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POST-CLOSURE CARE COMPLETION AT MSW LANDFILLS AND RESIDUAL RISKS

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SUMMARY: In this work we present a modelling approach to evaluate residual environmental risks in view of different post-closure management strategies. Potential emission rates of a landfill are estimated based on different scenarios used to illustrate the effects of different conditions within and around the landfill. The effect of the scenario emissions is evaluated at different points of compliance and tolerable leachate emission levels at the source are determined based on a reverse risk assessment approach. The evaluation methodology is illustrated for a closed MSW landfill and post-closure care (PCC) durations are estimated for this landfill. Depending on the chosen PCC strategy the duration of PCC at the site may vary between several decades and more than a century, with ammonia-nitrogen in the leachate being the critical parameter. However, apart from ammonia emissions additional criteria need to be met in order to release the landfill from post-closure care (e.g. custodial care program and after-use limitations).

1. INTRODUCTION

Of all man made buildings landfills represent probably those with the longest life time. After construction (or preparation) of the landfill and waste disposal, MSW landfills need to be managed and controlled for long periods in order to avoid adverse effects on humans and the environment (e.g. Belevi and Baccini, 1989; Laner et al., 2010). This period of landfill management is referred to as post-closure care (PCC) or aftercare period. In Austria it starts with the end of waste deposition and ends with the competent authorities' decision that no more further aftercare measures are necessary (Austrian Landfill Directive, 2008). As long as the authorities consider a landfill likely to be a threat to humans or the environment, post-closure care cannot be terminated (EU Landfill Directive, 1999).

The evaluation of landfill environmental compatibility includes an estimation of future pollution hazards as well as an assessment of the vulnerability of the affected environment (cf. Laner et al., 2011). In this article we present a methodology to estimate future emission rates and evaluate the response of the affected environment based on the current state of the landfill and its surroundings. The evaluation results are used to determine site-specific completion criteria, which define the state of the landfill when post-closure care can be terminated. Hence, these criteria form a basis to evaluate different PCC strategies in view of PCC duration and remaining environmental risks at the site.

2. MATERIALS & METHODS

2.1 Evaluation methodology

The methodology consists of several elements: (a) models on emission characteristics, b) models on the performance of the containment system, c) substance migration models in the environment (i.e. subsurface environment), and d) points of compliance where certain criteria (e.g. groundwater quality criteria) have to be met), which are combined to derive site-specific completion criteria. The procedure to derive completion criteria for a closed landfill is schematically illustrated in Figure 1.

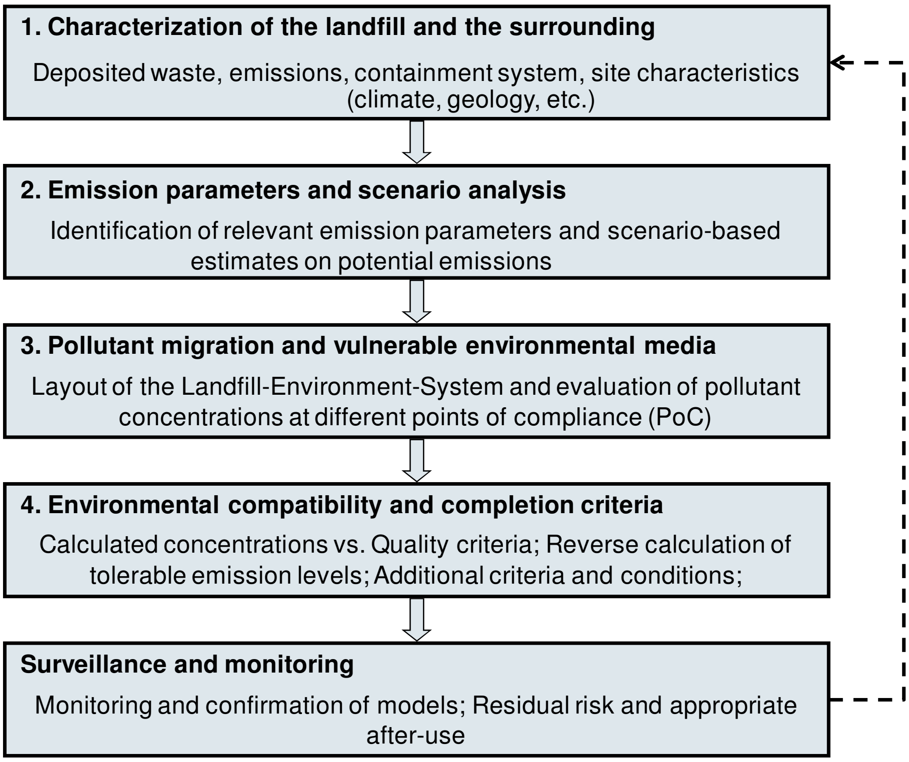

Figure 1. Schematic illustration of the procedure to evaluate landfill environmental compatibility and determine post-closure care completion criteria

