

# **RETROSPECTIVE ANALYSIS OF WISCONSIN'S LANDFILL ORGANIC STABILITY RULE: IS THE RULE MEETING ITS OBJECTIVES?**

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## ABSTRACT

The objective of this study was to conduct an independent review of Wisconsin's Organic Stability Rule (OSR) for the Wisconsin Department of Natural Resources (WDNR). The purpose was to evaluate changes that have occurred in waste management practice as a result of the rule and to assess whether the rule is meeting organic stability goals. Ten landfills were selected for the review. The selected landfills are located in areas having varying population demographics throughout the state and have a range of waste acceptance rates, leachate recirculation and liquid addition operational plans, and gas usage. Nine of the ten sites are privately owned, and all but one of the privately-owned sites has an active Research, Development, and Demonstration (RD&D) permit. The main alternative action implemented under the RD&D rule among the eight sites with an active permit is the disposal of liquid waste within the landfill waste mass. The organic stability actions implemented among the sites include leachate recirculation, liquid waste addition, organic waste diversion, and delayed placement of final cover. Leachate recirculation and liquid waste addition were the predominant actions implemented at all sites with the objective to enhance in situ organic waste decomposition. Waste diversion was reported at four sites, but only had a noteworthy effect at one site where greater than 50% of the municipal solid waste (MSW) tonnage was diverted to a refuse derived fuel facility.

The ten sites evaluated in this study combined accepted 44% of the total mass of waste and 51% of the mass of municipal solid waste (MSW), on average, in Wisconsin between 2007 and 2012. The average waste disposal rate during these years ranged from 210 to 3,030 ton/d among the sites. MSW disposal decreased for all but one site from 2007 to 2012. The annual amount of leachate recirculated was less than leachate generated; however, one site recirculated 100% of generated leachate during a 3-yr period. The percent contribution of liquid waste addition to total liquid added in a given year ranged from 0 to 100%. The high end of this range reflects a change in operational strategy whereby liquid waste disposal is used to increase revenue via tipping fees and increase waste moisture content to enhance organic waste decomposition. There are numerous considerations associated with the quantity of liquid waste accepted at a given landfill, including the mass of MSW available to store liquid, revenue associated with liquid waste acceptance, and costs associated with leachate generation. Liquid waste was accepted under the RD&D rule and the most common liquid waste sources were commercial process liquids, cleaning water, and sludges.

Recirculation of leachate and addition of liquid waste enhanced gas generation at all sites. Analysis of the organic stability benchmarks outlined in the OSR suggests that all sites will achieve greater than 75% of total gas generation and an adequate reduction in gas flow rate (e.g., less than 5% of peak monthly flow) within a period of 40-yr post closure. However, these two benchmarks generally are achieved at different elapsed times, and achieving 75% gas generation is shown to require less time than a reduction in gas flow rate.

Overall, the organic stability actions implemented at the landfills evaluated in this report are meeting criteria outlined in the OSR. A general perspective shared by the landfill owners and operators interviewed for this study is that the goals of the OSR currently coincide with industry goals. The OSR provides a performance check on landfill operations, promotes increased gas generation and waste settlement, and provides a disposal alternative for commercial liquid, which can be landfilled at sites with an active RD&D permit. The authors recognized that liquid addition requires additional landfill management and requiring an operator to adhere to the OSR via liquid addition can lead to unanticipated landfill performance outcomes. The OSR should be continued; however, periodic (e.g., 5 yr) evaluations of the OSR should be considered due to the dynamic nature of the waste industry. The following recommendations are provided to ensure that the OSR continues to achieve the desired objectives while remaining practical to implement.

1. WDNR should encourage the US Environmental Protection Agency (USEPA) to modify the Resource Conservation and Recovery Act (RCRA) by incorporating the provisions of the current RD&D rule within Subtitle D of RCRA.
2. WDNR should develop guidance regarding biochemical compatibility of liquid waste sources.
3. WDNR should clarify existing requirements for early and aggressive gas collection as part of organic stability plans and ensure that these requirements are followed for landfills adding liquid wastes.
4. WDNR should promote means to make beneficial use of landfill gas attractive.
5. WDNR should consider modifications to the gas generation benchmarks in the OSR and development of a standardized gas analysis procedure.
6. WDNR should consider metrics for cessation of gas collection as part of the OSR.
7. WDNR should recognize that the OSR can affect publicly- and privately-owned landfills differently.

8. WDNR should recognize that gas generation alone does not address post-closure care and more comprehensive criteria are needed to address functional stability.
9. WDNR should consider a statewide life cycle analysis (LCA) to assess the effects of more aggressive organic waste diversion.

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## **INTRODUCTION**

Wisconsin's landfill organic stability rule (section NR 514.07(9), Wis. Adm. Code) requires owners and operators of municipal solid waste (MSW) landfills to "incorporate landfill organic stability strategies into the plans of operation for their facilities." Specifically, the rule requires that landfill owners submit a plan to the Wisconsin Department of Natural Resources (WDNR) for "significantly reducing the amount of degradable organic material remaining after site closing in order to materially reduce the amount of time the landfill will take to achieve landfill organic stability." Organic stability is viewed as a state of near complete decomposition of organic waste constituents such that human health, environmental, and financial risks associated with undecomposed waste are reduced. Short-term and long-term risks of landfilled waste arise from gaseous emissions, organic or inorganic contaminants in leachate that have potential to be released to the environment, and settlement of the waste mass to the extent that settlement results in damage to the final cover and/or gas collection and control system. Degradation of the organic fraction of MSW can mitigate some risks and reduce others via exhausting the gas generation potential of the waste, treating leachate contaminants in-situ, and reducing the magnitude of future settlement. Thus, organic stability can be viewed as a state of the waste that reduces the need for subsequent engineering and maintenance efforts, and that reduces the potential for unanticipated future financial costs to be incurred.

WDNR promulgated the organic stability rule (OSR) in 2007 to require organic stability plans for MSW landfills in Wisconsin for the following three scenarios: (1) new or expanded landfills as of 1 January 2007, (2) landfill plans of operation approved between 1 January 2004 and 1 January 2007, and (3) active landfills where current filling operations have not achieved 50% of design capacity as of 1 January 2012. In the first case, a formal organic stability plan is required, whereas for the latter two cases a modification to the approved plan of operation is required to demonstrate compliance with the OSR. Waste stabilization to minimize long-term risks associated with the waste mass is a motivating force behind the OSR. Potential waste

management strategies for implementation of the OSR include (1) diversion of biodegradable organic material from the landfill, (2) mechanical or biological treatment prior to disposal, or (3) in-situ landfill treatment. Processes for the third option include liquid addition, leachate recirculation, or in-situ aeration, alone or in combination, to enhance waste biodegradation. A summary of alternative strategies has been developed by WDNR (2005).

Organic stability plans submitted to WDNR are required to have actions targeted to achieve organic stability, an implementation schedule, anticipated outcomes, monitoring and evaluation to document plan effectiveness, and a contingency plan in the event that initial observations and measurements indicate that organic stability may not be achieved. Annual organic stability reports are required from all landfills that have an approved organic stability plan to document evaluation of plan performance and to address whether changes are required to improve progression towards organic stability. The objective of organic stability plans is outlined by WDNR as meeting all of the following goals: (i) monthly average gas ( $\text{CH}_4 + \text{CO}_2$ ) production rate  $\leq 5\%$  of average maximum monthly gas production rate observed during the life of the facility, or  $\leq 7.5 \text{ ft}^3\text{-gas/yd}^3\text{-waste/yr}$ ; (ii) steady downward trend in the rate of total gas production ( $\text{CH}_4 + \text{CO}_2$ ); (iii) cumulative gas ( $\text{CH}_4 + \text{CO}_2$ ) yield  $\geq 75\%$  of projected total gas production from landfilled waste; and (iv) reduction of time required to achieve landfill organic stability to  $\leq 40 \text{ yr}$  post-closure (WDNR 2006). Landfill owners and operators have flexibility to select organic waste stabilization strategies that best fit their needs.

When WDNR implemented the OSR, they also committed to assessing the impact and effectiveness of the rule five years following implementation. This study was conducted for the WDNR to fulfill this commitment, and represents a unique opportunity to analyze changes that have occurred in waste management practice and landfill operation as a result of the OSR. The objectives of this study were to (1) assess the manner in which landfill owners have acted to implement the OSR; (2) evaluate results of the actions on landfill performance and progression towards organic stability; and (3) consider implications of the OSR for solid waste management

policy in Wisconsin. While this report was funded by the WDNR, WDNR personnel stressed that the report should be independent of the funding agency and other stakeholders.

## **POST-CLOSURE MANAGEMENT OF LANDFILLS**

A motivating factor for implementation of WDNR's OSR was to reduce the long-term risks and liabilities associated with Subtitle D (i.e., MSW) landfills. The objective of this section is to summarize the status of post-closure care policies and alternatives in the US. Formal strategies for long-term management of landfills are evolving and represent an area where additional attention by WDNR is warranted.

Strategies for management of closed Subtitle D landfills are required to manage risks to human health and the environment (HHE). In the US, landfill owners are required to monitor and maintain a closed landfill for what is referred to as the post-closure care (PCC) period (USEPA 1993). Regulated PCC activities include leachate management, groundwater monitoring, inspection and maintenance of the final cover, and control and monitoring of off-site methane migration. A 30-yr PCC period is specified in the federal RCRA Subtitle D rules, unless this period is modified by the governing regulatory agency. PCC requirements in the US under the federal RCRA Subtitle D regulation and state derivatives are actually performance rather than time based; 30 yr is typically used as a guide, but PCC is required until a demonstration of no threat to HHE at the relevant point of exposure (POE). Many landfill owners budget aftercare funds on the assumption that care will be discontinued after 30 yr. However, few modern landfill owner/operators have completed 30 yr of aftercare and/or petitioned to modify the aftercare period.

In Wisconsin, the statutory post-closure care period does not have an endpoint; rather the owner is responsible for care of the landfill in perpetuity (s. 289.41(1m)(c), Wis. Stats.). Wisconsin law establishes 40 yr as the period for which landfill owners must maintain proof of financial responsibility for long-term care (s. 289.41(1m)(b), Wis. Stats.).

## **Alternatives for Long-Term Management of Landfills**

Potential alternatives for long-term management of landfills include (1) termination of PCC after a fixed term, (2) perpetual care, (3) complete stabilization, (4) chemical criteria, and (5) a performance-based approach (Laner et al. 2012). The termination alternative describes a situation in which the landfill is termed 'complete' at the end of a fixed monitoring period without regard to the physical condition of the landfill or other objective measures. After the predetermined period, the owner would no longer be responsible for the site. The advantage of this alternative from an owner-operator perspective is that the duration of PCC is predictable. However, completion on the basis of time alone does not address the status of a landfill and the potential threat to HHE. In this alternative, society as a whole must assume future risk.

Under perpetual care, the owner is required to monitor and maintain the landfill in perpetuity, regardless of the landfill status and any potential threat to HHE. The advantage of this alternative is that perpetual PCC period removes uncertainty for both the owner and the governing regulatory agency. This alternative offers maximum protection of HHE, potentially without regard to cost. Ultimately, waste disposal costs are borne by waste generators and funds spent on perpetual landfill management are funds not spent on other societal needs. To the extent that funds are spent to protect against insignificant risks, perpetual PCC is not an efficient use of resources.

In the complete stabilization alternative the landfill is monitored until stabilization is achieved with respect to chemical, biological, and physical characteristics. At the point of complete stabilization, a failure of the containment system would not result in a deleterious effect on HHE. While attractive, complete stability is difficult to achieve. Physical stability could be monitored until the rate of settlement is less than a value calculated to show no risk from a geotechnical perspective. However, the physical stability of the cover will likely require continuous monitoring. Considering chemical stability, the long-term composition of leachate

has been described previously and is useful for this analysis (Kjeldsen et al. 2002). Although degradable organic matter is consumed and metal concentrations in municipal landfill leachate are low, ammonia and many trace organic compounds represent a potential threat in the context of an unregulated release to the environment. There is no mechanism for ammonia transformation under anaerobic conditions and ammonia is known to accumulate in landfill leachate (Benson et al. 2007; Barlaz et al. 2010). In theory, this ammonia could be flushed from the landfill but this requires many pore volumes of water that required subsequent treatment.

