Notitie

Subject: **Project plan Sustainable Landfill Management Braambergen**

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To:

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1 Introduction

1.1 The Dutch R&D programme on sustainable landfill management

The Netherlands have started a research programme on sustainable landfill management. The objective of this programme is to evaluate whether long-term risks of a landfill can be reduced to acceptable levels by removing the pollution potential of the waste, rather than by just preventing the dispersion of pollution using liner-systems (Kattenberg et al., 2013). The technical realisation of sustainable landfill management consists of two control measures: leachate recirculation and/or landfill aeration.

Emphasis in sustainable landfill management is on improving leachate quality and reducing risks for pollution of soil and groundwater on the long term. However during the project local safety has to be ensured. This means that possible leaks to groundwater during operation need to be monitored. Local nuisance (noise and odour) has to be kept within acceptable limits and a possible increase in methane emissions of methane need to be minimised.

As a first step, “acceptable” was defined in the objective “acceptable levels of pollutants to soil and groundwater”. For this purpose a maximum flux of contaminants to soil and groundwater (a site-specific flux in kg per year) was assessed. Assuming that ultimately excess rainfall of 300 mm is released to soil and groundwater, this maximum flux results in the definition of the maximum concentrations in the leachate, further referred to as emission test values (ETV, see also publications by Dijkstra et al., 2013 and Brand et al., 2014).

In the next step, the feasibility of sustainable landfill management will be evaluated in three pilots at the landfills Braambergen, Wieringermeer and De Kragge II. Since waste composition and age at these landfills differ, different approaches to sustainable landfill management will be demonstrated. At Braambergen and Wieringermeer waste will be aerated. At De Kragge II the pilot first will be flushed under anaerobic conditions, followed by a period of aeration. Operation of the pilots will take an estimated 10 years and is concluded by a 2 year monitoring programme.

This project plan article focuses on the pilot at the landfill of Braambergen, near Almere. The pilot will be performed at compartment 11 and 12 of this landfill, which measure 10 ha in surface and contain 1,200,000 ton of waste of a relatively inorganic nature.

1.2 Objectives of the pilot at Braambergen

The main objectives of the pilot at Braambergen (and also in the other pilots) are:

- To determine whether leachate concentrations can be reduced to values below the ETV;
- To demonstrate that the chance that concentrations in future might increase again to levels above ETV is negligible.
- To show that risks and emissions to air can be controlled and reduced to acceptable levels

Secondary objectives are:

- To design the required landfill aftercare that remains after successful sustainable landfill management;
- To Identify possible complementary measures (e.g. prolonged aeration; measured to reduce infiltration of rainwater and reducing fluxes to soil and groundwater) in case ETV for some components is not fully met;
- To improve the scientific and technical knowledge of the design and operation of sustainable landfill management and its impact on landfill processes.

1.3 Ongoing discussion on remaining pollution potential

The possibility of increasing leachate concentrations after sustainable landfill management needs some clarification. Within the project team, the conviction has grown that preferential channelling is an important factor for leachate quality. Leachate quality might be determined by only part of the waste and simultaneously large parts might have little or even negligible impact. In particular for leachate recirculation, pollutants seem to be most effectively removed from parts of the waste within reach of the existing preferential channels. So the chance remains that in the long term preferential channels are relocated, pollutants from other parts of the waste are released and leachate concentrations are increased again.

How to deal with this risk is an ongoing discussion. It is unclear whether the risk of relocating preferential channels is substantial. Maybe preferential channels are fixed in the waste, e.g. as a result of the way impermeable parts of waste are positioned. Maybe preferential channels relocate all the time and the part that remains unaffected by sustainable landfill management is much smaller than assumed. In order to be safe though, there is at the moment a clear desire for sustainable landfill management to reduce the complete pollution potential in the entire waste body (so both within and outside reach of preferential channels). But it is unclear how to monitor this and how to assess whether the pollution potential is sufficiently reduced. One conclusion however is very clear: we want to stay away from leaching criteria for the remaining waste, because it is very costly if not impossible to take a representative number of waste samples and have them analysed in leaching tests.

One option for monitoring the remaining pollution potential from waste is currently explored by Delft University. Delft University develops a model that predicts variability in leachate generation and composition as a function of variability in infiltration (as a result of variations in precipitation) and remaining pollution potential in the waste. When variations in leachate generation and composition are known with high frequency, remaining pollution potential might be estimated by reverse modelling. The pilot projects are important in development and validation of this approach, and this has impact on the monitoring programme of the pilot.

2 Description of the Braambergen landfill

2.1 General characteristics of the landfill

The landfill Braambergen is located in Southern Flevoland, near the city of Almere on land reclaimed in the late 60's. The landfill consists of 12 compartments, divided over three hills that are physically separated from each other. The pilot will take place on the hill, illustrated in figure 1 and consisting of the compartments 11 and 12. Table 1 gives some characteristics of these two compartments.

Figure 1: Bird-eye view on the Braambergen landfill. The compartments 11 and 12 are outlined in yellow.

Table 1: General data for compartment 11 and 12

Total surface	ca. 9.7 hectare
Time in operation	1999-2008
Total amount of waste	1,216,723 ton
Height of the landfill	15 m
Current landfill cover	Soil, incinerator bottom ashes, jet grout (1-1.5 m)
Landfill gas extraction	36 gas wells
Bottom liner	Combination of mineral and HDPE-liner
Leachate drainage and collection	3 separate drainage systems for 11N, 11Z and 12

Bottom liner and leachate collection

The compartments 11 and 12 are fully lined at the bottom with a combination of 2 mm HDPE-foil and 50 cm of sand-bentonite. Leachate is collected separately for the two sub-compartments of 11 (11-North and –South, indicated further as 11N and 11Z) ; and for compartment 12 (the drainage system for 12O and 12W are combined). Every drainage system drains into a leachate collection sump. From here, leachate is pumped to a central leachate sump, near collection sump 11Z and subsequently pumped to the municipal sewer.

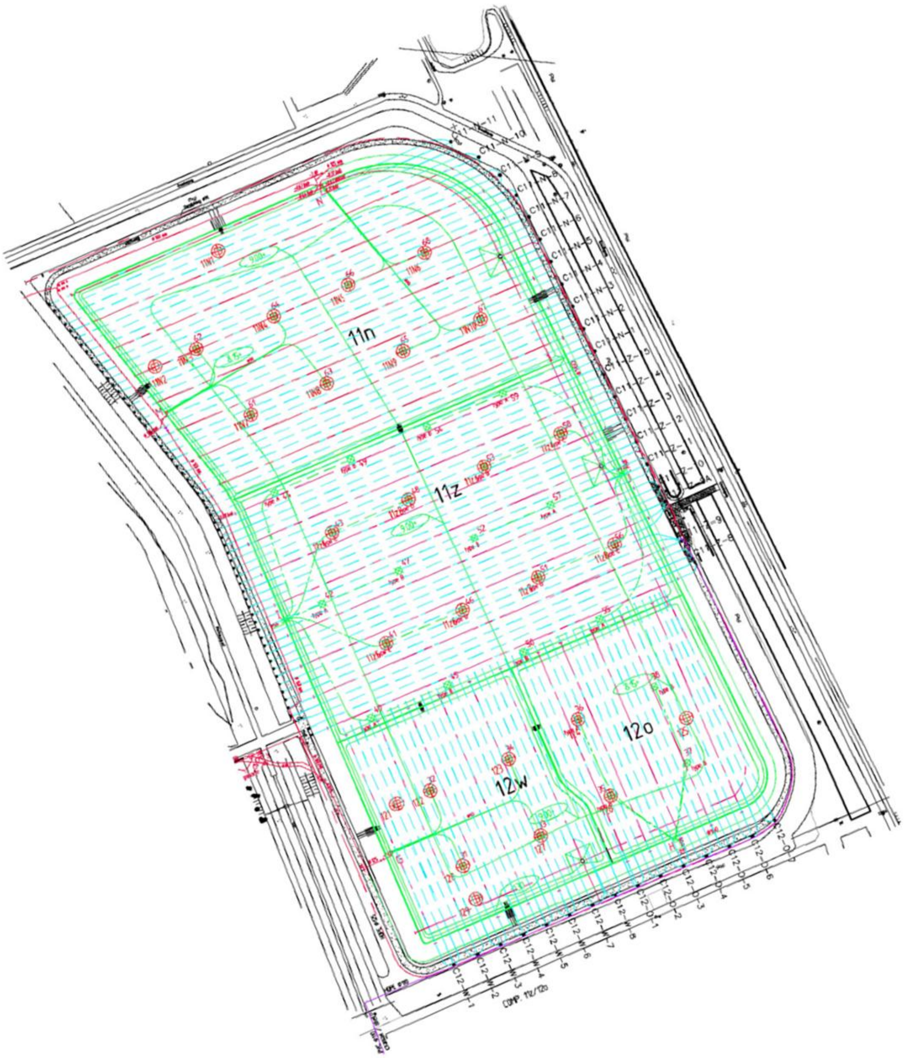

Figure 2: System for leachate collection at Braambergen. Leachate drains are indicated in red.

Top cover

Compartments 11 and 12 are fully covered with at least 1 m soil and below the soil partially with a mixture of incinerator bottom ashes and jet grout.

Landfill gas collection

Landfill gas is collected with 36 vertical wells on the compartments 11 and 12, with the highest well density on compartment 11Z (20). However, landfill gas is also collected the compartments 1-10 and only the total amount of landfill gas is registered, so the landfill gas collection of compartments 11 and 12 is not precisely known.