In order to evaluate any system, data need to be collected on the system itself and the boundary conditions relevant to the evaluation. Hence, as a first step data on the landfilled waste (e.g. amount and compostion of the deposited material over time, state of waste degradation, hydraulic regime), the containment system (e.g. design and construction, field tests and performance data), the emission monitoring (e.g. quality and amount of landfill gas and landfill leachate over time), and the site characteristics (e.g. climatic conditions, geologic and hydrogeologic conditions, vulnerable uses in the vicinity, natural hazards) need to be gathered. Subsequently, based on an analysis of this data (especially with respect to landfill monitoring) relevant emission parameters are identified and emission scenarios are developed to estimate potential emission levels of the landfill associated with different landfill conditions. The scenario-based emission estimates form the input for modelling pollutant migration in the surrounding environment during step 3 (see Figure 1). The effect of released landfill pollutants is evaluated at defined points of compliance (PoC) located along relevant migration pathways. In the fourth step the calculated concentrations at the PoCs are compared to quality criteria. If the effect of the scenario emissions does comply with the quality criteria applied at the PoCs, the scenario can be considered environmentally tolerable. Else, the tolerable scenario emission levels at the source can be determined based on the acceptable quality criteria at critical PoCs. The reverse calculation starting from the acceptable quality standard at the PoC in the direction of the source (landfill) results in a tolerable emission level for a specific substance and a specific scenario. The tolerable emission levels at the source for the most probable long-term emission scenario and the critical point of compliance represent the leachate-specific completion criteria for the site. In addition there might be criteria with respect to landfill gas, geotechnical stability, after-use, custodial care etc. In any case there will be a necessary period of monitoring at the site after the evaluation in order to validate the underlying models and confirm/increase the reliability of the evaluation results. Specific elements of the evaluation procedure are described in more detail below.

2.1.1 Emission prognosis

Within the evaluation methodology the leachate emission model suggested by Belevi and Baccini (1989) is used, but adapted to consider water flow heterogeneity and the continuous release substances due to ongoing organic degradtation processes (cf. Laner et al., 2011). The substance concentrations in the leachate decrease exponentially with the increase of liquid-to-solid ratio of the deposited waste. To establish the model, information about initial leachate concentrations (after landfill closure and after gas generation has significantly dropped), the mobilisable amount of substances of the waste, the heterogeneity of water flow through the waste, the rate of water infiltration per year, and the amount of landfilled waste is necessary. The model parameters are determined based on landfill documentation, investigations of the landfilled waste, and available monitoring data at the site. The model is fitted to observed emission characteristics during the post-closure care period and estimates on future leachate composition are derived with the calibrated model as a function of liquid-to-solid ratio. However, it should be noted that the described emission model assumes constant water flow patterns within the landfilled waste and no change of the dominant release mechanisms. Thus, within a scenario to investigate the effect of a change in the landfill's water flow pattern, the emission model would have to be adapted to account for a re-distribution of water in the waste and a potential increase in leachate concentration levels (cf. Laner et al., 2011).

As field data is lacking to evaluate the long-term performance of containment systems, a set of scenarios is used to illustrate the effect of different containment system performance levels on potential landfill emissions. One scenario assumes an unchanged performance of the barrier system, one investigates the slow deterioration of the technical barriers and a consequent desrease of the barrier performance levels (cf. Inyang, 2004), and a third one is used to illustrate the effect of a total failure of the containment system. The estimated barrier performance levels are combined with appropriate emission models (e.g. constant release mechanisms and water flow pattern is assumed) and scenario-based emission estimates are derived. Further scenarios which might be of interest for the evaluation of long-term emission levels at the site can be the flooding of the landfill (e.g. Laner et al., 2009) or the change from dominantly anaerobic to aerobic degradation of organic matter. However, the latter is not expected to occur naturally within many centuries to several hundred thousands of years (cf. Bozkurt et al., 1999). The layout and amount of the investigated emission scenarios is dependent on potential future conditions at the site characteristics on the one hand (e.g. site in a flood plain) and the expected state of the landfill after post-closure care completion on the other hand (e.g. human intrusion as an event to be included).

2.1.2 Pollutant migration modelling

Several pollutant migration pathways might be relevant for a closed landfill:

- migration of landfill gas through the top cover (i.e. methane oxidation processes)
- subsurface migration of landfill gas (i.e. intrusion into buildings and explosion hazards)
- surface runoff and erosion
- direct discharge of collected leachate into a surface water body
- release of leachate to the subsurface below the landfill.

From the list of migration pathways, only the migration of leachate in the subsurface is addressed below. On the one hand, this is due to the potential risk a landfill poses to the groundwater and on the other hand, because the leachate pathway is considered to be of major importance with respect to the long-term pollution potential of MSW landfills (cf. Kjeldsen et al., 2002). Nevertheless, it should be noted, that each of the pathways mentioned above could represent an environmental hazard.

