Notitie

Subject: **Project plan Sustainable Landfill Management De Kragge 2**

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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 At De Kragge 2. The pilot will be performed at compartment 3 of this landfill, which measures 5.6 ha in surface and contains 1,000,000 ton of waste, including large amounts of organic waste.

1.2 Objectives of the pilot at De Kragge 2

The main objectives of the pilot at De Kragge 2 (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 De Kragge 2

2.1 General characteristics of the landfill

The landfill De Kragge 2 is located in Noord-Brabant, near the city of Bergen op Zoom. The landfill is in exploitation since 1990. Formally the landfill is still operational, however since 2009 no waste was deposited. In total, De Kragge 2 contains about 2.5 million ton of waste on 16 ha surface. The height of the landfill is 20 m at maximum. Waste deposited is a mixture of predominantly household waste, commercial waste and demolition waste. The landfill consists of 4 compartments. The pilot will take place at compartment 3 of the landfill. Table 1 gives some characteristics of this compartment.

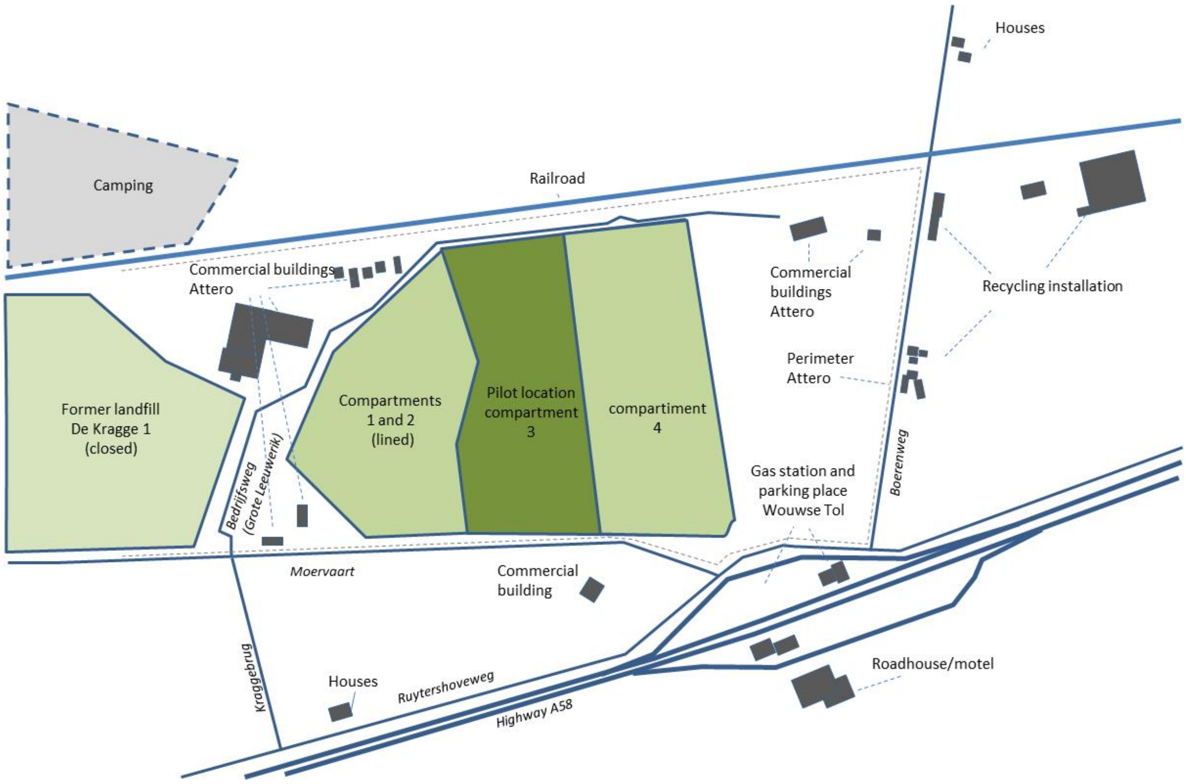

Figure 1: Situation De Kragge 2

Table 1: General data for compartment 3

Total surface	ca. 5.6 hectare
Time in operation	1999-2008
Total amount of waste	999,880 ton
Height of the landfill	On average 17 m. Maximum height about 20 m.
Current landfill cover	Sandy soil
Landfill gas extraction	17 gas wells
Bottom liner	2 mm HDPE-liner
Leachate drainage and collection	Single drainage system, separated from the other compartments

Bottom liner and leachate collection

All compartments at De Kragge 2 are lined at the bottom with a single 2 mm HDPE-foil. Leachate is collected separately for all four compartments. The compartments are separated at the bottom with quays of 2 meters high. Every compartment has its own drainage system and a separate sump, where leachate is collected. Leachate from all four collection sumps are pumped into an influent sump. From this influent sump, leachate is transported by tanker cars to another Attero-location for treatment.

Ring ditch

A ring ditch, surrounding the landfill, collects run-off water from the landfill. The ring ditch is located within the perimeter, sealed by the HDPE-bottom liner. The ring ditch has a provision that enables separation of mildly polluted water with and clean water. Clean water in the ring ditch is sampled periodically before it is purged on surface waters. Mildly polluted water is drained on the local sewer.

Top cover

Compartments 1 and 2 of De Kragge 2 and a small part of compartment 3 are sealed by a bottom liner. Compartments 3 and 4 are covered by sandy soil.

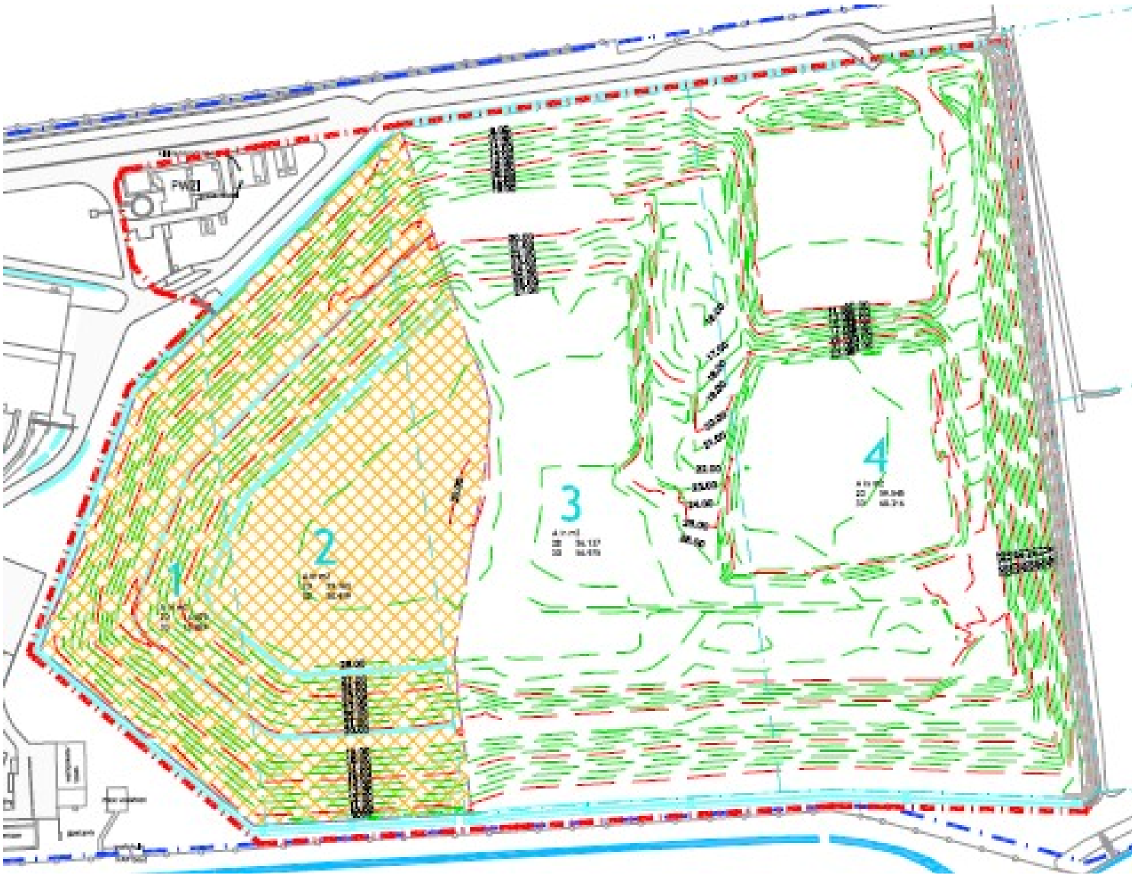

Figure 2: Top cover at De Kragge 2. The lined part of the landfill is shaded.