The presence of trace organic compounds is more nebulous given their low concentrations and potential biodegradability. Nonetheless, there may be chemicals that have only recently been identified in leachate and new chemicals may be detected as landfills represent an accumulation of societal waste. For example, fluorinated chemicals are present in many consumer products and recently have been detected in leachate (Prevedouros et al. 2006; Busch et al. 2010). In addition to leachate, achieving a situation where 100% of the degradable solids are mineralized is difficult to imagine. Even in landfills with moisture addition, as analyzed in this report, there may be pockets of waste that do not completely decompose. The sampling required to assess solids stability is expensive and difficult given landfill waste heterogeneity. Thus, rigorous assessment of the biological stability of all solids is difficult.

A fourth alternative is to operate a landfill until specific endpoints (i.e., target values) for waste solids, leachate, and landfill gas (LFG) are reached. In the case of leachate, a biochemical oxygen demand (BOD) to chemical oxygen demand (COD) ratio of less than 0.1 is often cited as representative of methanogenic leachate (Kjeldsen et al. 2002). This is a necessary but insufficient condition for chemical stability given the manner in which landfills are filled (fresher waste at the top). Leachate that is collected from the bottom of a landfill has been in contact with waste of different ages before reaching the leachate collection system. When leachate from younger waste, 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. The high COD of acid-phase leachate from young waste is consumed as the leachate passes through the older well-decomposed carbon-limited waste. As a result, collection of leachate with a low BOD:COD ratio at the base of a landfill does not demonstrate that all waste is well decomposed. In addition, this criterion does not address metals, ammonia, or other compounds. Finally, the mass release of a contaminant to the environment, as opposed to a contaminant concentration in the landfill, poses a potential threat to HHE. For example, an elevated ammonia concentration is only problematic if the leachate is released to the environment.

With respect to solids, a cellulose plus hemicellulose to lignin (CH:L) ratio of less than 0.1 has been suggested as an indicator of landfill stability (Kelly et al. 2006). However, measurement of the CH:L ratio throughout a landfill is difficult due to waste composition and decomposition heterogeneity. A specific endpoint criterion for gas may be more realistic, as a standard can be set with a specified emission level that must be met before termination of active gas collection and treatment. The implication of such a standard is that the rate of methane attenuation in a cover soil or biofilter is equal to the production rate (Morris et al. 2012). A limitation to specific metrics (e.g. volume of gas per volume of landfill per year) is that they do not consider site-specific conditions, including climate and hydrology.

The final alternative is an approach based on landfill performance in which evaluation of PCC is focused on identifying and quantifying the potential for a landfill to pose a threat to HHE, and the duration over which a potential threat may occur. A performance-based approach thus focuses PCC obligations on actual landfill conditions. A performance-based approach is based on the concept of 'functional stability,' which is a term used to define a closed landfill that does not present an unacceptable threat to HHE in the absence of PCC (Solid Waste Association of North America Bioreactor Committee, 2004, cit. in EREF, 2006). Once a landfill is functionally stable, regulated PCC is considered complete, although some level of control would typically

still be required to protect against disturbance of buffer zones and/or passive barriers, mainly the cover.

A performance-based methodology termed the Evaluation of Post-Closure Care (EPCC) Methodology, establishes a modular approach for evaluating functional stability based on four PCC elements – leachate management, landfill gas management, groundwater monitoring, and cover maintenance (ITRC 2006; Morris and Barlaz 2011). The methodology is applicable to all closed MSW landfills, including older sites that predate current regulations, and landfills at which operational technologies were implemented to enhance decomposition. By sequentially addressing these four PCC elements, the methodology can be used to determine how and when active care and/or monitoring within each element can be optimized or terminated. If an evaluation shows there would be no unacceptable impact to HHE as a result of modifying a PCC element, then that element can be modified accordingly and followed by targeted monitoring to confirm the validity of the analyses which led to the modification. If, on the other hand, an evaluation shows that unacceptable impacts would be expected if a PCC element were to be modified, then the landfill owner must continue the current PCC program for that element without modification until the element can be reevaluated, irrespective of time. In this way, rather than relying on a determination that PCC as a whole is either complete or must be continued at the same level of intensity, the methodology follows an incremental approach, evaluating each potential exposure mechanism and allowing for the possibility that certain aspects of PCC can be reduced or discontinued while others are maintained.

In a performance-based approach, the level of care provided can be modified based on periodic assessments aimed at shifting from active controls (e.g., leachate pumping, gas extraction) to more passive measures that reduce energy consumption and costs. Over time, the level of operation and maintenance (O&M) required is expected to decrease significantly at many landfills. Gas management, for example, could transition to direct venting, possibly to a biofilter, once gas production rates are below an agreed threshold. Similarly, the need for

operation of active leachate controls may cease where a well-maintained cover restricts infiltration, or where passive leachate controls, such as gravity-feed treatment wetlands, can be installed. In the case of both gas and leachate production, a common scenario is that the cover must be maintained to insure that gas and/or leachate production do not increase once active O&M and monitoring is terminated. Thus, in a performance based approach, reducing or discontinuing leachate management or groundwater monitoring may be appropriate, while at the same time continuing LFG management and cover inspections. Further, where groundwater monitoring is still required following an evaluation, monitoring may be required only for a reduced list of contaminants that are indicative of a potential leachate release.

While the concept of functional stability is relatively new, there appears to be interest amongst some regulators. For example, landfill regulations in the State of Washington require that post-closure care be “conducted for thirty years or as long as necessary for a landfill to become functionally stable” (WAC 173-351-500). One of the authors of this report (Barlaz) has been engaged in discussions of PCC through a task force of the International Waste Working Group (IWWG). Despite differences in some details, there is general agreement within the IWWG that (i) a progressive approach to reducing PCC activities and monitoring efforts as supported by landfill performance data is sensible, and (ii) some level of care to protect against disturbance of buffer zones or passive barriers (mainly the cover) will likely be required in an ongoing manner in the absence of complete chemical and biological stabilization.

As described in this report, many landfills have adopted operational practices to reduce the period of time of methane generation. However, given the underlying driver of the OSR, a more comprehensive strategy that includes leachate and the final cover is required to guide long-term landfill management.

## **METHODOLOGY AND SITE SELECTION**

The overarching objective of this project was to provide an independent and unbiased evaluation of WDNR's OSR. To this end, the WDNR contracted with the authors acting as a team of investigators to complete the independent evaluation described in this report. Data and information were collected via site visits, interviews with landfill owners, operators, and engineers, and review of annual reports and performance data. Discussions with WDNR personnel focused on gaining access to data, asking their perspective on landfills operating under the OSR, and ensuring that the investigators were addressing the essential questions for achieving the project objective.

Landfills were selected for this project from a master list of Wisconsin landfills with approved organic stability plans supplied by WDNR. Landfills were selected that (i) had organic stability plans in place for a longer period (so that the impact could be assessed more effectively), (ii) were geographically distributed throughout the state (to the extent practical), (iii) represented both private industry and public agency ownership and operation, and (iv) had management personnel willing to meet with the review team and share data for use in the assessment. Ten landfills ultimately were included in the review. In 2012, 66 non-hazardous landfills were active in Wisconsin, of which 34 were active MSW landfills. Thus, evaluating 10 of the 34 active MSW landfills represents approximately 29% of landfill-based MSW management practice in Wisconsin. However, as shown subsequently, the 10 landfills that were evaluated manage approximately 50% of Wisconsin's MSW. Thus, the study captured practices affecting a large fraction of Wisconsin's MSW.

Data and information collection for each landfill was generally initiated with a site visit that included one or more of the investigators. These site visits provided direct interaction between the investigators and landfill owners, operators, and site engineers, to develop an understanding of data and information that was needed for the assessment. An interview of landfill personnel allowed the investigators to gather feedback on important aspects of landfill

operations, site-specific implications of the OSR, and additional information that was not necessarily available in annual reports. A list of desired data and information was presented to landfill personnel following the site visit and materials were either provided immediately or sent (electronically or hard copy) to project team representatives at the University of Wisconsin-Madison.

## **SITE CHARACTERIZATION**

Site characteristics of the ten landfills evaluated in this report are summarized in Table 1. Nine of the ten landfills are privately owned. At each site, the landfill cells or areas that are included in the organic stability plan are expansions to existing disposal areas. These expansion areas range from 26 to 67 acres and the average waste disposal rate ranged between 210 and 3,030 ton/d from 2008 to 2012. Although the majority of the sites included in this analysis are privately owned, the broad range of waste disposal rates at these sites provides for an analysis that encompasses the implementation and impacts of organic stability actions at landfills spanning more than an order of magnitude in size of operation.

Compliance with the OSR at the sites evaluated in this study started in 2007 following rule implementation, and most of the sites had their organic stability plan in place by the end of 2007. Collectively, organic stability actions adopted at these ten sites include leachate recirculation, liquid waste addition, delayed final cover placement, and organics diversion. Leachate recirculation was reported by all site owners and operators as a method of in-situ waste decomposition to enhance organic stability. Initiation of leachate recirculation at all privately-owned sites except Site A started prior to OSR compliance. The one publically-owned landfill in this study (Site F) reported initiation of leachate recirculation concurrent with OSR compliance.

Every privately-owned site in this study except Site A has been approved by WDNR for a federal RCRA Subtitle D Research, Development, and Demonstration (RD&D) permit (Table 1).

Table 1. Summary of site characteristics for landfills evaluated in this study.

Site ID	Owner	Initiation of OSR Compliance	Organic Stability Actions <sup>a</sup>	Landfill Cells/Areas Under OSR	Area Under OSR (acre)	Tipping Rate (tons/d) <sup>b</sup>	Year Liquid/Leachate Addition Initiated	RD&D Permit <sup>c</sup>
A	Private	2007	LR	Southern & Northern Expansion	55	1180 (810-1780)	2013	—
D	Private	2007	LR; LWA; OD	Sector 2 Horizontal & Vertical Expansions	67: 12 final cover & 50 interim	1210 (1100-1400)	2001	2007
E	Private	2011	LR; LWA; OD	SW Horizontal Expansion	47.9	1470 (1300-2000)	1998	2007
F	Public	June 2012	OD; LR	North Expansion	26; 1/2 closed	210 (180-230)	June 2012	—
G	Private	Dec. 2008	LR; LWA	Southern Expansion	NA	3030 (2700-4100)	June 2006	2007
I	Private	2007	LR; LWA	Western Expansion	27.4	810 (700-900)	2002	2007
J	Private	2007	LR; LWA; DFC	Southern Expansion	61	700 (620-740)	NA	2008
K	Private	2007	LR; LWA; DFC	Southeast (43) and Clearwater Pond (21) Expansions	64	1110 (960-1350)	2002	2009
L	Private	May 2007	LR; LWA; OD	South (existing) and Southeast (planned) Expansions	98	1040 (900-1100)	1999	2007
M	Private	2012	LR; LWA; DFC	Northern Expansion	40	360 (230-570)	2001	2010

NA = not available.

<sup>a</sup>LR = leachate recirculation; LWA = liquid waste addition; OD = organics diversion; DFC = delay final cover (allow additional infiltration)

<sup>b</sup>Average listed and range in parentheses for 2007-2012.

<sup>c</sup>Year permit approved if applicable; otherwise not applicable (—)

An RD&D permit provides owners with the flexibility to reduce run-on surface water control, add supplemental liquids other than leachate, and use alternative final cover designs to enhance waste moisture content (USEPA 2004). Approved operations under an initial RD&D permit are limited to a 3-yr trial period. Three renewals of the RD&D Permit can be obtained under current USEPA regulations (i.e., four 3-yr permit periods), culminating in a maximum period of 12 yr for RD&D actions.