Leachate seeping from a landfill enters the zone below the landfill and potentially contaminates the groundwater underneath. Reactive transport processes in these environmental media can potentially attenuate contaminants present in the leachate. Although, it has been shown that natural attenuation of many pollutants present in landfill leachate might be substantial in the subsurface, there is no easy-to-use protocol available on how to assess attenuation potentials for a specific environment (Christensen et al., 2000).

In order to establish an appropriate reactive transport model for the unsaturated and saturated zone below the landfill substance- and site-specific data need to be gathered. The complexity of the model should reflect the quantity and quality of data, which are available for establishing and applying the model. The more one needs to rely on literature data instead of site-specific measurements, the simpler and more conservative the modeling approach should be. Hence, within the evaluation methodology rather simple and robust models are used to describe pollutant migration in the subsurface. On the one hand this is in accordance with the data generally available at closed landfill sites, and on the other hand in a higher tier evaluation the simpler model can be replaced by a more complex model, provided that additional data are collected at the site.

The pollutant migration in the vadose zone below the landfill is evaluated with the AF-model (Schneider and Stöfen, 2004), which is a one dimensional model based on the analytical solution of the advection-dispersion-equation. For scenarios with a varying leachate generation rate (e.g. gradual decrease in barrier performace), the model is complimented by a mass balance approach. Mixing of the leachate with the groundwater and pollutant migration in the groundwater are also modeled with a mass balance approach. The concentrations calculated at the various points of compliance represent estimated maximum concentration levels for the respective pollutants.

2.1.3 Determination of completion criteria

Completion criteria are determined based on a critical point of compliance, tolerable concentration levels at this point, the choice of a most probable or most relevant long-term emission scenario and the calculated attenuation factors for substances released to the surrounding environment during this scenario. The calculated attenuation factors in Figure 2 refer to a specific substance and a specific scenario and they can be used to determine the tolerable concentration of this substance. For instance, a quality standard of 10 mg Cl/l at PoC3in Figure 3 would result in a tolerable concentration of Cl in the landfill leachate of 200 mg/l (= 10*2*2*5). Thus, if the Cl concentration in the leachate is 200 mg/l or lower, future leachate emissions will be environmentally tolerable, provided that the conditions of the most relevant emission scenario are met. Therefore, in addition to the emission criteria the completion of PCC will be associated with criteria referring to the chosen long-term emission scenario. For example, the assumption of optimal containment system performance within the most relevant long-term emission scenario would have the maintenance and repair of the containment system even after PCC completion as a completion criterion. However, one might be in doubt if a competent authority would accept this as a PCC completion criterion.

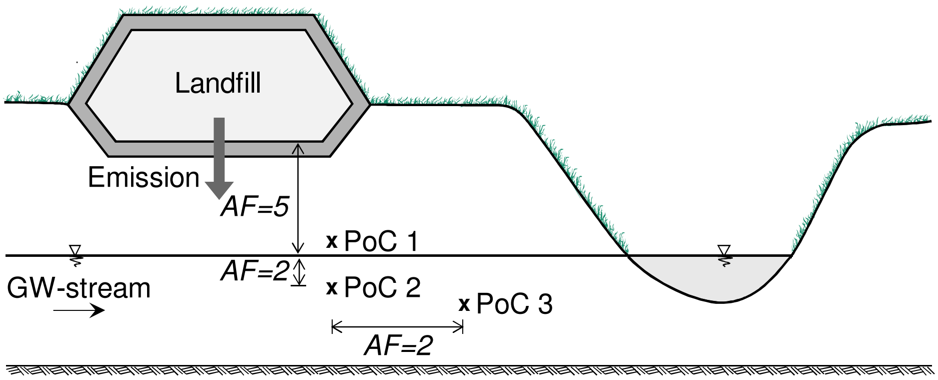

Figure 2. Scheme of the landfill-environment-system with scenario- and substance-specific attenuation factors between the different PoCs

2.2 Case study landfill

During the years 1988 and 2003 approximately 135000 tonnes of municipal solid waste have been disposed of at the landfill. The landfill is situated on a hill slope with a road passing nearby the western boundary of the premises. The direction of groundwater flow is west to northwest towards the valley. A river is located in the valley at a distance of approx. 250 m from the landfill. The leachate collection tanks are situated underground outside the landfill on the other side of the road in order to allow for gravitational drainage and collection of the landfill leachate.

The climate at the site is humid with an average annual precipitation of 1960 mm. The geologic strata below the landfill are composed of glacial gravel with high contents of carbonate. The distance between the lowest point of the landfill containment system and groundwater surface is 1.2 m. The groundwater body in the valley has been investigated as a potential drinking water resource of a village located 2 km north of the landfill.

2.2.1 Monitoring data

Monitoring data are available for the deposited amount of MSW at the site, the collected leachate, the collected landfill gas (only from 2004), and from three groundwater monitoring wells downstream the landfill.