Landfill gas collection

Landfill gas is collected using vertical wells. Every 3-5 wells are clustered by a gas collection well. In total De Kragge 2 contains 8 clusters of wells (indicated by CP1-8). The dispersion of gas wells over the landfill does not correspond with the compartments. Most collection wells collect gas from different compartments and as a result, landfill gas collection from compartment 3 is not easily determined separately. For compartment 3 CP1, CP2, CP4, CP5 and CP7 are of importance. CP2 and CP4 collect as well gas from compartment 2; CP 1 collects as well gas from compartment 4. CP5 collects gas from 5 wells, two of which are located on the border of compartment 3 and 4. CP7 collects gas from 6 wells, one of which is located on compartment 3.

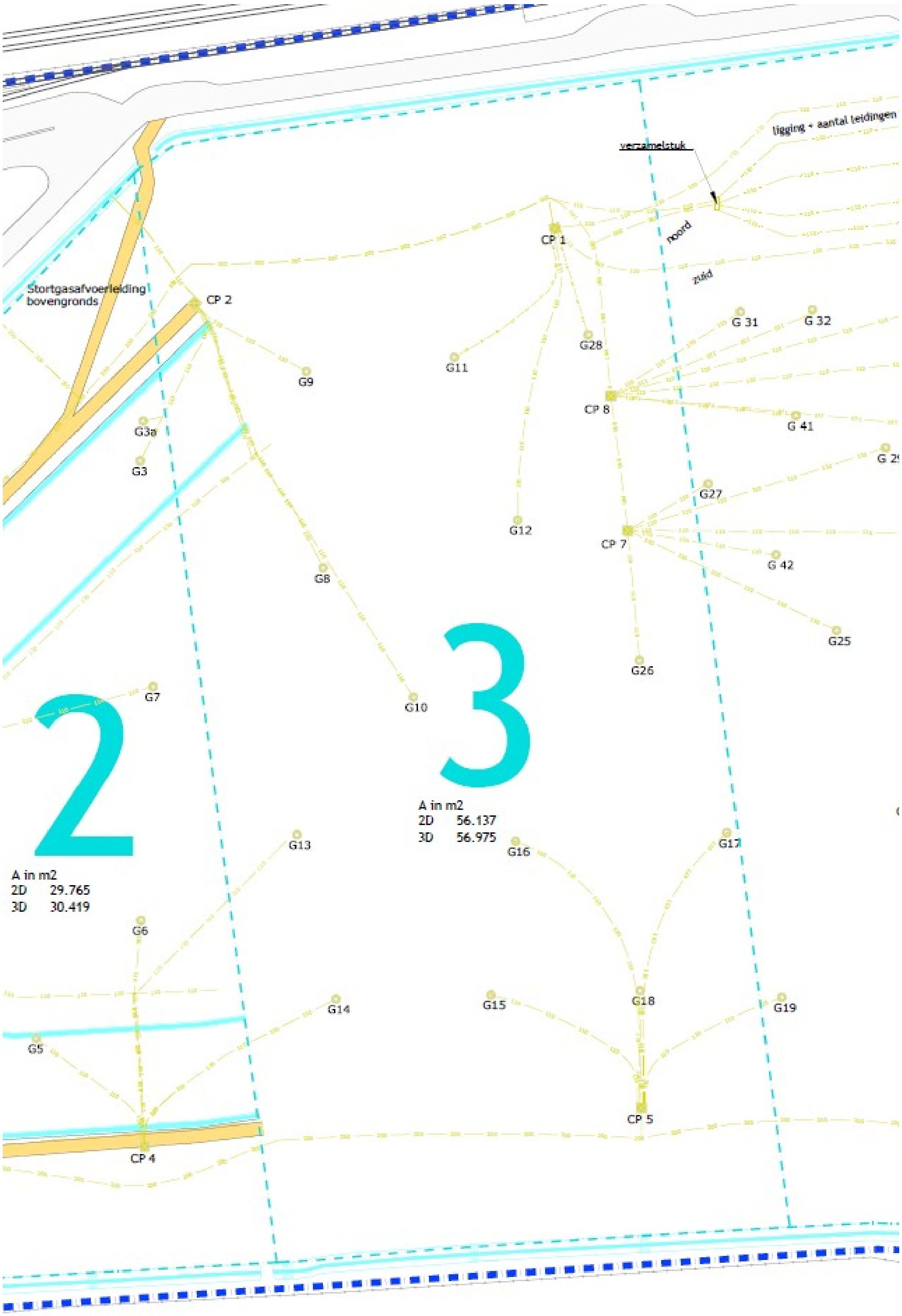

Figure 2: System for landfill gas recovery at compartment 3

In total landfill gas in compartment 3 is collected by 17 wells. The well density is 3 per ha and the distance between wells is 70 meters at maximum. The suction pressure on the collection wells is once a week adapted to changes in gas quality, and the aim is to collect gas with a methane content of 45 vol%, which is the This is the minimum quality required for use of landfill gas in the engines at De Kragge 2. The system therefore meets the criteria for state of the art landfill gas collection as defined by SenterNovem (2005).

Groundwater monitoring

Possible dispersion of pollutants from the waste to the surrounding is monitored by sampling control drains below the bottom liner and monitoring wells around the landfill (see figure 4). Since 1990, every individual control drain and monitoring well is sampled twice a year and sampled for pH, EC, N_{Kj}, CZV, EOX, VOX, BTEX, mineral oil, Cl^-, sulphate, cyanide, and the heavy metals As, Cd, Cr, Cu, Hg, Ni, Pb, Zn.

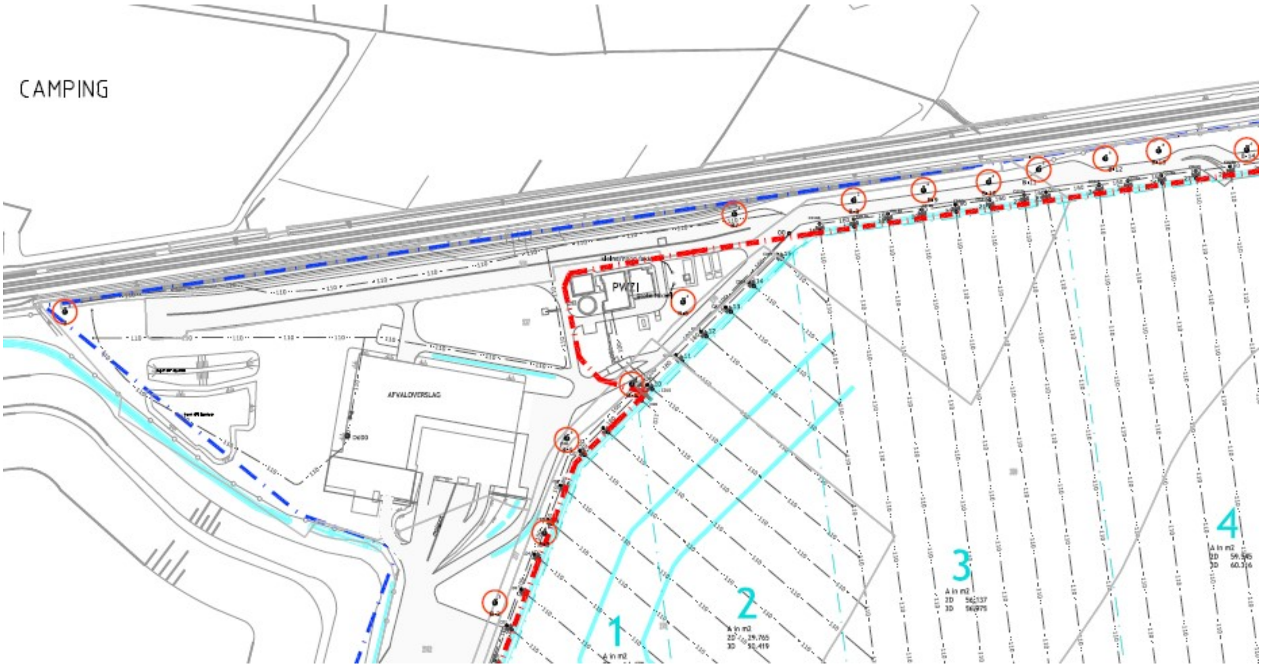

Figure 3: Control drains and monitoring wells around De Kragge 2.