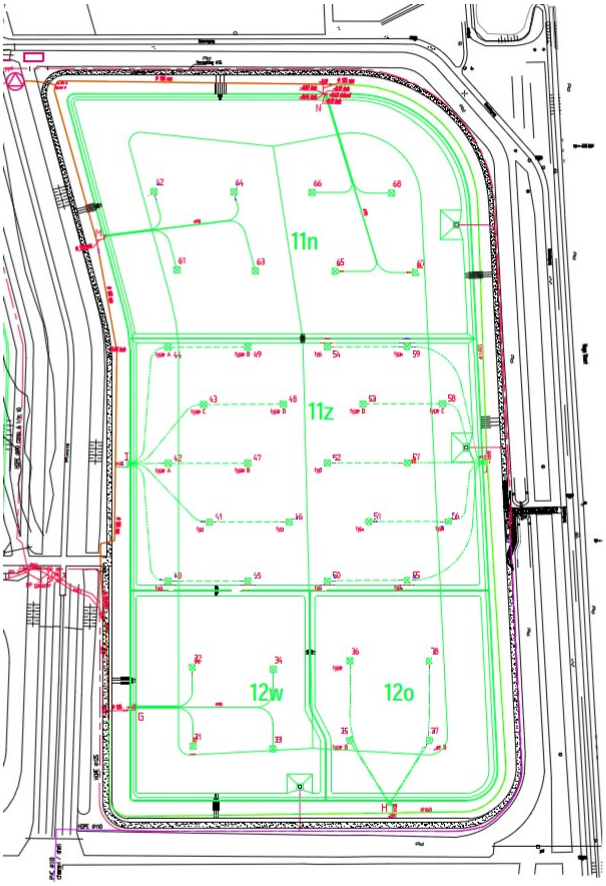

Figure 3: System for landfill gas recovery

Groundwater monitoring

Composition and hydraulic head of phreatic ground water is measured under the landfill (3 monitoring wells), within the ring ditch (5 monitoring wells) and outside the ring ditch (14 monitoring wells) and in most cases at three levels (shallow, medium and deep). Hydraulic head in the shallow monitoring wells is measured 2 times a month. Groundwater in all monitoring wells is sampled once a year and analysed for NH_4+, Cl^- and sulphate, the heavy metals As, Cd, Cr, Cu, Hg, Ni, Pb and Zn and the organic micro-contaminants VOX and aromatics. Measurements are available from 1999 onwards. Water in the ring ditch is also analysed once a year and for the same components.

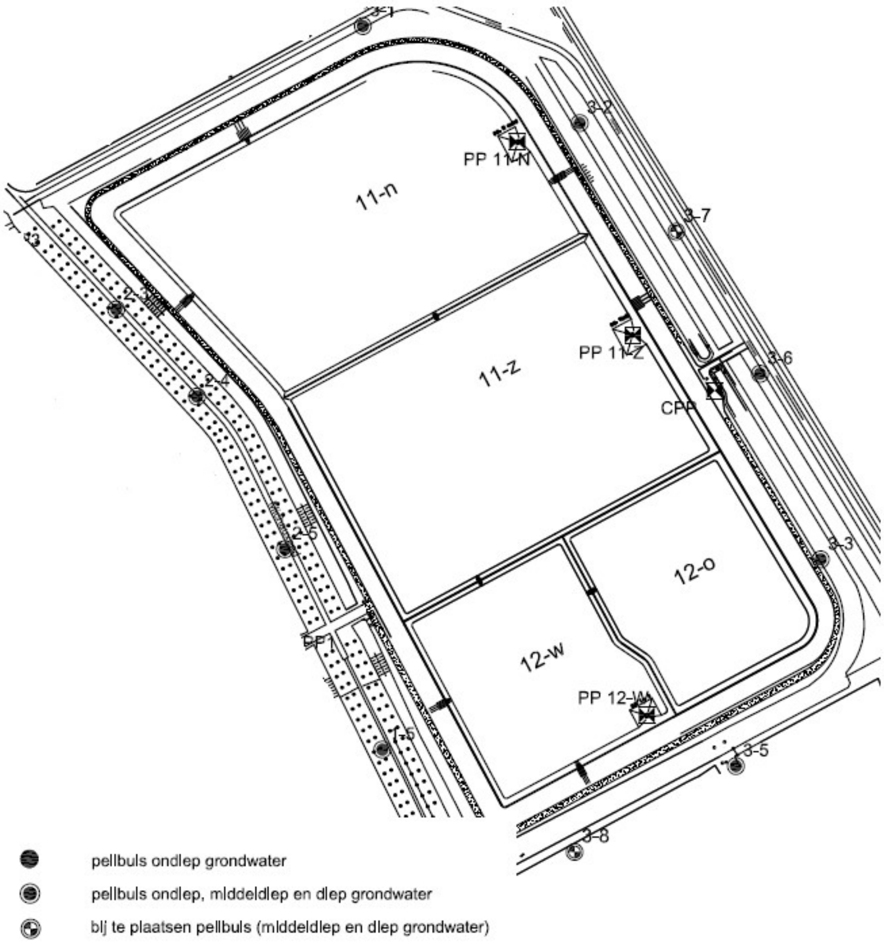

Figure 4: Ground water monitoring Braambergen, compartment 11 and 12

2.2 Leachate generation, gas generation and settlements

Sustainable landfill management aims at accelerating the biodegradation of organic material in the waste and making biodegradation more complete. The way to achieve this (so the choice between leachate recirculation or aeration) depends on the degree at which spontaneous biodegradation already has occurred. This paragraph summarises existing information on progress of biodegradation and the resulting generation of landfill gas and leachate. The table below gives a first overview.

Table 2: Data Braambergen

Leachate	27,000 tot 49,000 m^3/year
Gas collection	69 m^3STP/hr methane
Settlements	0.01-0.07 m per year

Amount of waste and waste composition

The amount of waste landfilled, was measured on weigh bridge and registered, along with its origin. So the amount of waste and the type of waste is well-known. In total in compartment 11 and 12 1,216,723 ton of waste was landfilled between 1999 and 2008. Table 3 shows that over 80% of the waste are soil and contaminated soil residues. Appendix 1 gives the amount of waste landfilled in each year.

Table 3: Amount and origin of waste, landfilled Braambergen, compartments 11 and 12 (in ton)

Soil and soil decontamination residues	981,019
Construction and demolition waste	53,855
Commercial waste	123,098
Shredder waste	11,737
Street cleansing waste	1,397
Coarse domestic waste	4,438
Sludge and composting waste	5,406
Household waste	35,773
Total	1,216,723

Prognosis of gas generation and actual gas collection

The amounts of waste in Appendix 1 are used to make a prognosis of methane generation, using the Afvalzorg methane generation model. Figure 5 gives the result for compartments 11 and 12.

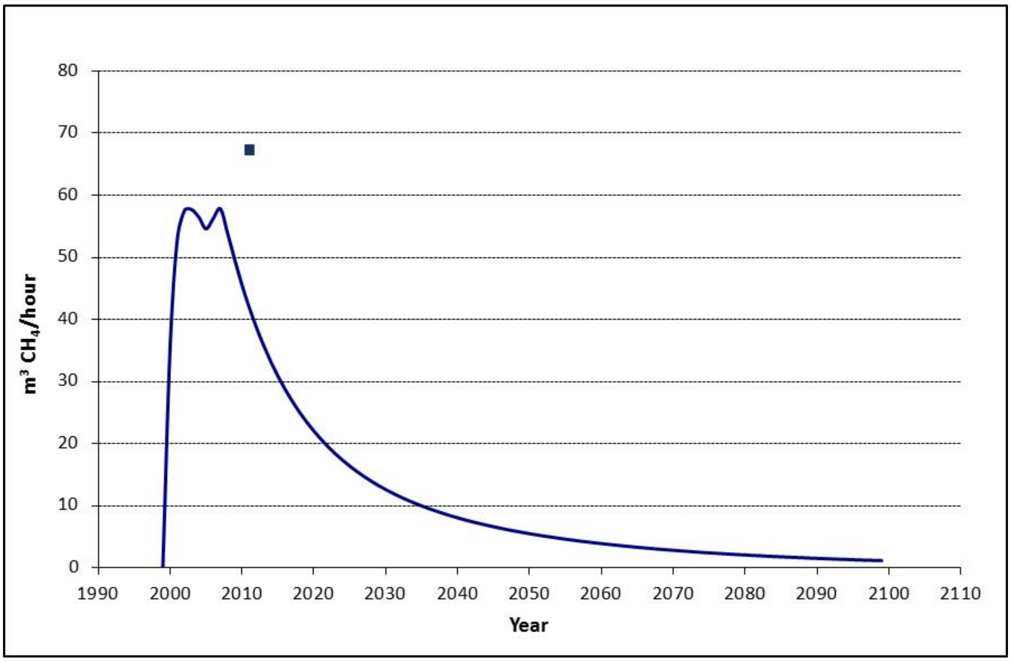

Figure 5: Prognosis of methane generation for compartments 11 and 12 (the line), along with the result of the extraction test in 2011/2012 (the dot)

Landfill gas is collected since 2004. The amount of landfill gas and its composition is registered. However this refers to all landfill gas, from all compartments of the landfill. At compartment 11 and 12, a relatively inorganic waste is landfilled. The other compartments are generally somewhat older and contain more organic waste and it is expected that most landfill gas is extracted from these other compartments.

In 2011/2012 an extraction test was performed at compartment 11 and 12.During this test the suction pressure on each well was gradually increased. Doing this, the amount of landfill gas extracted and the composition of the gas was measured. The maximum gas collection was 69 m^3 of methane per hour, which is slightly higher than the prognosis of methane formation in 2012 (about 47 m^3 of methane per hour, see figure 5). This extraction test suggests that the prognosis in figure 5 underestimates actual methane generation. So the generation model itself might also underestimate the remaining amount of biodegradable organic carbon, maybe by a factor 1.5-2.

