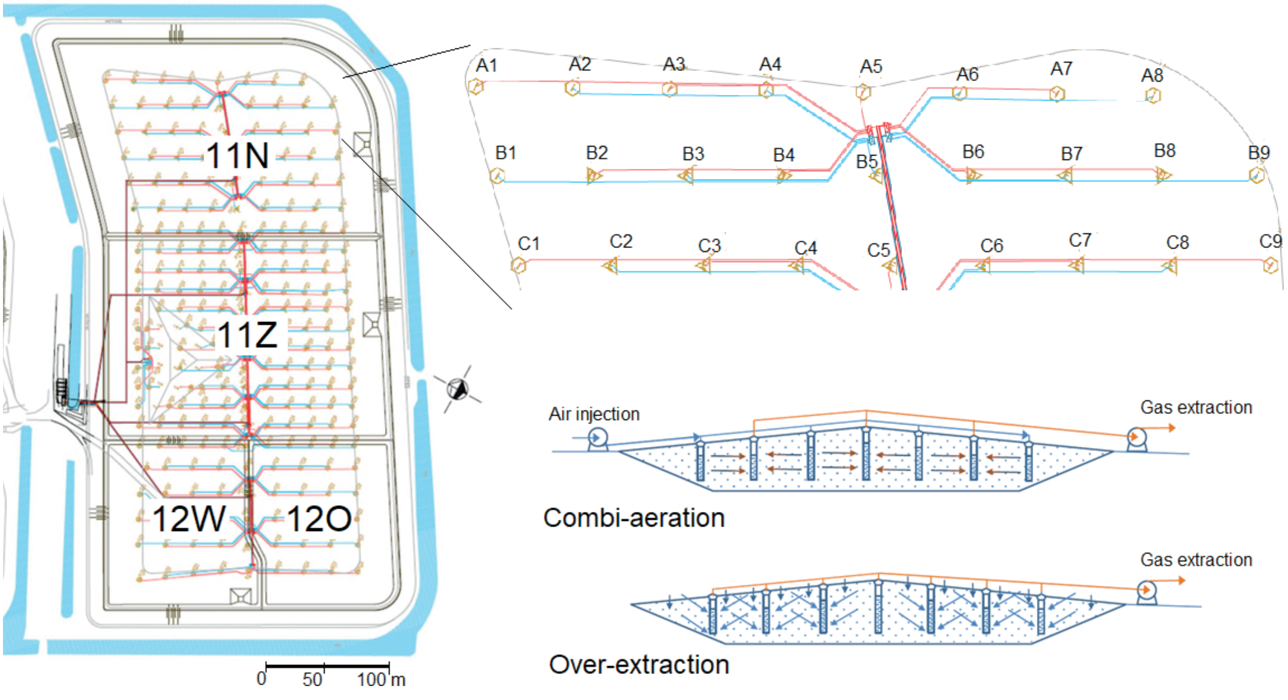

FIGURE 1: Network of aeration wells, systematics of well labeling and a schematic representation of combi-aeration and over-extraction.

divers, where the water head in the well was lowered and the recovery of the head was monitored using high-frequency logging by the CTD divers (Figure 2). Some of the 132 wells were too dry or broken and could not be investigated. In addition to the rate at which the water level recovers, indicative of the permeability of the surrounding waste, the electrical conductivity data informs whether the water present in the well at the start corresponds to the leachate in the waste body or is, for example, influenced by 'short-circuited' precipitation, reaching the wells through preferential flow channels less or not affected by contact with the waste. Equation 1 was used to estimate the volume of water influenced by one well:

$$V = \frac{Q \cdot t_{III}}{WC_V - WC_{II}} \cdot (WC_{II} + d) \tag{1}$$

where V is the total volume of the water body [L^3], Q is the pumping rate [L^3T^{-1}], t_{III} is the duration of phase III [T, Figure 2], WC_{II} is the water column during phase II [L], WC_V is the water column in phase V [L] and d the distance between the bottom of the well and the bottom of the water body.