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 De Kragge 2

Leachate	20,000-30,000m^3/year; about 50% of this is produced by compartment 3
Gas collection	200 m^3 STP/hr landfill gas @ 45 vol% CH^4
Settlements	0,7-1,2 cm per year

Amount of waste and waste composition

The amount of waste landfilled, was measured on weighing bridge and registered, along with its origin. So the amount of waste and the type of waste is well-known. Only the distribution of waste over the compartments was mixed up on the course of time. During the baseline measurements, the volume of waste was assessed and based on this the attribution of waste to compartments 3 and 4 was reconsidered. Table 3 gives an overview of waste in compartment 3. Appendix 1 gives a more detailed specification of the amount of waste landfilled in each year.

Table 3: Amount and origin of waste, landfilled De Kragge 2, compartment 3 (in ton)

Domestic waste	291,427
Coarse domestic waste	126,598
Commercial waste	212,480
Construction and demolition waste	213,601
Sludge and composting waste	146,737
Shredder waste	63
Soil and soil decontamination residues	8,974
Total	999,880

Prognosis of gas generation and actual gas collection

Based on the amounts of waste in Appendix 1 a prognosis was made of the amount of landfill gas, generated both at the entire landfill De Kragge 2 and at compartment 3. This calculation was based on the most recent version of the Afvalzorg methane generation model (version March 2014). The figure below describes the result. Landfill gas is collected since the end of the 90's. The amounts of gas collected are registered each month and for the entire landfill. No separate data are available for the individual compartments.

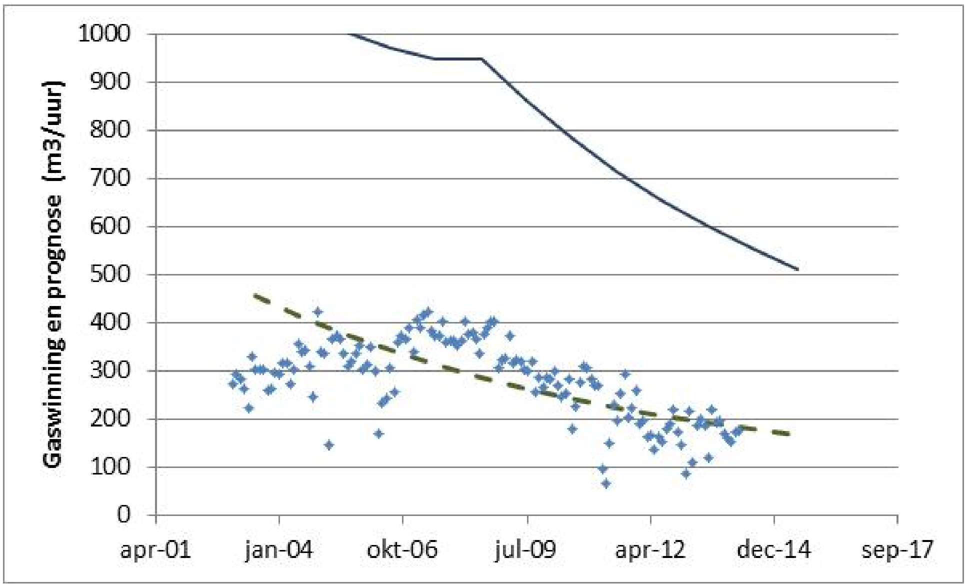

Figure 4: Prognosis of landfill gas generation (straight lijn) and monthly average collection (dots) at De Kragge 2. The prognosis for compartment 3 is indicated by the green, dashed line. All data are in m^3 per hour.

Annual leachate generation and excess precipitation

During the baseline measurement, the amount of leachate was measured, that was removed from the leachate sumps at compartments 3 and 4. Because leachate is transported to another Attero location for treatment and the load of the tanker cars was measured, amount of leachate produced for the entire location are available from 2001 onwards. Note: compartment 1 and 2 are sealed with an impermeable top-liner. Leachate generation here is considered negligible.

Table 4: Annually removed amounts of leachate (m^3) at De Kragge 2

	Compartment 3 (m^3)	Compartment 4 (m^3)	Total tanker cars (ton)
2001	-	-	29,186
2002	-	-	43,050
2003	-	-	21,848
2004	-	-	22,546
2005	-	-	18,650
2006	-	-	19,716
2007	-	-	21,147
2008	-	-	28,395
2009	-	-	23,166
2010	-	-	22,139
2011	-	-	36,311
2012	-	-	31,492
2013	14,435	20,199	34,594

Precipitation at De Kragge 2 is measured since the year 2000. In 2011 precipitation was 779 mm. The area of compartment 3 and 4, that is not lined is 11.5 ha, so total precipitation on the unlined part of the landfill is 90,000 m^3. In 2011 about 1/3rd of this (315 mm per year) was obtained as leachate, which is in good agreement with the rule of thumb for Dutch excess rainfall: 300 mm per year.

Composition of leachate in comparison to the ETV

Measurements of leachate composition are available from 2006 onwards. On average twice a year, leachate was sampled and analysed for both the leachate sump of compartment 3 and 4. During the baseline measurements, starting June 2012 to the end of 2013, sampling and analysis was intensified. Macro-contaminants were measured twice a week (in total 39 times); heavy metals once in 8 weeks (in total 10 times) and organic micro-contaminants in total 3 times. Table 5 gives the average concentrations in 2013 (Attero, 2014). Values of the organic micro-contaminants are based on all available measurements. 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 5.

The last column in table 5 gives the emission test values (ETV) for De Kragge 2.

Table 5: Leachate composition De Kragge 2 in 2013

	Compartment 3	Compartment 4	ETV
Heavy metals	**ug/l**		
As	104	95	100

Cd	0.10	0.10	3.6
Cr	623.3	813.3	140
Cu	5.3	25.8	64
Hg	0.05	0.05	4.1
Pb	0.8	11.8	130
Ni	203	136	47
Zn	52	106	120
Cyanide (free)			6.8
Macro parameters	mg/l		
Chloride	1490	1370	160
Sulphate	5	74	200
$N_{Kjeldahl}$/ammonium	2100	1490	50
Mineral oils	**ug/l**		
Sum mineral oils	380	880	270
VOX	**ug/l**		
vinylchloride			0.014
dichloromethane	0.05	0.05	0.014
1,1 dichloroethane	0.14	0.10	1.4
1,2 dichloroethane	0.16	0.15	4.1
1,1 dichloroethene	0.19	0.17	0.014
1,2 dichloroethene (cis,trans)	0.20	0.18	0.014
dichloropropane (1,2)			1.1
dichloropropane (1,3)			1.1
trichloromethane (chloroform)	0.01	0.01	1.4
1,1,1 trichloroethane	0.01	0.01	0.014
1,1,2 trichloroethane	0.01	0.01	0.014
trichloroethene (tri)	0.01	0.01	14
tetrachloromethane (tetra)	0.01	0.01	0.014
tetrachloroethene (per)	0.01	0.01	0.014
PAH	**ug/l**		
naphtalene	10	3.1	0.014
phenantrene	6.5	5.9	0.016
antracene	0.8	0.7	0.0038
fluoranthene	3.9	4.7	0.033
chrysene	0.5	0.7	0.033
benzo(a)antracene	0.7	0.9	0.0011
benzo(a)pyrene	0.3	0.4	0.0054
benzo(k)fluoranthene	0.1	0.2	0.0044

indeno(1,2,3cd)pyrene	0.1	0.2	0.0044
benzo(ghi)perylene	0.2	0.3	0.0033
sum PAH (10-VROM)	23	17	1.1
BTEX	**ug/l**		
benzene	2.4	1.9	0.27
xylene	22	12	0.27
toluene	12	3.3	1.4
ethylbenzene	15	7.3	1.4
Phenols	**ug/l**		
Phenols (total)	1813	840	0.27

