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Review

A review of approaches for the long-term management of municipal solid waste landfills

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ABSTRACT

After closure, municipal solid waste (MSW) landfills must be managed and controlled to avoid adverse effects on human health and the environment (HHE). Aftercare (or post-closure care) can be brought to an end when the authorities consider the landfill to no longer pose a threat to HHE. Different approaches have been suggested for long-term landfill management and evaluation of aftercare completion. In this paper, research on aftercare and its completion is analyzed and regulatory approaches for the completion of landfill aftercare are reviewed. Approaches to aftercare could be categorized as (i) target values, (ii) impact/risk assessment, and (iii) performance based. Comparison of these approaches illustrates that each has limitations and strengths. While target values are typically used as screening indicators to be complemented with site-specific assessments, impact/risk assessment approaches address the core issue about aftercare completion, but face large uncertainties and require a high level of expertise. A performance-based approach allows for the combination of target values and impact/risk assessments in a consistent evaluation framework with the aim of sequentially reducing aftercare intensity and, ultimately, leading to the completion of aftercare. At a regulatory level, simple qualitative criteria are typically used as the primary basis for defining completion of aftercare, most likely due to the complexity of developing rigorous evaluation methodologies. This paper argues that development of transparent and consistent regulatory procedures represents the basis for defining the desired state of a landfill at the end of aftercare and for reducing uncertainty about the intensity and duration of aftercare. In this context, recently presented technical guidelines and the ongoing debate with respect to their regulatory acceptance are a valuable step towards developing strategies for the cost-effective protection of HHE at closed MSW landfills. To assess the practicality of evaluation methodologies for aftercare, well-documented case studies including regulatory review and acceptance are needed.

Contents

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1. Introduction

Municipal solid waste (MSW) landfills represent the dominant option for waste disposal in many parts of the world. In general, the comparatively high costs of treatment and disposal alternatives are a major reason for the reliance on MSW landfills, particularly in developing economies (Brunner and Fellner, 2007). Nevertheless, even some highly industrialized countries such as the US, Australia, the UK, and Finland largely depend on landfilling. For example, in the US, 54% of the 250 Tg (1Tg = 10^6 metric tons) of MSW generated was landfilled in 2008, with recycling and composting accounting for about 33% of MSW management (USEPA, 2009). In Australia, about 70% of MSW has been directed to landfills without pre-treatment in 2002 (Productivity Commission, 2006). In Japan, direct disposal of MSW accounted for less than 30% of MSW generation in 2000 with high incineration rates during the last decades due to the historic scarcity of land (Tanaka et al., 2005). Among the EU member states, Greece, the UK, and Finland are some of the most dependent on direct landfilling. The fraction of MSW landfilled in 2008 was 77% in Greece, 55% in the UK, and 51% in Finland (Eurostat, 2010). In contrast, landfilling accounted for less than 5% of MSW management in 2008 in Germany, the Netherlands, Sweden, Denmark, and Austria (Eurostat, 2010).

While the use of landfills is decreasing in many parts of the world, there are nonetheless thousands of closed landfills and thousands more that are operating but will close over the next 10–30 years. For example, there were about 1800 MSW landfills reported to be operating in the US in 2008, down from 6300 in 1990 (USEPA, 2009). Similarly, the number of operating MSW landfills in Germany has decreased from 560 in 1993 to 182 in 2009 (BMU, 2006; Statistisches Bundesamt, 2011). In the UK, more than 2000 MSW landfills were operating in April 2004, but by December 2009 only 465 remained in operation with a Landfill Directive (EC, 1999) compliant permit (Environment Agency, 2010a).

This state of the practice overview on MSW landfills highlights the significant variation among individual countries in both solid waste management practices and the extent of pre-treatment prior to waste disposal. However, there are at least two areas of commonality. First, the basic design elements of modern engineered landfills are similar (in this context, a modern landfill is one at which operation and maintenance is regulated at the national or sub-national level). Such landfills include a waste containment liner system to separate waste from the subsurface environment, systems for the collection and management of leachate and gas, and placement of a final cover after waste deposition is complete. Second, regardless of current approaches, the legacy of closed MSW landfills in almost all industrialized countries will continue to require aftercare (or post-closure care) until protection of human health and the environment (HHE) is not compromised in the absence of such care.

Aftercare management of closed landfills typically includes monitoring of emissions (e.g. leachate and gas) and receiving systems (e.g. groundwater, surface water, soil, and air) and maintenance of the cover and leachate and gas collection systems. In general, regulations specify a minimum period of aftercare for which funding must be accrued. For example, the European Landfill Directive (EC, 1999) specifies a period of at least 30 years of aftercare as a basis for the build-up of financial provisions. This has been translated by many European member states into national regulations that require at least 30 years aftercare. Subtitle D of the Resource Conservation and Recovery Act (RCRA) (USEPA, 1991) specifies a 30-year post-closure monitoring period unless this period is shortened or extended by the regulatory agency on a site-specific basis. These regulations have led many landfill owners to budget aftercare funds on the assumption that care activities will be discontinued after 30 years. However, although few modern landfill owner/operators have yet completed 30 years of aftercare and/or petitioned to modify the aftercare period, a lack of criteria and procedures for evaluating landfill completion will make it difficult for regulators to make decisions to end, extend, or reduce the aftercare period (cf. Barlaz et al., 2002).

The development of cost-effective strategies for long-term management of landfills is in the interest of both regulatory agencies and landfill owners for several reasons. First, funding accrual mechanisms currently in place do not typically consider the potential for aftercare periods in excess of 30 years. If necessary, reform of the current time-based systems would be most effective if changes were made while landfills are still in active operation and accruing funds. Second, appropriate management of existing aftercare funds is critical to provide proper protection of HHE, the financial health of landfill owners, and to prevent the emergence of landfills with exhausted aftercare funding.

The objective of this paper is to critically review approaches for the long-term management of MSW landfills. In the next section, an overview of management alternatives for closed MSW landfills is provided. Thereafter, specific approaches for the evaluation and potential completion of aftercare at MSW landfills that have been described in the literature are analyzed. This is followed by a presentation of country-specific regulatory procedures and technical guidelines. Finally, findings from the analysis of long-term landfill management approaches and procedures are highlighted and recommendations for future efforts to reduce uncertainty on the duration and extent of landfill aftercare are presented.

While the focus of this review is on the aftercare period following landfill closure, management of a landfill earlier in its life is addressed when relevant to the approach proposed for aftercare. Fig. 1 illustrates that while the post-operational period starts directly after the end of waste disposal, the aftercare period starts after final cover installation.

In some cases, measures for enhanced emission reduction are initiated during or after the end of waste deposition. For example, in Wisconsin, USA, landfill owners are encouraged to either eliminate biodegradable material from landfills or to stabilize it by measures for the enhanced reduction of the emission potential remaining in the landfill (e.g. liquids addition, aeration) within 40 years after closure (Wisconsin Department of Natural Resources, 2007). In Germany, there is discussion of aerating landfills after closure to reduce the emission potential within the landfill before a final cover is installed (Stegmann et al., 2006).

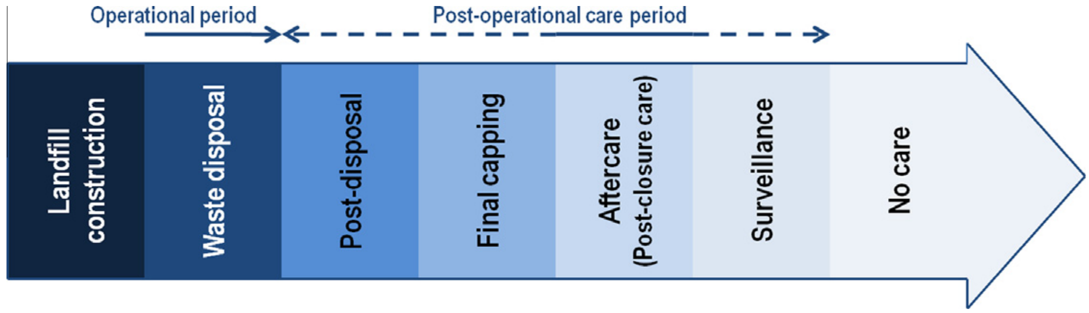

Fig. 1. Different management phases throughout the life-cycle of a MSW landfill.

Each of these activities has implications for aftercare. Thus, aftercare completion may not always have the same meaning and will depend on the long-term management concept applied. In this paper, aftercare completion is defined as the time at which the authorities accept the end of regulated aftercare and release the owner/operator from responsibility for the site, because the closed landfill is not likely to present a threat to HHE in the absence of aftercare. In consideration of the underlying management approach, this can be viewed either as a definitive endpoint (i.e. a defined landfill condition requiring no further care) or the transformation of a closed landfill from regulated aftercare into a "de minimus" post-regulatory care program (e.g. site surveillance and protection of top cover) (cf. Morris and Barlaz, 2011). Whereas the former would also imply the end of post-operational care, the latter would leave the landfill in the post-operational care period with some low level of activities required at the site.