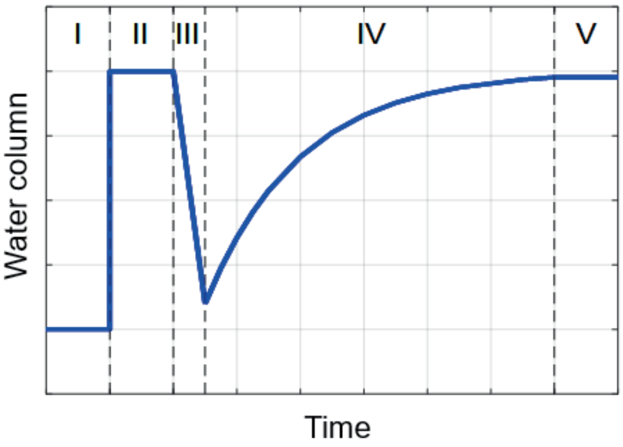

FIGURE 2: Representation of water level change during pumping test . Phase I: Diver not lowered into well yet, Phase II: Diver inserted in well, measuring full water column, Phase III: Draw-down due to pumping, Phase IV: Recovery of water level after pumping, Phase V: Recovery of water column completed.

As the distance d is not known, the radius of the water body was chosen to describe the water body that surrounds the well rather than volume. If it is assumed that the water body has a cylindrical shape, then the radius of the water body is obtained by Equation 2:

$$r = \sqrt{\frac{Q \cdot t_{III}}{(WC_V - WC_{II}) \cdot \pi} \cdot \frac{1}{\varphi}} \tag{2}$$

where r is the radius of the cylindrical water body [L] and φ the porosity of the waste [-].

4. RESULTS AND DISCUSSION

4.1 Variability of leachate levels and response to pumping

Significant levels of stagnant water tables were found at Braambergen landfill (Figure 3 left), with particularly high levels exceeding the height of the screened part of the aeration wells found for 83 out of 132 wells in compartment 11Z (Figure 3, right). Compartment 11Z also showed low gas flow rates, and higher ratios of CH_4 to CO_2 (Meza et al., this issue), suggesting a higher share of anaerobic processes and hence reduced aeration efficiency. Brandstätter et al. (2020) also reported impeded aeration and higher CH_4 concentrations after water-blockage of aeration pipes. For all compartments, the envelope of the scatter plot relating well flow rates to height of water column described the expected inverse relationship (Meza et al., this issue). However, water tables alone could not explain the variability in the detected flow rate. This was especially pronounced for compartment 11Z in which a high number of 'no flow' wells were detected.

Spatial variability of leachate levels, investigated in more detail for compartment 11Z, also varied in time (Figure 4), with differences mostly in the order of a few meters between March and November 2020, but also a change of 8 m was observed. Geospatial analysis of the leachate levels indicated that there is little or no connec-