The figure below gives an indication of trends in concentrations of Cl^- and NH_4^+. This figure illustrates the variability of measured concentrations during the baseline measurements. In 2006, high concentrations were observed, which were never found anymore afterwards, This might suggests a slight autonomous decrease in concentrations. But due to lack of frequent data before June 2012, an autonomous trend can not be determined.

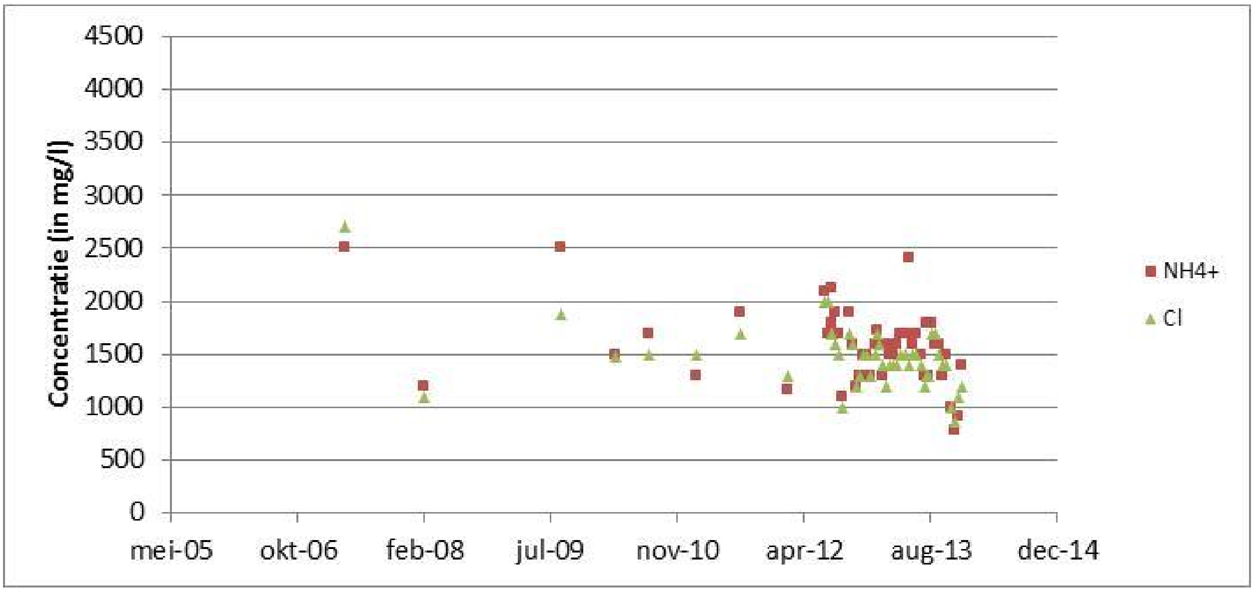

Figure 5: Trend in leachate quality in compartment 3

Settlements

Settlement at De Kragge 2 are measured at 21 locations on compartment 3 and 13 positions on compartment 4. The development of settlements in the period 2007-2013 is depicted in Figure 7. Settlements on compartment 3 have gradually reduced over time and are limited to on average 5 cm per year. Compartment 4 is about 6-8 years younger and settlements are higher on average and also more variable in place and time. Settlement of the top of the landfill are caused by settlement of the waste and settlement of the subsoil. Both effects are not measured separately. However the main conclusion is, that settlements at compartment 3 is limited, and this assumption is robust and independent of a possible contribution of settlements of the subsoil to total settlements.

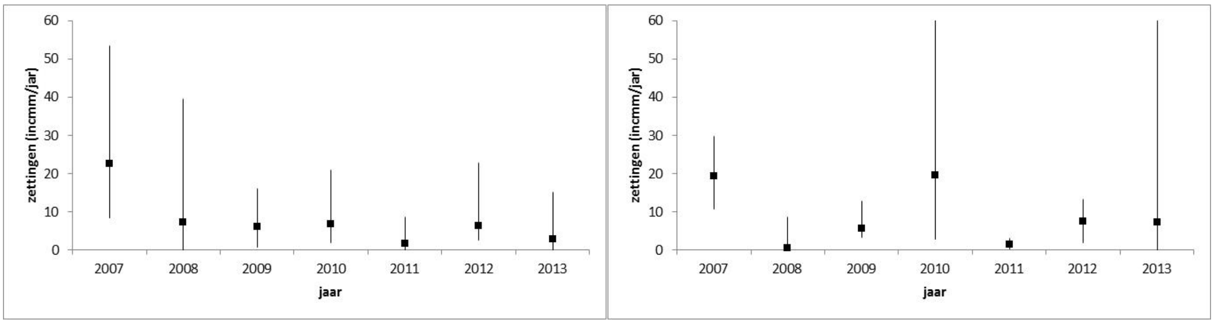

Figure 7: Development of settlements (average, minimum and maximum) on compartments 3 left) and 4 (right).

3 Choice of technology

3.1 General approach

Sustainable landfill management at compartment 3 of Kragge 2 will consist of two phases. In a first phase, leachate will be recycled and afterwards the waste will be aerated. This approach was already proposed in the feasibility study by Van Vossen et al. (2009). The main reason for Van Vossen et al. to follow this approach was the relative high amount of remaining biodegradable organic carbon in the waste. As a result, full stabilisation through aeration requires too much air and aeration becomes more costly. Therefore a first stage was proposed in which leachate was recirculated and anaerobic decomposition is enhanced by leachate regeneration. Upon leachate recirculation, part of the costs are off-set by additional revenues of gas collection.

After 2009 the project and its objectives was further developed in discussions with the Dutch government. As a result of these discussions, the main objective shifted from enhancing biostabilisation to the reduction of the emission potential of the landfill for a wide range of components. This conformed the approach defined by van Vossen et al. (2009). The first stage of leachate recirculation enables a robust reduction of N_{kj}, DOC and Cl^-. However to achieve sufficient reduction, recycle rates need to be high; N_{kj} needs to be removed from the recycle stream and large part of the leachate needs to be drained as well (see also chapter 4). Most organic micro-contaminants seem to be best removed by aeration, so an aerobic treatment phase will be required as well. But also during aeration, some degree of flushing will still be required to bring e.g. Cl^--concentrations in the leachate to acceptable levels.

In a first estimate, leachate recirculation will last 5 years. After these 5 years, the effects of leachate recirculation will be evaluated and decisions will be made for the next 5 years. At this moment it is assumed, that in the 2nd period of 5 years the waste will be aerated.

Figure 8 depicts the system of leachate infiltration, along with an indication of water streams involved (estimated on basis of calculations in chapter 4). About 300-500 mm per year will be drained to remove pollutants (N_{kj}, Cl^-, DOC) from the waste. The remainder will be infiltrated in the waste. When excess precipitation does not suffice to keep the water balance, additional surface water will be used as a supplement. Prior to infiltration, N_{kj} will be removed from the leachate, thus achieving an additional reduction of N_{kj}-concentrations in the leachate.