2. Range of aftercare alternatives

A summary of alternatives that have been discussed for the long-term management of landfills is provided in this section. These alternatives include (i) termination of aftercare after a specified time, (ii) perpetual care, (iii) termination when specific endpoint criteria are reached for leachate, gas, and the waste, (iv) complete waste stabilization before aftercare termination (as a special case of (iii) with criteria solely related to the deposited waste), and (v) a performance-based approach where end-point criteria are applied at the point of compliance (POC).

(i) The specified time termination alternative describes a situation in which aftercare is carried out for a predetermined time period after which the owner would no longer be responsible for the site. This period could be 30 years or any other time specified by regulation. The advantage of this alternative is that it is predictable. The owner knows what is required for what period of time. However, to the extent that public authorities would assume responsibility at the end of aftercare, this alternative leaves society responsible for problems that could arise. Termination after a predetermined time period does not address the biological, chemical or physical status of a landfill and its potential threat to HHE.

(ii) If termination is at one extreme, then perpetual care would be considered as the other extreme. As it implies, in this alternative, the owner's responsibility to monitor and maintain the landfill never ends. The advantage of this alternative is that it removes uncertainty for both the landfill owner and the regulatory agency. The owner knows what is required in advance and the authorities have no need to assess and evaluate the status of the landfill over time. While this alternative may offer maximum protection of HHE, it does so without regard to cost or the pursuit to limit transfer of environmental problems to future generations. In addition, "perpetuity" in the private sector would be challenging to define and enforce. Ultimately, waste disposal costs are borne by waste generators (citizens and manufacturers), either through direct fees, or through taxes. If funds are spent to protect against insignificant risks, one could argue that this is not an efficient use of societal resources (cf. Scharff et al., 2011).

(iii) The third alternative is to manage a landfill until specific endpoints for leachate, solids, gas, and geotechnical aspects are reached. In the case of leachate, a BOD/COD ratio of less than 0.1 has been suggested as an indicator of stable leachate (Reinhart and Townsend, 1997). However, this is a necessary but insufficient criterion to prove that the waste has biodegraded to a large extent, because of the manner in which landfills are filled, i.e. fresher waste at the top, and the fact that leachate is collected from the bottom of the landfill. When leachate from younger refuse, which may be in the acid phase of decomposition, percolates through well decomposed waste, the leachate can be expected to reflect the composition of well decomposed waste. This is because the high BOD of acid phase leachate will be consumed as the leachate passes through the well decomposed, and thus carbon limited, waste. Consequently, leachate with a low BOD/COD ratio does not imply that all of the refuse is well decomposed. Furthermore, this criterion does not address metals, ammonia or other compounds. With respect to solids, a cellulose plus hemicellulose to lignin (CH/L) ratio of less than 0.1 has been suggested as an indicator for well degraded waste (Kelly et al., 2006). However, measurement of this parameter throughout a landfill is challenging. A performance criterion for gas (such as required by Wisconsin Department of Natural Resources (2007)) may be most realistic as a standard could be set to require that the landfill gas production rate decrease to a rate at which it can be attenuated in a biofilter or biocover. A major limitation of many metrics is that they do not consider site-specific conditions such as annual precipitation or the sensitivity of the surrounding environment. For instance, the requirements for the long-term management of landfills in arid regions may well differ from landfills in regions that receive significant precipitation.

(iv) In the complete waste stabilization alternative, the landfill is monitored until it is completely stable with respect to chemical, biological and physical characteristics of the waste mass. At the point of complete waste stabilization, a failure of the containment system would not result in a deleterious effect to HHE, because the waste itself (i.e. without containment) would not pose a threat to HHE. While desirable, this is not practical, particularly for landfills with a large fraction of biodegradable waste. Physical stability may be easiest to address as post-closure settlement could be monitored until the rate of settlement is less than a value calculated to show no risk from a geotechnical perspective. Considering chemical stability, the long-term composition of leachate has been described previously and is useful for this analysis (Kjeldsen et al., 2002). Degradable organic matter can be consumed, concentrations of soluble salts will decrease with increasing water throughput, and metal concentrations in municipal landfill leachate are low. However, both ammonia and possibly trace organic contaminants represent potential problems in the context of an unregulated release to the environment. There is no mechanism for ammonia transformation under the anaerobic conditions of a landfill and ammonia is known to accumulate in landfill leachate. In theory, this ammonia could be flushed from the landfill but this requires several pore volumes of water, and raises concerns about heterogeneous water flow that may preclude complete flushing of ammonia or salts (Fellner et al., 2009; Laner et al., 2011a). In addition, there may be chemicals that have yet to be identified in leachate as a result of the fact that landfills represent an accumulation of society's waste (Öman and Junestedt, 2008). An example of such a class of chemicals is the fluorinated compounds that are present in many consumer products. The chemical bonds of these compounds to fibers of paper, textiles or carpet are continuously degraded and persistent chemicals are released and may manifest as problematic constituents of landfill leachates (Weber et al., 2011). Consequently, the presence of trace organics in leachate is still nebulous and further attention should be given to their identification and persistence in landfill leachate. In addition to leachate, it is difficult to imagine a situation where all the degradable solids are stabilized. Heterogeneous water flow implies that even in a landfill with aggressive water infiltration, there may be pockets of waste that remain dry and do not completely decompose (cf. Maloszewski et al., 1995; Rosqvist et al., 2005). In addition, the sampling required to assess solids stability is expensive and challenging given landfill heterogeneity (e.g. Chiampo et al., 1996). Thus, rigorous assessment of the biological, physical, and chemical stability of the waste is difficult, as is defining and documenting an apparently simple performance criterion such as 90% solids decomposition.

(v) The fifth alternative is to develop aftercare strategies based on actual landfill performance. In a performance-based approach, aftercare requirements would be dictated by the status of the landfill, projections of its future performance based on data trends, and a need to document protection of HHE under the range of conditions that may impact a specific landfill in the future (e.g. ultimate use of the site, required cover performance levels). A desired landfill condition at the end of aftercare is not defined from the outset, but the reduction of aftercare intensity as dictated by site-specific data is expected to ultimately lead to de minimus care requirements at the site.

3. Review of approaches for landfill aftercare and completion

Given the range of alternatives for the long-term management of closed landfills, three categories of approaches to evaluate and manage MSW landfills after closure have been suggested: (i) target value approaches define criteria which have to be met to complete aftercare, (ii) impact/risk assessment approaches evaluate aftercare in view of the local conditions at the landfill site to quantify impacts/risks associated with aftercare completion and after-use activities; or (iii) performance based systems for aftercare draw on site-specific data, which are used to evaluate the actual level of aftercare and provide guidance on the progressive reduction of aftercare intensity using performance indicators as well as assessments of acceptable risks/impacts. A review of specific approaches suggested by different authors (largely) adhering to one of these categories is presented in this section.

3.1. Target values to evaluate aftercare

In the target value approach, the desired state of the MSW landfill at which aftercare can be terminated is defined. This approach could address the quality of the deposited waste, the tolerable levels of emissions (landfill gas and leachate), and criteria such as the maximum rate of settlement. The specified criteria are generic and can therefore be applied without further evaluation. Some examples addressing leachate quality, waste degradation status, and landfill gas production were provided in Section 2 (iii), which illustrated the concept of target values on a generic basis. Here, specific methodologies adhering to the target value approach and end-point criteria are presented.

Stegmann et al. (2006) state that at the end of aftercare, the biological processes and other conversion processes have to be largely completed and unlikely to be reactivated in the future due to changing conditions at the landfill. The quantitative criteria to terminate aftercare are related to the technical (i.e. enhanced emission reduction technologies), legal (primarily with respect to German regulations), and economic (i.e. the costs of different aftercare strategies) conditions at the site. The suggested values address emission levels for landfill gas and leachate (primarily pollutant loads), the quality of the deposited waste (leaching tests and biodegradability), and settlement rates (Table 1). The target values for aftercare completion suggested by Stegmann et al. (2006) were derived in consideration of strategies to significantly reduce the emission potential of a MSW landfill before the final cover is installed. Using these criteria, a conventional MSW landfill would require aftercare for many decades to several centuries (cf. Heyer, 2003; Heyer et al., 2005). As this does not correspond with the goal of aftercare completion within a few decades, the authors favor a strategy of significantly reducing the emission potential before a low permeability final cover is installed. This approach eliminates the large emission potential within the waste body after final cover installation, which could be released if containment systems fail at a later time. The strategies proposed to achieve a low emission potential are controlled infiltration of water into the waste body and in situ aeration of the landfill (cf. Stegmann et al., 2003). In situ aeration is presented as a promising technology to reduce leachate concentrations and landfill gas production, accelerate biodegradation, and complete major settlements within several years (cf. Heyer et al., 2005). However, Stegmann et al. (2006) emphasize that additional criteria need to be defined on a site-specific basis which relate to landfill elements (e.g. condition of the containment system), the potential of natural attenuation processes taking place in the subsurface below the landfill, or potentially affected vulnerable uses in the vicinity of the landfill. These approaches are addressed on a conceptual level and tangible criteria or evaluation procedures are not included within the presented approach.