Annual leachate generation and excess precipitation

The amount of leachate generated by the three collection wells (11N, 11Z and 12) is registered. Table 4 gives the annual amounts since 2001.

Table 4: Annual leachate generation (m^3) on Braambergen

	PP11N	PP11Z	PP12	Total
2001	10,000	5,000	12,000	28,000
2002	11,000	24,000	13,000	48,000
2003	8,500	21,000	19,000	49,000
2004	7,000	13,000	8,500	27,500
2005	12,575	20,533	11,949	45,057
2006	12,363	20,139	9,942	42,444
2007	13,185	14,370	9,847	37,402
2008	10,926	14,370	7,082	32,378
2009	9,337	11,936	8,259	29,559
2010	13,220	5,232	9,619	28,071
2011	8,995	15,705	6,494	31,194
2012	10,625	16,607	6,420	33,652
2013	13,698	16,458	10,169	40,324

Braambergen has its own pluviometer. In 2013 total precipitation was 850 mm. Assuming a total surface of 9.7 ha this boils down to 82,500 m^3 of rain. In 2013 almost half of this (40,324 m^3 or 415 mm per year) was received as leachate.

Composition of leachate in comparison to the ETV

Leachate composition data are available from 2001 onwards. Until 2012, concentrations were measured 1-2 times a year. From June 2012 onwards leachate was more frequently sampled as a part of the baseline measurement for the pilot. In 2013 leachate composition was analysed on the macro-contaminants (in total 28 times), heavy metals (11 times) and organic micro's (6 times).

So for the period 2001-2013 trends in concentrations are available for the macro-contaminants. An example is given in the figure below. Trends in NH_4^+/N_{kj} are shown for all three collection sumps. The differences in trends are striking and cannot be explained. In collection sump 11N there seems to be a gradual reduction in concentrations. In collection well 12, concentrations seemed to be stable. However the biweekly measurements during the baseline-measurement revealed a highly variable NH_4^+-concentration. In collection sump 11Z, concentrations are consistently low, compared to concentrations in both other sumps.

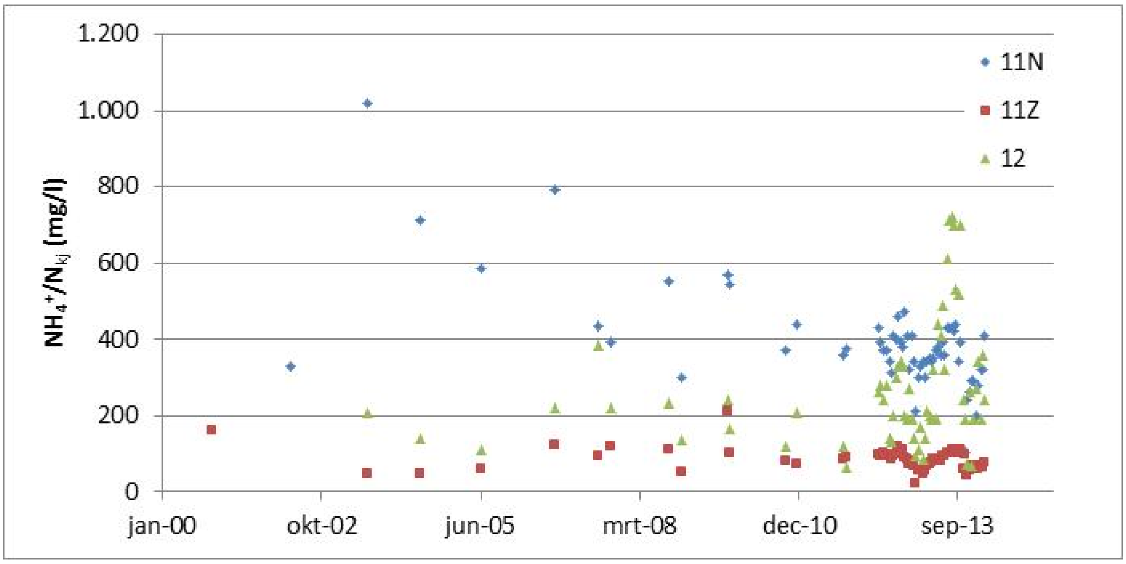

Figure 6: NH_4^+/N_{kj}- concentrations in the leachate 2001-2013

For 2013 average concentrations are calculated and listed in the table below. Concentrations of N_{kj} and Cl^- are calculated, based on monthly average concentrations and leachate generation per month. Subsequently, annual average concentrations are calculated as the sum of fluxes per month, dived by the annual leachate generation. Some concentrations of heavy metals and many organic micro's are below detection limits/reporting limits. The Dutch government proposed guidelines on use of the ETV ('Handreiking gebruik emissietoetswaarden'), in which a method is described how to deal with concentrations below detection limits/reporting limits. These guidelines are applied in calculating the average concentrations in table 4. The last column in table 4 gives the emission test values (ETV) for Braambergen..

Table 4: Leachate composition Braambergen in 2013

	PP11N	PP11Z	PP12	ETV
Heavy metals	**ug/l**			
As	25	129	118	190
Cd	0.10	0.10	0.10	6.4
Cr	24	10	56	210
Cu	11	6.1	2.1	50
Hg	0.02	0.09	0.23	5.8
Pb	19	12	41	60,000
Ni	1.3	0.52	0.52	21
Zn	9	22	12	160
Cyanide (free)				61
Macro parameters	mg/l			
Chloride	554	956	767	450
Sulphate	269	1184	734	700
$N_{Kjeldahl}$/ammonium	320	78	223	50

Mineral oils	**ug/l**			
Sum mineral oils	61	5	24	470
VOX	**ug/l**			
vinylchloride	0.26	2.2	0.44	0.047
dichloromethane	0.11	0.13	0.11	0.047
1,1 dichloroethane	0.13	0.13	0.13	4.7
1,2 dichloroethane	0.13	0.13	0.13	14
1,1 dichloroethene	0.026	0.026	0.026	0.047
1,2 dichloroethene (cis,trans)	0.52	3.0	0.56	0.047
dichloropropane (1,2)	0.067	0.21	0.067	3.8
dichloropropane (1,3)	0.035	0.035	0.035	3.8
trichloromethane (chloroform)	0.032	0.032	0.032	4.7
1,1,1 trichloroethane	0.032	0.032	0.032	0.047
1,1,2 trichloroethane	0.032	0.032	0.032	0.047
trichloroethene (tri)	0.047	0.327	0.032	47
tetrachloromethane (tetra)	0.032	0.032	0.032	0.047
tetrachloroethene (per)	0.032	0.032	0.032	0.047
PAH	**ug/l**			
naphtalene	0.91	1.7	4.7	0.047
phenantrene	0.092	0.067	0.55	0.028
antracene	0.011	0.027	0.065	0.0066
fluoranthene	0.001	0.017	0.037	0.056
chrysene	0.001	0.006	0.004	0.056
benzo(a)antracene	0.012	0.012	0.41	0.0019
benzo(a)pyrene	0.001	0.012	0.006	0.0094
benzo(k)fluoranthene	0.001	0.009	0.001	0.0075
indeno(1,2,3cd)pyrene	0.002	0.002	0.002	0.0075
benzo(ghi)perylene	0.002	0.002	0.002	0.0056
sum PAH (10-VROM)	1.0	2.0	5.8	1.9
BTEX	**ug/l**			
benzene	2.4	1.9	1.4	0.94
xylene	1.1	0.49	0.80	0.94
toluene	0.13	0.08	0.14	4.7
ethylbenzene	0.20	0.14	1.87	4.7
Phenols	**ug/l**			
Phenols (total)	0.18	0.18	0.20	0.94

Settlements

For settlement monitoring, the top-surface of the compartments 11 and 12 was measured in July and December 2008. At that time, settlements were on average 9 cm per year, with settlements at a single location varying between 2.4 and 36 cm per year. In 2012 12 settlement plates were placed on the waste, on the locations, described below. The top of the landfill was measured in August 2012, April 2013 and January 2014. From August 2012 to April 2013, settlements proved to be in average 2,8 cm per year (with values at single locations from 1.0 to 6.0 cm per year). From April 2013 to January 2014 settlement was on average 4.9 cm per year (varying from 2.9 to 7.3 cm per year).

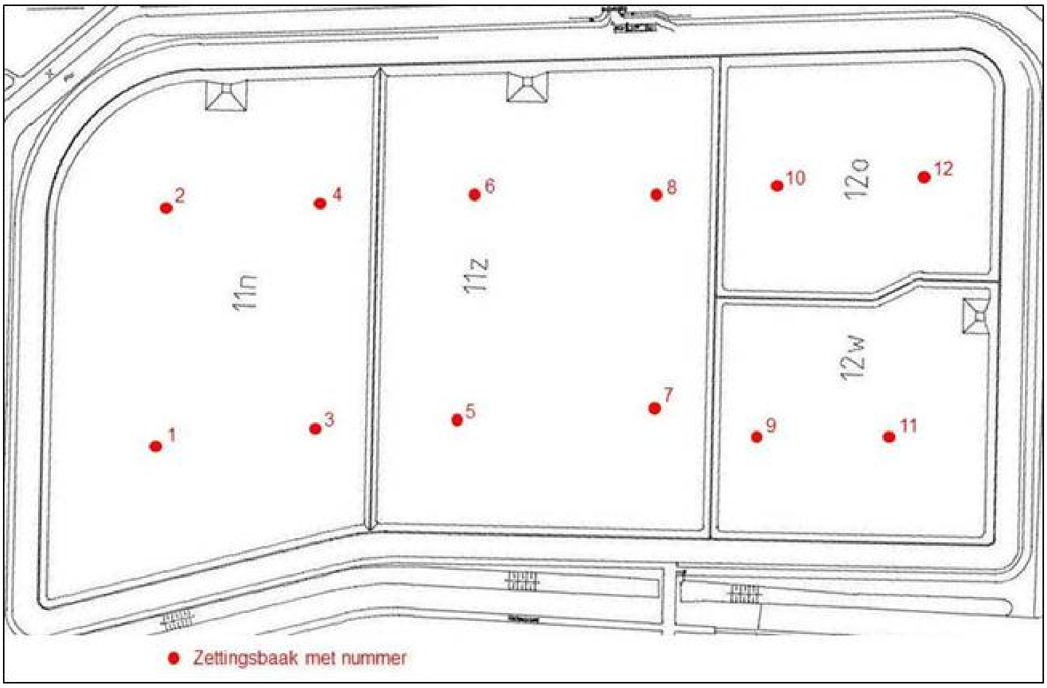

Figure 7: Settlement plates at Braambergen during the baseline measurement.