The leachate is collected at the bottom of the landfill in a gravel drainage layer with embedded leachate collection pipes. The collected leachate of both landfill sections is gravitationally transported outside the landfill through the containment system into a leachate storage tank. During operation the annual leachate generation rate made up for 50 to 90 % of average annual precipitation. After the installation of the temporary cover the amount of leachate ranged between 60 to 80 % of the average annual precipitation. Leachate sampling is conducted twice a year at the inflow of the leachate storage tank. NH_4-N, COD, and Cl are selected as leachate parameters for the emission modeling, because the concentrations of these parameters in the leachate are above quality standards for direct discharge (by factor 10 for COD and by factor 50 for NH_4-N above limit values).

Although there has been a gas collection system with a flare in operation since the mid of the 1990ies, data on the amount and composition of the landfill gas are available only for the period after the installation of the temporary cover (since 2004).

The landfill containment system is currently made up of a composite liner system (geoomembrane & low permeability soil layer) at the landfill base and a temporary cover system (1.2 m of silty soil & 0.25 m of top soil) at the top of the landfill. The temporary cover allows in average 62 % of the precipitation to infiltrate into the landfill body, which corresponds to an absolute infiltration rate of 1221 mm per year. It is planned to install a final cover at the site in 2020, which includes a composite lining system and is supposed to reduce the fraction of precipitation infiltrating into the waste to 1 %. There are no data available on the efficiency of the base lining system. However, as there are no indications of poor barrier performance at the monitoring wells downstream of the landfill, it is conservatively assumed that currently 99 % of the generated leachate is contained within the landfill, collected and treated accordingly.

2.2.2 Emission models and scenario analysis

In order to estimate potential future emissions of landfill leachate and landfill gas several scenarios are developed. The scenarios are used to illustrate the effect of different barrier performance developments after landfill aftercare has been terminated on landfill emission levels. The basic emission model (leachate quality as a function of liquid-to-solid ratio) is the same for all investigated scenarios (i.e. no change of water flow pattern, constant release mechanisms and mobilizable waste fraction). The scenario layouts are shown in Table 1.

Table 1. Layouts of the emission scenarios for the case study landfill

Scenario	Technical barrier at the top	Technical barrier at the base
Status quo	Best performance	Best performance
Status quo*	Best performance	Ineffective
Scenario A	Gradual decrease of barrier performance	Gradual decrease of barrier performance
Scenario A*	Gradual decrease of barrier performance	Ineffective
Scenario B	Ineffective	Ineffective

The Status quo assumes constant barrier function at the top and at the bottom of the landfill. Scenario A considers the gradual decrease of barrier function at the top and bottom of the landfill due to slow deterioration of the barriers. Scenario B is designed to illustrate the effect of complete barrier failure on landfill emission levels, thus illustrating the "worst case" with respect to barrier performance. In addition, modified versions of the scenarios "Status quo" and "Scenario A" are analyzed to investigate the effect of an inefficient technical barrier at the landfill base. Under the assumption that leachate collection is impeded (e.g. clogging of drainage system) and liner systems fail, all the generated leachate is released to the subsurface below the landfill. The corresponding scenarios are "Status quo*" and "Scenario A*", respectively. The modelling period for all scenarios is 300 years.

The time of evaluation for the investigated landfill is the year 2010, as this is the last year with monitoring data. Thus, the scenario-based emission estimates include the time of temporary cover (which essentially is a PCC activity), but are shown and discussed starting from year 10, as the estimated emission levels refer to the final state of the landfill after the final top cover has been installed.

2.2.3 Landfill-environment-system

The migration pathway for leachate released from the landfill to the subsurface includes the earthen barrier at the bottom of the landfill, the vadose zone below the landfill, the local groundwater, and the river which is partly fed with groundwater potentially affected by leachate emissions. The soil below the landfill consists mainly of gravel mixed with varying portions of fine particles. The clay layer of the base lining system is included in the substance migration modeling, because it may slow down the transport of pollutants in the subsurface (i.e. sorption processes) and thereby have a retarding effect on pollutant migration. The geomembrane is not included in the transport modeling, as its function is already evaluated within the emission scenarios. The minimum distance from the clay liner to the groundwater surface is 1.2 meters. The thickness of the groundwater below the landfill is only a few meters and the groundwater surface has a strong gradient downhill. The average groundwater velocity is estimated to be 300 meters per year, which is probably at the lower range of realistic velocities due to the hydraulic gradient of the groundwater (> 0.1 m/m). In the valley the groundwater thickness increases (PoC3 in Figure 3), representing a groundwater body with potential significance as a source of drinking water for a nearby village. This groundwater body is also partially draining into the river located in the valley (PoC4 in Figure 3).