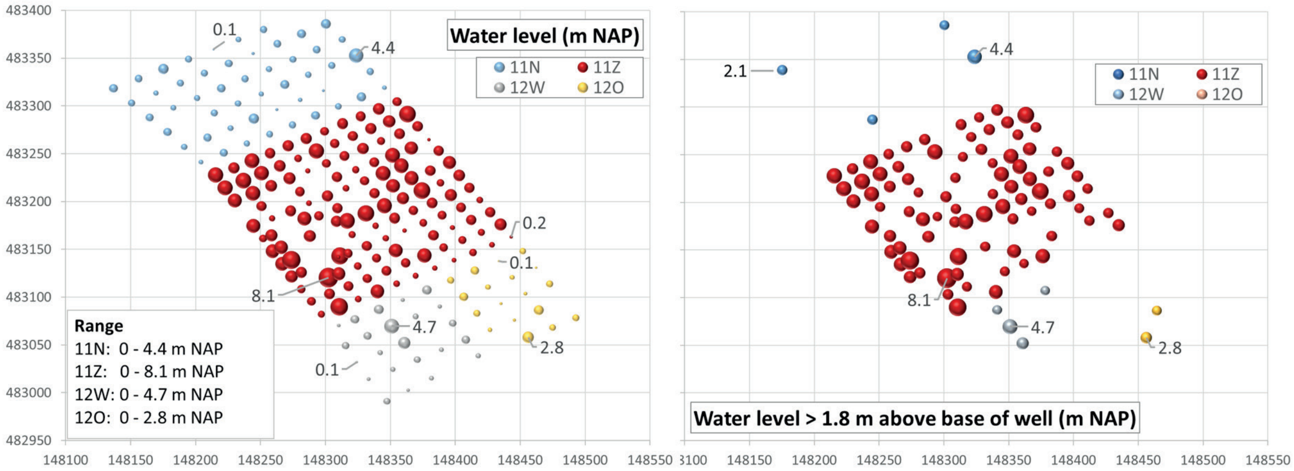

FIGURE 3: Water levels in compartments 11N, 11Z, 12O and 12W normalized to m +NAP (Normaal Amsterdams Peil, Amsterdam Ordnance Datum) March 2020 (left), levels exceeding the height of the filter screen (right). The size of the symbol is indicative of water level. Coordinates given in EPSG:28992 (Amersfoort datum).

tion between the water bodies surrounding neighbouring wells (as seen also from Figure 5 left), supported by the small apparent radii of the water body surrounding individual wells as estimated from Equation 2 (Figure 5, middle). While it has been acknowledged that the hydraulic conductivity within the waste body is heterogeneous in the vertical dimension, thus creating prefential vertical leachate pathways (Fellner & Bruner 2010), models describing leachate flow through landfills ignore heterogeneity in the horizontal plane (e.g., Slimani et al., 2017). It appears, however, that in the investigated landfill the water bodies surrounding the individual wells are stagnant zones that are hydraulically separated from each other in the horizontal plane, as a result of which differences of several meters can be sustained in stagnant zones that are less than 15 m apart. The water within the waste can be viewed as a series of disconnected ponded zones of variable vertical and horizontal permeability, overflowing when specific leachate levels are exceeded.

The hydraulic response to pumping differed significantly between wells. For 13 wells it was possible to calculate k values from the recovery of the head (Figure 5, right). Values spanned almost four orders of magnitude, 1×10^{-7} to 6×10^{-4} m/s, and are typical for the range that can be expected for silty soils to coarser sands. Given that compartment 11Z mainly harbours soils and soil treatment residues, the range appears plausible and may represent the range of horizontal hydraulic conductivities to be expected in landfill Braambergen.

Recovery behavior was grouped into the six classes (Figure 6), including a class for dry wells and for broken wells. 'Instant recovery' relates to a behavior where the recovery rate equalled the pumping rate. Wells were classified as 'no recovery' wells when the water level did not show any signs of recovery within 10 minutes after being pumped empty, intermediate behavior was classified as 'slow recovery'. In comparison to leachate properties (section 4.2), a higher level of spatial clustering could be found for the response