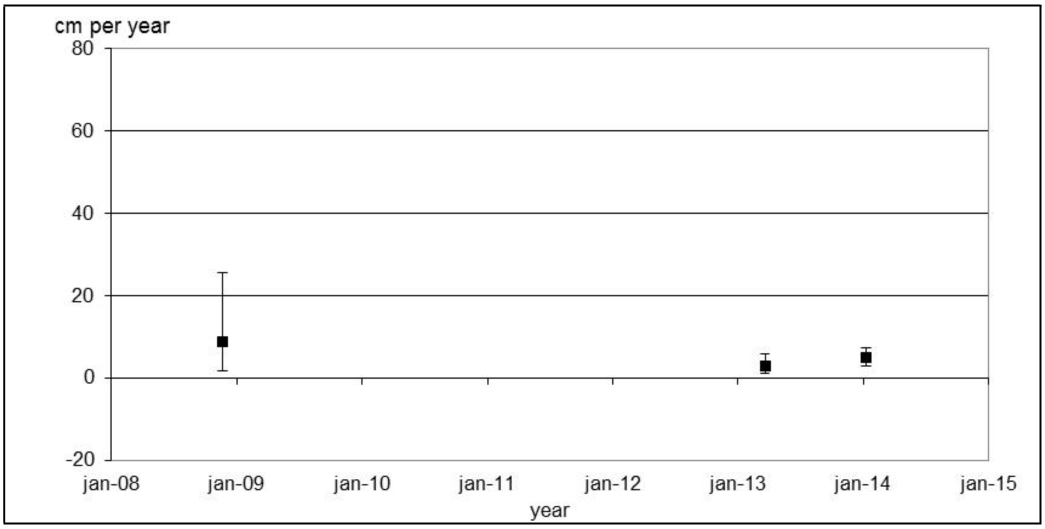

Figure 8: Settlements at Braambergen

After finalisation of the system of aeration and, the current settlement plates will be lost and 28 new settlement plates will be realised.

3 Choice of technology

In Braambergen, the waste will be aerated, according to the conclusions of the feasibility study by CDM (Bröcker et al., 2011). In this feasibility study, the choice for aeration was based on a prognosis of remaining biodegradable organic carbon in the waste. When this amount is too high, full stabilisation through aeration requires too much air and aeration becomes more costly. In such a case, anaerobic decomposition might be enhanced by leachate regeneration, prior to aeration. Upon leachate recirculation, part of the costs are off-set by additional revenues of gas collection and leachate recirculation gives additional advantages for removal of N_{kj}, DOC and Cl^-.

In the feasibility study, the remaining amount of biodegradable organic carbon at Braambergen was expected to be limited, and as a result aeration was preferred. This assumption was validated during the baseline measurements. Although it was concluded that the actual amount of biodegradable carbon was higher as expected, the remaining gas collection rates are still low (about 10-15 m^3 of landfill gas per ha per hour[1]). This is consistent with a relative low remaining amount of biodegradable organic carbon (less than 10 kg degradable C per ton of waste). So when biological stabilisation of the waste is aimed for, a relatively small amount of air will be required and aeration is the preferred choice.

An alternative approach would be recirculation of leachate prior to aeration. However leachate infiltration adds significantly to the costs of the pilot and will not result in substantial savings upon aeration.

Two methods are considered for aeration: (i) low-pressure aeration and (ii) over-extraction. The choice for these two methods is based on the evaluation by van Vossen et al. (2009). According to this evaluation, the advantages of both systems over other possible methods for aeration are:

- It is technology demonstrated in the period 2000-2010 and at the moment applied at an increasing number of landfills in Europe. In these demonstrations, the technology proved to be robust
- It is cost cost-effective, compared to some other methods of aeration
- Little or no emissions of odour and methane are expected, because the landfill body is kept under an under-pressure;
- The effectiveness of these two systems can be monitored better, than the effectiveness of most other systems for aeration. This is because the reaction products CO_2 and CH_4 are extracted and therefore quantities can be measured in the waste gas.

The figure below describes both low-pressure aeration and over extraction. Both systems consist of vertical wells in the waste, of which the lower end is perforated. Upon over-extraction about 5-10 times the amount of gas is extracted, compared to the volume of landfill gas that is produced. As a result, ambient air is pulled into the waste. During low-pressure aeration, wells operate in pairs. Half of the wells are used to inject air and the other half is used to extract the injected air again. The well pressures are adjusted in such a way that amount of extracted air exceeds the injected air with about 10% to avoid diffuse emissions. In both systems, the exhaust air can be treated, to minimise methane emissions and odour nuisance .

[1] This is about 25% of landfill gas generation per ha and per hr at landfill De Kragge II, where leachate will be recycled prior to aeration.

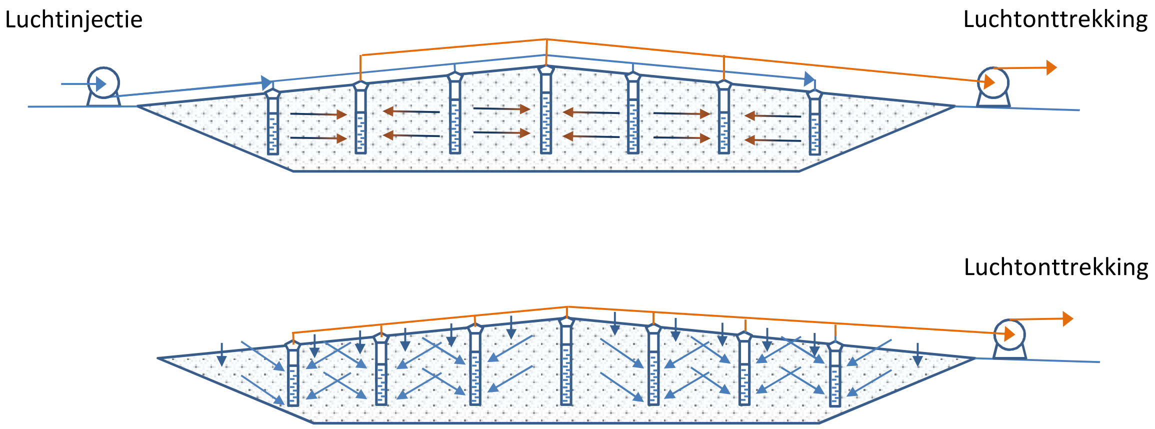

Figure 9: Low-pressure aeration (above) and over-extraction (below) for aerobic conversion of organic material in a landfill

At the moment over-extraction is the preferred option for aeration at Braambergen. Compared to low-pressure aeration, over-extraction is the cheaper option. However, its aeration capacity (expressed as m^3 of air per m^3 of waste per hour) is lower and as a result, treatment of the waste will take longer, compared to low-pressure aeration. Afvalzorg is currently preparing two pilots (on Braambergen and on Wieringermeer) and wants to gain experience with both systems. Because the remaining amount of biodegradable organic carbon at Braambergen is lower than the amount at Wieringermeer, the slower aeration method (over-extraction) is selected for Braambergen. For Wieringermeer most likely low-pressure aeration will be selected.

The system for over-extraction will be positioned between the two hills at the western side of the landfill (see figure 10). Connections and other provisions are already in place, because previously a landfill gas flare was located at that spot. The system for aeration will consist of a compressor station with a capacity of 900 to 1,200 m^3 per hour. The compressor station will be located in a casing or a container to minimise noise. Next to the compressor, a system for exhaust gas treatment will be realised. As long as the methane content of the gas is high, this will be a flare for low-calorific gas. When the methane content in the exhaust gas drops below 15 %, exhaust air will be treated in a biofilter.

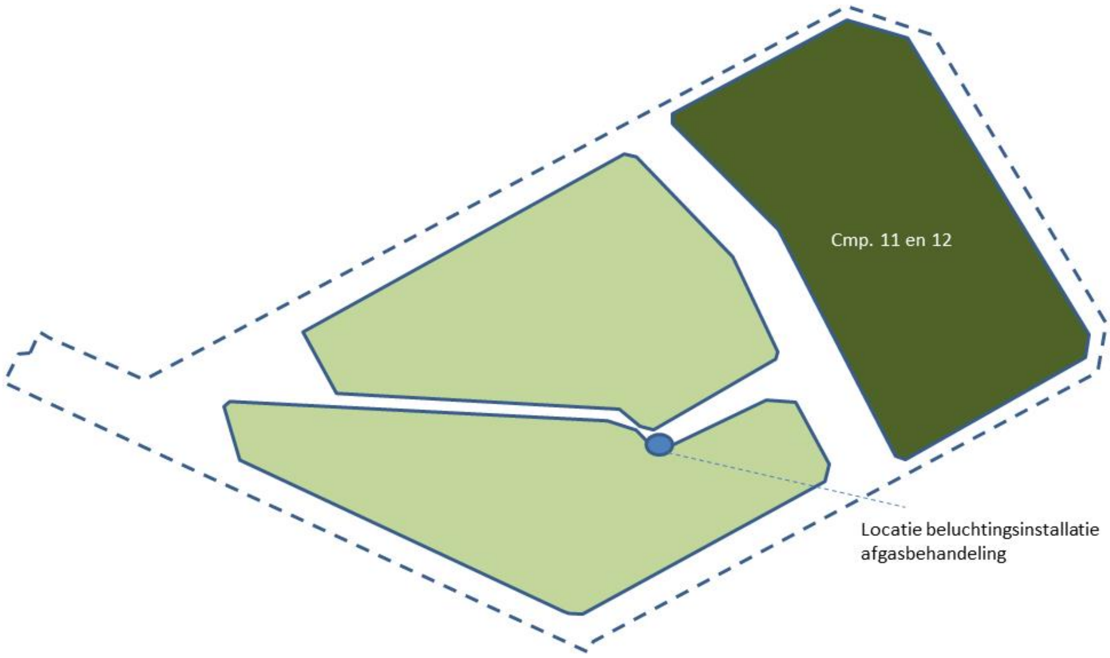

Figure 10: Location of the aeration-compressors and treatment of exhaust.