Similar to the above approach, Cossu et al. (2007) proposed a methodology to evaluate the "final storage quality" of a landfill based on a combination of generic criteria and site-specific risk analysis. A landfill is considered to have reached final storage quality when it contains solids of such quality that no further treatment of emissions into air and water is necessary (Baccini, 1989). Starting from a review of different parameters (i.e. emissions and waste quality) and a comparison of attainable values for defined landfill management technologies, a set of parameters (landfill gas, leachate, and deposited waste) was chosen to evaluate aftercare. Several quantitative criteria are presented (Table 1) for a screening evaluation of aftercare at a landfill. If the landfill complies with these cri-

Table 1
Completion criteria suggested within different target value approaches.

	Stegmann et al. (2006)	Cossu et al. (2007) and Pivato (2004)	Knox et al. (2005)	Krümpelbeck (2000)
Leachate	COD: 5–20 g/(m^2 year) NH_4–N: 2.5–10 g/(m^2 year) Cl: 10–20 g/(m^2 year) AOX: 0.01–0.05 g/(m^2 year) (emissions to subsurface)	COD: <200 mg/l BOD_5/COD ratio: <0.01 NH_4: <300 mg/l	NH_4–N: $\leqslant$10 mg/l	Concentrations and loads: COD: $\leqslant$16–70 mg/l NH_4–N: $\leqslant$9–20 mg/l COD: $\leqslant$3–14 g/(m^2 year) NH_4–N: $\leqslant$1.8–4 g/(m^2 year)
Landfill gas	Methane production rate: <25 m^3 CH_4/h and <0.0005 m^3 CH_4/(m^2 h) Hydrocarbon emissions (flame ionization detector measurements): <25 ppm	Gas generation rate: <25 m^3/h Area-specific methane generation rate: <0.001 m^3 CH_4/(m^2 h) CH_4/N_2 ratio: <0.01 CO_2/N_2 ratio: <0.01	Landfill gas emission rate: $\leqslant$0.0084 m^3/(m^2 h) Trace gas concentrations: $\leqslant$0.5 H_2S ppbv	–
Waste quality	Concentrations in the eluate: TOC: $\leqslant$150 mg/l NH_4–N $\leqslant$50 mg/l Cyanide $\leqslant$0.1 mg/l AOX $\leqslant$0.5 mg/l (additionally: heavy metals, organic compounds, pH, and elec. cond.) Biodegradability: Respiratory index (RI_4): $\leqslant$2.5 mg O_2/g dry matter (DM) Methane generation potential in 21 days: 0.01 m^3 CH_4/kg DM	Biodegradability: respiratory index (RI_4): $\leqslant$2.5 mg O_2/g DM Methane generation potential in 21 days: 0.01 m^3 CH_4/kg DM	Biodegradability: loss on Ignition (corrected for plastics): $\leqslant$25% Acid detergent fiber (corrected for plastics): $\leqslant$2.5% Cellulose/lignin ratio (corrected for plastics): <0.2 Biochemical methane potential (BMP): $\leqslant$0.0002 m^3 CH_4/kg DM	–
Landfill settlement	Site-specific assessment (90% of overall settlement completed)	–	–	–
Comments	Site-specific criteria addressing geotechnical stability, landfill elements (e.g. base lining system), and hydrogeology to be set	All target values are intended for screening purposes to decide whether a subsequent risk analysis should be implemented	Biodegradability tests are not precise and additional site-specific assessment is required	Concentration levels are only applicable if leachate generation rate is below 200 mm/year

teria, then a site-specific risk analysis (cf. Pivato, 2003, 2004) is suggested to evaluate environmental compatibility of the emissions at the site.

An evaluation of final storage quality was also proposed by Knox et al. (2005) and criteria were derived from investigations at 14-year old MSW landfill test cells. The authors state that the biodegradation of MSW is the key process with respect to achieving final storage quality, and suggest target values for landfill gas and leachate emissions as well as tests to assess the residual biodegradability of the deposited waste (Table 1). These criteria, which are defined generically based on literature data and regulatory standards, require the removal of 95–99.5% of degradable organics, but corresponding biodegradability tests are still rather imprecise and sometimes inconsistent with each other. The authors conclude, however, that criteria to assess final storage quality will necessarily be site-specific and that current test methods are not suitable to appropriately characterize final storage quality for a landfill. Thus, operative criteria are still to be developed and should be based on documented cases where MSW landfills have achieved final storage quality.

Krümpelbeck (2000) proposed another approach to evaluate the state of the landfill at which aftercare might be completed using generic values. Based on an evaluation of emission data from German MSW landfills, the author identified leachate emissions as the primary long-term threat at MSW landfills. Consequently, suggested target values refer to the load of chemical oxygen demand (COD) and ammonia–nitrogen (NH_4–N) in the leachate (Table 1). Although emission loads are suggested as the primary indicators, critical concentration levels are also presented for these parameters. The suggested criteria are based on the assumption that over 90% of the original emission potential of the deposited MSW will be released before aftercare can be completed, such that only 9% (calculated via trend extrapolations of leachate data over 500 years) may be released from the landfill thereafter. In addition to these criteria, other values are discussed as leachate-based completion criteria (e.g. water quality standards for the inflow of drinking water purification plants), and it is emphasized that application of the presented criteria is only suitable if the landfill base is situated at least several meters above the groundwater table and emissions are compatible with the planned future use of the site. Krümpelbeck (2000) concludes that the target values represent an initial assessment that must be complemented by site-specific criteria to determine when completion of aftercare is possible. Hence, the approach provides screening level indicators for leachate, but does not represent an operative procedure to evaluate aftercare.

In general, all of the authors of target value approaches emphasize that additional site-specific evaluations are needed to complement the suggested values before a decision on aftercare completion can be made. Although a procedure to combine generic target values and site-specific assessments is solely presented by Cossu et al. (2007), all approaches are in agreement that a site-specific assessment is needed to address the risk of environmental pollution, especially with respect to groundwater. Another commonality is that most approaches include criteria for the quality of the deposited waste with a focus on its biodegradability. However, the issue of a representative characterization of the landfill body (cf. Chiampo et al., 1996; Sormunen et al., 2008) and the consistency of different test methods (e.g. Laner et al., 2011b) has not yet been handled on an operative level. In the approaches described by Stegmann et al. (2006) and Cossu et al. (2007), the target values are derived in consideration of an achievable landfill condition (based on enhanced emission reduction measures) and may not necessarily be associated with environmentally compatible emissions. The latter is discussed by Ehrig (2002) who points out the danger of specifying target values based on achievable rather than on environmentally protective levels.

Table 2
Methodological basis and application of impact/risk assessment proposed to evaluate aftercare.

Authors	Modeling approach	Application	Comments
Scharff et al. (2011)	Long-term modeling of contaminant migration to point of compliance and comparison to standard	Case study on a largely inorganic landfill (Cl and SO_4 identified as critical leachate parameters)	Suggested as a part of the toolbox to assess aftercare completion
Hall et al. (2007a)	Long-term modeling of contaminant migration to point of compliance and comparison to standard	Hypothetic landfills with different waste qualities sited in a specific model environment (leachate parameters at equilibrium level)	A procedure for aftercare completion incorporating the modeling results has not been suggested
Boerboom et al. (2003)	Probabilistic risk assessment to estimate potential costs associated with environmental risks during aftercare	Used as a cost calculation method for aftercare in several provinces of The Netherlands	No guidance on aftercare or completion, but could be a basis to accrue appropriate aftercare funding

Apart from the approach suggested by Stegmann et al. (2006), the approaches presented in Table 1 are conceptual and not specific with respect to the underlying definition of the state at which a landfill might be released from aftercare. Although, some authors (Knox et al., 2005; Cossu et al., 2007) use “final storage quality” to describe the desired state, it has been previously concluded that this is not an operative definition and that it can probably not be defined in a generic way (e.g. Baccini, 1989; Brunner, 1992; Hjelmar and Nedenskov, 2007). In conclusion, the presented target value approaches range from specific guidance on aftercare (cf. Stegmann et al., 2006) to screening level assessments (e.g. Knox et al., 2005). All authors acknowledge that aftercare completion at MSW landfills is a site-specific exercise and thus supplementary evaluations to generic target values are necessary to evaluate aftercare completion.