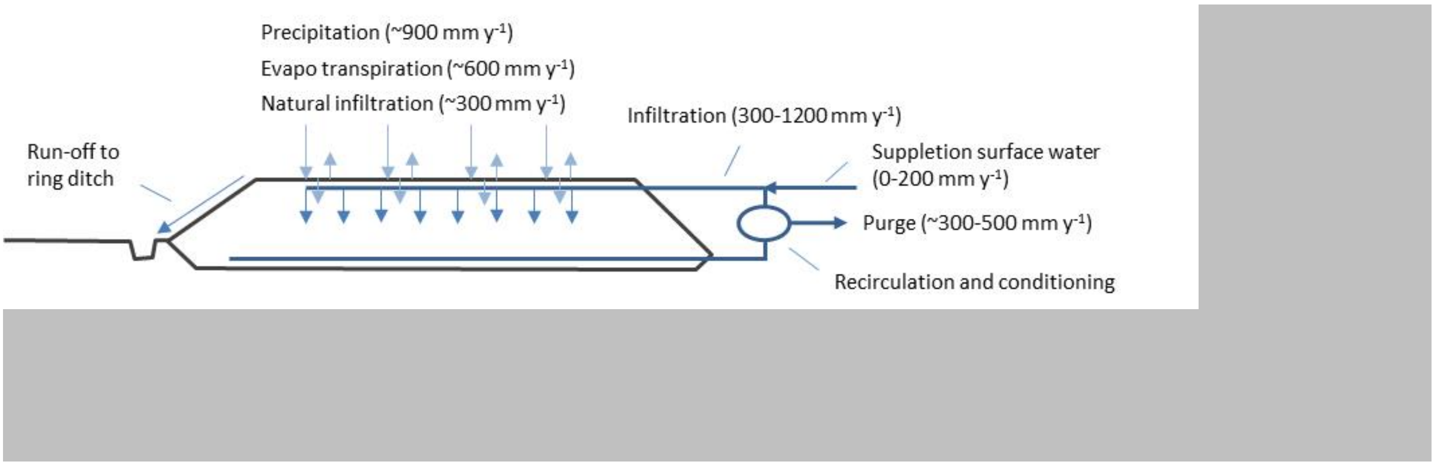

Figure 8: Water streams upon infiltration

3.2 Detailed design of the system for infiltration

The figure below gives the most important elements for the system for leachate infiltration at De Kragge 2. The system will most likely consist of the following:

- Leachate will be transported from the leachate sump PP3 to the existing waste water treatment at De Kragge 2.
- Here, leachate will be collected, if necessary temporarily stored and subsequently conditioned. The current waste water treatment plants consists of (i) an influent buffer; (ii) two nitrification basins; (iii) two denitrification basins; (iv) a settlement tank for sludge removal and (v) a drain for the effluent. According to current plans, the recirculated leachate will first be heated (using waste heat from the engine, utilising landfill gas) and subsequently treated in a partial nitritation reactor. During the start-up years, part of the effluent of the nitritation reactor will be treated in a MBBR (anammox process moving bed biofilm reactor) this is expected to stimulate an in-situ anammox process, once leachate is infiltrated, thus removing additional part of the ammonium in the waste.
- Both pre-treated leachate flows will be combined and pumped into a water buffer on top of the landfill.
- From the water buffer, leachate is fed to the various leachate infiltration wells.

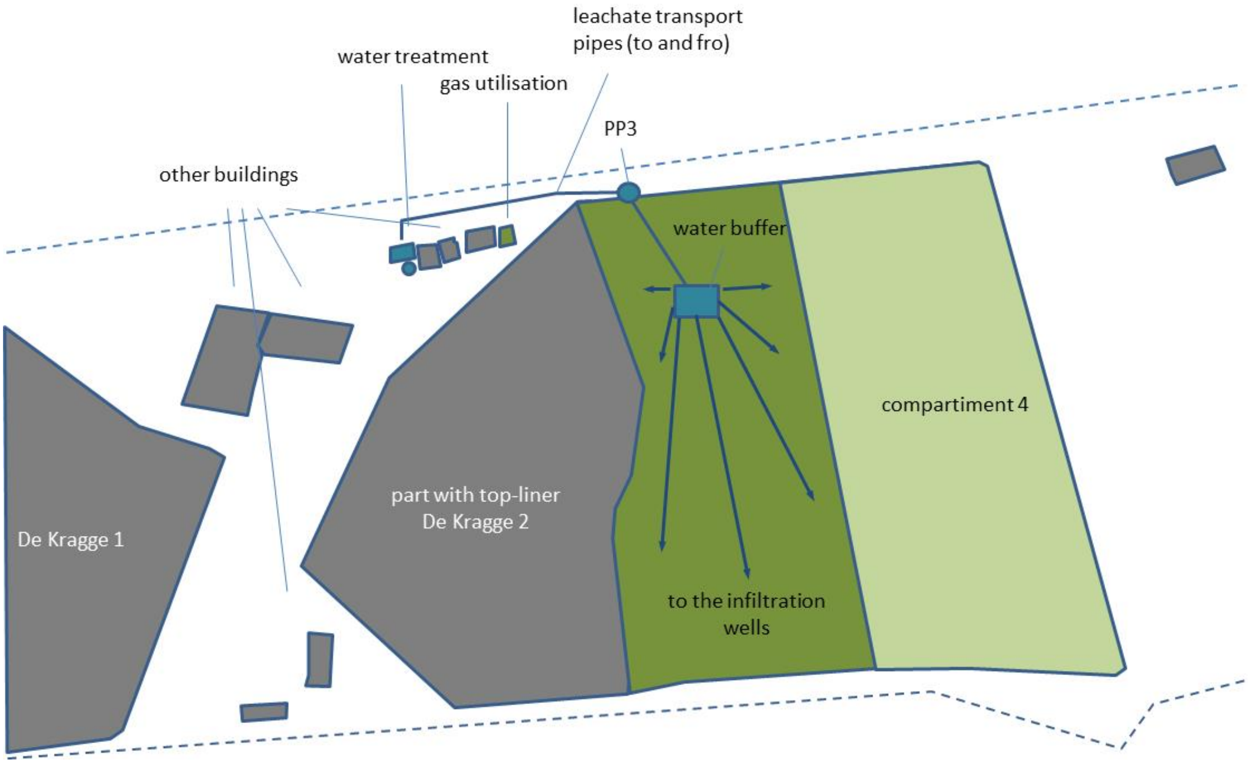

Figure 9: Overview of the infiltration system at De Kragge 2

No decision is made on the system for infiltration. At the moment four systems are considered, two of which are proposed by van Vossen et al. (2009): infiltration fields and shallow vertical wells (see figure 10). On top, horizontal drains and clusters of vertical wells are considered. Horizontal drains proved to be effective in our previous bioreactor demonstration in Landgraaf. Clusters of vertical wells are a new development, in which leachate is injected at varying depth.