4 Processes in waste and expected effects of sustainable landfill management

4.1 Qualitative effect of aeration on leachate quality

Sustainable landfill management aims at reduction of the pollution potential, that is released with the leachate. So understanding the factors that determine leachate quality is crucial to understanding sustainable landfill management. Relevant factors are:

- Waste composition and the extent in which contaminants are available for flushing;
- Degradation of organic material and generation of dissolved organic carbon (DOC). Degradation of organic material ultimately produces landfill gas. Intermediate products of this process are dissolved in water and contribute to pollution of the leachate. Organic material and its degradation also results in pollution of the leachate with chemically more stable organic complexes, such as humic acids and fulvic acids. Progress of degradation of waste and the amount of DOC in the leachate is often correlated. The concentration of DOC in leachate is one of the most important parameters in leachate, because it can complexate and mobilise heavy metals and organic micro-contaminants;
- Moisture content, which has impact on biodegradation. Movement of moisture in waste has impact on biodegradation as well, most likely because nutrients are supplied and products of biodegradation are removed with the moisture, thus preventing inhibition.
- Concentrations of readily soluble contaminants (e.g. Cl^-) is determined by the amount present in the waste. For less well soluble components (e.g. many metals), concentrations in leachate are limited by their solubility in water and this is affected by local conditions in the waste (pH, redox, temperature).
- The extent in which pollutants already are flushed out with the leachate. Flushing has most effect for the readily soluble components. When concentrations are determined by solubility or when components are adsorbed to solid organic material, flushing is less effective. Preferential channelling is important for flushing out contaminants and development of leachate concentrations. Most of the leachate flows through a limited part of the waste, so a large part of the waste is not in direct contact with mobile leachate. Pollutants from outside the preferential channels are only released by diffusion, or upon relocation of a preferential channel. Large parts of these pollutants will not be released at all. As a result effective L/S is increased and the leachate quality improves much faster than expected, based on the pollution potential in the waste.

The overall effect of all these parameters and processes on leachate quality differs for the various contaminants:

- Organic macro-contaminants, such as DOC, BOD and COD and also N_{kj} are generated upon biodegradation of organic material and this process depends on the waste composition upon deposition. Under anaerobic conditions, most organic macro-contaminants react further and ultimately produce landfill gas. Humic substances dissolved in leachate however are very resistant to decay. At least under anaerobic conditions.
- The solubility of most metals and heavy metals is limited under the often neutral to slightly basic (pH 6.5-8.5) conditions in the leachate. Concentrations of metals as Fe, As, Cd and Cr in leachate are often determined by complexation with DOC. When after some time DOC in leachate is reduced, metal concentrations are often reduced as well.
- Concentrations of organic micro-contaminants, such as BTEX, VOX, (H)CFC's, mineral oils, PAH in leachate are the result of a gas-liquid equilibria and adsorption-desorption equilibria to the solid phase. The most volatile organic contaminants will evaporate with the landfill gas produced; less volatile organic contaminants will adsorb to the solid fraction. Solubility of these components is relatively low. Concentrations of most organic micro-contaminants in leachate is determined by adsorption to DOC. Under sustainable landfill management, concentrations of organic contaminants might be reduced in various ways:

- ○ The more volatile organic contaminants will be stripped from the waste by the aeration exhaust. This effect is supported by increased temperatures as a result of aerobic decomposition;
- ○ Concentrations of less volatile contaminants are reduced, when DOC concentrations in leachate are reduced;
- ○ Most organic contaminants (all except the most robust PAH) will biodegrade under aerobic conditions.
- Concentrations of oxyanions as sulphate and phosphate are determined by leachate conditions (pH and redox), which in their turn are determined by biodegradation. Upon aeration sulphate might me generated from sulphides in the waste, resulting in an increase in concentrations.

4.2 Quantitative estimate of effects on leachate quality

At the moment Delft University is developing a more integrated landfill model, that describes the development of the leachate quality in time. This model should ultimately also be able to predict the effects of sustainable landfill management on leachate quality. However at the moment, the model is not yet available and can't be used to support detailed design of the pilots.

Instead a more improvised model was used to make a first rough prognosis of the effects of sustainable landfill management and the feasibility of reducing leachate concentrations of NH_4^+, Cl^- and DOC down to the levels, specified by the ETV. This simplified model is based on three sub-models:

- Biological degradation of organic material is described by the model, developed by Ecofys (Luning et al., 2011). This model was developed for the Dutch government to estimate methane emissions due to sustainable landfilling. The Ecofys model starts from existing first order decay models for landfill gas/methane generation and assumes an acceleration of this biodegradation upon aeration, along with a gradual increase of the dissimilation factor in the first order decay (the fraction of organic material ultimately transformed to biogas);
- Flushing of contaminants is described by the well-known exponential relation for removal of e.g. salts as a function of L/S. In this relation, corrections are made for (i) the part of the waste that has impact on leachate quality (thus increasing the effective L/S) and (ii) the fact that the amount of precipitation is infiltrated unevenly throughout the year. In periods of heavy rainfall, leachate concentrations are less, than in more dry periods. So part of the year, leachate seems to be diluted, thus reducing the effective flushing out of pollutants. This effect is also described as a reduction of L/S. The equation used is:

  $$C = C_0 * e^{-C2\,(L/V)/C1}$$

  In which C is the concentration of component C, C_0 is the initial concentration; L is the amount of water flushed through the waste; V is the total volume of water in the waste (so the product of total waste and moisture content); C1 is the correction factor for the part of waste, that has impact on leachate concentrations (20-40%) and C2 is the correction factor for incomplete flushing (20-40%).
- Generation of NH_4^+ and COD is linked to biodegradation of organic material, as estimated in the Ecofys-model. In this model degradation of rapid, moderate and slow degradable organic material is quantified, and per type of waste a specific release of NH_4^+ and COD is assumed per ton of organic carbon dissimilated (based on C/N=20 in rapidly degradable waste; 60 in moderately degradable waste and 150 in slow degradable waste). Degradation of COD under anaerobic conditions is described as a first order decay reaction, assuming half-times, based on decrease of COD in actual landfills. Decrease of NH_4^+ and COD under aerobic conditions is described as first order reaction with half-times, based on claims of suppliers of systems of aeration equipment.

As said before, the model itself is highly uncertain and uncertainties need to be taken into account, when interpreting its results. The most important uncertainties are:

- ○ Model-uncertainties that are omnipresent in all three sub-models. E.g. the first-order the Ecofys-model is based on first order decay model. This model is widely accepted and is a reasonable predictor of biogas formation. However the way the model is used here is outside the scope of what it is originally designed for, and this makes the output highly uncertain.

- The effectiveness of aeration itself, so the amount of air that can be introduced in the waste and also whether all parts of the waste receive the same amount of air.

Degradation of solid organic material:

Degradation of solid organic material is accelerated upon aeration. Although it is generally expected, that this will result in a reduced emission potential of the waste, the exact mechanism and relation between remaining solid organic material and leachate composition is unknown. This also implies that it is unclear to what extent degradation must be completed in order to achieve sufficient reduction in emission potential. The figure below shows the effect of aeration on the amount of biodegradable organic carbon in the waste. This prognosis is made, using the Ecofys-model.

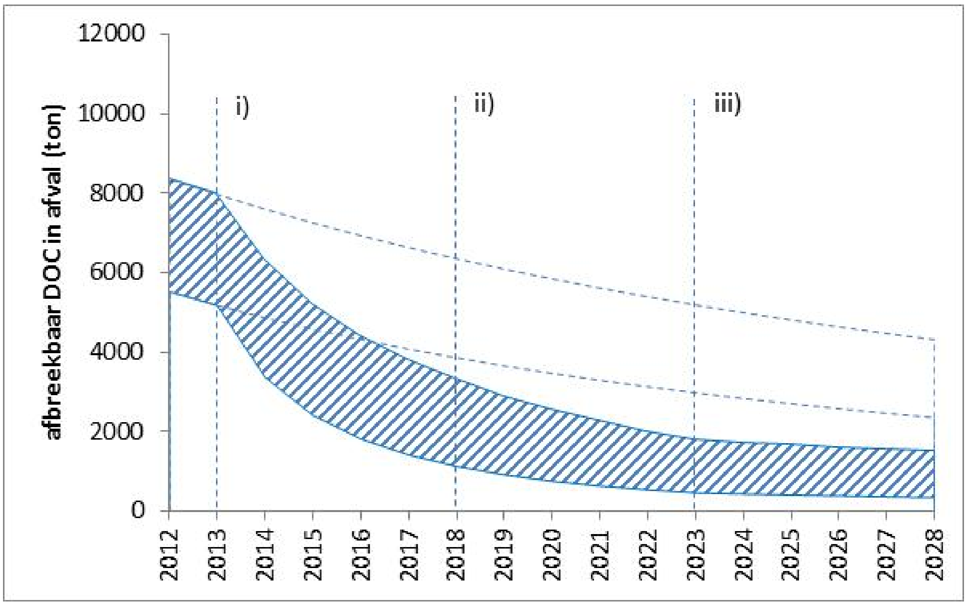

Figure 11: Development of the amount of degradable organic material in the waste. The vertical lines indicate: (i) start of aeration in 2013; (ii) intermediate evaluation in 2018 and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2013.