The most common action implemented under RD&D permits for the landfills evaluated in this study was the acceptance of external commercial liquid wastes, with disposal by direct application into the landfill waste mass. In all cases, owners of sites practicing liquid waste addition noted that this practice is economically and environmentally attractive due to revenue from tipping fees and the promotion of in-situ anaerobic waste decomposition that enhances organic stability and restores disposal capacity due to settlement (i.e., “creating airspace”). There are many considerations associated with the quantity of liquid waste accepted at a given landfill, including the mass of waste in-place to store supplemental liquid, revenue associated with liquid waste acceptance, and costs associated with leachate management and treatment. The balance between liquid waste addition, recirculation of generated leachate, leachate treatment, and enhanced waste moisture content is a challenging problem and is discussed throughout this report. In several cases, owners had been accepting liquid waste prior to RD&D permits and were solidifying the waste prior to disposal via mixing with special solid wastes that have high moisture retention capacity (e.g., incinerator ash or saw dust).

## **SOLID WASTE TREATMENT AND DISPOSAL PRACTICES**

### **Landfill-Based Waste Management**

A summary of waste disposal tonnage and facility-specific capabilities for waste treatment and disposal is presented in Table 2. Also included in Table 2 are metrics pertaining to the combined ten sites and Wisconsin as a whole. Annual waste tonnage was computed for

Table 2. Summary of waste tonnage and management.

ID	Annual Waste Tonnage (ton/yr) <sup>a</sup>	MSW Fraction (%)	Contribution of Total Wisconsin Waste (%)	Contribution of Total Wisconsin MSW (%)	Contribution of Out-of-State Waste (%) <sup>b</sup>	Contributing States	Notes
A	431,363	74.3	4.6	6.4	35 (13-62)	IL	Biopile system to treat petroleum-contaminated soils; treated soils used for daily cover
D	407,391	72.3	4.5	6.1	32 (31-40)	IA, MN, MI	Approximately 10% C&D waste; contaminated soils and auto shredder fluff for interim cover; small composting operation for pre-consumer food waste
E	568,444	47.4	6.2	5.3	—	—	Plan to expand composting facility to source-separated materials (e.g., farm crop residue, manure, other organics)
F	76,253	54.0	0.94	0.83	12 (4.5-20)	IA, MN	Foundry sand, RDF bottom ash, and street sweepings for ADC
G	1,107,898	62.8	12.2	14.5	0.02 (0.0-0.06)	IL, IN, IA, MN, MI, other	—
I	296,634	47.8	3.5	3.2	—	—	Dredged sediments not monofilled, mixed in with waste; geotextile tarps for daily cover
J	255,866	45.3	2.0	1.7	0.17 (0.0-0.4)	IA, MN, MI, other	OSR approved in 2007, waste filling in Southern Expansion initiated in 2009
K	368,426	64.2	4.6	5.5	0.53 (0.0-1.5)	IL, IN, IA	—
L	370,420	68.7	4.1	5.4	7.2 (6.5-7.7)	IL, IA	Facilities include 20,000-yd <sup>3</sup> composting facility for yard waste with potential to accept food waste
M	132,001	65.1	1.4	1.7	7.0 (0.3-20)	MN, MI	Increase in % MSW from 64 to 85 % from 2008 to 2013
All Sites	4,003,972	62.1	44.0	50.6	8.9 (4.5-13.2)	IL, IN, IA, MN, MI, other	—
WI	9,151,954	53.7	100	100	10.7 (4.4-17.6)	IL, IN, IA, MN, MI, other	—

<sup>a</sup>Average tonnage for years 2007-2012.

<sup>b</sup>Computed as percent of annual waste tonnage; average listed and range in parentheses for 2007-2012.

2007-2012, which encompasses the first six years after the OSR went into effect. On average, the ten sites evaluated in this study accepted 44.0% of all waste generated within Wisconsin and 50.6% of all MSW. Although these ten sites represent only 29% of the MSW landfills in Wisconsin, combined they are accepting, managing, and treating half of the MSW generated within Wisconsin. Thus, these 10 landfills provide a representative picture of MSW practice in Wisconsin.

Temporal trends of annual total waste tonnage and MSW tonnage normalized to tonnage reported in 2007 are presented in Fig. 1. Total waste and MSW tonnages used in Fig. 1 include out-of-state waste tonnage. The overall trend for Wisconsin during the period in which the OSR has been active is a decrease in both total waste disposal and MSW disposal. Municipal solid waste disposed of in Wisconsin landfills in 2010 to 2012 ranged between 61 and 64% of MSW disposed in 2007 (Fig. 1b). This decrease is also evident at the ten landfills evaluated in this study, and only Site L reported an increase in MSW tonnage. Four of the ten sites reported an increase in total waste disposal since 2007, as shown by normalized waste tonnage  $> 1.0$  in Fig. 1a. The increase in total waste tonnage in 2012 computed for the average of the ten sites is influenced by the pronounced increase in waste disposal reported at Site G. The increase at Site G was due to disposal of treated contaminated soil and sediment contaminated with PCBs, which accounted for 43% of total waste tonnage at Site G in 2012. Annual increases in total waste tonnage at Sites D, J, and L can be attributed to increased tonnages of foundry waste, wastewater treatment sludge, other non-hazardous solid waste, fee-exempt waste for dikes and berms, shredder fluff and treated contaminated soils used for daily cover, and construction and demolition (C&D) waste.

The relationship between normalized MSW tonnage and normalized total waste tonnage is shown in Fig. 2. Normalized waste masses are the same as those in Fig. 1 (i.e., computed with respect to tonnage reported in 2007). Nearly all data points in Fig. 2 plot below the 1:1 line and indicate that the normalized MSW tonnage is less than the normalized total waste tonnage.

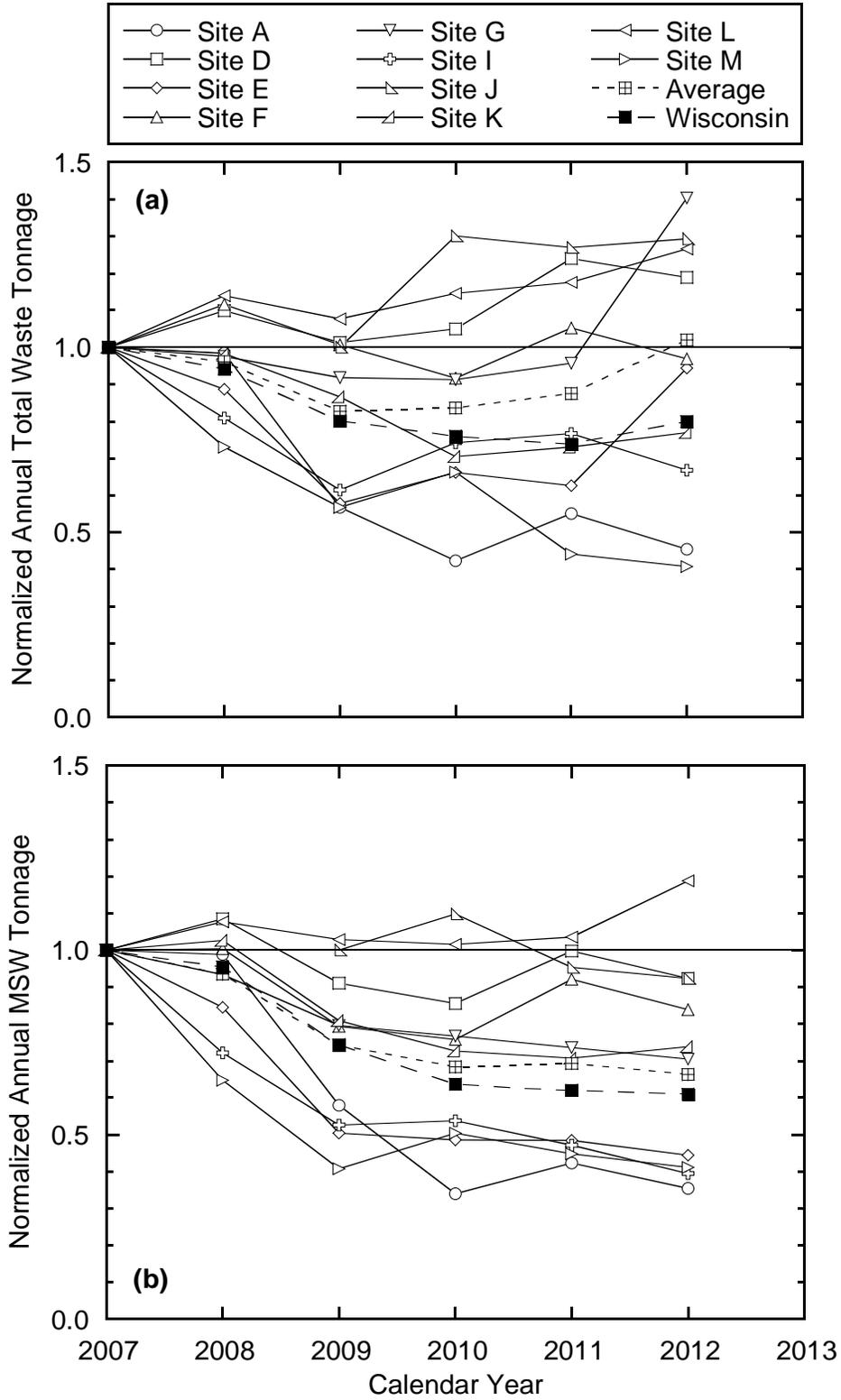


Fig. 1. Temporal trends of (a) annual total waste disposal and (b) municipal solid waste (MSW) disposal. Waste masses are normalized with respect to total waste tonnage or MSW tonnage reported for 2007 (2009 for Site J).