3.2. Impact/risk assessment to evaluate aftercare

As long as a landfill represents a hazard and there is a receptor that can be damaged (e.g. human health or environmental media such as groundwater), some level of risk is associated with the landfill. Risk assessment has been applied to landfills, often with a focus on leachate emissions and groundwater pollution (e.g. Butt and Oduyemi, 2003). With respect to landfill aftercare, Pivato (2003) have proposed an approach in which an acceptable level of risk is defined for the landfill at the end of aftercare. Hence, to evaluate the risk of a closed landfill, potential negative impacts on HHE and the probability of their occurrence must be assessed. A major challenge in this endeavor is the long-term reliability analysis of the technical barrier system, which may cause substantial evaluation uncertainties (cf. Pivato, 2011). Specific approaches which adhere to the concept of landfill risk assessment for evaluating aftercare are described below and summarized in Table 2. Scharff et al. (2007) state that a robust risk assessment is needed to end aftercare at landfills. As acceptable emission levels are dependent on local conditions, consequent completion criteria for landfill aftercare must be site-specific. Within a pilot study on the landfilling of primarily inorganic waste, Scharff et al. (2011) developed an approach for determining aftercare completion criteria as a part of an integrated procedure to evaluate aftercare. Although recognizing the importance of additional evaluation criteria such as landfill gas parameters (for landfills containing biodegradable waste) or parameters associated with defining when a landfill is no longer considered a threat to HHE based on its performance and data trends, the work presented by Scharff et al. (2011) focuses on the impact of leachate releases on groundwater quality. The long-term impact of leachate emissions is evaluated based on geochemical modeling and the subsequent comparison of maximum concentration levels to water quality criteria. The procedure is comparable to the source-pathway-receptor approach which was applied to determine waste acceptance criteria within the EU Landfill Directive (cf. Hjelmar et al., 2001, 2005; EC, 2003), with the major difference that the suggested approach employs a more sophisticated reactive transport model to describe contaminant migration through the soil towards the point of compliance. The application of the approach to leachate from largely inorganic landfills (without the consideration of a containment system) reveals chloride and sulfate as the contaminants potentially not complying with drinking quality standards at the point of compliance (POC – a hypothetical drinking water well in the groundwater downstream of the landfill). For landfills containing biodegradable waste, Mathlener et al. (2006) suggest that after the organic matter has been degraded, the behavior of the landfill body may converge towards the behavior of a largely inorganic landfill. Scharff et al. (2011) conclude that a risk based approach is needed to determine aftercare completion in view of the conditions at the site and that the aftercare completion cannot be based solely on target values.

Another impact assessment approach primarily based on modeling of landfill leachate release and forward modeling of contaminant transport processes in the subsurface has been presented by Hall et al. (2006, 2007a). The modeling was carried out with LandSim2.5 (Environment Agency, 2004), which is used to predict the time period until “equilibrium status” with the environment can be reached at the landfill site based on specific assumptions with respect to future performance of liner and cap. The contaminant source term strength was characterized by leaching experiments and decreasing concentrations are related to the contaminant-waste partitioning coefficient. Equilibrium is defined as the state when emissions from a landfill occur at a rate that allows sufficient natural attenuation in the surrounding environment to prevent environmental harm, so management is no longer required (Hall et al., 2007a). Consequently, if equilibrium conditions are reached at a site, landfill aftercare can be terminated (Hall et al., 2007b). Within the presented study, the risk assessment methodology has been primarily applied to demonstrate the effect of waste diversion and pretreatment (e.g. MBT residues, incineration) options on the time required to achieve environmental equilibrium for a model landfill. However, the authors state that aftercare completion can only be achieved if a landfill has stabilized physically, chemically, and biologically to a degree that the undisturbed contents are unlikely to pose a pollution risk at the site, meaning the modeling approach must be complemented with other criteria to establish a framework for addressing the completion of aftercare. This framework has not yet been proposed.

In contrast to the approaches described above, the methodology suggested by Boerboom et al. (2003) does not assess the pollution risk emanating from a closed landfill but rather the costs of environmental risks associated with aftercare. The methodology is designed to estimate appropriate funding for aftercare activities, which should be based on the potential financial risks present at a site. The risk assessment builds on expert estimates of failure probabilities for specific events (e.g. unsatisfactory inspection of the landfill cover) that are linked to the occurrence of unwanted events in a fault tree analysis. The investigated unwanted events do not include exceptional risks (e.g. earthquake) but relate rather to groundwater contamination, damage to the final cover, or an

Table 3
Methodological basis and application of performance-based systems to evaluate aftercare.

Authors	Methodology	Application	Comments
EPCC methodology (Morris and Barlaz, 2011)	Modular approach for the evaluation of environmental/human health impact/risk associated with aftercare addressing data collection, leachate management, gas management, groundwater monitoring, and cover performance	Evaluation is used as a basis to progressively reduce aftercare, ultimately leading to completion while being protective of the environment. Application was demonstrated at a hypothetical case study site	Operative methodology providing specific protocols for long-term landfill management
Sizirici et al. (2011)	Ranking algorithm based on expert evaluations of site-specific factors resulting in a preliminary assessment of appropriate aftercare at a site	Factor-specific ordinal scores based on site performance assigned by experts and then weighted to derive an overall landfill score. Application to two sites was presented	Tool is dependent on expert judgement and qualitative analysis
SANA model (van Vossen, 2010)	Demonstration of natural attenuation as a feasible approach for aftercare to minimize long-term environmental risks at MSW landfills based on performance data	A natural attenuation (or enhanced emission reduction) approach is promoted to sustainably reduce the emission potential at three full-scale demonstration landfills	Bottom up approach to provide guidance on aftercare. Consistent methodology is to be developed based on the case study results

early need for replacement of the final cover. The probability of occurrence for an unwanted event is calculated via Monte Carlo analysis, and the sum of costs to undo the unwanted events for a defined period is calculated as the financial risk during aftercare. Although the methodology is not intended to specify a procedure for landfill completion (risks are calculated for specific aftercare durations), it may represent a valuable tool for appropriate funding of aftercare activities, especially if it was widely applied and the model was parameterized from a growing database.

Of the impact/risk assessment approaches summarized in Table 2, only the approach suggested by Boerboom et al. (2003) directly addresses MSW landfills, albeit in terms of financial risks during aftercare. The other approaches were developed to assess (primarily) the risk of groundwater pollution for largely inorganic landfills (Scharff et al., 2011) or for model landfills featuring different waste pretreatment options (Hall et al., 2007a). Although, these approaches might prove valuable for an assessment of environmental impact associated with closed MSW landfills, they have not yet been integrated to form an evaluation framework for aftercare. In addition, the evaluations are limited to the environmental risk to groundwater and do not consider flora, fauna, and exposure of humans. There is a high level of uncertainty involved in a risk assessment and the transparency of modeling assumptions is significant for an understanding of the outcome. Therefore consistent procedures are needed that allow for an objective evaluation of the environmental risk at a closed landfill. This is highlighted by the work of Hall et al. (2006, 2007a), who point out the complexity in their modeling due to assumptions on containment system performance and subsequent effects on the interrelationships between leachate quality, release rates and concentrations at the POC in an aquifer. Consequently, sensitivity analysis and subsequent handling of inherent uncertainties would prove valuable to understand modeling results. In conclusion, while the presented risk assessment approaches could substantially contribute to an aftercare evaluation procedure, they are expensive and uncertain. As such, the utility of risk assessments in the development of aftercare completion remains to be determined.

3.3. Performance-based system for aftercare

As a consequence of potentially long aftercare periods for MSW landfills, performance-based evaluations have been suggested for long-term management of closed MSW landfills (Barlaz et al., 2002). In general, such approaches are based on landfill monitoring and performance data which are used to evaluate the landfill condition with respect to appropriate aftercare activities. Hence, the evaluation procedures are site-specific and provide guidance on the sequential reduction of aftercare intensity that may, if warranted by performance data, ultimately lead to aftercare completion. Different approaches adhering to this concept are described in this section and summarized in Table 3.

A performance-based system for evaluating aftercare requirements at MSW landfills, referred to as the evaluation of post-closure care (EPCC) methodology, was presented by Morris and Barlaz (2011). The EPCC methodology addresses the four primary aspects of landfill aftercare monitoring and maintenance (i.e. leachate quality and quantity, gas management, groundwater monitoring and protection, and cover maintenance) in a user-friendly modular system. It provides long-term stewardship of landfills by assessing their current and future impacts/risks to the environment based on the evaluation of "functional stability". Functional stability is used to define a closed landfill that does not present an unacceptable threat to HHE in the absence of aftercare, but with some remaining level of control to protect the cover (SWANA Bioreactor Committee, 2004, cited by Geosyntec (2006)). The methodology establishes a site-specific basis for decisions on maintaining, extending, reducing, or modifying aftercare activities while being protective of the environment. Logic diagrams are used for each aspect of aftercare (i.e. for each module) and the modules can be sequentially evaluated (prerequisites module, leachate module, gas module, groundwater module, and cover module). The methodology application requires the end-use and final condition of the landfill to be considered from the outset. The application of the methodology generally involves analyzing statistical trends in leachate, landfill gas generation, and groundwater quality, as well as additional biological, chemical, and physical data, to demonstrate that gas production is stable or decreasing, and leachate quality is constant or improving. Once a change in aftercare is implemented, the owner is expected to verify no adverse effect by "confirmation" monitoring followed by "surveillance" monitoring at a decreasing frequency. Monitoring procedures also identify high and low level "trigger" conditions requiring immediate responsive action to resolve a condition.