Reduction of COD:

Enhanced degradation of organic material is expected to result in a decrease of DOC in the leachate. The figure below describe the effect of aeration for the Braambergen pilot. The reduction of DOC in leachate is the result of an autonomous reduction due to flushing with leachate and an effect of aerobic conversion of organic material.

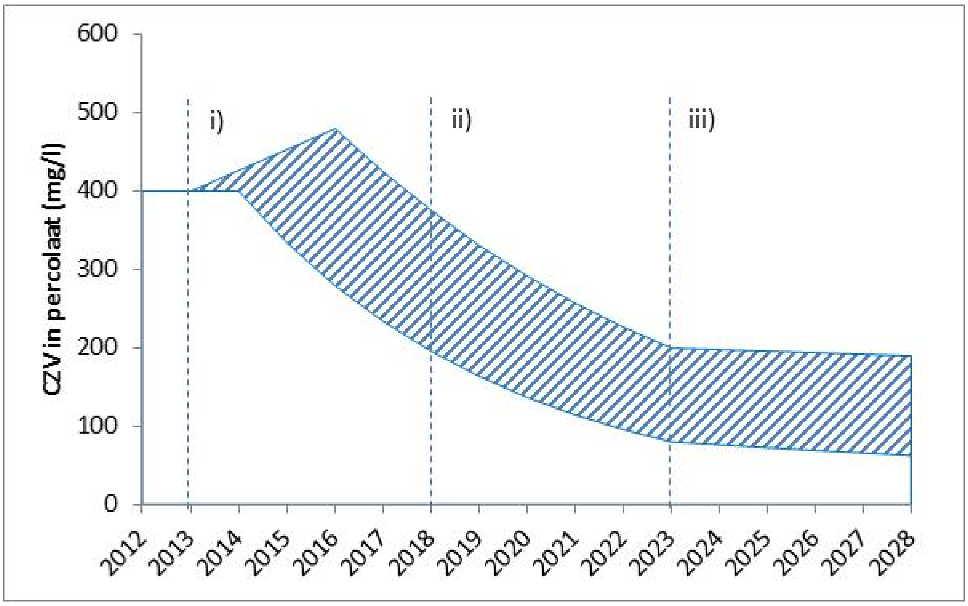

Figure 12: Development of COD in leachate. The vertical lines indicate: (i) start of aeration in 2013; (ii) intermediate evaluation in 2018 and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2013.

Reduction of ammonia in leachate:

Ammonia concentrations are affected by release of ammonia upon biodegradation, nitrification, denitrification and stripping upon aeration and flushing. The figure below gives the expected overall effect on ammonia concentration in leachate. Initially concentrations might increase upon enhanced release of N from solid biomass. During aeration, part of the ammonia might be used for growth of the bacteriological biomass. This amount of N might be released again after completion of aeration, resulting in an increase of ammonia after ending the aeration.

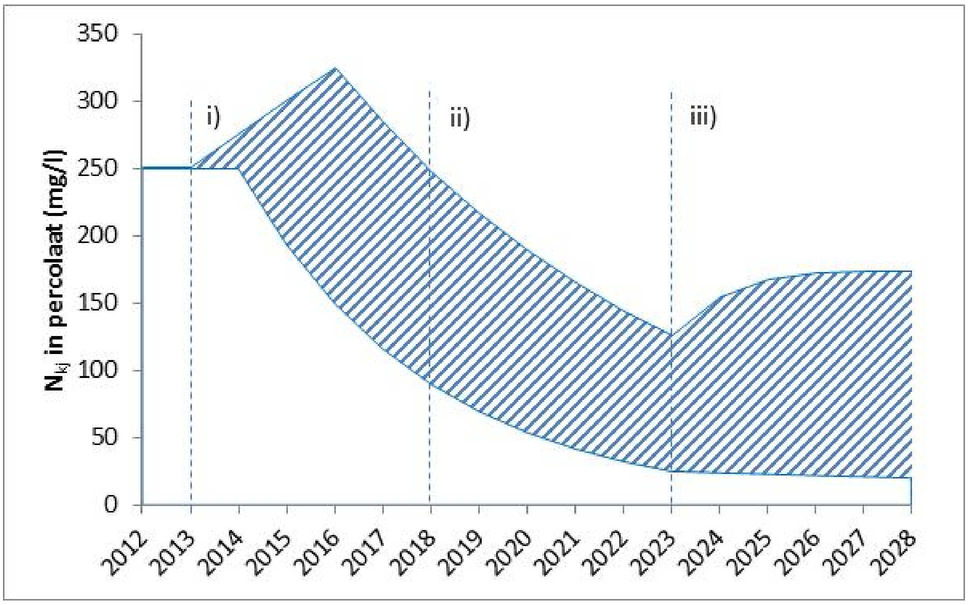

Figure 13: Development of CH_4^+ in leachate. The vertical lines indicate: (i) start of aeration in 2013; (ii) intermediate evaluation in 2018 and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2013.

Removal of organic micro-contaminants

When waste is aerated, organic micro-contaminants can be removed in various ways, as described before in chapter 4.1. The combined effect of stripping at elevated temperatures and flushing was estimated, using an adapted version of MOCLA (Kjeldsen et al., 2012). MOCLA calculates partitioning of organic trace-contaminants over adsorption on solid phase, water and gas-phase, assuming established equilibria (liquid solid partitioning, K_d and liquid-gas equilibrium, K_H) over all phases. Doing this, the leachate is flushed with an amount Q_w, and gas is generated at a rate of Q_g. MOCLA also assumes the water phase to be ideally stirred, resulting in the same flushing equations as used for the macro-contaminants and salts (see above). For estimation of the effects of aeration, MOCLA was adapted on two parts:

- The Henry-equilibrium (K_H) is made temperature dependent. This is relevant since the volatility of organic components increases at elevated temperatures in an aerobic landfill;
- Complexation of organic trace-components with DOC is considered as well. Especially for the less-soluble components (e.g. the more heavy PAH), this is an important mechanism for mobilisation with the leachate.

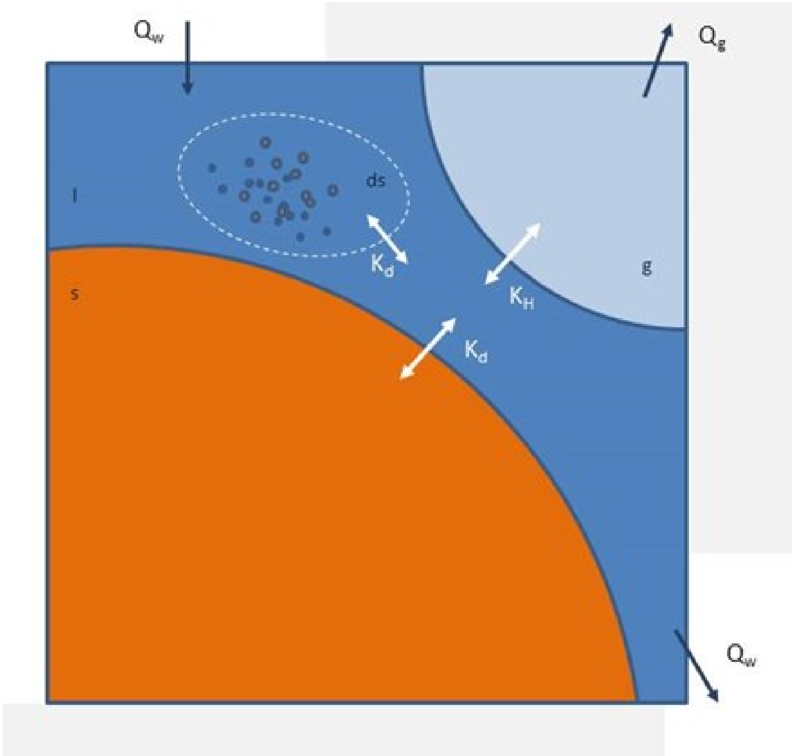

Figure 14: Equilibria in MOCLA

In addition to physical removal (stripping or flushing), a separate estimate was made of biodegradation under aerobic conditions, based on half-times of biodegradation as published in literature.

Due to the questionable assumptions in MOCLA (established equilibria all the time, no kinetic barriers, ideally stirred water phase) and uncertainty in model parameters (the distribution between leachate and solid organic fraction, k_D and dissolved organic carbon, k_{DOC}) the resulting estimate of removal of trace-components is not fullyreliable. However the evaluation does give insights in what mechanisms exist for removal of specific trace-contaminants, when waste is aerated.

This evaluation was done separately for each trace-component. Figure 15 gives an example MOCLA-calculation for benzene and xylene. The figure shows the part that is removed in one year upon aeration, while natural infiltration and leachate generation still occurs. The calculation distinguishes between stripping, as a result of flushing and as a result of reduced DOC-complexation. In red, the part is shown, that remains in the waste. For benzene it is estimated that upon aeration, physical processes might reduce leachate concentrations by 45% each year, largely as a result of stripping. For xylene annual reduction due to physical removal is estimated to be 20-25%. On top, literature shows, that BTEX in general rapidly degrades in aerobic conditions. So for benzene and xylene it is concluded, that strong mechanisms exist for removal upon successful aeration.