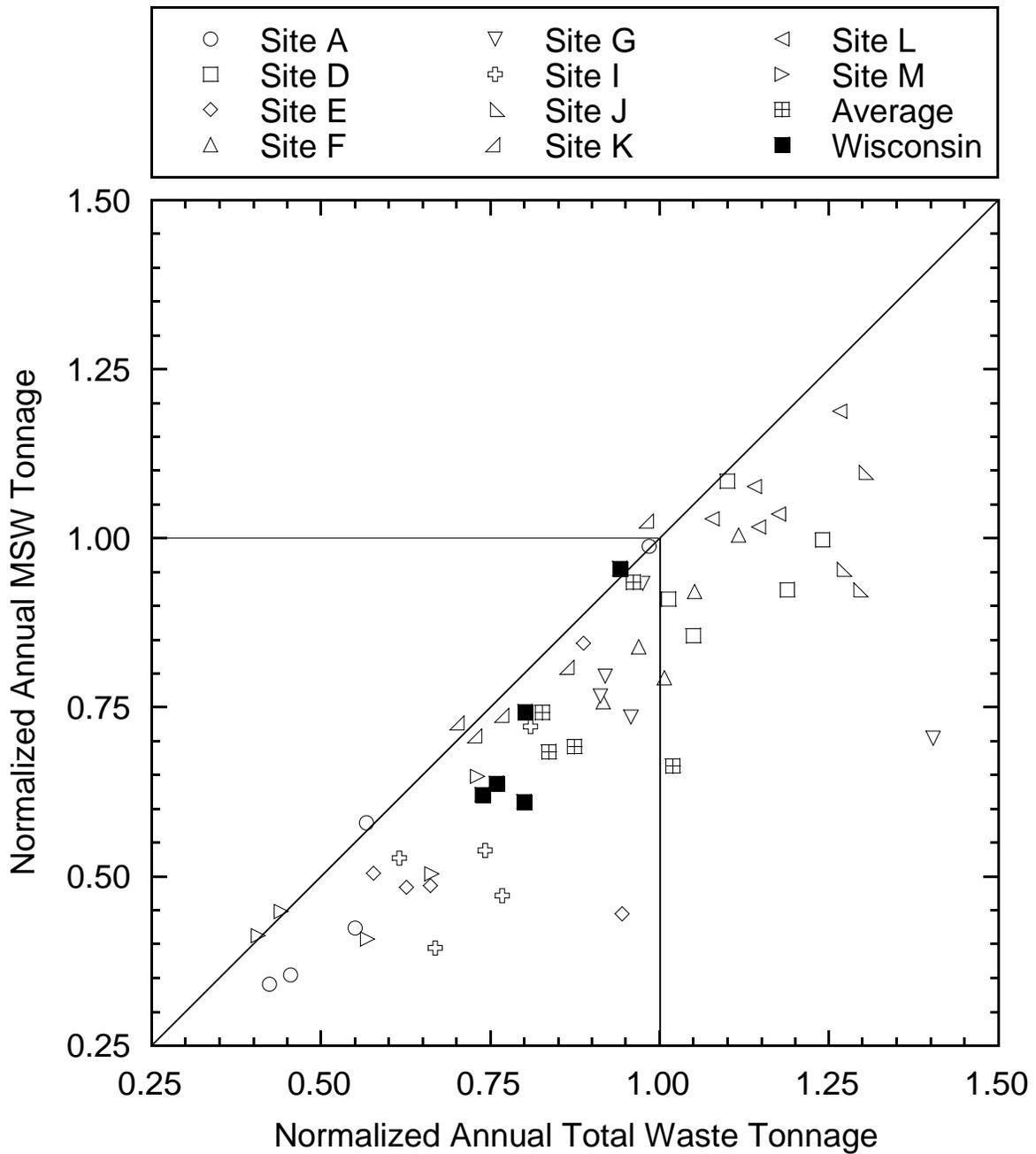


Fig. 2. Relationship between normalized annual tonnage of municipal solid waste (MSW) and total waste tonnage. Waste masses are normalized with respect to total waste tonnage or MSW tonnage reported for 2007 (2009 for Site J).

Thus, the decrease in MSW tonnage has been more pronounced than the decrease in total waste tonnage, which indicates that the proportion of non-MSW solid waste has increased relative to MSW since 2007. The decrease in MSW cannot be attributed to a single factor, but has been influenced by economic recession, increased recycling, an increase in Wisconsin's landfill disposal environmental fees, and the dynamic nature of landfill economics (e.g., fuel costs). One company noted that they now transport waste to the closest landfill from the point of collection to reduce transportation costs regardless of whether the landfill is owned by a competitor. This practice decreases waste disposal at a given site, but increases disposal elsewhere. Additionally, some landfill owners reported that some waste generated in Wisconsin has been diverted to neighboring states since the landfill environmental fee on MSW was increased to \$13/ton, and that some waste from neighboring states that used to be disposed in Wisconsin is no longer shipped into the state for disposal.

The environmental fee on waste disposal in Wisconsin landfills has been at \$13/ton since 2009 and applies to MSW, publically-owned treatment works (POTW) sludges, other non-hazardous solid waste, and C&D waste. The additional contribution of out-of-state waste and contributing states are summarized in Table 2. The decrease in out-of-state waste entering Wisconsin during the 2007-2012 time period has been significant; the amount of waste decreased from nearly 2 million tons (17.6% contribution) in 2007 to less than 400,000 tons in 2012 (4.4% contribution). An additional site to the ten in this study was to be included in the evaluation; however, the majority of waste had been entering this landfill from a neighboring state, and total daily waste disposal decreased from approximately 10,000 ton/d in 2000 to 600 ton/d in 2013 as a result of reduced imports. Waste disposal is subsidized by the owner at this site to maintain operations, but the owner indicated that there is little economic benefit to keeping the site operational.

## **Waste Diversion and Composting**

Organic waste diversion represents an opportunity to reduce the amount of biodegradable organic waste disposed in a landfill. Four of the ten sites evaluated in this study report some type of organic waste diversion (Table 1). Sites D, E, and L have on-site composting facilities, whereas waste is diverted from Site F to a local refuse-derived fuel (RDF) facility operated by an electrical utility.

Composting operations at Sites D, E, and L were all initiated as a way to manage yard waste, and subsequent efforts were initiated to expand composting operations to manage additional source-separated food waste. Site D reports a relatively small composting operation for pre-consumer food waste that is mixed approximately 1:1 with yard waste and managed for 60 to 120 d. Mature compost is sold to a local business for landscaping; however, any compost that is not sold is used on-site as top soil. Site L has an existing 20,000-yd<sup>3</sup> yard waste composting facility and received WDNR approval to accept food waste starting in March 2010. However, Site L has yet to implement co-treatment of yard and food waste within the composting facility. In addition to source-separated food waste, owners and operators at Sites E and L are considering farm crop residue, manure, and other organic materials for future composting.

Residential solid waste diversion from Site F to the local RDF facility was initiated in 1988. Site F is relatively small, having received an average of approximately 76,000 ton/yr between 2007 and 2012. An estimated 57% of the MSW collected in the region is processed at the RDF facility, with the low BTU fraction and ash subsequently disposed of at the landfill.

## **LIQUIDS ACCEPTANCE AND MANAGEMENT**

A summary of leachate generation, total liquid addition to the waste, leachate recirculation, liquid waste addition, off-site treatment costs, and liquid management and application methods is tabulated in Tables 3 and 4. Leachate generation and leachate

Table 3. Summary data on leachate and liquid waste management and leachate treatment cost.

ID	Leachate Generated (gal/yr)	Total Liquid Added (gal/yr)	Leachate Recirculated (gal/yr)	Liquid Waste Added (gal/yr)	Leachate Recirculated/Generated (%)	Liquid Waste Fraction of Total Liquid Added (%)	Cost of Off-Site Leachate Treatment (\$/gal)
A <sup>a</sup>	7,947,000	0	0	0	0	0	0.02
D	7,136,470	8,347,872	6,670,030	385,444	95.3 (82.7-100)	4.3 (1.1-7.1)	0.04
E	12,537,606	8,912,971	7,270,529	384,915	18.7 (6.0-56)	22 (1.3-59)	NA
F <sup>b</sup>	8,943,255	168,013	168,013	0	5.4	0	0.002
G	15,810,116	3,438,429	1,928,821	1,509,608	40.7 (21.6-60)	68 (0-100)	0.02
I	5,785,315	1,445,416	1,019,820	3,147,801	16.8 (0.0-43.1)	0 or 100	0.009
J	3,832,765	165,287	165,287	NA	3.8 (0.0-8.0)	NA	0.027
K	16,186,471	432,557	147,038	299,532	1.1	82 (26-100)	NA
L	7,743,828	5,729,169	5,284,305	444,864	67.7 (36.5-92.0)	8.9 (4.0-19)	0.05
M	6,598,279	944,107	1,467,828	420,386	10.4 (0.0-27.4)	0 or 100	NA

NA = not available

<sup>a</sup>Leachate recirculation initiated on a trial basis in 2013.

<sup>b</sup>Leachate only added in 2012

Table 4. Summary of liquid operations, application methods, types of liquid wastes, and off-site leachate treatment.

ID	Operational Notes	Liquid Application Methods	Types of Commercial Liquid	Off-Site Leachate Treatment Method
A	—	—	—	NA
D	Leachate generation and recirculation volumes for active area; all recirculation in active area; leachate from closed area added to active area as supplemental liquid under RD&D permit	French drains; surface application	Cleaning water from glue & paint facilities; corn syrup	NA
E	Reduced leachate recirculation in 2009 due to decreasing organic waste and elevated NH <sub>3</sub> -N levels in leachate; increased liquid waste disposal. Leachate volumes prior to 2009 may be high due to in-line flow meter issues.	Surface application; infiltration trenches; vertical wells	General commercial wastes; haul vehicle cleanout water; storm water; gas condensate; dredged materials;	Direct connection to local POTW
F	Leachate only added in 2012	Tank truck and surface application	Does not accept third-party liquids	NA
G	No leachate recirculated during 2009-2012	Horizontal & vertical injection; surface application	Soap residual; food waste residues; general commercial wastes	Direct connection to local POTW
I	Leachate recirculation during 2008-2011, switched to all liquid waste addition in 2012	Horizontal & vertical injection; surface application	Automobile wash water; industrial process sludge	Direct connection to local POTW
J	Limited data on recirculation and liquid addition	Horizontal injection; recirculation pads; surface application	General commercial wastes	Transported via tanker truck
K	Discontinued leachate recirculation in 2007, prefer liquid waste addition; Leachate collection not reported during 2010-2012	Horizontal injection; surface application	Liquid-containing food wastes; industrial wastes; sludge	Direct connection to local POTW
L	All liquids added in South Expansion. Reduced leachate recirculation volumes (e.g., 2012) may partly be due to flow meter modifications.	Horizontal injection; surface application; leachate vaults	POTW sludge; industrial wastewater; hydrovac loads from hydro-excavations	Transported via tanker truck
M	Leachate recirculation prior to 2010 and only liquid waste addition during 2010-2012; liquid wastes accepted prior to 2010 were solidified	Horizontal injection; surface application	Horizontal injection; surface application	Transported via tanker truck

NA = not available

recirculation represent annual average leachate volumes managed on a site-wide basis during 2007-2012. Total liquid added represents the sum of all liquids added to the waste mass at a given site, including recirculated leachate and liquid waste plus other acceptable liquids (e.g., gas condensate). Annual average leachate generation volumes were greater than leachate recirculation volumes for all sites. The average percent of generated leachate that is recirculated ranges between 0 and 95%. Site D was the only site to recirculate 100% of their generated leachate back into the active landfill, and Site A is the only landfill that has yet to recirculate leachate or add liquid to the landfilled waste mass.

Temporal trends in the percent of leachate generated that was recirculated in a given year are shown in Fig. 3a. Site D systematically recirculated as much leachate as possible (typically 100%) to enhance in-situ waste decomposition and minimize off-site leachate treatment. For the other sites, the fraction of leachate recirculated has been decreasing since 2010. Although small increases in leachate recirculation are shown for Sites F and J in 2012, the majority of the sites reported recirculating less than 10% of the leachate generated in 2012 and three sites reported zero leachate recirculation. However, at the three sites reporting zero leachate recirculation, liquid was still added to the waste mass via liquid waste addition.