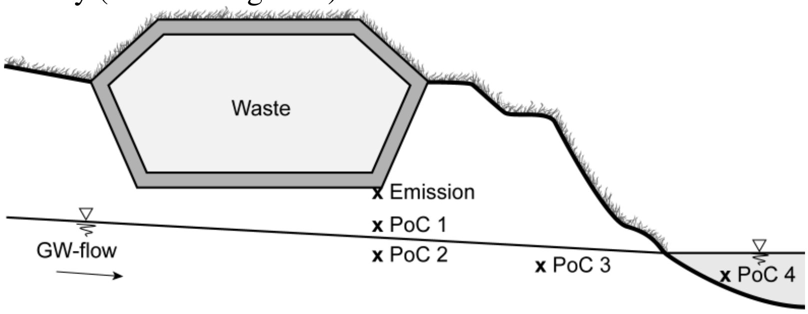

Figure 3. Scheme of the landfill-environment-system and relevant points of compliance (PoC) (cross section along the ground water flow direction)

After the release of the leachate the resulting maximum concentrations are calculated above the groundwater surface (PoC1), in the mixing zone of leachate and groundwater (PoC2) with an average thickness of 0.25 meters, in the groundwater body in the valley after a transport distance of 100 meters (PoC3), and in the affected river water (Poc4) (see Figure 3). Sorption processes are only considered for ammonia-nitrogen migrating through the low permeability soil of the base lining system and degration processes are not included in the transport modeling at all. Hence, the reduction in concentration levels is dominantly due to hydrodynamic dispersion and dilution processes.

3. RESULTS & DISCUSSION

3.1 Scenario-based emission estimates

2.2.1 Leachate emissions

Leachate emissions are estimated for ammonia-nitrogen, chemical oxygen demand, and chloride. The emission models adapted to the monitoring data at the site are schown in Figure 4 together with the monitoring data during the post closure period. It is visible from the graphs in Figure 4, that the concentrations are strongly decreasing and that the liquid-to-solid ratio of the deposited waste increased by 1.15 l/kg DM since the landfill has been closed (5 years ago).

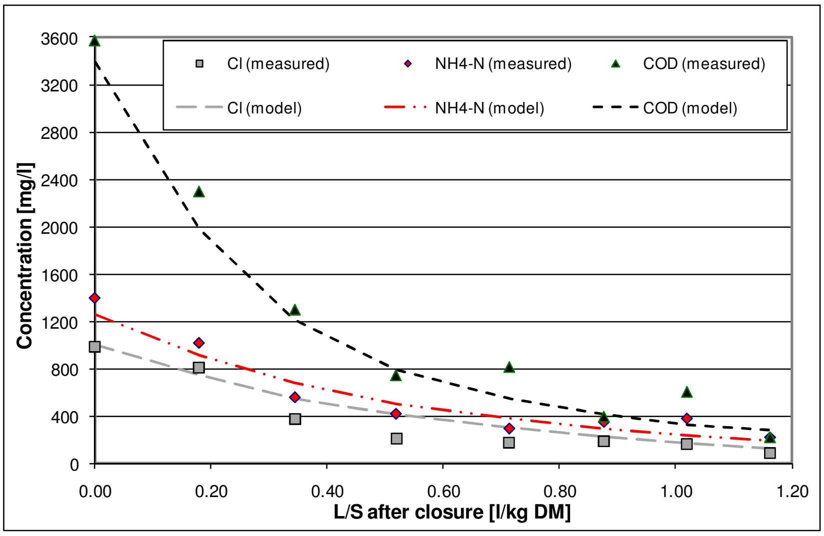

Figure 4. Concentrations of Cl, NH4-N, and COD in the leachate of Landfill B after closure as a function of liquid-to-solid-ratio

Status Quo:

Within the Status Quo the fraction of precipitation entering the waste body is 0.62 during the period of temporary cover and 0.01 after the final cover has been installed (after year 10). At the base of the landfill 99 % of the generated leachate is constantly removed via the collection system, the rest percolates through the technical barrier into the subsurface.

Because of the permanently low water infiltration rate, the concentrations of the leachate parameters decrease only slowly during the scenario and fall from 9 mg Cl/l, 50 mg NH_4-N/l, and 120 mg COD/l after 10 years to 2 mg Cl/l, 34 mg NH_4-N/l, and 88 mg COD/l at the end of the modeling period. Similarly, the emission loads decrease from 2 kg Cl/yr, 12 kg NH_4-N/yr, and 29 kg COD/yr to 0.5 kg Cl/yr, 8 kg NH_4-N/yr, and 21 kg COD/yr after 300 years. The emission levels to the subsurface are constantly 1 % of these loads due to unchanged barrier performance.

The emissions into the subsurface for the scenario "Status Quo* are the same as the total leachate emissions for the Status Quo, as the assumption for the Status Quo* is a complete inefficiency of the barrier system at the landfill base.