The EPCC methodology allows for multiple outcomes in which the requirements for each aspect of aftercare may vary significantly. Three possible levels of analysis are built into the methodology: (a) in a source evaluation the compliance with target values may be demonstrated at the source (e.g. leachate quality < drinking water standards); (b) in a POC evaluation, it is demonstrated that the landfill does not pose an unacceptable impact at the POC; and (c) in a point of exposure (POE) evaluation, it is demonstrated that the landfill does not pose an unacceptable risk at the POE (Morris and Barlaz, 2011). The potential for a harmful release to the environment is analyzed before any aspect of aftercare may be reduced or discontinued. Thus, the EPCC methodology determines a level of aftercare that is consistent with the actual state of the landfill and the sensitivity of the surrounding environment based on the combination of target values (criteria which are used for comparison to actual performance indicators) and impact/risk assessment approaches (also reflected by the definition of functional stability). The integrated evaluation is the basis for progressively reducing aftercare, potentially completing regulatory aftercare obligations, and turning the landfill over to a custodial care program consistent with the new use of the land property (which can be no use). The custodial care program represents activities that would be required at other marginal and "brownfield" sites and thus would not be specific for MSW landfills (cf. Pivato and Morris, 2005; ITRC, 2006).

Application of some components of the EPCC methodology to evaluate appropriate aftercare at a MSW landfill in Florida has been described by Sizirici (2009). A set of relevant parameters (e.g. leachate: ammonia–nitrogen, chloride, iron, VOCs or landfill gas: remaining gas generation potential) was identified and estimates of future emission levels were derived for the case study landfill (cf. Sizirici and Tansel, 2010). Based on a risk assessment at the site, it was concluded that landfill gas management could be discontinued, whereas leachate and groundwater monitoring had to be continued. Surveillance of cap integrity also remains an integral part of aftercare activities at the landfill. Hence, the aftercare period at the site can be reduced for some landfill elements (e.g. gas collection) but is required for others (e.g. leachate management) to be protective of HHE (Sizirici, 2009).

Recently, Sizirici et al. (2011) presented a screening procedure for a preliminary assessment of aftercare needs at closed landfills. The procedure is based on expert evaluations (scale from 1 to 10) of site-specific parameters (e.g. climate, operational factors, leachate management, gas management, etc.) which are combined using a ranking algorithm (i.e. by assigning weights to different factors). The overall score from the algorithm is used to categorize the landfill conditions as critical, acceptable, or good as a result of an evaluation. "Critical condition" at a site indicates that the landfill may represent a threat to HHE and thus, aftercare activities need to be enhanced. "Acceptable condition" confirms current aftercare intensity and "good condition" as an outcome of the evaluation indicates the potential for a reduction of aftercare activities. However, the suggested aftercare evaluation procedure does not provide specific guidance on the intensity of aftercare or the completion of aftercare activities and both the scoring system and ranking algorithm require judgment.

A performance-based approach for aftercare based on the potential of naturally occurring or enhanced natural attenuation NA processes (e.g. via waste aeration) at a landfill has been described by van Vossen (2010). This approach aims at a lasting emission reduction at closed MSW landfills and is based on the full-scale demonstration of the methodology at three case study landfills in the Netherlands (cf. van Vossen et al., 2007, 2009a,b). The model used to demonstrate the capability of natural attenuation processes to phase out unacceptable levels of contaminants is referred to as the SANA (Sustainable Aftercare of landfills based upon Natural Attenuation) model (van Vossen, 2010). As one of the demonstration landfills has been partly built without a base lining system, the SANA model has the capability to analyze the potential for natural attenuation in the landfill body as well as in the pollution plume below the landfill and in the groundwater. Conditions in the landfill are characterized and the model evaluates the state of biochemical, geochemical, and hydrological processes in consideration of performance indicators (e.g. in situ temperature, settlements, COD/BOD ratio, ammonia–nitrogen, gas production rate, CH_4/CO_2 ratio) that are used to describe the extent of organic matter stabilization. The goal of enhanced emission reduction activities within the SANA model is to replace the need for an impermeable final cover by a low emission potential of the waste, which will finally allow landfill emissions to meet acceptable levels and consequently allow aftercare completion. If acceptable leachate emission levels cannot be achieved at the site, an environmental risk assessment is suggested to determine the necessity of mitigation measures for preventing unacceptable groundwater pollution. In essence, the suggested approach promotes a specific aftercare strategy (enhanced emission reduction based on natural attenuation processes) and describes its application to demonstration landfills, but does not yet constitute a consistent methodology (including criteria) to evaluate aftercare and aftercare completion. However, van Vossen (2010) states that such a methodology will be based on the final results of the demonstration projects and is currently under development.

The performance-based evaluations of aftercare shown in Table 3 are essentially site-specific, allowing for long-term landfill management to be adapted to local conditions. Among the presented approaches, the EPCC methodology presents the most tangible evaluation procedure, providing operative assessment protocols to decide on an appropriate level of aftercare, combining target values, impact and risk assessments. Whereas the EPCC methodology establishes a consistent aftercare evaluation framework, the approach suggested by van Vossen (2010) employs a bottom-up strategy of demonstrating the performance of natural attenuation processes to explain emissions at full-scale landfills. However, an environmental risk assessment and potential site remediation might be necessary if admissible emission levels cannot be met using the SANA model. In addition, for those landfills not equipped with a bottom liner, no operative protocol to monitor natural attenuation at MSW landfills currently exists, although a policy for Monitored Natural Attenuation (MNA) has been approved for remediation of soils and groundwater at RCRA sites in the United States (USEPA, 1999), and it is not clear if the local groundwater will be accepted as a long-term treatment filter for waste management processes (cf. Christensen et al., 2000).

Another fundamental difference between the concept suggested by van Vossen (2010) and the EPCC methodology is that the former embraces a strategy to enhance emission reduction to decrease emissions to low levels without a long-term low permeability cover, whereas the latter does not require a strategy to decrease the emission potential of the waste body, as the focus lies on actual emission levels and emission trends at the landfill. However, the EPCC methodology does not preclude enhanced emission reduction at a site. Where no steps are taken to decrease the emission potential of the waste body, maintenance of a low permeability top cover is expected to be part of the custodial care program within the EPCC methodology.

The approach presented by Sizirici et al. (2011) does not rely on measured landfill performance-data like the other approaches listed in Table 3, but on expert evaluation of different factors that influence landfill aftercare. The procedure does not give guidance on specific aftercare activities or completion criteria. In general, the application at case study sites is of paramount importance for all performance-based approaches, as this will be necessary to assess their practicability with respect to aftercare duration and completion.

3.4. Discussion of approaches to evaluate aftercare

The objective of any evaluation of landfill aftercare management and completion should be to address potential threats associated with a closed landfill in a consistent and transparent manner and thereby allow decision makers to comprehend underlying assumptions as well as associated residual risks. Table 4 summarizes the major characteristics of the target value, impact/risk assessment, and performance-based approaches. Although target value approaches are not site-specific per se, all of the approaches ultimately depend on site-specific data. This implies that generic target values without site-specific assessments are necessarily very

Table 4
Overview of main characteristics of different approaches to evaluate aftercare.

Characteristic	Target value approaches[a]	Impact/risk assessment approaches	Performance-based approaches
Site specific	No	Yes	Yes
Data collection in addition to standard emission monitoring	Waste sampling and analysis (i.e. leaching and biodegradability tests)	Waste sampling and analysis (potentially) More extensive monitoring (potentially)	More extensive monitoring (potentially)
Outcome verification	Not necessary	Not included	Included
Status of approach	Conceptual to partially operative	Partially operative	Partially operative to operative
Level of expertise	Low	Very high	Very high
Usability of approach	Mostly prescriptive	Flexible	Flexible

[a] The target value approaches acknowledge the need for additional site-specific evaluations, but do not provide detailed guidance. Thus, the characteristics refer to generic target values only.

stringent and may result in unnecessary continuation of aftercare at many MSW landfills. In addition to the need for site specific evaluations, target value approaches are also confronted with unresolved issues of representative waste sampling and the inconsistency of tests to estimate potential (residual) release rates. Impact/risk assessment approaches have largely been presented with respect to the evaluation of specific environmental risks (i.e. groundwater pollution), but not as an integrated framework to allow for evaluation of aftercare completion. Although risk assessment approaches address the very core of the issue with respect to acceptable risk and tolerable emissions, the evaluation requires a high level of expertise and comes with large uncertainties (e.g. Hall et al., 2006). The performance-based approaches for aftercare evaluation represent a more pragmatic approach, and may as a result be most likely to receive regulatory acceptance, as they sequentially adjust aftercare activities to the risk associated with the state of the landfill. A performance-based approach combines target values and impact/risk assessment, and allows for a comprehensive evaluation of aftercare completion as elements of each approach are integrated into an evaluation framework. However, it is important to note that performance-based evaluations and, to a large extent, risk-based evaluations generally neglect investigation or characterization of the residual emission potential or condition of the waste mass. Performance-based approaches focus instead on actual emissions and defining a desired state of the landfill at the end of aftercare in terms of the landfill's relationship with its receiving systems and a level of care required for the cover system. The large uncertainties inherent in risk-based evaluations of closed landfills are handled in performance-based approaches by the collection of appropriate monitoring data and the need for confirmation monitoring in case of aftercare modifications. Overall, it is clear that well documented case studies are needed to demonstrate the feasibility of demonstrating aftercare completion based on any of these approaches.