The annual percent contribution of liquid waste to total liquid addition is shown in Fig. 3b. Data in Fig. 3b support an overall increase in the percent contribution of liquid waste at a given landfill. For the seven sites that reported both leachate recirculation volumes and liquid waste addition volumes, the percent contribution of liquid waste to total liquid added ranged from 0 to 100%. Sites I, K, L, and M initially reported zero liquid waste addition, and subsequently changed their operational strategy to 100% of total liquid addition attributed to liquid waste. The decrease in percent contribution of liquid waste for Site K in 2012 was due to an off-site forcemain problem that required on-site liquid management of all leachate via recirculation. Sites A and F do not have an RD&D permit and have not added supplemental liquids to the

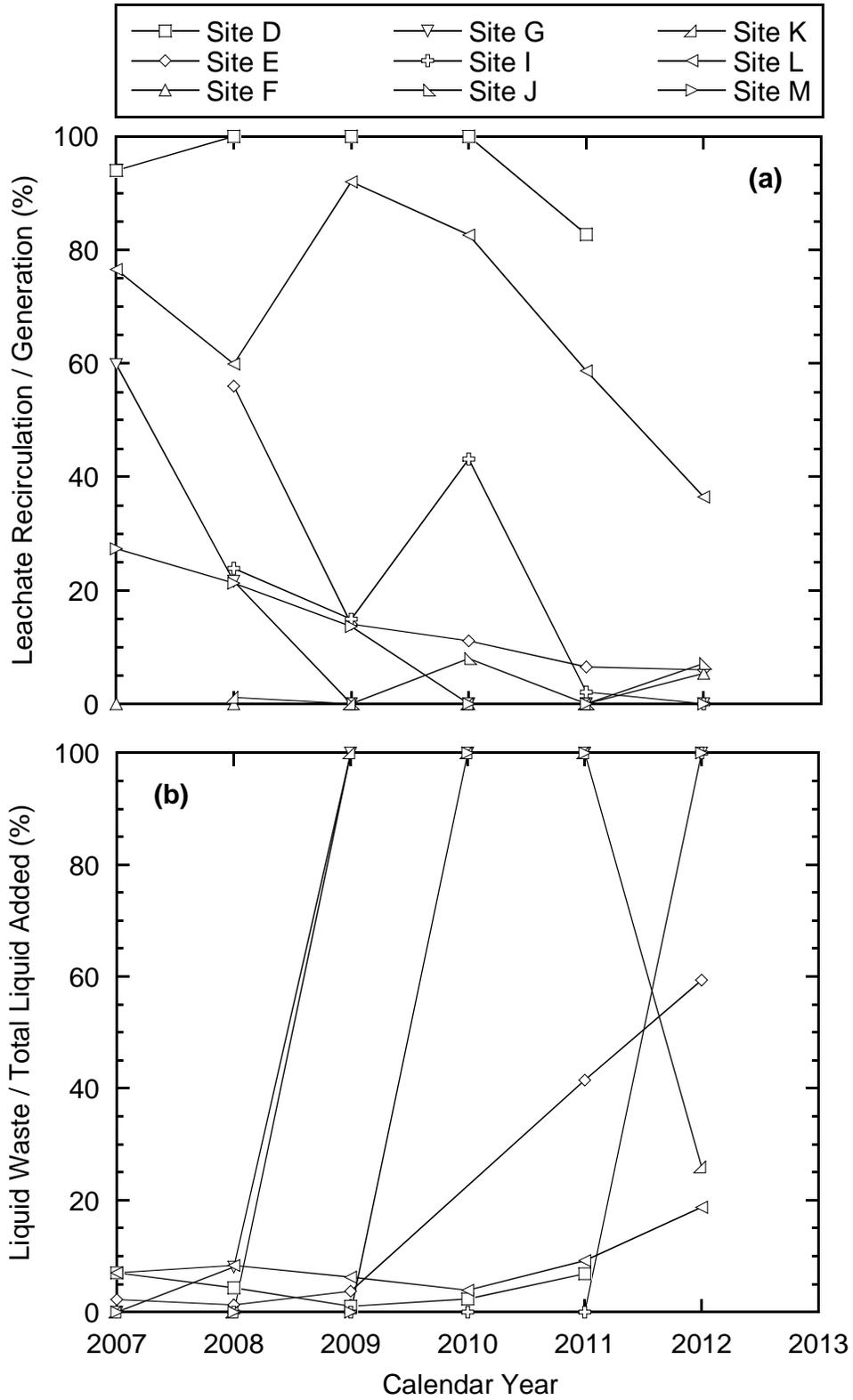


Fig. 3. Temporal trends of (a) percent leachate generated that was recirculated and (b) percent contribution of liquid waste addition to total liquid added.

waste mass. All other sites either reported liquid waste volumes or reported active liquid waste addition.

Temporal trends of total liquid addition normalized to total liquid addition in 2007 or earliest reported liquid addition are shown in Fig. 4. Three trends can be identified in Fig 4: (i) an overall increase in liquid addition (Site D); (ii) an overall decrease in liquid addition (Sites E, G, K, L, M); or (iii) an annual fluctuating liquid addition (Sites I and J). The increase in total liquid addition at Site D is attributed to recirculation of nearly all generated leachate at the site within the current active area combined with liquid waste disposal under their RD&D permit. Also under the RD&D permit at Site D, leachate from an older closed cell was added to the active area (factored into total liquid addition in Table 3). The decreasing trends are attributed to initial aggressive leachate recirculation and liquid waste addition that resulted in a considerable increase in waste moisture content. Total liquid addition was subsequently decreased to reduce leachate generation and interference with gas collection. The fluctuating liquid addition trends at Sites I and J are due to an aggressive liquid addition strategy followed by a period of focused gas generation and collection and subsequent waste placement.

Site A does not have an RD&D permit and did not recirculate leachate from 2007 to 2012. Leachate recirculation was initiated on a trial basis at this site in 2013. Although the organic stability plan was approved for Site A in 2009, the landfill operator indicated that practices under the plan were not initiated until improvements to the gas management facilities could be made so that they would be more capable of managing increased gas generation and the potential for odors.

### **Strategies for Moisture Enhancement**

The two most common approaches for waste moisture enhancement at the sites evaluated in this study are leachate recirculation and liquid waste addition. Leachate recirculation results in a decrease in the amount of leachate requiring off-site treatment, to the

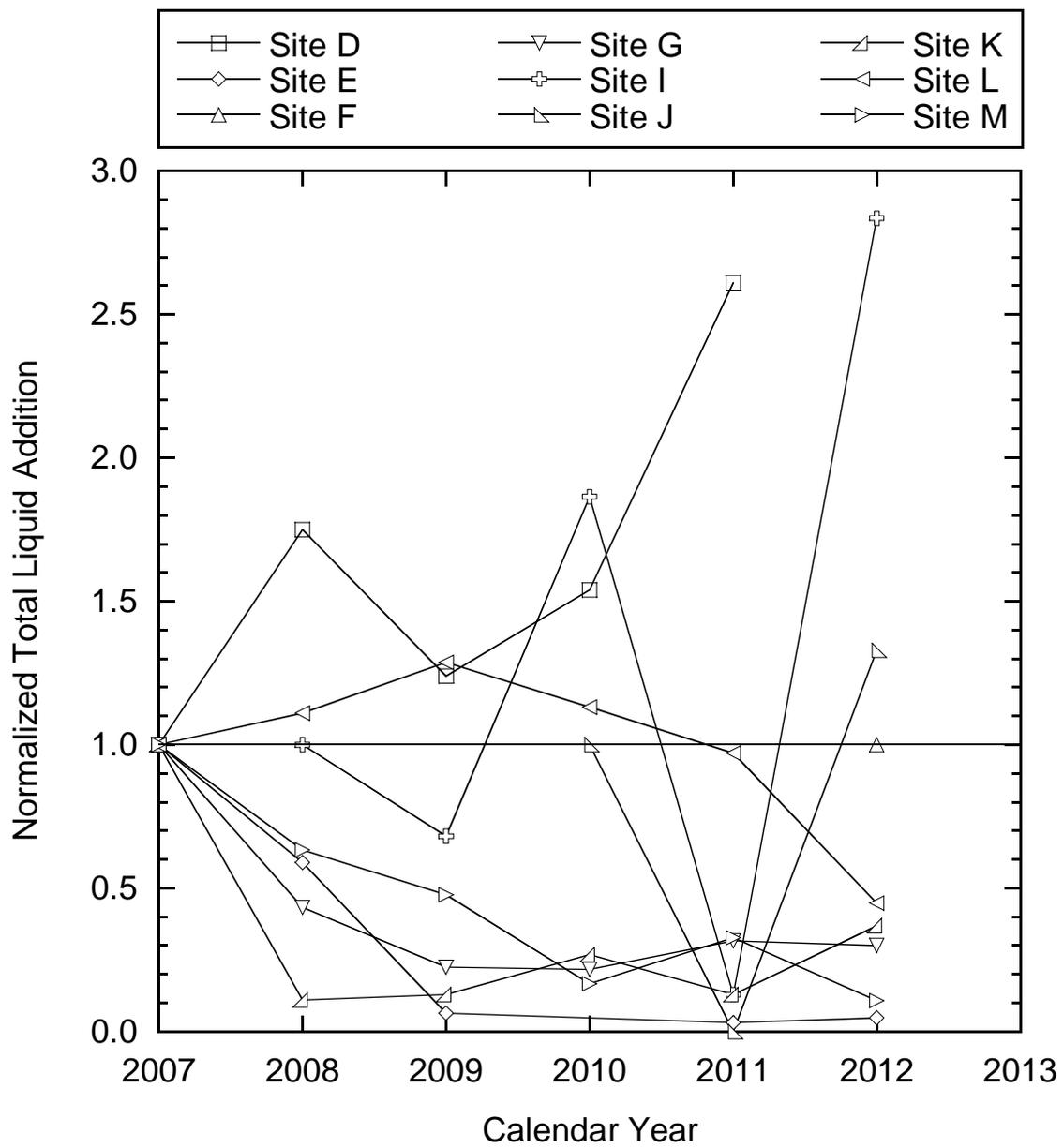


Fig. 4. Temporal trends of normalized total liquid addition. Total liquid addition is normalized with respect to liquid added in 2007 or first year of reporting.

extent that recirculated liquids are retained within the waste. Liquid waste addition is advantageous as this practice generates revenue via tipping fees, relieves loading to wastewater treatment plants, provides a service to liquid waste generators that may otherwise require long-distance hauling of liquids, and provides a liquid source to enhance waste degradation and biogas generation that allows compliance with the OSR. Although both leachate recirculation and liquid waste addition enhance waste decomposition and increase methane generation, liquid waste addition offers opportunities to substantially increase waste moisture content when sufficient leachate is unavailable. All landfill owners and operators indicated that actions implemented to enhance the waste moisture content have been driven by economic considerations and that, where applicable, the more economically favorable options take precedence.

Common types of liquid waste added to the landfill at each site are summarized in Table 4. Liquid waste sources primarily are commercial and industrial wastes; common sources among the sites included cleaning water from manufacturing processes, automobile wash water, and industrial sludge. In addition to these liquids, non-leachate liquids generated on-site that are added to the waste mass include gas condensate and haul-vehicle cleanout water.

Liquid waste predominantly was added via a trench and cover technique, whereby a trench is excavated on the working face, liquid waste is discharged into the trench, and waste is pushed back into the trench and mixed with the liquid. Leachate recirculation was reported to have been implemented via horizontal and vertical injection systems as well as surface application (Table 4), and site owners and operators reported a preference for surface application. In general, surface application is replacing liquid distribution by horizontal trenches and vertical well injection systems, which were common in the previous decade (e.g., Benson et al. 2007; Bareither et al. 2010). The latter approach requires additional resources (e.g., personnel, materials, time) and was reported to be affected adversely by pipe clogging and “watering out” of the waste. In contrast, surface application has neither of these problems,

results in a more uniformly wetted waste, can result in higher waste density during compaction, and reduces the elapsed time for onset of gas production.

A delay in placement of final cover to allow for additional precipitation to infiltrate into the waste mass was reported at Sites I and J. This practice is approved by WDNR via an organic stability plan, and at both sites, delayed placement was approved for 5 yr following attainment of final waste grades.

### **Management Issues**

As a rule, the commercial liquid waste streams that are sent to a landfill are those for which another, less expensive option, does not exist. The alternatives include treatment at a POTW and land application. In the case of POTWs, many facilities, especially those with relatively low capacities, do not have the capacity to accept industrial liquid wastes. In some cases, liquid waste was problematic due to organic strength or suspended solids concentration. Organic contaminants and metals may also be a concern. For land application, several owners mentioned that paper sludge that had been landfilled historically is now land applied.

Liquid waste accepted at a landfill must be non-hazardous and each landfill has site-specific acceptance criteria. The chemistry of the liquid waste streams typically was not evaluated for compatibility with waste decomposition and this has the potential to result in problems. For example, at Site D, liquid waste containing an abundance of corn syrup was accepted. This waste would be expected to biodegrade rapidly, resulting in an accumulation of acidic decomposition intermediates that could then decrease the pH in a section of a landfill and inhibit methanogenesis. Elevated COD could also be a concern. Thus, a critical issue in liquid waste disposal with an RD&D permit is compatibility with anaerobic waste decomposition.