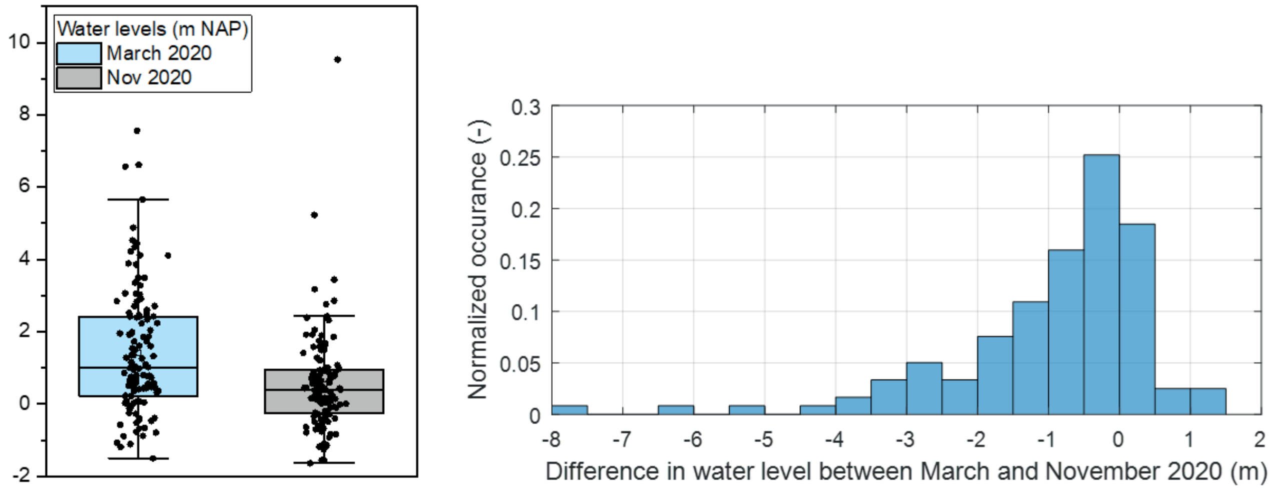

FIGURE 4: Water levels normalized to m NAP (Normaal Amsterdams Peil, Amsterdam Ordnance Datum) in compartment 11Z in March and November 2020 (left), frequency distribution of the difference between the two dates (right). Box = 25th/75th percentile, whiskers = 10th/90th percentile, line = median, closed symbols = data points.

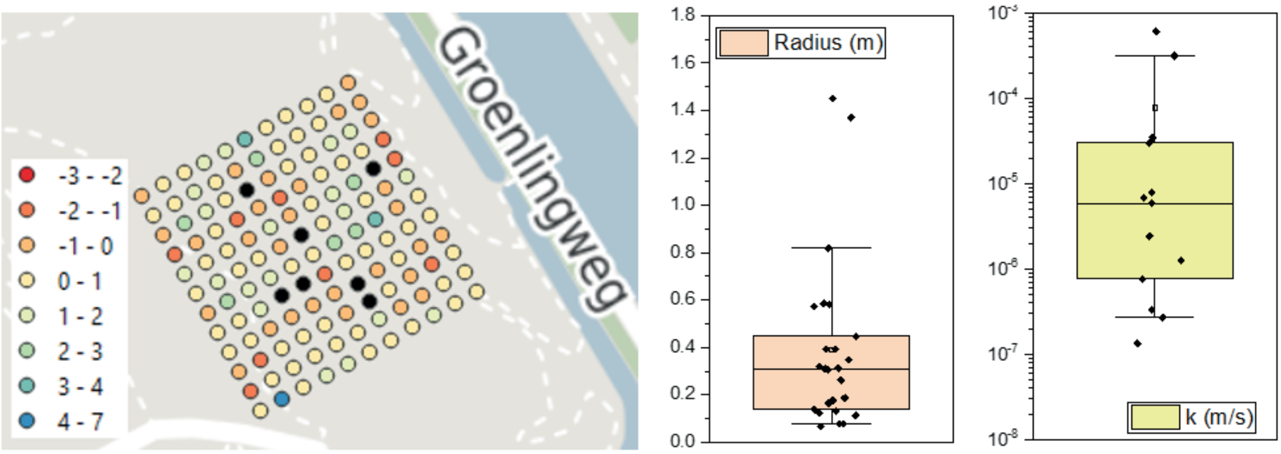

FIGURE 5: Spatial variability of water levels normalized to m NAP (Normaal Amsterdams Peil, Amsterdam Ordnance Datum) in compartment 11Z in November 2020 (left) and variability of water body radii around wells as calculated by Eq. 2 (middle) and hydraulic conductivity (right). Box = 25th/75th percentile, whiskers = 10th/90th percentile, line = median, closed symbols = data points.