Scenario A: Gradual decrease of barrier performance

The Scenario A investigates the gradual deterioration of the technical barrier systems and the consequent decrease in performance levels. However, during the first ten years (temporary cover) constant infiltration rate of 1221 mm/yr and constant barrier efficiency at the landfill base are assumed. Starting from the installation of the final cover, a slow decrease in barrier performance is investigated. The initial infiltration rate after top cover installation (year 10) is 19.57 mm/yr and then decreases to 100 mm/yr within 100 years and to 323 mm/yr after 300 years. The corresponding percolation rates at the landfill base are 0.2 mm/yr initially (after final cover installation), 5.2 mm/yr 100 years later, and 95 mm/yr after 300 years. The leachate emissions associated with this evolution of the barrier functions are shown in Figure 5.

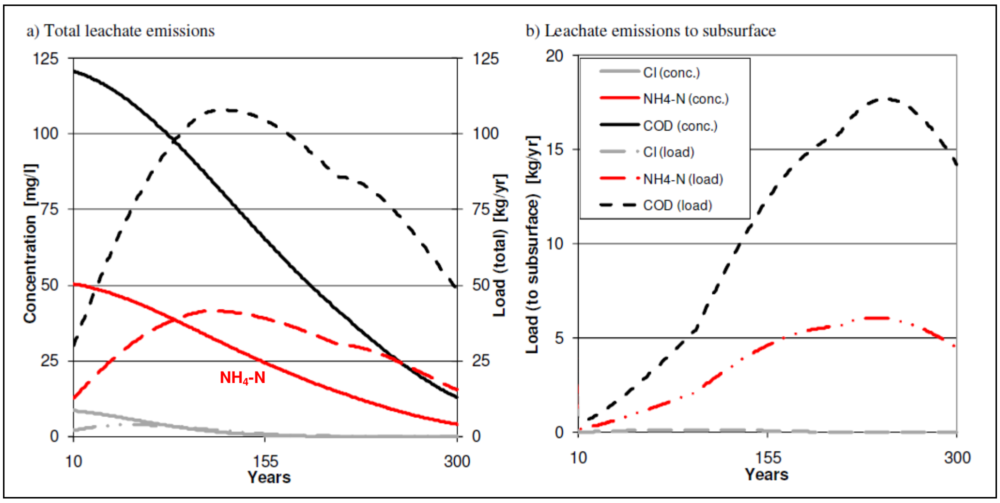

Figure 5. Leachate emissions for Scenario A (gradual barrier deterioration) at Landfill B (left: total leachate emissions, right: leachate emissions to subsurface)

In case of Scenario A* the total leachate emissions of Scenario A in Figure 5 on the left are the same as the leachate emissions into the subsurface, as Scenario A* is used to illustrate the effect of a gradual decrease in top cover performance and the complete inefficiency of the technical barrier system at the landfill base on landfill emissions.

Scenario B: Complete failure of technical barriers

Within this scenario the top lining system and the bottom lining system fail to provide containment. The "worst case" infiltration rate at the top is 1221 mm/yr, the same as observed for the temporary cover system. At the bottom of the landfill all the leachate is released to the subsurface during this scenario. Due to the high water throughput, the concentrations and annual loads of the leachate parameters decrease rapidly and all of them range below 10 mg/l already after less than 50 years.

2.2.1 Landfill gas emissions

Two gas generation models with different parameters were derived to estimate future gas generation rates. Both models result in landfill gas generation rates which are above currently collected amounts and also above the amounts of landfill gas if a collection efficiency of 35 % is assumed at the site. Hence, the model estimates are rather conservative, whereby the LandGEM model (US EPA, 2005) is estimated with typical parameters for wet landfills (k-value of 0.7 and gas generation potential 200 m³ per Mg of wet waste) and the model by Tabasaran and Rettenberger (1987) (= T&R model) is calculated based on a k-value of 0.1 and a potential gas generation potential of 200 m³ per Mg of wet waste. The future gas generation rate is supposed to range somewhere between the model estimates. Based on the model predictions (see Figure 6), it can be expected that the gas generation rates at the landfill will drop to very low levels within a few decades. Even for the upper range curve in Figure 6, the area-specific methane generation rate is expected to drop below 1 kg CH_4 per m² and year within 13 years or within 3 years after final cover installation, respectively. These estimates do not include any methane oxidation processes potentially occurring in the landfill top cover.