The balance between acceptance of liquid wastes and recirculating leachate to enhance waste moisture content at a given site is dependent on the cost for off-site leachate treatment as well as other factors including the mass of MSW available to absorb liquid. The percent

contribution of liquid waste to the total liquid added in a given year and the cost of off-site treatment are tabulated in Table 3. Sites D and L have the highest cost of off-site leachate treatment ( $\geq \$0.04/\text{gal}$ ) and report the smallest percent contribution of liquid waste addition among the sites with an active RD&D permit. These two sites also reported the largest percentage of generated leachate that was subsequently recirculated, which reflects an operational objective to minimize off-site leachate treatment. In contrast, Sites G, I, K, and M all report 100% liquid addition in a given year as liquid waste disposal. Leachate generated at these sites can be directed to off-site treatment facilities at a considerably lower cost compared to Sites D and L, which reduces the need for on-site leachate management via recirculation.

A summary of moisture content measurements conducted on waste exhumed during gas well installation is included in Table 5. Waste moisture contents are listed in Table 5 based on both a wet ( $w_w = \text{weight water}/\text{total weight}$ ) and dry weight ( $w_d = \text{weight water}/\text{dry weight}$ ) basis. The average  $w_w$  based on 307 individual measurements is 37.4%, and ranges between 25.7% and 47.5% on a site-specific basis. These values are consistent with an assumed initial  $w_w = 25\%$  and a target range of 40-45% typically noted in moisture enhancement strategies included in organic stability plans. The maximum and minimum  $w_w$  determined for the different sites indicate that in situ waste moisture contents can encompass a broad range and that some relatively dry waste is present even at landfills that attempt to wet the entire waste mass.

Box plots of  $w_w$  for a recirculation area and control area at Site M are shown in Fig. 5 as a function of waste depth. Higher moisture contents were measured at all depths in the recirculation area as compared to the control area. The average  $w_w$  for the recirculation area was 45.4%, whereas the average  $w_w$  for the control area was 36.2%. Also, the range of  $w_w$  in the recirculation area suggests a progressive wetting with depth. The landfill engineer at Site M targets a water content of approximately 35% due to operational difficulties encountered at higher water contents. Fluctuations in leachate generation volumes that require management have prompted interest among landfill operators in developing guidance on the amount of liquid

Table 5. Compilation of moisture content measurements completed on waste exhumed during gas well installation.

ID	Analysis Date	No. of Samples	Wet Weight Water Content (%)			Dry Weight Water Content (%)		
			Average	Maximum	Minimum	Average	Maximum	Minimum
A	—	—	—	—	—	—	—	—
D	Mar. 2007	14	31.7	47.0	20.1	46.4	88.7	25.2
	Apr. 2008	12	40.0	61.3	27.6	66.7	158.4	38.1
	Dec. 2009	13	37.8	54.3	22.0	60.8	118.8	28.2
E	Apr. 2012	58	41.2	73.0	11.0	70.2	270.4	12.4
F	Apr. 2009	3	25.7	27.5	22.4	34.6	37.9	28.9
G	Aug. 2008	25	38.7	65.0	16.4	63.2	185.7	19.6
	Apr. 2009	12	26.3	37.3	15.4	35.6	59.5	18.2
	Dec. 2012	11	36.0	61.5	24.4	56.2	159.7	32.3
I	—	—	—	—	—	—	—	—
J	—	—	—	—	—	—	—	—
K	Jul. 2008	57	35.9	59.6	14.5	56.0	147.5	17.0
L	Mar. 2007	10	41.2	60.0	14.3	70.1	150.0	16.7
	Nov. 2007	14	33.5	56.0	22.6	50.5	127.3	29.2
	Aug. 2009	12	33.6	50.8	25.5	50.5	103.3	34.2
M	2007	21	44.7	60.8	25.7	80.8	155.1	34.6
	2008	18	47.5	80.7	31.5	90.6	418.1	46.0
	2009	17	42.1	61.0	16.2	72.7	156.4	19.3
	2011	10	42.9	56.4	26.4	75.1	129.4	35.9
Average	—	307	37.4	57.0	21.0	59.8	132.6	26.6

Note: wet weight water content = weight water/total weight; dry weight water content = weight water/dry weight

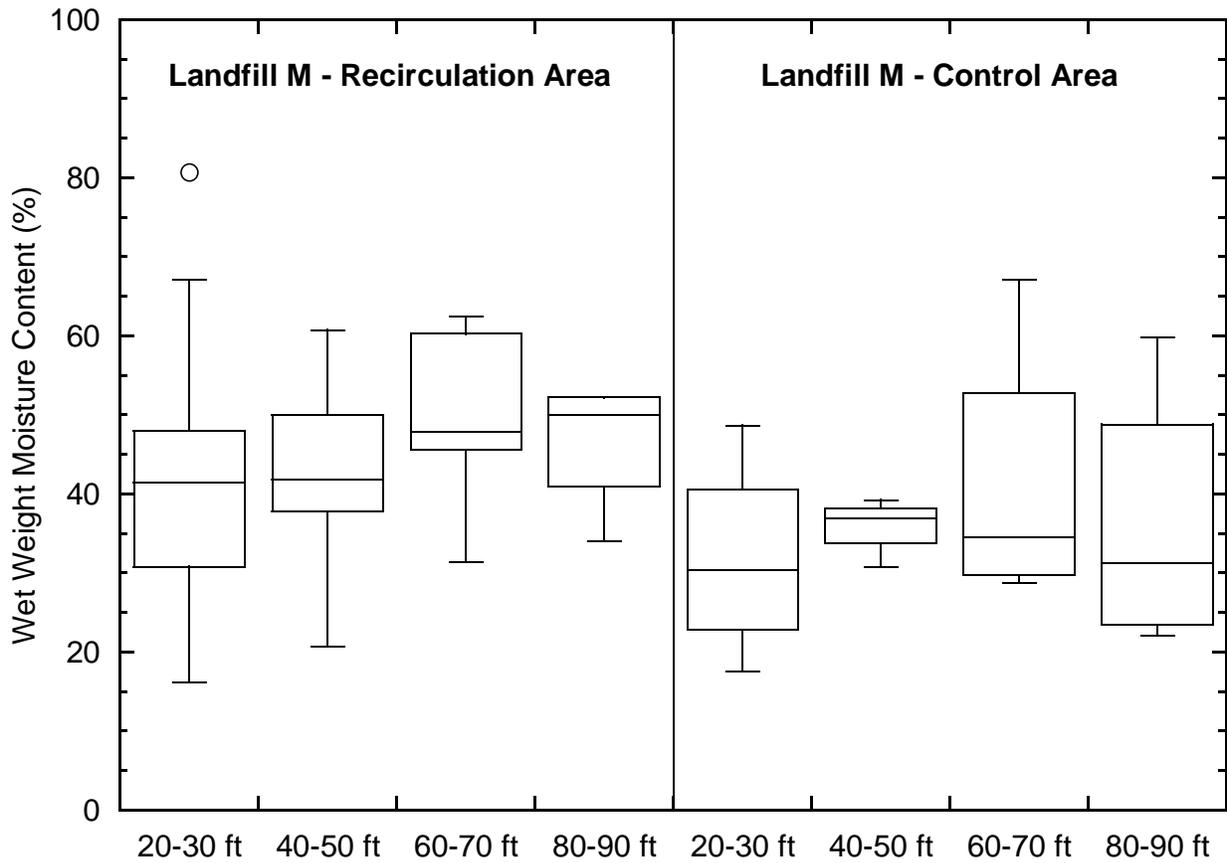


Fig. 5. Box plots of wet weight moisture contents for waste exhumed from different depths in a recirculation area and control area at Site M. The box represents the middle 50% of the data; the central line in the box represents the median; the outer boundaries represent the interquartile range, i.e., 25<sup>th</sup> and 75<sup>th</sup> percentile; and the upper and lower whiskers extending from the box constitute the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the data.

that can be added to the waste as a function of climatic conditions (e.g., precipitation), cell surface area and volume, waste in-place, and the rate of waste disposed in the landfill. An additional metric used to monitor the progression of waste wetting is the liquid level in gas wells. The ideal scenario is to moisten waste just to the point when gas wells remain open and gas can readily be collected under application of a small vacuum.

An additional management concern is the increase in ammonia-nitrogen ( $\text{NH}_3\text{-N}$ ) levels associated with leachate recirculation, which was reported at a number of sites. Site E, for example, reported an increase in  $\text{NH}_3\text{-N}$  in leachate since recirculation initiated in 1998. The  $\text{NH}_3\text{-N}$  levels have increased from  $< 200$  mg/L in 2000 to  $> 1400$  mg/L at the start of 2012. Operators at Site E indicated a concern that recirculated leachate with elevated  $\text{NH}_3\text{-N}$  levels may lead to inhibition of anaerobic biodegradation. A similar concern was noted at Site L, where operators reported a desire to focus on limited recirculation such that  $\text{NH}_3\text{-N}$  levels remained low and the pH was closer to neutral. Elevated ammonia associated with leachate recirculation has been reported previously (Benson et al. 2007; Barlaz et al. 2010), although no toxicity problems have been reported to date in Wisconsin.

## **GAS PRODUCTION AND MANAGEMENT**

Annual average gas metrics, including flow rate of the collected gas, gas utilization, percent gas flared, and methane fraction are presented in Table 6. Gas collection ranges from 119 to 1,933 million-ft<sup>3</sup>/yr. The relationship between annual gas collected and annual MSW tipping rate is shown in Fig. 6. In general, the volume of gas collected increases with increased MSW tipping rate due to a greater mass of waste available to generate gas during anaerobic decomposition. However, for a given site, data in Fig. 6 typically are scattered vertically, which suggests that the tipping rate is only one factor governing gas collection. Other factors include the mass and average age of the waste in place, and ongoing changes to the gas collection system. For example, the MSW tipping rate at Site J is approximately 290 tons-MSW/d and

Table 6. Summary data on landfill gas generation and utilization.

ID	Gas Collected (million ft <sup>3</sup> /yr)	Gas Flow Rate (ft <sup>3</sup> /d)	Percent Flared (%)	Methane Fraction (%)	Gas Utilization	Notes
A	NA	NA	NA	NA	NA	Ownership changed in 2010. Gas collection system upgraded in 2011-2012; gas volumes increased 30%.
D	866	1,647	56	50	Approximately 33% sold to 3 <sup>rd</sup> party contractor for electricity generation; 3 engines, all old and need maintenance	1 well/acre
E	1,068	2,033	97	49	Transported via pipeline to local POTW for energy source in treatment operations	—
F	119	227	0	52	Transported via pipeline to commercial energy provider	—
G	1,933	3,678	16	NA	Gas turbines (4 x 1300 cfm); 1500 cfm flare	Percent flared only computed for 2008-2009
I	820	1,561	NA	55	Sell gas to neighboring rendering plant; collaboration between landfill, plant owner, and power company to install 3 landfill-owned engines at rendering plant	—
J	164	330	NA	49	Implemented 4-engine gas plant in 2002; permit for additional 6-engines = 10-engine plant; relocated two engines to other sites due to decrease in gas	—
K	1,015	1,930	NA	NA	Two on-site turbines and 4 engines built in 1985 and 1986, respectively; plus flare	No flare vs. turbine data available
L	827	1,573	66	50	Two on-site engines (~350 cfm combined); sell gas to energy company to operate two microturbines (100-125 cfm); flare (900 cfm)	Cost to maintain gas facility ~ \$25/MWh vs. revenue ~ \$30/MWh
M	788	1,578	7.1	53	Four engines in 2006; added 3 engines in 2007; excess flared. Currently, 4 engines remain with 3 operating; other 3 engines were removed due to declining gas.	Percent flared reduced from 40% in 2007 to < 2% during 2008-2012