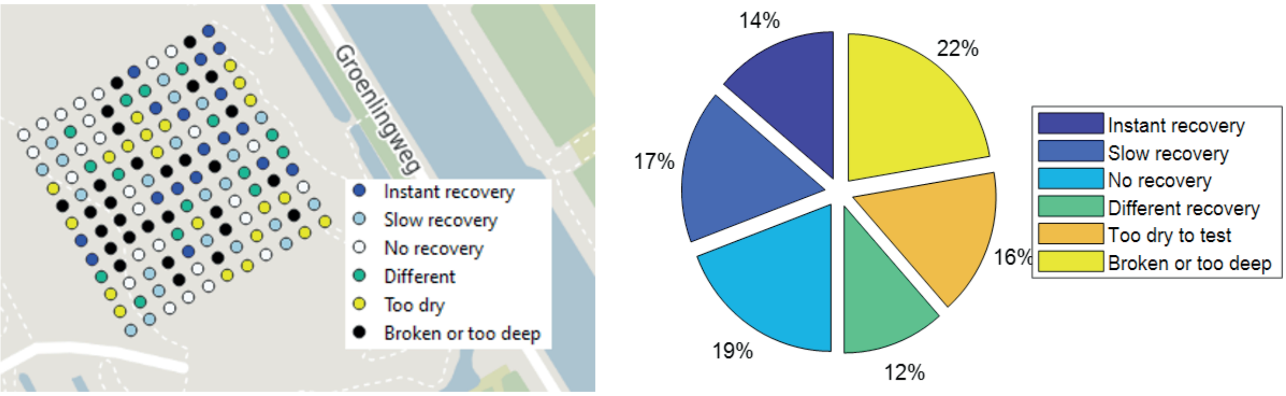

FIGURE 6: Spatial variability of response to pumping (left) in compartment 11Z, share of response classes (right).

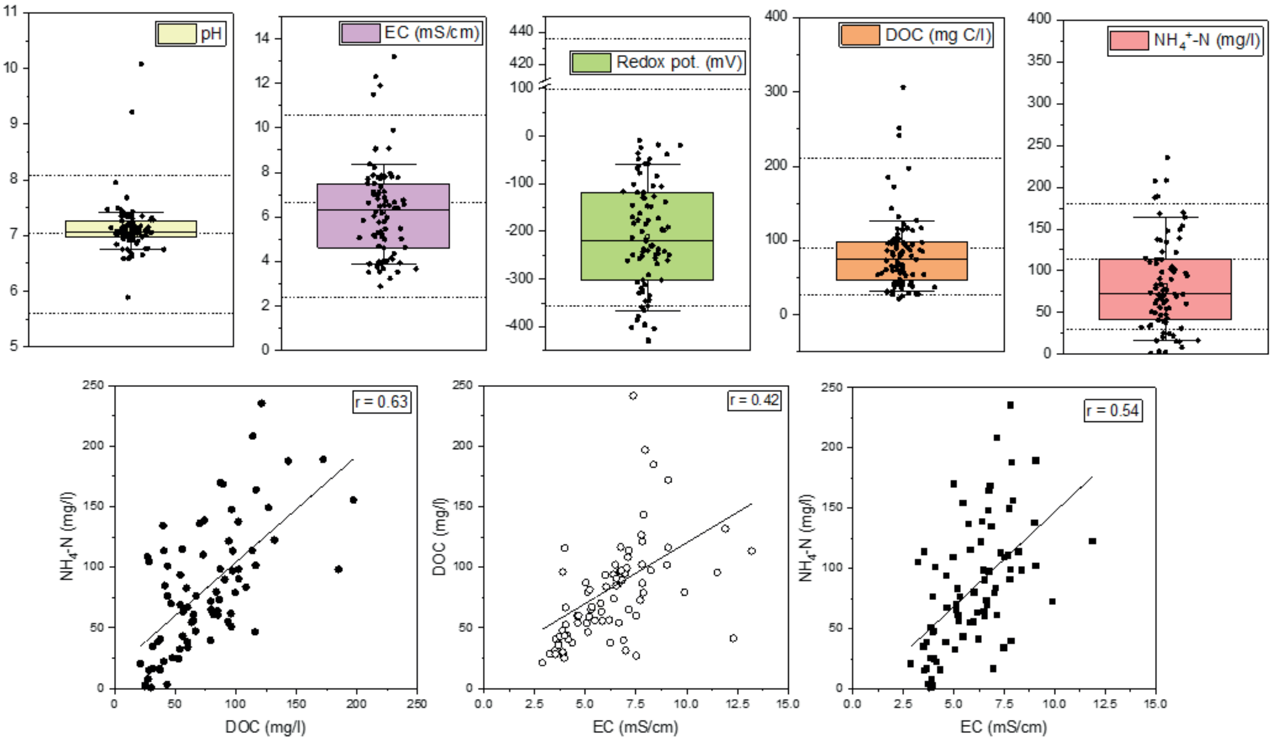

FIGURE 7: Variability of selected leachate parameters in compartment 11Z m December 2020 (top) and correlation between selected parameters (bottom). EC = electrical conductivity, DOC = dissolved organic carbon. Box = 25th/75th percentile, whiskers = 10th/90th percentile, line = median, open square = mean, closed symbols = data points. Dashed lines = maximum, minimum and average value in bulk leachate from compartment 11Z in months November, December and January from 2013-2019.

to pumping. However, also here wells showing instant recovery were directly neighbouring wells that were too dry to carry out the pumping test, corroborating the concept of discrete zones of hydraulically disconnected water bodies. All response classes were approximately equally present, with the class of ‘no recovery’ assuming the largest share of the wells where pumping tests could be carried out.