4. Regulatory procedures for aftercare completion

Financial provisions for the aftercare period of a MSW landfill are typically accrued based on an assumed minimum duration of aftercare. In many countries, regulators require financial provisions for a minimum aftercare period of 30 years (e.g. Subtitle D of RCRA in the US or the European Landfill Directive). However, different time-based approaches for aftercare funding have been implemented. In the Swiss Canton of Zürich, the landfill owner is released from aftercare after 5 to 15 years and the responsibility for long-term management of the site is transferred to the authorities (Bachofner, 2010). The landfill owner has to build up financial provisions sufficient to fund 50 years of aftercare. The funds are provided to the authorities to maintain aftercare as long as the landfill is likely to pose a threat to HHE and pooled with the aftercare provisions from other closed landfills in the canton (cf. AWEL, 2009). A similar model has been adapted in the Netherlands, where landfill owners have to accrue funding for perpetual aftercare (MVM, 1979). After landfill closure, the funds are at the disposal of the authorities who are responsible for the long-term management of the landfill (see Section 4.9 below).

In contrast to funding accrual mechanisms for aftercare (which are typically based on a pre-defined time period), regulatory frameworks in general require that the landfill not pose a threat to HHE to complete aftercare. Hence, the aftercare period may well be different from the period for which financial provisions have been built up. Although there have been approaches proposed to evaluate aftercare, they are not necessarily integrated into regulatory frameworks. A number of different criteria and procedures as implemented at the national or sub-national regulatory level in Asia, Europe, and North America are described in this section and summarized in Table 6. Listings are provided in alphabetical order to avoid implying bias or suggestion of coordinated policies on any given continent.

4.1. Austria

In Austria, MSW landfills have to be managed for at least 40 years after closure and until the authorities confirm that no more aftercare measures are necessary (cf. Lebensministerium, 2008). As no procedures to evaluate the necessity for aftercare have been adopted by Austrian authorities, a group of landfill owners, regulators, and researchers suggested a conceptual outline and criteria for aftercare evaluation (Fellner et al., 2008). The suggestions are similar to the criteria described in the German Landfill Directive (BMU, 2009) and in the approach presented by Stegmann et al. (2006). The guidance document describes two phases of aftercare. In the first phase, active measures (e.g. intensive water infiltration, in situ aeration) might be used to reduce the emission potential of the deposited waste and active control and monitoring are expected as a part of aftercare. In the second phase, a period of passive landfill management (e.g. methane oxidation processes to attenuate landfill gas emissions) is suggested to demonstrate lasting low emission levels and no unacceptable threat in the absence of active landfill management. After the authorities decide that no more aftercare measures are necessary in accordance with the Austrian Waste Management Act (Lebensministerium, 2002), aftercare can be completed and the public authorities assume responsibility for appropriate use and surveillance monitoring. The criteria to evaluate aftercare completion address leachate emissions (quality and quantity), landfill gas emissions (quality and quantity), landfill settlements, and the quality of the deposited waste (standards for eluates and biodegradability tests). The proposed criteria also include recommendations on monitoring protocols and describe the need for additional site-specific evaluations (e.g. groundwater).

Although some specific criteria are suggested, the proposed evaluation framework is not yet operative and should be supplemented with site-specific criteria and appropriate risk assessment tools to allow for an integrated assessment of aftercare.

4.2. California, USA

In California, regulations require the owner of each solid waste landfill that accepted waste from 1988 to demonstrate financial assurance for aftercare until released from aftercare, which is when the waste no longer poses a threat to HHE (Calrecycle, 2011). Financial assurance must be provided for a minimum of 30 times the annualized aftercare costs, although a step-down approach can be used to reduce financial assurance starting 5 years after landfill closure if this is supported by performance-based data. For this reason, the rules for performance and funding of aftercare (which were revised in July 2010) incorporate proactive (or performance-based) monitoring for closed landfills as a means to address financial assurance requirements with the primary focus that operators can follow a step-down approach to reduce the duration and/or provisions for future aftercare activities if certain requirements are met. The underlying demonstrations rely on monitoring and it is expected that the step-down approach will present an incentive for landfill owners to perform high-quality aftercare. Monitoring programs will be site-specific and will probably include trends in leachate quality and quantity, landfill gas quality and quantity, ground and surface water conditions, and the final cover and settlements behavior. With respect to the evaluation and management of closed landfills, the Californian authorities suggest a performance-based approach and reference the EPCC methodology and ITRC guidance, although they have not endorsed the concept of custodial care, questioning the extent to which a non-regulated program can guarantee appropriate cover maintenance (O'Brien, 2011).

4.3. England and Wales

In England and Wales, a combined target value and impact/risk assessment approach has been developed by the Environment Agency and procedures to release a landfill owner from aftercare obligations (termed "surrender of permit") are described in a technical guidance document (Environment Agency, 2010b). Aftercare completion can only be achieved when the closure and post-closure requirements have been fulfilled and the site is unlikely to pose a threat to HHE. Based on the type of waste, the level of controls, and the sensitivity of the environment, three levels of evidence are distinguished (basic, low risk and standard surrender application). The information required within the evaluation increases with the complexity of landfills. MSW landfills are evaluated under the standard surrender application section of the guidance, as there is an expectation that the level of investigation and protection will be more detailed for MSW deposits than for landfills containing largely inorganic non-hazardous waste. The Environment Agency will not consider a surrender application while active control measures are being used at the site. Appropriate monitoring data will be required to demonstrate that active control measures (e.g. pumping of leachate) are no longer necessary. The aftercare completion criteria suggested in the technical guidance for a MSW landfill include:

(i) *Leachate:* For each priority pollutant detected in the leachate, the landfill owner has to determine completion criteria based on a hydrogeological risk assessment. The owner must demonstrate that pollutant concentrations will not result in an unacceptable impact on groundwater or surface water. The risk assessment has to include assumptions on the deterioration of the containment system.

(ii) *Landfill gas:* If the maximum methane concentration in the landfill is below 1.5% and the maximum concentration of carbon dioxide is below 5% by volume, the completion criteria for landfill gas are considered to have been met. Representative monitoring must demonstrate that these standards have not been exceeded at least for 2 years before the application. Alternatively, landfill gas completion criteria are considered to be met when:
- concentrations of CH_4 and CO_2 are similar to background levels in the surrounding environment, or
- gas generation is less than 0.022 m^3 of CO_2 per hour and 0.015 m^3 of CH_4 per hour for a minimum period of 2 years, including measurements during periods with falling atmospheric pressure.

(iii) *Geotechnical:* Aftercare completion criteria with respect to settlements and slope stability require waste settlement to be completed (i.e. no significant differences are observed in consecutive annual topographical surveys). Waste slopes must be in a long-term geotechnically stable condition even if leachate heads build up in the landfill. There must be no slope instability due to long-term erosion.

Monitoring, including consideration of average travel times to the monitoring points, will be required to confirm that the aftercare completion criteria listed above have been met. The guidance outlines basic data needs as well as the format of presentation. Although the document does not address specific methodological aspects (e.g. data analysis and evaluation, modeling tools and assumptions, etc.), it presents a scheme for how to integrate different evaluations to a consistent framework, which can be accepted as a basis for surrender applications by the authorities. Thus, the England and Wales methodology includes elements of target value, performance and risk-based approaches.

4.4. France

In 1997, France promulgated a Ministerial Decree (French Ministry of the Environment, 1997) on MSW landfilling in which aftercare is defined as the period after waste filling during which there is significant production of leachate or gas or any phenomenon likely to damage surroundings. Any closed landfill regulated under this decree must be monitored for at least 30 years, starting from the time of final cap installation. Moreover, the operator must propose restrictions on use during and after the aftercare period as well as future end-use scenarios. A bank guarantee for financial assurance, that is compulsory for all authorized landfills in case of major failure, is maintained during the aftercare period, but cannot be used to cover the projected aftercare costs. In 2007, the French Agency for Environment and Energy Control (ADEME) issued guidance on aftercare funding accrual on a 30 years basis (ADEME, 2007). Although the operator must submit a report to the authorities 6 months before the end of the 30-year period, no guidance is currently provided to help the operator and authorities agree on a completion demonstration methodology and the expected status of the landfill at completion. To date, a few landfills pre-dating the 1997 regulation but for which aftercare monitoring was required or voluntarily implemented have applied for the termination of aftercare, mainly using risk-based assessment following national guidance on risk assessment on human health for controlled installations (e.g. INVS, 2000; INERIS, 2003; ASTEE, 2005). However, to date no landfill has been released from its regulatory aftercare obligations.

Recently, landfill owners, ADEME, and the National Institute on Risk Assessment (INERIS) have proposed launching a working group on aftercare management and completion, advocating a performance-based approach derived from the EPCC methodology (see Section 3). The type of approach and some of the demonstration mechanisms and concepts within the EPCC methodology (e.g. site-specific assessment based on future end-use, potential restrictions on future uses, site surveillance, and resorting to high level expertise and assessment only if necessary) are already widely applied and accepted in France. For example, EPCC concepts are applied through guidance on contaminated land and site rehabilitation/restoration (French Ministry of the Environment, 2007) and the guidance on non-authorized landfill rehabilitation/restoration (ADEME, 2005).