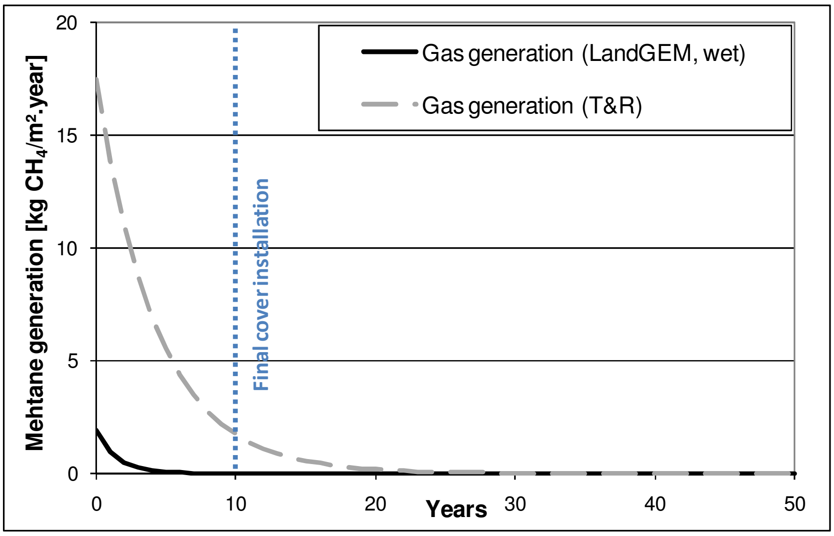

Figure 6. Methane generation rates per m² of landfill surface for the two gas generation models

3.2 Pollutant concentrations in the subsurface

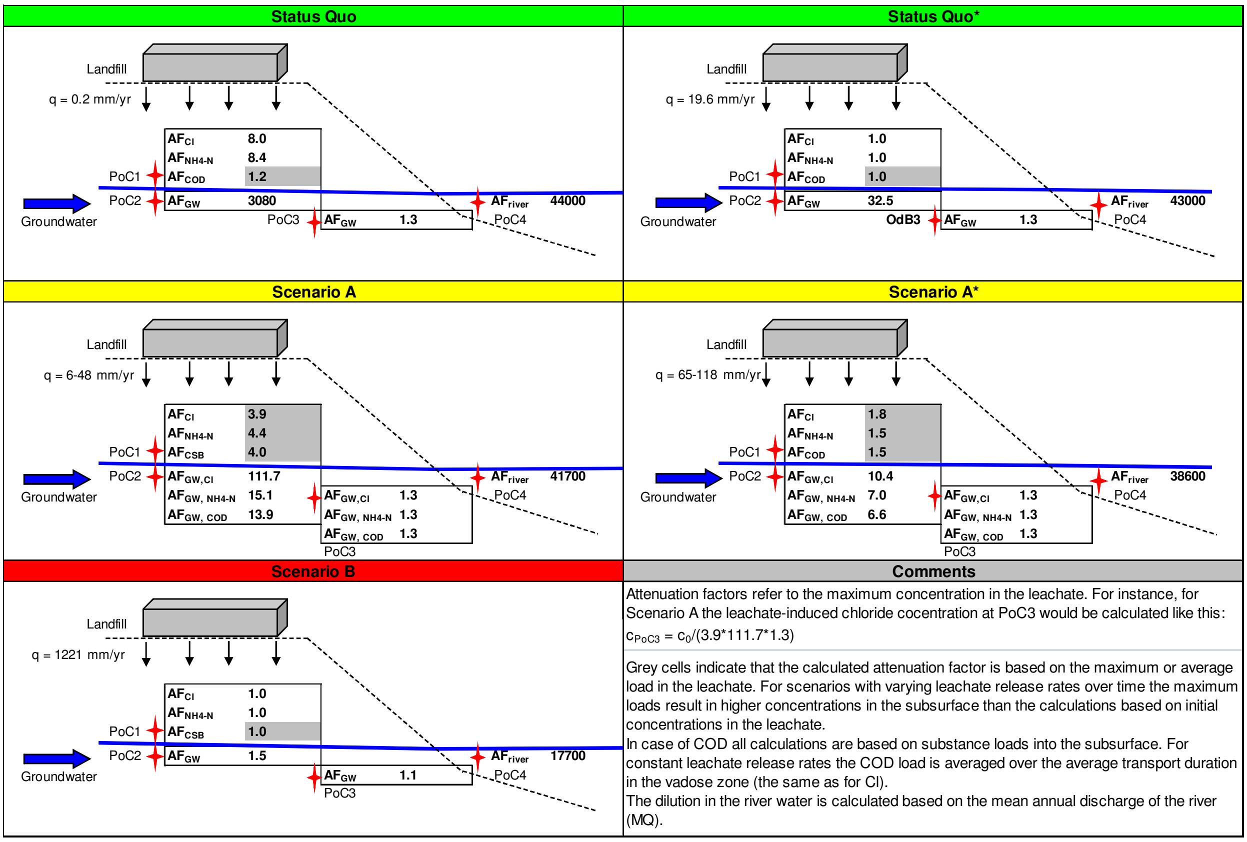

Figure 7. Attenuation factors to estimate the maximum concentrations at relevant PoCs due to a release of leachate from the landfill for the different scenarios

The resulting attentuation factors from the pollutant migration modelling are shown in Figure 7 for the different emission scenarios and parameters (Cl, NH_4-N, and COD). To calculate the concentrations at PoC3 (100 m downstream the landfill in the groundwater) spreading of the leachate plume is neglected (width 100 m and thickness 0.25 m) and dilution is only caused by the groundwater recharge of 250 mm/year (the low recharge rate of 13 % of the precipitation is because of the surface slope and the partly sealed area). The concentration at PoC4 is calculated under the assumption that all the contaminated groundwater exfitlrates into the river and fully mixes with the river water (the calculations are based on the mean annual discharge). In case of varying leachate release rates, the lowest dilution factor is used as an attenuation factor.