4.2 Variability of leachate quality

Leachate quality within compartment 11Z varied significantly, particularly with respect to electrical conductivity (EC), dissolved organic carbon (DOC) and ammonium (Figure 7). The variability can be caused by both the heterogeneity of the deposited waste, and the heterogeneity of waste permeability, leading to variable mixtures of original waste water and percolating precipitation. Rainwater EC is generally lower than 10 µS/cm (Zdeb et al., 2018), while EC of landfill leachate frequently ranges between 2,500 and 35,000 µS/cm (Christensen et al., 2001). The data cluster within the range that was measured in the winter months 2020-2021 in the bulk leachate, indicated by dashed lines. However, redox potential, DOC and ammonium concentrations were in the lower range of values observed for the bulk leachate, reflecting the fact that the properties of the bulk leachate are also determined by waste volumes in the unsaturated, better aerated and therefore more stabilized part of the landfill body, yielding leachate with lower ammonium and lower DOC concentrations and a lower redox potential.

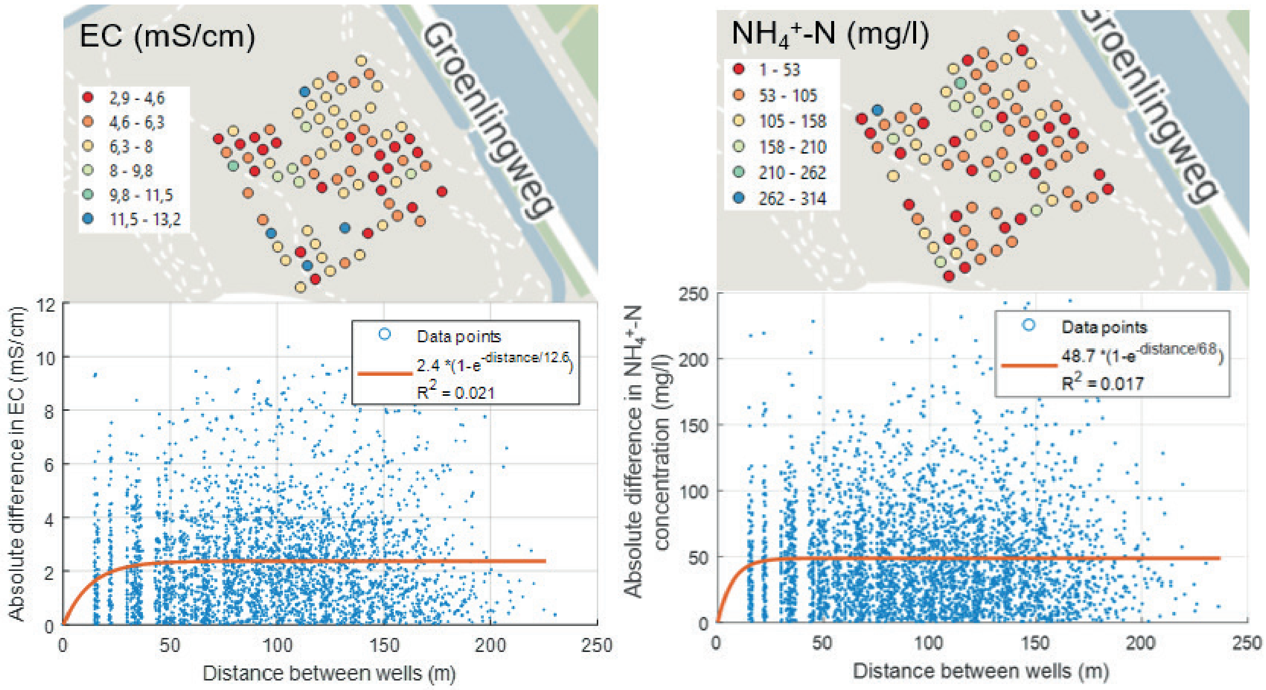

FIGURE 8: Top: Spatial variability of EC (left) and NH_4-N concentration (right), measured in aeration wells in compartment 11Z of Braambergen landfill. Bottom: Semivariogram of EC (left) and NH_4-N (right) with the concentration of each well plotted against the concentration of all other wells.