4.5. Germany

In Germany, the state of a landfill at the end of aftercare is qualitatively defined in the German Landfill Directive (BMU, 2009) by the following criteria:

(i) Transformation and degradation processes within the deposited waste are largely completed.
(ii) Generation of landfill gas does not occur or is sufficiently low that active gas extraction is not necessary, and there are no negative effects due to migrating gas. Sufficient methane oxidation has to be demonstrated.
(iii) The rate of landfill settlements has decreased to a level such that future damage of the top cover system due to settlement can be excluded. This must be demonstrated by 10 years of settlement data.
(iv) The cover system is functional and stable, and will not be impaired by the current and planned after-use of the site.
(v) The long-term geotechnical stability of the landfill is guaranteed.
(vi) The maintenance of buildings and landfill facilities is no longer necessary.
(vii) Leachate discharged into surface water bodies complies with the concentrations stipulated in the German ordinance on requirements for the discharge of waste water into waters (BMU, 2004: appendix 51).
(viii) Leachate released to the subsurface will not cause a violation of site-specific groundwater trigger values (cf. Bräcker et al., 2004) downstream of the landfill.
(ix) In case of asbestos-containing wastes, appropriate measures are in place to prevent human exposure to asbestos.

These qualitative criteria form the basis for the completion of aftercare in Germany. Leachate emissions are evaluated based on concentrations stipulated for direct discharge into surface water or statistically derived concentrations at a POC in the groundwater for leachate released to the subsurface. The regulations do not provide specific guidance or protocols for aftercare completion, but represent a framework for the authorities' evaluation of aftercare at a MSW landfill. For example, the criteria are unclear as to what if any release of methane is acceptable or what methods are appropriate to quantify methane emissions and demonstrate that there are no methane emissions. A specific approach adhering to the criteria stated above was presented by Stegmann et al. (2006) as described previously and is cited in the explanatory note to the German Landfill Directive (in the document "Verordnung zur Vereinfachung des Deponierechts – Begründung (Kabinettbeschluss vom 24.09.2008)" specific issues and research related to the qualitative criteria (a–i) are outlined). Based on the qualitative criteria, it is expected that authorities in Germany are likely to combine elements of target value and risk assessment approaches to address the regulatory criteria to complete aftercare. In addition, there will be a need for landfill owners to demonstrate appropriate performance of specific landfill elements or characteristics (e.g. settlement trends).

4.6. Interstate Technology and Regulatory Council, USA

The Interstate Technology and Regulatory Council (ITRC), a coalition of public authorities and industry stakeholders dedicated to cooperative development of cost-effective, innovative environmental techniques, has analyzed the Subtitle D regulation and proposed a performance-based approach for modifying aftercare as described in a guidance document (ITRC, 2006). The ITRC guidance acknowledges that "there is no single widely accepted approach for conducting performance-based evaluations of post-closure care". The guidance presents an approach to evaluate aftercare that is largely based on the EPCC methodology and includes input from various state and federal agencies, industry representatives, consultants, and community stakeholders who participated in developing the guidance. These contributors support the concept of reducing or ending aftercare based on the outcome of performance-based evaluations of leachate, landfill gas, groundwater, and landfill cap conditions. The ITRC guidance introduces and documents support for regulatory approval of performance-based aftercare, functional stability and custodial care, and encourages different strategies to influence the duration of aftercare (e.g. bioreactor operations, alternative covers, etc.), but does not provide a detailed procedure for demonstrating these characteristics at a landfill. The guidance document describes custodial care as a post-regulatory program capable of defining and maintaining land use consistent with what was assumed during the aftercare completion analysis and in accordance with covenants, deed restrictions or other controls. Although the ITRC does not have regulatory authority, it recommends that regulatory agencies consider using the EPCC methodology or another performance-based approach to evaluate aftercare.

4.7. Japan

In Japan, a demonstration that the landfilled waste is sufficiently stabilized to complete aftercare is required (Tanaka et al., 2004). Aftercare completion is demonstrated for a landfill by monitoring leachate quality, landfill gas, and temperature in the waste. Leachate concentrations must be below Japanese effluent standards for at least 2 years before the evaluation, with a monitoring interval of 3 months or less for BOD and COD, and 6 months or less for other leachate parameters. Landfill gas generation should be stable or decreasing for the two previous years and be very low at aftercare completion. To complete landfill aftercare, the temperature in the waste body may not be more than 20 °C higher than the temperature in the subsurface around the landfill. Temperature in the landfill is to be measured throughout a vertical landfill profile. If the above criteria can be met, leachate management, landfill gas management and landfill monitoring might be terminated (cf. Tanaka et al., 2004). Hence, the completion procedure for aftercare at MSW landfills in Japan is largely built on a target value approach. Apart from emission levels and temperature, the physical condition of the landfill is not addressed.

4.8. Ontario, Canada

The Canadian province of Ontario uses a "contaminating lifespan" (CLS) concept in which all elements of a landfill must be functional as long as the landfill has the potential to release contaminants of concern (Ministry of the Environment, 2008). The CLS of a landfill is defined as "the period of time during which the landfill will produce contaminants at levels that could have unacceptable impact if they were discharged into the surrounding environment" (cited in Rowe, 2005). Impacts are related to the mass of contaminant released per unit area, the infiltration rate through the cover, and the pathway for contaminant release (Rowe, 1991). Based on the approach outlined in the regulation, the effect of each of these three determinants on the CLS is: (i) all other things being equal, the greater the mass of waste, the greater the mass of contaminant, and hence the greater the CLS, (ii) assuming a leachate collection system exists, the greater the infiltration (and hence volume of leachate generated) the shorter the CLS, and (iii) the greater the potential for attenuation along contaminant migration pathways, the shorter the CLS.

An estimate of the CLS should address contaminants in both the leachate and gas (especially as it applies to subsurface migration), including estimates on the service life of every engineered facility associated with the emission pathways. Hence, evaluation of the CLS is based on a risk assessment approach that includes the assumption that the containment system will fail. The amount of financial assurance for aftercare is determined on a case-by-case basis and must be sufficient to manage the site for the CLS of the landfill, with a minimum of 25 years (Ministry of the Environment, 2010). Under the regulation, two approaches for designing a landfill to protect groundwater are possible: (i) a generic design that incorporates a liner and leachate collection system, and (ii) a site specific design (natural attenuation) approach, that relies on natural attenuation to mitigate contaminant releases from the landfill based on local environmental conditions and in accordance with the guidelines for reasonable use (Ministry of the Environment, 1994). For generic designs, the infiltration rate through the cover must be greater than or equal to 15 mm/year. The CLS can thus be shortened by increasing the infiltration (i.e. flushing) rate. For site specific designs, the reasonable use limits are standards, which take account of background groundwater quality and the use of groundwater on adjacent property. In accordance with the design principle, the aftercare period at a MSW landfill will depend on the environmental setting, the level of engineering, the service lives of engineered landfill elements, and the type of waste and remaining contaminant concentrations, which are of course difficult to predict. The post-closure period may extend from many decades to several hundreds of years or longer given the need to consider the risk of failure of the containment system within the CLS. Aftercare strategies to promote waste and leachate stabilization are thus desirable for an engineered site. In contrast, for a natural attenuation site, limiting infiltration and leachate production may be more appropriate. Aftercare completion is ultimately decided upon by the authorities based on annual post-closure reports (including updates of the estimated CLS) and will be accepted when there are no more contaminants from the site of potential concern to the environment. Specific completion criteria or methods to derive such criteria are not provided.

4.9. The Netherlands

In the Netherlands, all landfill owners are required to submit an aftercare plan as a part of the landfill permit procedure. During operation, the aftercare plan has to be updated every 5 years and is assessed by the competent authorities based on a checklist (Table 5) (Zegers and Boerboom, 2009). The goals of the checklist are:

(i) To enable sound assessment of the amount and quality of information in the aftercare plans.
(ii) To provide guidance to the authorities for the assessment process.
(iii) To provide standard values (frequency, unit costs, etc.) to the authorities to determine necessary aftercare efforts and their associated costs in order to determine the financial security for aftercare or, in case standard values do not apply, to provide criteria for assessment of site-specific aftercare efforts.
(iv) To provide guidance to landfill operators for drafting aftercare plans.

The first checklist was drafted in 2002 and it is also updated every 5 years. The costs for aftercare are determined individually for each landfill (i.e. specific costs of monitoring, maintenance and replacement of the environmental protection system) (cf. Geusebroek and de Jong, 2005). In addition to this procedure, the authorities apply a model for the determination of financial risks during aftercare (cf. Boerboom et al., 2003; Section 3). The most important costs relate to the impermeable top cover, which is a composite system, and its periodic replacement. The final amount required for the aftercare fund is determined based on an assessment of the environmental protection measures after construction of the top cover. The responsibility for aftercare is then transferred to the authorities and the landfill owner is discharged from all aftercare obligations.

Table 5
List of contents of the Dutch checklist for landfill aftercare.