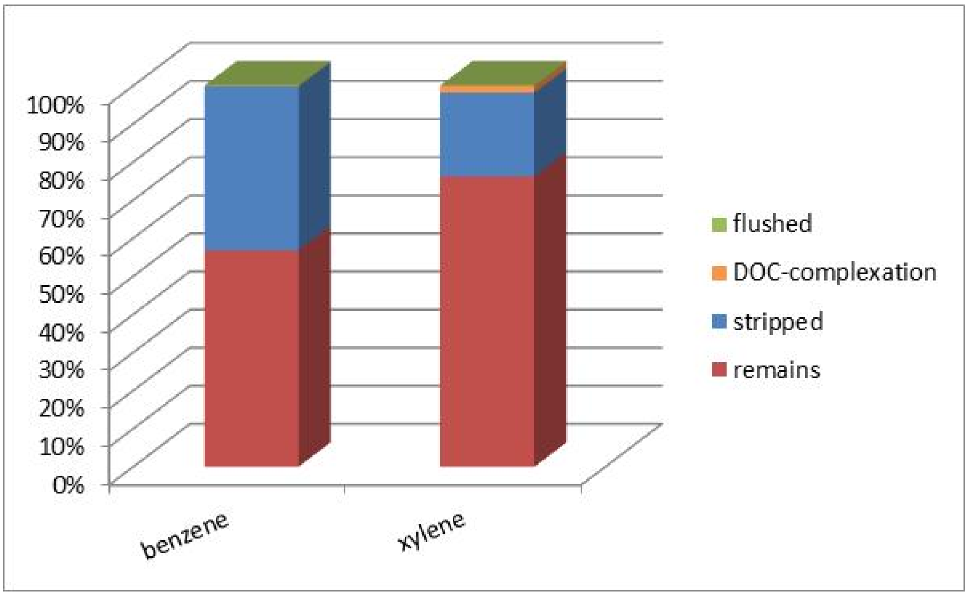

Figure 15: Equilibria in MOCLA

Effect on heavy metal concentrations

The effect of aeration on heavy metal concentrations was determined, based on experiences in the Landgraaf test-cel. At Landgraaf waste was treated by a combination of leachate recirculation and aeration. Waste was sampled before and after treatment and subjected to pH-dependent leaching tests. Tests were validated by geochemical modelling. These tests and modelling efforts gave insight in the factors that have determine leaching of the individual metals and the impact of leachate recirculation and aeration.

At Braambergen only Ni concentrations in the leachate do not meet the ETV. Concentrations of Ni are known to be determined by DOC-complexation, so when levels of DOC can be reduced NI is expected to be reduced as well. At Landgraaf this effect however was not that obvious and only 20% reduction in leaching was obtained. Here is it believed that the high initial concentrations on Ni in the waste were the cause of this and the expectation is that at lower Ni-concentrations, the correlation between DOC and Ni will be more firm.

4.3 Conclusions on feasibility of ETV's

Table 5 summarizes the of decrease in leachate concentrations required to meet the levels as specified by the ETV's (see table 4 for current concentrations in leachate and the ETV). For each contaminant in the leachate, the most relevant mechanisms are described that can contribute to the required decrease in concentration and an estimate is given of the decrease that might be achieved. This possible reduction is based on the evaluation in this chapter.

Table 5: Summary feasibility ETV in the Braambergen-pilot

	Reduction mechanisms	Possible reduction	Required reduction
Heavy metals			
As	n.c.[1)]		-
Cd	n.c.[1)]		-
Cr	n.c.[1)]		-
Cu	n.c.[1)]		-

	Reduction mechanisms	Possible reduction	Required reduction
Ni	Reduced DOC-complexation	>60%	~30-50%
Pb	n.c.[1)]		-
Zn	n.c.[1)]		-
Hg	n.c.[1)]		-
Macro-contaminants			
chloride	flushing	5-10%	40%
sulphate	Generation upon aeration	0%	0-10%
N_{kj}	Nitrification/denitrification upon aeration	50-90%	75%
Organic micro-contaminants			
mineral oil	n.c.[1)]		-
VOX	stripping, aerobic degradation	>95%	90%
PAK	reduction DOC complexation, aerobic degradation	>90%	97%
BTEX	stripping, aerobic degradation	>95%	60%
phenols	aerobe degradation	>> 90%	0%

[1)] n.c: not considered in this evaluation, since concentrations already meet the ETV.

5 Measurement strategy and monitoring programme

5.1 Measurement strategy (what do we intend to measure and why)

The measurements on the pilot serves different objectives:

- To determine success of the pilot: In other words to quantify the effect of aeration on leachate quality and emission potential of the waste. During the pilot phase, progress of improving leachate quality/reduction of the emission potential needs to be monitored to enable operational decisions and e.g. decide when aeration can be stopped.
- For legislative issues: To prove to the legislator, that risks of landfill aeration are properly managed, control measures are working and emission limits are not exceeded;
- To steer the way the pilot is operated: That is by following key performance indicators, such as biodegradation of organic carbon;
- For daily operation of the pilot: This implies amongst others the continuous optimisation of under- and overpressures of the individual gas wells air injection and extraction.
- To improve scientific understanding: Better understanding of landfill processes and the effect of aeration on these processes is required to enable improvements in design and operation of future projects.

Measurements will take place prior to start of sustainable management, during and afterwards.

- The baseline measurements. Most baseline measurements were performed in the period 2012-2013. These measurements will be finalised by waste sampling and analysis during realisation of the system for aeration. Baseline measurements are intended to determine the situation prior to start of sustainable landfill management. This established baseline allows quantification of the effect of sustainable landfill management. The baseline measurement is also intended to verify some assumptions for systems design and operation.
- Monitoring during the operational phase of the pilot focusses on (i) legislative issues, (ii) process control and if needed adaptation of the system or its operating strategy and (iii) improving our understanding of landfill processes and the effects of aeration; The
- The final measurement after the operational period is to determine the effectiveness of sustainable landfill management and to evaluate whether or not objectives are met. Prior to this final measurement, aeration should be stopped for an estimated 6-12 months in order for hydraulic conditions within the waste to stabilise again. The final measurement will take at least one year, in order to allow determination of leachate quality in all seasons.

The overall monitoring programme of Braambergen is summarised in the table below.

Table 6: Summary monitoring programme Braambergen

	parameter	before	during	after	where	how	frequency	why
leachate	amount	X	X	X	well 11N, 11Z & 12		continuous	quantification
	EC	X	X	X	well 11N, 11Z & 12		continuous	insight in hydrology
	composition (macro)	X	X	X	well 11N, 11Z & 12	lab analysis	1st year biweekly, afterward monthly	biodegradation - qualitative, effectiveness aeration, emission potential
	composition (complete)	X	X	X	well 11N, 11Z & 12	lab analysis	1st year 6 times; afterwards 4 times a year	biodegradation - qualitative, effectiveness aeration, emission potential
	fractionation DOC	X	X	X	well 11N, 11Z & 12	lab analysis	1st year 6 times; afterwards 4 times a year	biodegradation - qualitative, effectiveness aeration, emission potential
	level leachate well	X	X	X	well 11N, 11Z & 12	pressure sensor	continuous	insight in hydrologie, legislation
ground water	composition	X	X	X	monitoring wells	lab analysis	according to legislation	legislation
landfill gas	volume	X			extraction test	anemometer	4 times during baseline-measurement	biodegradation - quantitative
	composition	X			extraction test	sampling	4 times during baseline-measurement	biodegradation - quantitative
aeration air	flow, volume, pressure and temperature		X		distribution station	continuous	registration per week	process control, biodegradation - quantitative
extracted air	flow, volume, pressure and temperature		X		distribution station	continuous	registration per week	process control, legislation
aeration well settings	flow, druk, temperatuur, kleppenstand		X		distribution station	installed equipment	according to specification supplier	contract management
	flow, volume, pressure and temperature		X		distribution station	continuous	registration per week	biodegradation - quantitative
methane emissions	diffuse emissions	X	(X)	X	top layer	FID-screening	once during baseline-measurement	legislation
settlements	height at settlement plates	X	X	X	top of landfill		2 times per year. 12 settlement plates	biodegradation - qualitative
heterogeneity and scale	geophysical measurements	(X)	(X)	(X)	top of landfill		ad-hoc. 1-3 times during project period	effectiveness aeration
	tracer test			X	leachate system		once	insight in hydrology
	gas-tracer test		X		gas injection		ad-hoc	effectiveness aeration
waste sampling	water content	X		X	waste samples	lab analysis	before and after test	insight in hydrology
	water storage capacity	X		X	waste samples	lab analysis	before and after test	insight in hydrology
	respiration test	X		X	waste samples	lab analysis	before and after test	biodegradation - quantitative
	leaching test (column-test)	X		X	sample mixture	prEN 14997	before and after test	emission potential
	leaching test (batchtest)	X		X	waste samples	NEN 7373	before and after test	emission potential
	leaching test (pH-stat)	X		X	sample mixture	EN 12457-2	before and after test	emission potential
meteorological ata	temperature, atmosferic pressure, precipitation, humidity, wind speed	X	X	X	local weather station		daily	generic interpretation

leachate composition macro's is pH, Eh, DOC, Cl^-, N_{kj}

leachate composition complete is pH, Eh, COD, TOC, BOD, TKN, NH_4^+, $NO3^-$, NO_2^-, Cl^-, phosphate, heavy metals, BTEX, phenols, sulphides, VOX, PAH

5.2 Measurements performed

5.2.1 Measurement leachate and leachate composition

General

The amount and composition of the leachate is important to evaluate to what extent leachate concentrations meet the ETV. The way various parameters need to be measured and the way the measured values are interpreted is described in the 'Guidelines on use of the ETV' ('Handreiking gebruik emissietoetswaarden', I&M, 2014). The pilots are used to evaluate and if possible improve the guidelines and for this reason, concentrations are measured more frequently as specified in the guidelines.