The high variability of leachate properties did not cluster spatially. Directly neighbouring wells showed large variations, as seen in Figure 8 for the concentration of solutes (EC) and ammonium. The absence of any geospatial relation of leachate properties in neighbouring wells was confirmed by a semivariogram analysis, plotting the difference in a given leachate parameter (Figure 8, lower panel). As to be expected, concentrations of dissolved organic carbon, ammonium, and electrical conductivity correlated positively (Figure 7, lower panel), highlighting the relationship between organic matter (OM) degradation, producing DOC, ammonium as the terminal nitrogeneous compound of anaerobic OM degradation and the concomitant increase in total solute concentration benchmarked by the bulk parameter of electrical conductivity. The latter is also determined by non-degradable waste components, explaining the lower level of correlation to the parameters related to biological degradation of waste organic matter. No correlation could be found for water levels or the response to pumping and leachate composition, indicating that waste hydraulics and waste biogeochemical processes.

5. CONCLUSIONS AND OUTLOOK

The aeration system on landfill Braambergen with 230 wells in four compartments and 132 wells in the focus compartment 11Z alone, at a 15 m spacing, provided a unique opportunity to study spatial variability of waste hydraulics and leachate properties. The data allow for the following conclusions:

Large hydraulic gradients persist within the waste body in compartment 11Z, which are also stable over time. This suggests zones of very low hydraulic conductivity in the horizontal plane, effectively isolating zones of ponded water from each other. Under these conditions, the spatial outreach and hence efficiency of aeration are low.

For the investigated compartment 11Z and waste bodies exhibiting similar hydraulic properties, water storage within the waste is a significant term in water balance modeling.

The well spacing of 15 m is larger than the extent of similarity of the measured properties within the waste, both with respect to hydraulic properties and leachate composition.

The radius of the saturated zone ('free' water) within the sphere of influence of each well is very small, often less than one meter. The estimates for the horizontal hydraulic conductivities found with the pumping test range from 1×10^{-7} to 6×10^{-4} m/s, however, these estimates only hold in the close proximity of the aeration wells in which they were measured.

Given the horizontal no-flow zones, pumping from one or several wells may not be effective to reduce the water table within compartment 11Z.

Solute composition and concentrations varied greatly, indicating variable extent of aeration and/or a high level of waste heterogeneity as well as the share of precipitation and original leachate in the final aqueous mixture. The properties of the bulk leachate from the entire compartment covers the range of properties found for the individual wells.

The absence of any relation between water levels or response to pumping, and leachate composition suggests that waste hydraulics and waste biogeochemistry in compartment 11Z are either not coupled or that any relation is masked by high variability in both sets of parameters.

All results combined support the concept of a 'bucket model' within the landfill, with the individual buckets demarcated by zones of low vertical and horizontal permeability. Once a bucket is full, adding more water will not increase the water level further as the bucket will overflow. The relatively low permeability zones do not have to be fully impermeable; therefore in some zones a decrease in water table is observed when the fresh accumulation of leachate is low, for example under conditions of reduced precipitation and/or high evapotranspiration from the soil cover.

Future infiltration tests as well as gas tracer tests shall further elucidate the permeability of the waste to water and gas flow and provide more insight into the wells' radius of influence. Further, it shall be investigated how DOC fractions can be used to characterize the waste organic matter, the dynamics of its degradation and the impact of anaerobic and aerobic conditions on DOC patterns.

ACKNOWLEDGEMENTS

This research is part of the CURE project supported by the Dutch National Science Foundation (NWO) under project no. OCENW.GROOT.2019.092. The research is also supported by the Dutch Sustainable Landfill Foundation via the iDS project: https://duurzaamstortbeheer.nl/english-page/.

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