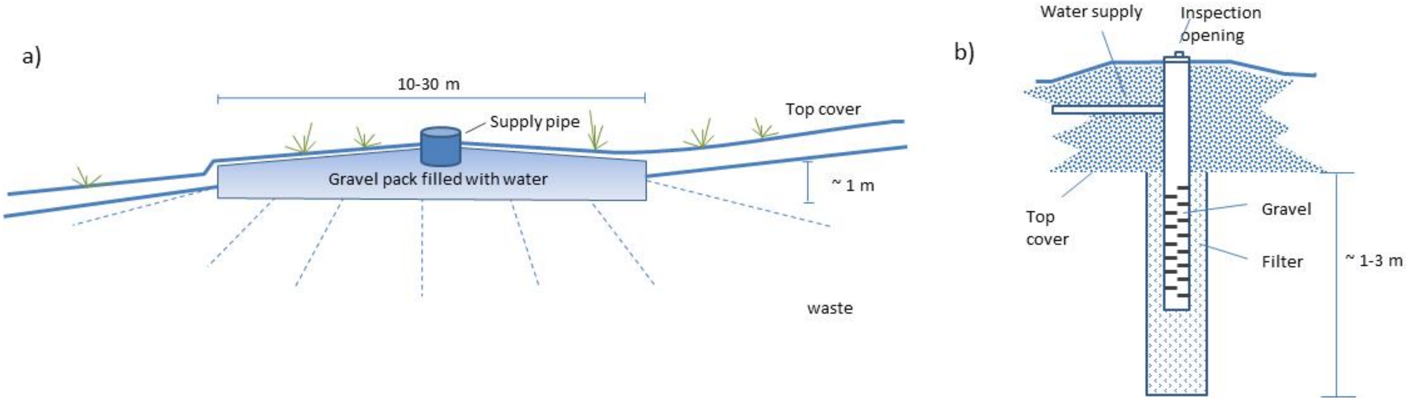

Figure 10: Infiltration of leachate in waste by infiltration fields (right) and shallow vertical wells (right)

3.3 Design of system for aeration

No decision has been made on the way waste will be aerated, during the second phase of sustainable landfill management. At the moment, two aeration pilots are prepared Wieringermeer and Braambergen and these pilots will run in parallel to the first phase at De Kragge 2. Experiences gained in those two aeration pilots will be used to design the aeration in the second phase at De Kragge 2. Most likely one of the methods, explored at Wieringermeer and Braambergen (low-pressure aeration and over extraction) will be implemented at De Kragge 2 as well.

4 Processes in waste and expected effects of sustainable landfill management

4.1 Qualitative effect of sustainable landfill management 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 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 part of these pollutants will not be released at all. As a result effective L/S is increased and the leachate quality increases 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 with landfill gas or 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 concept 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 improvise 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 leachate recirculation and 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 (25-75% when the waste is intensively flushed) and C2 is the correction factor for incomplete flushing (50-80%, when the waste is intensively flushed).
- Removal of NH_4^+ both ex-situ upon conditioning of the leachate, prior to recirculation and in-situ as a result of Anammox. For both processes, an overall removal efficiency is assumed (80-95%) and the contribution of in-situ Anammox to this removal efficiency (10-50%)
- 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. 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 leachate recirculation and 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 sustainable landfill management on the amount of biodegradable organic carbon in the waste. This prognosis is made, using the Ecofys-model.

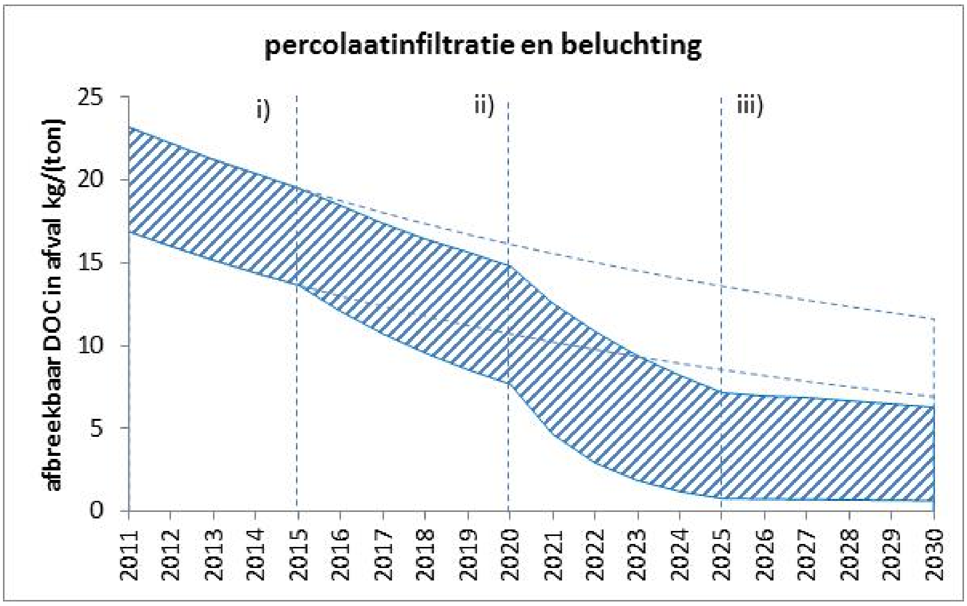

Figure 11: Development of the amount of degradable organic material in the waste. The vertical lines indicate: (i) start of leachate recirculation in 2015; (ii) start of aeration and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2015.

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 sustainable landfill management at De Kragge 2, compartment 3. 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.

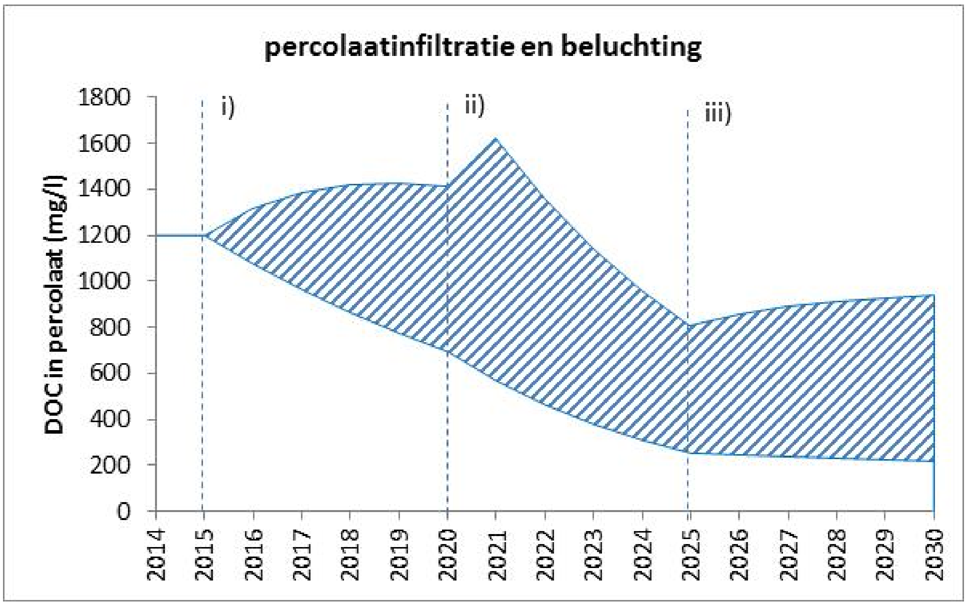

Figure 12: Development of DOC in leachate. The vertical lines indicate: (i) start of leachate recirculation in 2015; (ii) start of aeration and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2015.

Reduction of ammonia in leachate:

Ammonia concentrations in the first stage of treatment (leachate recirculation) are affected by release of ammonia upon biodegradation, removal upon flushing, conditioning of leachate and removal through Anammox. In the second stage (aeration), nitrification, denitrification and stripping are of importance. The figure below gives the expected overall effect on ammonia concentration in leachate. 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.

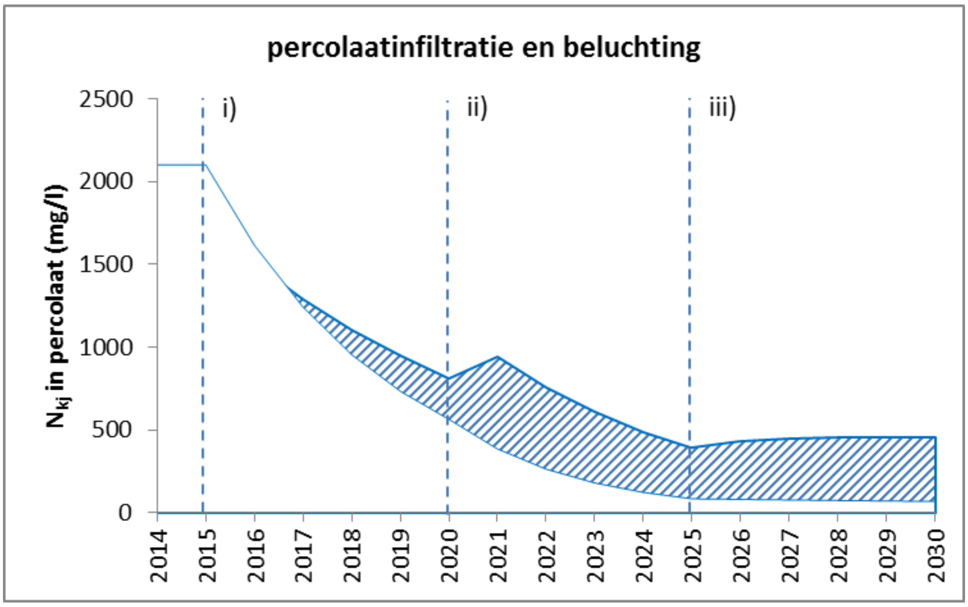

Figure 13: Development of CH_4^+ in leachate. The vertical lines indicate: (i) start of leachate recirculation in 2015; (ii) start of aeration and (iii) end of aeration. The dashed lines give the autonomous development. Note: this model calculation stems from 2011, when start of the project was assumed in 2015.