NA = not available

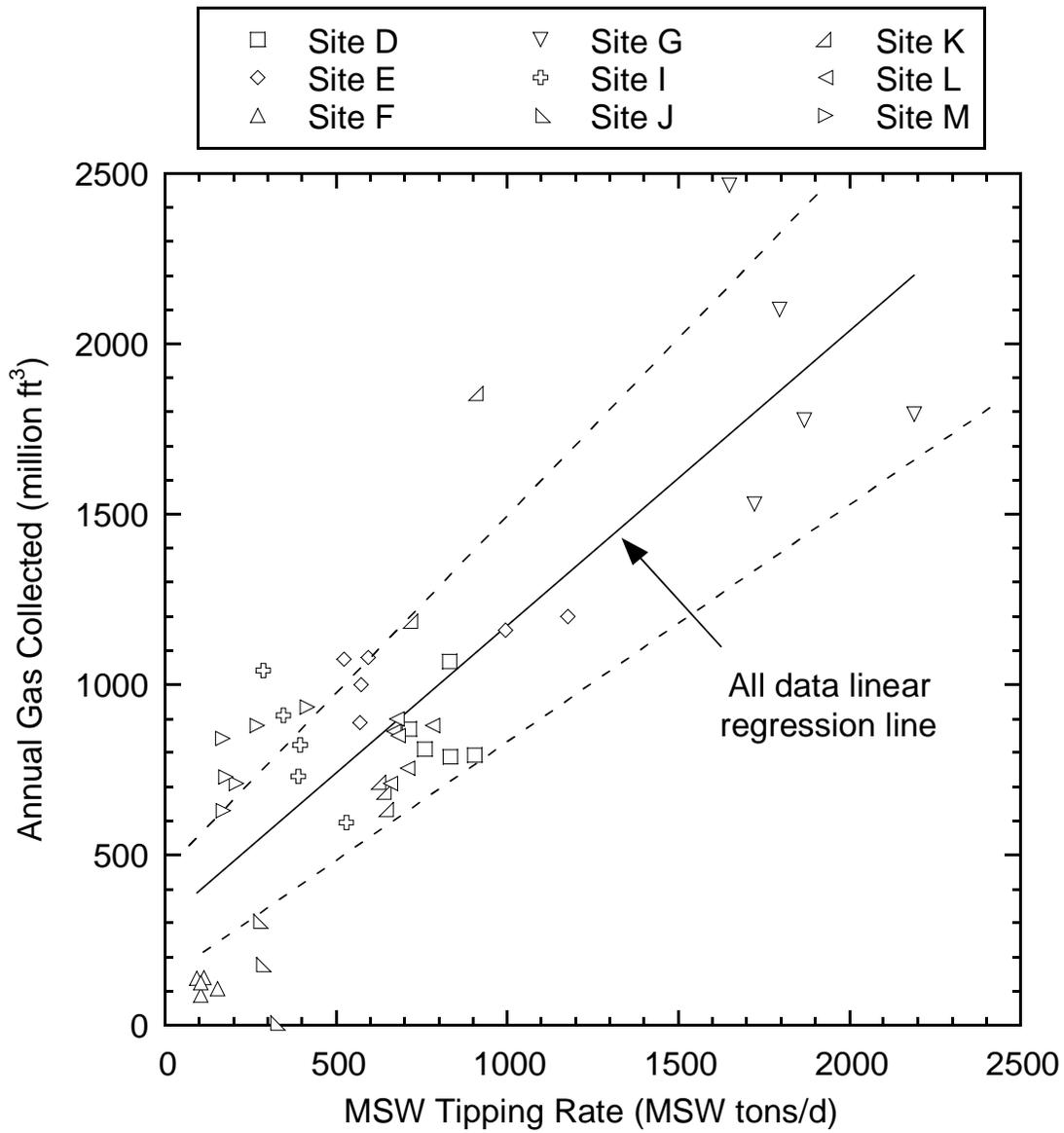


Fig. 6. Relationship between annual gas collected and annual municipal solid waste tipping rate. Dashed lines represent the upper and lower 95% confidence bounds for the linear regression line.

annual gas collection ranges from 7 to 305 million-ft<sup>3</sup>. Waste filling began at Site J in 2009 with gas collection beginning in 2010. Annual gas collection at Site J has increased since collection initiated and can be expected to increase as waste filling and gas collection continue. Data in Fig. 6 may be useful to identify bounds on anticipated gas volumes that will require collection and management based on MSW filling rate.

All sites that provided information on gas utilization reported use of landfill gas for energy generation although the fraction of gas used for energy generation and the methods to generate energy varied. The most common method of energy generation is on-site operation of gas engines; however, two sites report transporting gas off-site via pipeline for subsequent use at a POTW (Site E) and commercial energy provider (Site F). Site I reported collaboration between the landfill, neighboring rendering plant, and local power company. Landfill-owned engines have been installed on property owned by the rendering plant, and landfill gas is also sold to the rendering plant for use as fuel in boilers. Electricity generated by the landfill gas engines is sold to a local power company.

The average percent of landfill gas flared ranged between 0% for Site F to 97% for Site E. The gas that is not flared is used beneficially for energy generation. The pipeline at Site E had not yet been brought online, which is the primary reason for the high percent flared. Once the pipeline is operational, the fraction of gas flared at Site E is expected to decrease substantially and possibly become nil. Site F has a small amount of gas to manage, and can transport all collected gas directly via pipeline to a commercial power company. The range in gas use among the other sites is dependent on the capacity of the installed gas engines and economic feasibility of additional engine installation.

### **Assessment of Decay Rates Required to Comply with Organic Stability Rule**

The OSR specifies that the goals of landfill organic stability plans should be to achieve  $\geq 75\%$  of projected total gas generation ( $\text{CH}_4 + \text{CO}_2$ ) and that the monthly average gas ( $\text{CH}_4 +$

CO<sub>2</sub>) production rate diminish to  $\leq 5\%$  of the average maximum monthly gas production rate observed during the life of the facility within 40 yr following site closure. The objective of this section is to illustrate different ways in which this rule could be interpreted and the implications for the aforementioned criteria. As described in this section, the different gas production benchmarks lead to different elapsed times for compliance with the OSR and this may lead to some confusion amongst landfill owners.

A series of hypothetical cases was examined using LandGEM (v 3.02; USEPA, 2005). The total gas analysis was simplified to cumulative CH<sub>4</sub> generation and CH<sub>4</sub> flow rate since landfill gas is approximately 50:50 CH<sub>4</sub> and CO<sub>2</sub> and the ratio does not change appreciably over the life of gas production. Although a comparable volume of CO<sub>2</sub> is also generated, CH<sub>4</sub> is the greenhouse gas of concern for MSW landfills as CO<sub>2</sub> is biogenic and not considered to have global-warming potential based on IPCC protocols. Four cases were identified corresponding to different assumptions regarding the ultimate methane yield ( $L_0$ ) and first-order decay rate ( $k$ ) input to LandGEM:

- Case 1: 260,000 US tons of waste disposed in Year 1,  $k = 0.04$  1/yr, and  $L_0 = 100$  m<sup>3</sup>-CH<sub>4</sub>/Mg. This is a simplistic though unrealistic case in which the landfill only receives waste for one year, and provides a baseline to evaluate the time required to achieve 75% of total gas generation.
- Case 2: 260,000 US tons of waste disposed in Year 1,  $k = 0.10$  1/yr,  $L_0 = 100$  m<sup>3</sup>-CH<sub>4</sub>/Mg. Case 2 is similar to Case 1 except that a higher decay rate is used to illustrate the implications of accelerated decomposition.
- Case 3: 260,000 tons of waste disposed annually in Years 1-20,  $k = 0.10$  1/yr,  $L_0 = 100$  m<sup>3</sup>-CH<sub>4</sub>/Mg. Case 3 is a more realistic representation of an actual landfill in that the landfill receives waste for 20 yr. The selected decay rate is representative of accelerated decomposition.

- Case 4: 260,000 tons of waste disposed annually in Years 1-10, 130,000 tons of waste disposed annually in Years 11-20,  $k = 0.10$  1/yr,  $L_0 = 100 \text{ m}^3\text{-CH}_4\text{/Mg}$ . Case 4 illustrates a common scenario in which landfills do not receive a constant mass of waste (as in Case 3), and this decrease in waste mass will influence the time required to achieve 75% of total gas generation.

Methane production for these four cases is illustrated in Fig. 7. As illustrated in Fig. 7a,  $\text{CH}_4$  production decreases more rapidly in Case 2 relative to Case 1, and cumulative  $\text{CH}_4$  increases more rapidly in Case 2 relative to Case 1 (Fig. 7c). Case 3 is a more realistic scenario as the landfill life is assumed to be 20 yr rather than 1 yr. However, waste disposal rates are unlikely to be constant over 20 yr. The decrease in waste disposal in Case 4 results in a more rapid decrease in  $\text{CH}_4$  production rate (Fig. 7b) and achievement of 75% of expected  $\text{CH}_4$  in a shorter period of time (Fig. 7c) even though the same decay rate was used in Cases 3 and 4.

The different gas production benchmarks outlined in WDNR's OSR can lead to different elapsed times corresponding to compliance. For example, the  $\text{CH}_4$  generation rate for Case 1 decreases to  $\leq 5\%$  of the peak generation in Year 1 after 76 yr (Fig. 7a), whereas 75% of cumulative  $\text{CH}_4$  generation was achieved after 34 yr (Fig. 7c). Similar differences exist for the other cases, and in general, the cumulative  $\text{CH}_4$  production criterion is met in 45-50% of the time required to meet the  $\text{CH}_4$  generation rate criterion for the four cases analyzed. The third gas generation benchmark outlined in the OSR states that a steady downward trend in total gas generation rate is achieved. This criterion is most valid after closure when the waste mass and gas collection efficiency should be constant.

WDNR also issues a target production rate of  $\leq 7.5 \text{ ft}^3\text{-gas/yd}^3\text{-waste/yr}$  that can be used in-place of the 5% flow rate benchmark. A normalized numerical target may provide for better comparison between sites operating to achieve organic stability; however, justification for the numerical target is needed. An alternative strategy would be to consider (1) precedent from