Contents	1.3.2. Groundwater extraction	3.1.1. Monitoring drainage
1. SITE SPECIFIC ASPECTS	1.3.3. Treatment of groundwater	3.1.2. Signaling drainage
1.1. General	1.3.4. Discharge/infiltration of water	3.1.3. Leachate drainage
1.1.1. Operators and owners	1.3.5. Provisions against vandalism	3.1.4. Rainwater drainage
1.1.2. History and surroundings	1.3.6. Constructional provisions	3.1.5. Piezometers
1.1.3. Geometry	2. MONITORING	*3.2. Maintenance*
1.1.4. Start and end of operation	*2.1. Sampling and water analysis*	3.2.1. Landfill gas extraction system
1.1.5. Soil morphology	2.1.1. Monitoring drainage	3.2.2. Waste water treatment plant
1.1.6. Geohydrology	2.1.2. Piezometers for groundwater	3.2.3. Grounds and general provisions
1.1.7. Soil quality	2.1.3. Leachate drainage	3.2.4. Other maintenance
1.1.8. Surface water	2.1.4. Waste water treatment	4. REPLACEMENT AND REMOVAL
1.2. Standard provisions	2.1.5. Rainwater drainage	*4.1. Replacement*
1.2.1 Monitoring drainage	2.1.6. Surface water	4.1.1. Replacement of surface sealing
1.2.2. Bottom liner	2.1.7. Groundwater extraction	4.1.2. Rainwater drainage
1.2.3. Leachate drainage	*2.2. Measurements and visual inspections*	4.1.3. Piezometers
1.2.4. Leachate treatment	2.2.1. Settlements	4.1.4. Other objects
1.2.5. Surface sealing	2.2.2. Thickness recultivation layer	*4.2. Removal*
1.2.6. Rainwater drainage and discharge	2.2.3. Groundwater levels	5. RISK EVALUATION
1.2.7. Landfill gas extraction	2.2.4. Visual inspections	6. ORGANIZATION
1.2.8. Landfill gas treatment	2.2.5. Gas measurements and analyses	*6.1. Reporting and evaluation*
1.2.9. Monitoring piezometers	2.2.6. Material quality surface sealing	*6.2. Communication*
1.3. Site specific provisions and measures	3. MAINTENANCE	7. COSTS
1.3.1. Civil engineering provisions	*3.1. Cleansing drainage and piezometers*	8. AFTERCARE RECORDS

Table 6
Regulatory procedures to evaluate and potentially complete aftercare.

Country/authority	Approach	Status
Austria	Target values for leachate, landfill gas, waste quality, and settlements plus a site-specific assessment	Conceptual guidance – no regulatory status
California (USA)	Financial assurance for aftercare can be reduced after closure based on landfill performance data. For post-closure evaluation and management, the EPCC methodology and ITRC guidance are referenced	Current regulation
England and Wales	Combined target value and impact/risk assessment approach integrated into a procedure to evaluate aftercare completion, including target values as completion criteria for landfill gas	Technical guidance – outline of procedures and required demonstrations to complete aftercare
France	General risk assessment approaches are mainly used in applications for aftercare completion	Currently no guidance to evaluate aftercare and aftercare completion
	Performance-based approach (EPCC methodology) is advocated by stakeholders	Working group on aftercare management and completion (following an EPCC type methodology)
Germany	Qualitative criteria defining the desired state of a landfill at the end of aftercare	Qualitative criteria are legally binding (listed in the German Landfill Directive)
ITRC (USA)	EPCC methodology or a similar performance-based approach is recommended to evaluate aftercare at MSW landfills	Technical guidance; stakeholder platform providing non-binding recommendations for regulatory approaches
Japan	Target values for leachate, landfill gas, and waste temperature plus a site-specific assessment	Legally binding
Ontario (Canada)	Contaminating lifespan of a landfill (risk-based assessment) as the basis for the duration of aftercare period	Legally binding landfill regulatory and approval requirements; not specific to aftercare
The Netherlands	(a) Perpetual care conducted by authorities (b) Groundwater risk assessment to derive emission test values for aftercare completion	(a) Legally binding (b) Under development

The regulatory approach in the Netherlands is based on the concept of perpetual aftercare. As this procedure might be associated with a substantial emission potential present within the landfill body for very long time periods, the Dutch authorities and landfill owners are currently discussing a risk-based approach to define emission test values for groundwater impact based on a source-pathway-receptor model. Due to the ban on the deposition of biodegradable materials in the Netherlands, long-term gas emissions are considered less problematic than soil and groundwater impact and it is expected that passive methane oxidation measures can sufficiently reduce future landfill gas emissions. The emission test values for soil and groundwater protection shall be defined in terms of kg m^{-2} $year^{-1}$ entering the soil. The underlying evaluation methodology will be similar to the approach suggested by Scharff et al. (2011) as summarized in the previous section.

4.10. Wisconsin, USA

The Wisconsin Department of Natural Resources (2007) has issued guidance to achieve the stabilization of deposited organic waste at MSW landfills. While not an aftercare methodology per se, Wisconsin's policies were developed in consideration of the aftercare issue, as the landfill owners are required to submit a plan to significantly reduce the residual amount of degradable organic matter within 40 years after closure. Landfill organic stability is achieved when landfill gas production has effectively ceased, organic pollution of landfill leachate is insignificant, the organic fraction of the waste mass will not readily decompose when placed in ideal moisture and temperature conditions, and there is no longer measurable settlement. Specifically, the requirements include: (i) a steady downward trend in the rate of gas production, (ii) the monthly average landfill gas production rate should be no higher than 5% of the maximum monthly average total gas production rate observed previously or less than 0.28 m^3 of total gas per year per m^3 of waste, and (iii) cumulative landfill gas production is at least 75% of the projected total. Unfortunately the first two criteria will be difficult to quantify given that landfill gas collection efficiencies change over time as gas collection systems are installed. As discussed previously, solids sampling, if required, would present significant challenges.

As the criteria only address gas generation as an indicator for organic degradation processes, meeting the criteria will not entitle a landfill owner to complete aftercare. The decision on aftercare completion will be made separately and in accordance with engineering landfill characteristics and site-specific factors such as the presence of sensitive receptors, the performance of the engineered systems, and monitoring results.

5. Concluding remarks

This review of approaches for the long-term management of MSW landfills has highlighted that an evaluation of landfill aftercare and its completion needs to integrate aspects from different approaches to address the core of aftercare completion, that no unacceptable risk is associated with the landfill in the absence of aftercare. Target values have typically been suggested as screening indicators and are often meant to point to specific strategies (e.g. measures for enhanced emission reduction before final cover installation), but there is a general agreement in the literature that generic criteria will not suffice to assess aftercare at MSW landfills. Rather, target values may be most useful as a screening method prior to a site-specific assessment addressing the impact/risk associated with a closed landfill. As the collection and analysis of comprehensive monitoring data is likely to be required in any procedure to evaluate aftercare completion, the guidance and protocols provided in performance-based approaches to evaluate the condition of the landfill and associated risks may represent a major element of an integrated evaluation methodology. A performance-based system combines target values and impact/risk assessments into an evaluation framework, making this type of approach a potential basis for the development of evaluation procedures on a regulatory level.

While the ultimate objective for aftercare completion is similar in most cases (i.e. landfill is not likely to represent a threat to HHE), the presented regulatory completion procedures vary with respect to the underlying definitions and methods, the operative level of the procedure, the status of implementation, and the legal foundation of the procedure linked to national societal values. In general, the country-level procedures for aftercare evaluation do not specify one approach, but rather an integration of different assessment tools (e.g. target values combined with risk assessments). In some countries (e.g. England and Wales), specific but non-binding technical guidelines have been issued. Obligatory procedures to evaluate aftercare, such as those in Germany and Ontario, are more qualitative and provide only a general framework for evaluation. Operative definitions, quantitative criteria and assessment procedures are not specified (cf. Table 6). Therefore other than perpetual care, it is not clear what might be accepted as a basis for the completion of aftercare at MSW landfills. Although it can be expected that regulatory practice will provide an indication of acceptable aftercare completion procedures at MSW landfills in the future, it would be beneficial for all affected parties to have an understanding of evaluation requirements before the actual evaluation takes place. As monitoring data during aftercare will be necessary as a basis for decisions on the completion of aftercare in most cases, relevant parameters and assessment tools need to be defined to efficiently collect such data and plan financial obligations.

Therefore, although rigorous aftercare evaluation methodologies have generally not been proposed by regulatory authorities and are difficult to build, the development of transparent and consistent procedures is necessary to communicate the requirements for aftercare completion to landfill owners and thereby reduce uncertainty about the intensity and duration of aftercare. In this context, current suggestions in technical guidelines (e.g. England and Wales, ITRC) and the ongoing debate with respect to their regulatory acceptance are a valuable step toward developing strategies for the cost-effective protection of HHE at closed MSW landfills.

At the moment there is very little experience with implementing any of the approaches reviewed in this paper to evaluate aftercare completion. To assess the practicality of different evaluation frameworks, well documented case studies including regulatory review and acceptance are needed. Such case studies would more definitively define the data that are most essential to an aftercare evaluation, and also define what is acceptable to a regulatory agency. Ultimately, case studies will lead to a refined definition of appropriate aftercare assessment methodologies and reduce uncertainty on appropriate levels of funding that are required for aftercare management and ultimately landfill completion.

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