Adaptation leachate wells and pumps

The drainage system on compartments 11 and 12 consists of 3 separated parts, each draining in a separate collection sump (PP11N, PP11Z, PP12). The amount of leachate as the leachate composition will be monitored for all three collection wells. So the monitoring programme for amount of leachate and its composition will proceed in threefold. To enable monitoring, leachate sumps are adapted prior to the baseline measurements and equipped with a pump, sensors and a sampling point, as indicated in the figure below.

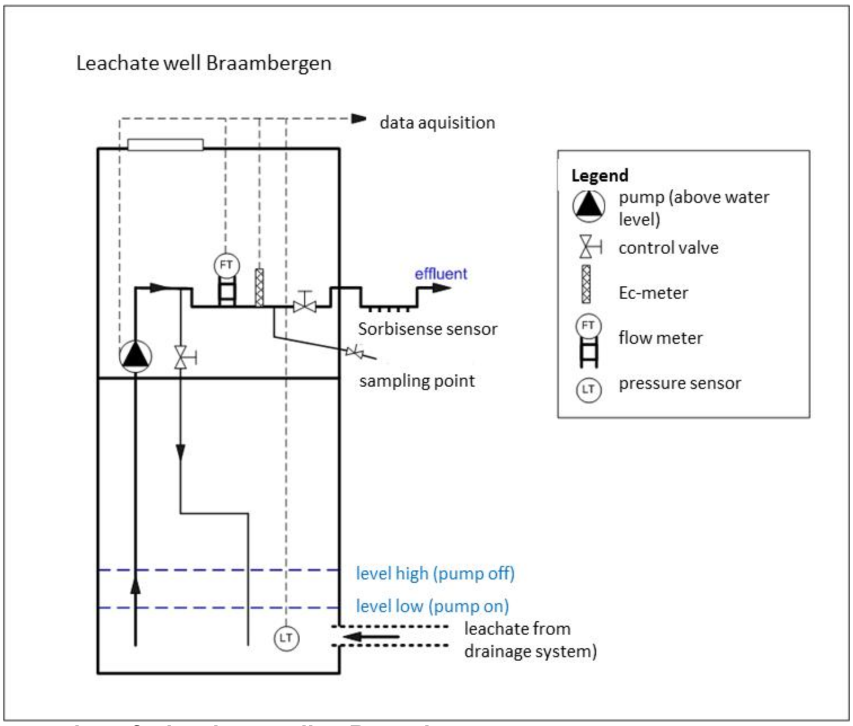

Figure 16: instrumentation of a leachate well at Braambergen

Leachate composition

Leachate composition will be measured at various frequencies:

1. EC and leachate temperature will be measured with a sensor and registered every 15 minutes.

2. High frequency: Eh, pH, Cl^-, NH_4^+, SO_4^{2-}, HCO_3^- and DOC are measured once every two weeks by leachate sampling, followed by measurement of pH and EC in the field, and other parameters in the lab. The measurement frequency will be reduced to once a month, when concentrations prove to be relatively stable.
3. Moderate frequency: Na, K, Ca, Mg, Si, Al, Fe(tot), Mn(tot), As, Ba, Cd, Cr (tot), Co, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sn, V, Zn, HCO_3^-, Cl^-, NO_3^-, PO_4(tot), NH_4^+, N_{kj}, SO_4^{2-}, S^{2-}, TOC, F^-, and DOC are measured once in two months, by sampling and lab-analysis. The measurement frequency may be reduced, when concentrations prove to be relatively stable or are well below the concentration targets as defined by the ETV.

Amount of leachate

For improving the scientific understanding of the hydrology of the waste, leachate generation is monitored with a high frequency (every 15 minutes). To enable this, Afvalzorg has reduced the capacity of the pumps in the three leachate sumps and changed to way the levels are controlled. The leachate pumps are now controlled by the level in the leachate well. The level in the sumps is measured using pressure sensors. The pump switches on, when the high level is reached again and switches of again when the level is low. The difference between high and low level is kept to a minimum. In this way, the actual generation of leachate in time is reproduced as accurately as possible. At the same time the amount of leachate in the drainage system and on top of the bottom liner is minimised.

All three sumps are equipped with a cumulative flow-meter. Every 15 minutes the cumulative flow is registered, along with level, number of times the pump switches on and off and the running hours of the pump.

5.3.2 Leaching potential of the waste

Waste composition and leaching potential of the waste will be determined by sampling and analysis of waste. The way waste will be sampled and pre-treated will be based on experiences gained in the Landgraaf test-cell. Here, waste proved to consist of a fraction of fines(<< 5-10 cm): a mixture of sand, largely degraded organic material and small parts of plastic, glass, etc. The rest of the waste was much larger in size. Sampling focussed on the fines, while the fraction of fines in the total waste was determined. Analysis of leaching potential and remaining gas potential will also be based on this fines fraction. So in this project the contribution of the larger fraction to leaching potential and remaining gas potential is assumed to be negligible and is neglected[2]. The sampling size was about 20 litres. Samples are dried and loss of weight upon drying is measured. Inert materials (stones, plastics, metals) are removed and both the amount of inert and the residue are weighed. The residue is subsequently decreased in size to a fraction < 1 cm.

Analyses focus on:

- The remaining gas potential which is determined in a respiration test over 21 days for several sample mixtures.
- Different leaching tests: (i) column test of a sample mixture to determine the leaching behaviour of various components; (ii) for a sample mixture a batch leaching test at varying pH, which gives insight in the physical processes hat determine component leaching; (iii) batch leaching tests on all samples to get insight in heterogeneity of the material.
- A speciation of the organic material, so analysis of humic substances, most likely according to methods developed by ECN/WUR (van Zomeren, 2008)

[2] This is an essential difference with e.g. determining calorific value of waste. This is largely determined by the course material and this makes sampling procedures for calorific value completely different.

5.3.3 Diffuse emissions to air

Methane emissions are characterised by FID-screening of the surface, according to “Guidance on monitoring landfill gas surface emissions” by UK-EA (2008). Surface screening gives a only qualitative impression of methane emissions, but might be used to assess whether emissions increased during the test.

During periodic inspections of the system, attention will be paid to odour emissions. In case odour emissions are observed, the cause will be identified and the problem will be solved. When odour emissions are considered significant, odour panels might be used to characterise the magnitude of emissions.

5.3.4 Landfill gas generation, amount of air injected and extracted

Landfill gas generation

Maximum landfill gas generation for compartment 11 and 12 was investigated in the period 2011/2012 in a dedicated test-programme. In this programme, under-pressure was gradually increased and landfill gas collection was maximised for each individual well, while collection at the other wells was stopped.

Amount of injected air composition and temperature of injected and extracted air.

Flow, pressure and temperature of the injected air will be measured at place where air is distributed to the single wells (the gas distribution station near the gas compressor). For extracted air, composition will be measured as well. Upon design of the gas distribution system, provisions have to be made to enable these measurements. Periodically pressure on each injection/extraction well will be monitored and adjusted to enable an even distribution of air over the waste. The results of these measurements will be logged as well.

Settlements

Settlements will be determined, by measuring the position of the settlement plates.

5.3.5 Additional tests

During the project additional tests will be performed, aiming at improved understanding of landfill processes and the effectiveness of aeration. Most additional tests are not standardised, but are of an experimental nature. So tests will be performed in close cooperation with universities. Two important ones are:

Geophysical measurements

Geophysical measurements are a tool to characterize heterogeneity in the system. These tools produce the distribution of some physical parameter of the waste, e.g. conductivity/resistivity in the waste or stiffness. Interpretation in terms of more practical applicable physical parameters (e.g. water content, gas filled porosity, permeability) is still in development. It is expected that geophysical measurements will be performed on some pilot locations. Geophysical measurements seem to be better applicable at De Kragge II, where leachate is recirculated. Application at Braambergen is less likely, but can at the moment not be excluded.

Tracer-tests

After completing the pilot, a tracer test might be considered. The objective of a tracer-test is to characterise hydrology in the waste, to quantify preferential flow and mass-transfer from stagnant zones to mobile leachate. In such a tracer-test a component (the tracer) is added to water, that is infiltrated in the waste. Subsequently the release of the tracer is measured again and the results are interpreted. A tracer-test can imply that the hydraulic head on the bottom liner is increased by several meters for a short period of time (a few weeks to 3 months). As a tracer, components might be used that do not occur naturally in leachate, but can be considered harmless.

Examples of tracers are Li, Br or specific dyes. A tracer-test can result in valuable information about hydrology in waste, but requires quite some effort.

5.3.6 Precipitation and other meteorological data

Meteorological data (precipitation, temperature, atmospheric pressure, humidity, wind-direction and speed) is registered with an on-site weather station and logged every 15 minutes.

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Note: (Many publications are available through www.duurzaamstortbeheer.nl)

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Appendix 1: Amounts of waste at Braambergen, compartments 11 and 12.

	Soil and soil decontamination residues	Construction and demolition waste	Commercial waste	Shredder waste	Street cleansing waste	Coarse domestic waste	Sludge and composting waste	Household waste	Total
1999	13,205	5,078	48,325	109	325		3,223	21943	92,208
2000	31,278	14,351	27,741	798	134		3	13830	88,135
2001	34,382	15,066	16,453	1,539	638	1,933	1,697		71,708
2002	97,127	4,354	9,505		300	499	41		111,825
2003	120,299	6,026	4,623	6,948			275		138,171
2004	236,913	2,267	607	1,881			73		241,741
2005	227,036	6,708	4,888	295		2,006	94		241,028
2006	129,704	5	10,761	163					140,632
2007	75,894		195	4					76,092
2008	15,181								15,181