3.3 Completion criteria and discussion of PCC durations

To evaluate the environmental compatibility of the emissions the groundwater downstream the landfill is chosen as the critical point of compliance, as the groundwater body in the valley has been identified as a potential source of drinking water for a nearby village. Therefore, the quality standards for drinking water are applied as limit values for acceptable concentration levels at PoC3 in Table 2. However, it should be noted that the calculations relate to the release of landfill leachate only and do not take into account any other pollution sources or contamination already present in the groundwater upstream of the landfill. Nevertheless, such data would be necessary to evaluate the total extent of groundwater contamination and thus its suitability as a drinking water resource. The reverse calculations of tolerable pollutant levels in the landfill leachate shown in Table 2 are based on the scenario-specific attenuation factors given in Figure 7. Provided that leachate collection remains functional after landfill completion and a slow deterioration of the base lining system is assumed (Scenario A), the consequent tolerable concentration levels in the leachate would be 44 mg/l for NH_4-N and 362 mg/l for COD. In case barrier deterioration at the top and inefficient base lining system is expected after landfill completion (Scenario A*), the corresponding concentrations in the leachate were not to exceed 7 mg/l for NH_4-N and 64 mg/l for COD.

Table 2. Tolerable leachate concentrations (c0) at the source in order not to exceed the limit values specified at PoC3 for the emission scenarios

Parameter	PoC3	Status Quo	Scenario A	Status Quo*	Scenario A*	Scenario B
	C_{limit} [mg/l]	c_0 [mg/l]	c_0 [mg/l]	c_0 [mg/l]	c_0 [mg/l]	c_0 [mg/l]
Cl [a)]	200	6569744	115795	8591	4954	335
NH_4-N [a)]	0.5	17246	**44**	**21**	**7**	0.8
COD [a)]	5	24450	**362**	**215**	**64**	8.4

a) Limit values for leachate induced concentrations at PoC equal Austrian drinking water quality standards ((2001)). In case of ammonia-nitrogen limit values for ammonia are applied at PoC3. No nitrification of ammonia is assumed.

The duration of PCC until this leachate emission levels can be reached is dependent on the post-closure strategy. In case of installing an impermeable top cover with constant optimal performance it will take more than 100 years to reach an ammonia-nitrogen concentration of less than 44 mg/l in the leachate. On the other hand, if the temporary top cover is maintained longer than originally planned and the high infiltration rates persist, a tolerable emission level (with respect to Scenario A as the relevant long-term emission scenario) might be reached already within a few decades. In all cases the critical parameter to reach acceptable leachate quality for aftercare termination is ammonia-nitrogen.

Whereas leachate emissions of the case study landfill will require further aftercare for at least several decades, a level of acceptable methane emissions of 0.3 kg per m² and year suggested by Fellner et al. (2008) could be reached within a decade after cover installation at the maximum. Hence, it can be expected that the leachate emissions will be of primary importance with respect to the termination of aftercare.

Depending on the chosen long-term emission scenario, different maintenance and monitoring activities will be necessary at the site. For example, in case of Scenario A as the most relevant emission scenario, leachate collection and management would still be necessary at the site after the completion of PCC. No matter which scenario is chosen as a basis for PCC completion, further extensive monitoring will be necessary at the landfill (e.g. geotechnical stability, diffuse gas emissions, recultivation layer etc.) and in the potentially affected environmental media (e.g. groundwater wells) to verify model estimates and scenario assumptions.

4. CONCLUSIONS

A methodology to evaluate the environmental compatibility of closed landfills and to derive site-specific post-closure care completion criteria has been presented. The methodology consists of several models (i.e. landfill emission behavior, containment system performance, and pollutant migration in the surrounding environment) which are combined to determine acceptable emission levels at the landfill. Completion criteria for a landfill are determined based on a most probable long-term emission scenario, a critical point of compliance (PoC), and specific quality criteria which have to be met at the PoC. The completion criteria can subsequently be used to compare different PCC alternatives and evaluate the PCC duration and the remaining environmental risks at the site after PCC completion.

The methodology was applied to a closed MSW landfill with around 135000 m³ of MSW deposited at the site. Throughout the case study many (conservative) assumptions have been made to establish different models and evaluate environmental compatibility of landfill emissions. Therefore, the evaluation has been carried out on a screening level with large inherent uncertainties. However, this evaluation can be the basis for future monitoring efforts and investigations to fill existing data gaps. Furthermore, it is a valuable first step for establishing more realistic models in the future and optimizing aftercare to minimize actual and remaining environmental risks at the landfill site.

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