Removal of organic micro-contaminants

When leachate is recirculated or waste is aerated, organic micro-contaminants can be removed in various ways, as described before in chapter 4.1. The combined effect of stripping (upon aeration contaminants are stripped 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.

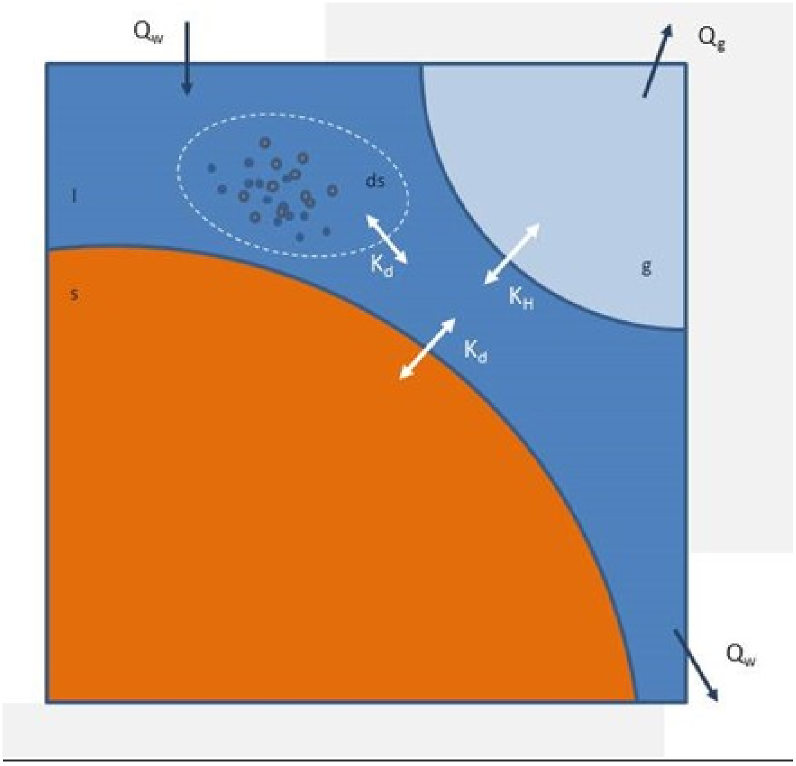

Figure 14: Equilibria in MOCLA

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 a reliable one. However the evaluation does give insights in what mechanisms exist for removal of specific trace-contaminants, when leachate is recirculated or waste is aerated.

This evaluation was done separately for each organic micro-contaminant. Figure 15 gives an example MOCLA-calculation for benzene and xylene. The figure shows the part that is removed in one year upon leachate recirculation and 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.
Under anaerobic conditions, removal is limited. Benzene is relatively volatile and as when leachate infiltration results in a substantial increase in gas generation, this might have some effect on benzene concentrations. However the effect will be limited to 5-10% per year. Xylene is less volatile, so stripping of xylene is less likely. Xylene is less soluble and for a larger part adsorbed to solid material. As a result, a larger effect is expected of reduction of DOC in leachate upon leachate recirculation. Overall expected reduction of xylene will be limited to 5% per year. Upon aeration benzene might be reduced by 50-75% per year, largely as a result of stripping. For xylene annual reduction due to physical removal is estimated to be 25-50%. On top, literature shows, that BTEX in general rapidly degrade in aerobic conditions. So for benzene and xylene it is concluded, that strong mechanisms exist for removal upon successful aeration.

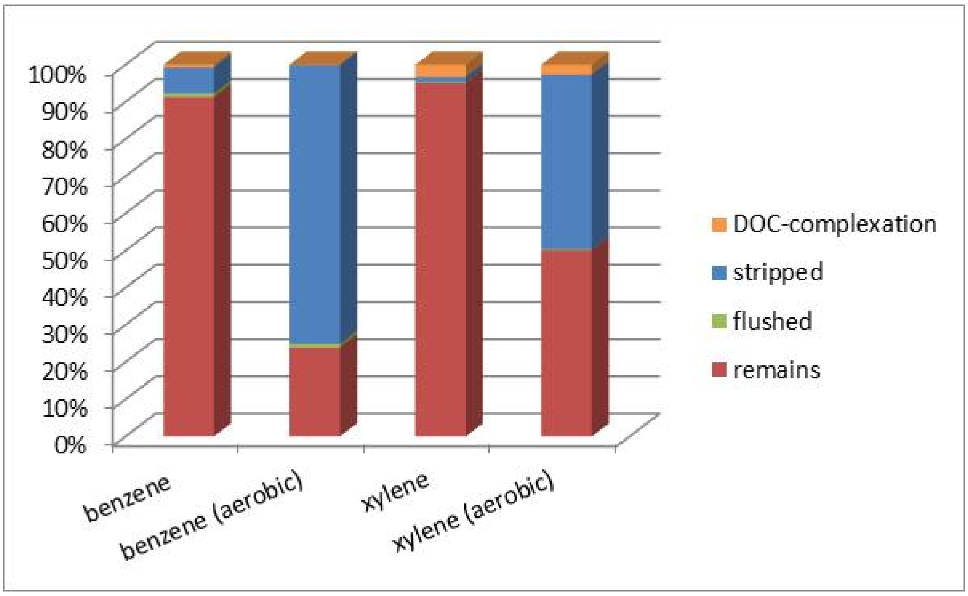

Figure 15: removal of organic trace-components by physical effects, as predicted by MOCLA.

Effect on heavy metal concentrations

The effects of sustainable landfill management on heavy metal concentrations was determined, based on experiences in the Landgraaf test-cell. 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. Operation at the Landgraaf test-cell however did not aim at minimizing DOC-concentrations in leachate. E.g. leachate was hardly drained from the system, so the effects observed in Landgraaf can still be improved at De Kragge 2.

As:

In De Kragge 2, compartment 3, leachate concentrations of As are in the same order of magnitude as the ETV (see table 5). This implies that concentrations should not increase and preferably have to be reduced somewhat. In Landgraaf hardly any effect was observed of leachate recirculation and aeration on As. This is most likely because of two effects that compensate each other. At one hand, increased stabilisation might result in formation of Fe-hydroxides which immobilise As. At the other hand pH was slightly increased, resulting in an increased solubility of

As. With effective aeration however, the expectation is that the first effect might take the upper hand and reductions up to 50% of As are feasible.

Cr:

Cr-concentrations in leachate are about 5 times too high. This means that concentrations need to be reduced by 80%. In Landgraaf a reduction in 60% was achieved and DOC in leachate proved to have significant impact on Cr-concentrations. When at De Kragge 2 DOC-concentrations can be reduced by 90%, 80% reduction of Cr in leachate seems to be feasible.

Effect op Ni

Nickel is about 3-4 times too high. So 65-75% reduction in leachate concentrations is required. 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. For Landgraaf it was believed that the high initial concentrations on Ni in the waste were the cause of this. For De Kragge 2, significant reduction of Ni might be achieved, but it is uncertain whether 65-75% will be feasible.

4.3 Conclusions on feasibility of ETV's

Table 6 summarizes the of decrease in leachate concentrations, that is required to meet the levels as specified by the ETV's (see table 5 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 6: Summary feasibility ETV in the De Kragge 2-pilot

	Reduction mechanisms	Possible reduction	Required reduction
Heavy metals			
As	increase $Fe(OH)_3$-complexatiom	0-50%	0
Cd	n.c.1)		
Cr	decrease DOC complexation	>60%	~80%
Cu	n.c.		
Ni	decrease DOC complexation	>60%	~75%
Pb	n.c.		
Zn	n.c.		
Hg	n.c.		
Macro-contaminants			
chloride	flushing	60-80%	90%
sulphate	generation upon aeration		0%
N_{kj}	Flushing, annamox upon leachate infitration. Nitrification/denitrification upon aeration	>90%	98
Organic micro-contaminants			
mineral oil	decrease DOC complexation, aerobic	>90%	70%

	Reduction mechanisms	Possible reduction	Required reduction
	degradation		
VOX	stripping, aerobic degradation	>95%	0%
PAK	decrease DOC complexation, aerobic degradation	~90%	95-99,75%
BTEX	stripping, aerobic degradation	>95%	90-99%
phenols	aerobe degradation	>> 90%	99,99%

[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 sustainable landfill management 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 leachate recirculation or aeration can be stopped.
- For legislative issues: To prove to the legislator, that risks of sustainable landfill management 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 sustainable landfill management 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 were performed in the period 2012-2013 and were 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 sustainable landfill management; 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, sustainable landfill management 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 De Kragge 2 is summarised in the table below.

Table 7: Summary monitoring programme De Kragge 2

		before	during	after	where	how	frequency	why
leachate	amount	X	X	X	PP3		continuous	quantification
	EC	X	X	X	PP3		continuous	insight in hydrology
	composition (macro)[1]	X	X	X	PP3	labanalyse	1e jaar 2-wekelijks, daarna maandelijks	biodegradation - qualitative, effectiveness SLM[3], emission potential
	composition (complete)[2]	X	X	X	PP3	labanalyse	1e jaar 6 keer; daarna 4 keer per jaar	biodegradation - qualitative, effectiveness SLM, emission potential
	fractionation DOC	X	X	X	PP3	labanalyse	1e jaar 6 keer; daarna 4 keer per jaar	biodegradation - qualitative, effectiveness SLM, emission potential
	temperature	X	X	X	PP3	in-situ	1e jaar 2-wekelijks, daarna maandelijks	effectiveness SLM
infiltration	composition (macro)		X		water buffer	labanalyse	1e jaar 6 keer; daarna 4 keer	effectiveness infiltration
	temperature	X	X	X	supply pipe	in-situ	1e jaar 2-wekelijks, daarna maandelijks	process control
	amount		X		supply pipe	turbinemeter	continuous	process control, mass balance
purge	amount		X		drain pipe	turbinemeter	continuous	mass balance
ground water	composition	X	X	X	control drains	labanalyse	conform bestaande vergunningen	legislation
landfill gas	gas amount	X	X	X	compressor	continuous	registration once a week	biodegradation - quantitative
	composition	X	X	X	bij compressor	continumeting	registration once a week	biodegradation - quantitative
	gas temperature	X	X	X	bij compressor	continumeting	registration once a week	biodegradation - qualitative, effectiveness SLM, pollution potential
aeration air	flow, volume, pressure and temperature		X		distribution station	continuous	registration once a week	process control, biodegradation - quantitative
extracted air	flow, volume, pressure and temperature		X		distribution station	continuous	registration once a week	process control, legislation
aeration well settings	flow, druk, temperatuur,		X		distribution station	installed	according to specification	contract management
	flow, volume, pressure and temperature		X		distribution station	continuous	registration once a week	biodegradation - quantitative
methane emissions	diffuse emissions	X	X	X	top layer	FID-screening	once during baseline-	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	X	X	X	local weather station		daily	generic interpretation

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

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

[3] SLM= sustainable landfill management

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 sumps and pumps

The drainage system on compartment 3 drains in a separate collection sump (PP3). The amount of leachate as the leachate composition will be monitored for this sumps, but also for the other compartments. So the monitoring programme for amount of leachate and its composition will proceed in threefold. To enable monitoring, leachate sump are adapted prior to the baseline measurements and equipped with a pump, sensors and a sampling point.

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). The sump of compartment 3 (and also compartment 4) 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.

Infiltratie als gevolg van neerslag, run-off

De Kragge 2 has its own weather station, that measures precipitation, temperature, atmospheric pressure, humidity, wind direction and speed) and logs data once every 15 minutes.

Infiltration and purging of leachate

The amount of leachate infiltrated and purged will be continuously measured. Composition of leachate that is infiltrated and purged will not be separately measured, but is determined based on composition of leachate produced, corrected for the measured effect of leachate conditioning.

Leachate conditioning

The amount of leachate conditioned will be measured, along with the composition of the effluent after conditioning for relevant parameters (in case of nitrification or anammox this will be pH, NH_4+, NO_3^- and NO_2^-).

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[1]. 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).
-

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

The amount of landfill gas collected is an important indicator for successful infiltration. Landfill gas is collected from all compartments at De Kragge 2. Amount of landfill gas produced and composition of the landfill gas is measured near the compressor station and for the combined gas. So large part of the collected landfill gas comes from compartments, where no leachate is infiltrated. From measurements at individual gas wells, gas collection from compartment 1 and 2 seems to be limited. It is estimated that prior to leachate infitration about 1/3rd of the collected gas is produced at compartment 3. When leachate infiltration at compartment 3 results in 50-100% more gas

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[1] 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.

generation, total gas generation should increase by 15-30%. Current gas collection is well monitored and such an increase in gas generation can be observed as a significant increase in total gas collection.

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 sustainable landfill management. 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. Since geophysical measurements seem to be best applicable when leachate is recirculated, application at De Kragge II is likely.

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.

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

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Appendix 1: Amounts of waste at De Kragge 2.

Amount of waste (wet, in ton)

Year	Soil and soil decontamination residues	Construction and demolition waste	Commercial waste	Shredder waste	Coarse domestic waste	Sludge and composting waste	Domestic waste	Total
Below impermeable top liner								
1990		54,487	47,562		10,898	16,407	20,259	149,613
1991		115,490	77,196		23,773	19,554	84,456	320,469
1992		70,860	56,559		21,559	31,350	86,448	266,776
1993		7,430	5,371	2	1,911	4,067	8,338	27,118
In compartment 3 outside liner:								
1993		66,873	48,340	15	17,195	36,599	75,038	244,058
1994		55,466	52,799	15	26,498	27,553	61,226	223,557
1995		41,585	50,484	2	24,277	36,000	61,214	213,562
1996		26,539	32,812	8	21,191	22,347	62,931	165,828
1997	5,283	11,494	22,778	23	27,714	21,248	18,231	106,771
1998	3,691	11,645	5,267		9,724	2,990	12,787	46,104
In compartment 4:								
1998	2,401	7,577	3,428		6,327	1,946	8,321	30,000
1999	4,666	30,918	14,866		15,239	15,172	10,456	91,317
2000		16,091	92		16,885	15,731	56,085	104,884
2001		103,998	3,032	1268	37,008	19,241	75,357	239,904
2002		3,677	22,481	1228	18,070	12,765	29,085	87,306
2003		666	10,806	26	6,273	11,272	14,903	43,946
2004	7,473		16,862	10	1,841	3,616	5,361	35,163
2005		4,430	12,201				25,240	41,871
2006	3,303	74	3,933	199	12,420	111	25,933	45,973
2007	3,455	148	23,753		14,462	5,579	23,693	71,090
						total below liner:		763,976
					total in compartment 3 (excl. lined part):			999,880
						total in compartment 4:		791,454
						total De Kragge 2:		2555,310