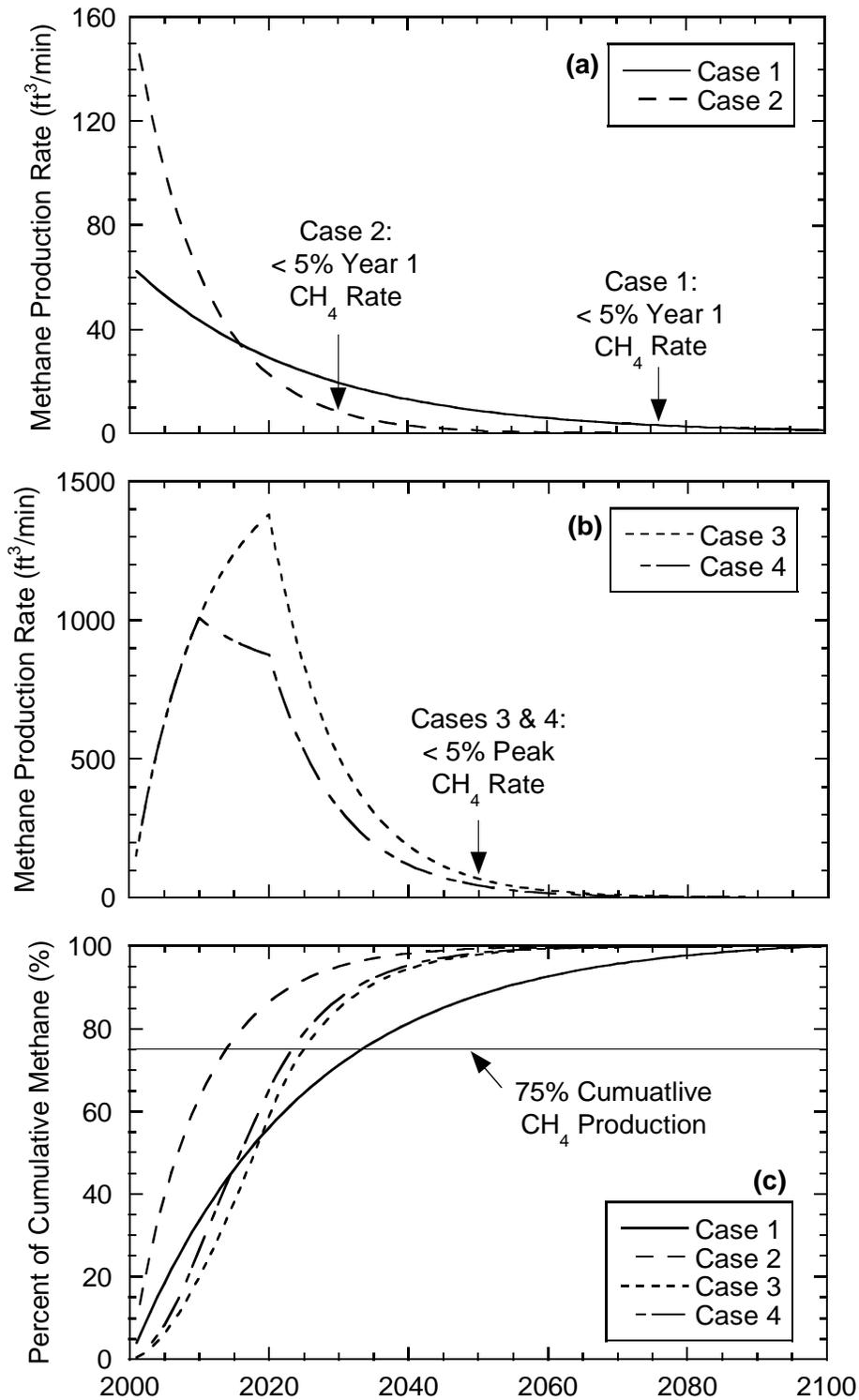


Fig. 7. Temporal trends of methane production rate for Cases 1 and 2 (a) and Cases 3 and 4, and percent of cumulative methane generation for Cases 1-4. Note: Landfill Cases 1-4 are described in text on Page 20; filling assumed to begin in calendar year 2000.

existing regulations or (2) best available control technology. For example, in the absence of liquid addition, landfill owners have some period of time between waste deposition and initiation of gas collection. Prior to gas collection system operation, methane that is not oxidized in the landfill cover is emitted to the atmosphere. Estimates of the mass of methane emitted prior to a requirement for gas collection could be used as a precedent for allowable emissions. Considering best available control technology, owners could be required to demonstrate that methane emitted after cessation of gas collection and control system operation can be oxidized using the attenuation capacity of the cover soil. Alternately, landfill gas could be treated in a biofilter once there is not sufficient gas to operate a control or energy recovery device. The WDNR should also consider developing guidance on how sites can transition from active to passive or no gas management system.

### **Gas Production and Organic Stability Assessment**

A summary of LandGEM model parameters, gas modeling techniques, and evaluations of organic stability for each of the studied landfills is presented in Table 7. A compilation of LandGEM predictions from the sites evaluated in this study is included in Appendix A. The majority of the LandGEM analyses were conducted with  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg}$  as this is the AP-42 default commonly used for predictions of landfill gas generation. The actual  $L_0$  of the landfilled waste likely varies between sites. Staley and Barlaz (2009) report that  $L_0$  ranges from 59 to 64  $\text{m}^3\text{-CH}_4/\text{Mg}$  based on USEPA and US state-specific waste characterization data. However, recent analysis of field data suggests that an  $L_0$  of  $100 \text{ m}^3\text{-CH}_4/\text{Mg}$  provides a best fit between LandGEM predictions and gas collection measurements (Wang et al. 2013). Common decay rates used in the analyses are  $k = 0.04 \text{ 1/yr}$ , which is the AP-42 default, and  $k = 0.08 \text{ 1/yr}$ , which is a recommended rate based on assessment of gas generation in wet landfills (Reinhart et al. 2005). A decay rate of  $0.08 \text{ 1/yr}$  agrees with a recent state-of-the-practice review of North American bioreactor landfills (Barlaz et al. 2010), but is lower than the  $0.09\text{-}0.12$  reported in

Table 7. Summary of LandGEM model parameters, gas modeling techniques, and observations of organic stability.

ID	Methane Yield, $L_0$ ( $m^3/Mg$ -MSW)	First-Order Decay Rate, $k$ (1/yr)	Gas Modeling Technique	Organic Stability Observation
A	100	0.05, 0.08	$k = 0.05$ for waste placed prior to OSR operations and $k = 0.08$ for waste placed following OSR operations	Estimated 38 yr after closure to reach 5% of peak landfill gas generation and estimated 44 yr after closure to reach 7.5 $ft^3$ per $yd^3$
D	100	0.04, 0.08	$k = 0.04$ for waste placed prior to 2006 and $k = 0.08$ for waste placed since 2006 and future waste	98% gas generation and flow rate at 4.1% of peak for 40-yr post closure
E	80, 100	0.04, 0.08	Use $k = 0.08$ for entire landfill; justify based on increase in $k$ with liquid addition efforts	99% gas generation and flow rate at 4.1% of peak for 40-yr post closure
F	80	0.08	NA	99% gas generation and flow rate at 4% of peak for 40-yr post closure
G	NA	NA	NA	NA
I	100	0.15	$k$ computed for waste placed during OSR and obtained via fitting model to gas data assuming 85% collection efficiency	Determined $k = 0.077$ to meet benchmarks of > 75% generation and < 5% maximum flow rate 40 yr post closure
J	100	0.088	$k$ determined from fitting model to gas data assuming 100% collection efficiency	Determined $k = 0.077$ to meet benchmarks of > 75% generation and < 5% maximum flow rate 40 yr post closure
K	100	0.068	Increase $k$ by 75% to account for enhanced methane generation due to leachate recirculation	96% gas generation and flow rate at 5% of peak for 40-yr post closure
L	80, 100	0.04, 0.08	$k = 0.04$ for old waste and $k = 0.08$ for new waste	For $L_0 = 100$ and $k = 0.08$ for new waste, estimate 98.7% gas generation within 40 yr
M	100	0.062, 0.050	$k = 0.062$ for 75% collection efficiency and $k = 0.050$ for 85%; also conduct varying- $k$ analysis to simulate variability in actual waste decomposition	> 75% gas generation met 2-yr post closure; > 5% flow rate met 45 yr post closure, 7 $ft^3/yd^3/yr$ met 37-yr post closure

NA = not available

Wang et al. (2013). In general, gas modeling at all sites supports meeting OSR benchmarks within a post closure period of 40 yr.

There are a number of gas modeling and assessment scenarios that can be employed to evaluate progression towards organic stability. The most straight-forward approach is for a site-wide basis that incorporates a single  $L_0$  and  $k$ . This type of analysis can be implemented directly in LandGEM, but does not allow for assessment of enhanced waste decomposition when only a portion of a landfill is operated under OSR actions, unless the gas from that portion is measured separately. A more advanced site-wide analysis can be completed if specific  $L_0$  and  $k$  values are incorporated for specific areas of a landfill. This level of analysis requires separation of waste mass and gas collection data based on landfill areas and is ideal to evaluate the performance of organic stability plans that have been implemented. However, this option is the most technically challenging and time-intensive to evaluate. Although there is merit to complex gas modeling options, the number of model variables increases with model complexity and may transition the analysis from a check on organic stability performance to curve-fitting of gas collection curves. Finally, as described in Wang et al. (2013), the gas collection efficiency changes with time at most landfills and this too should be considered in estimation of a decay rate.

The sites evaluated in this study predominantly assessed gas generation considering a site-wide basis with either a single  $L_0$  and  $k$  or a single  $L_0$  and two  $k$ s to represent older and newer waste (i.e., conventional operations and organic stability operations). At certain sites, these options were completed together to develop an argument for enhanced waste decomposition within areas under the OSR. In all cases, predicted gas generation was completed with USEPA's LandGEM gas model (see Appendix A).

Analysis of gas generation using a single  $L_0$  and two different decay rates was conducted at Sites D, E, and L. At all three sites,  $k = 0.04$  1/yr was used for waste in areas of the landfill in which decomposition was not accelerated and  $k = 0.08$  1/yr used for waste in-

place during active leachate recirculation or liquid waste addition. These three sites all report meeting OSR benchmarks for cumulative gas generation and reduced flow rates 40-yr post closure. Predictions of gas production were based on forecasting waste disposal assuming continuation of current acceptance rates and percent contributions of MSW plus degradable special wastes. At Site L, comparisons between gas collection and LandGEM model predictions suggest a best fit with  $L_0 = 80 \text{ m}^3/\text{Mg}$ .

An example of a coupled gas analysis that incorporates assumptions of a single  $k$  and two  $k$ s is presented in Table 8 for Site I. Estimates of  $k$  were developed assuming (i) a single  $k$  for the entire landfill and (ii) an elevated  $k$  for recently placed waste under the OSR combined with a lower  $k$  for waste in-place prior to initiation of the OSR. As shown in Table 8,  $k$  computed in both manners indicates an increase in methane generation rate from 2009 to 2012. Calculations following the second approach suggest a pronounced increase in the rate of waste decomposition ( $k = 0.15 \text{ 1/yr}$ ) achieved for waste placed since initiation of the OSR. The results of this analysis support attainment of the proposed OSR goals. However, calculation of a decay rate based on gas data for one year likely leads to increased uncertainty as a preferable decay rate calculation is based on several years of data (~5).

An alternative evaluation to assess if organic stability operations are meeting OSR goals was conducted by the site engineer at Sites I and J. The site engineer back-calculated a target  $k = 0.077 \text{ 1/yr}$  that will meet organic stability goals. This  $k$  was back-calculated from anticipated future waste filling and MSW composition with an assumed  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg}$ . The organic stability evaluation was made via comparison of the target  $k$  to a calculated  $k$  obtained from fitting the LandGEM model to measured gas data. As long as the calculated  $k$  is larger than the target  $k$ , the site engineer indicates that organic stability is progressing as anticipated. This approach may underestimate actual organic stability if the organic fraction of the waste stream changes (e.g., if  $L_0$  is considerably lower than  $100 \text{ m}^3\text{-CH}_4/\text{Mg}$ ) or if collection efficiency is less

Table 8. Calculated first-order decay rates for Site I determined with respect to a single gas generation rate for the entire landfill and enhanced rate for waste deposited under the organic stability rule.

Year	2009	2010	2011	2012
Single k for entire landfill (1/yr) <sup>1</sup>	0.038	0.035	0.041	0.061
Enhanced k for waste placed since OSR initiated (1/yr) <sup>2</sup>	0.051	0.093	0.107	0.153

<sup>1</sup>Calculated using average gas flow for one year and assuming 85% collection efficiency

<sup>2</sup>Assume k = 0.027 1/yr for waste in-place prior to organic stability plan and compute k for waste placed during active organic stability plan operations

than 100%; however, the approach is applicable for evaluating compliance with WDNR's OSR goals.

The gas assessment conducted by the landfill engineer at Site M highlights the different elapsed times required to meet the OSR benchmarks as discussed in the previous section. The two decay rates in Table 7 were computed on a site-wide basis assuming different gas collection efficiencies. The same observations with regards to the OSR benchmarks are made with either analysis. Considering an approximate closure date for the landfill by forecasting filling rates, > 75% of cumulative gas generation will be complete 2-yr post closure, the flow rate will decrease to 7 ft<sup>3</sup>/yd<sup>3</sup>/yr 37-yr post closure, and the flow rate will reduce to 5% of the current peak flow rate 45-yr post-closure. The first two comparisons support OSR benchmarks, whereas the reduced flow rate to < 5% does not. The difference in elapsed times to meet OSR benchmarks are in agreement with the LandGEM analysis discussed in the previous section and suggest that additional guidance may be needed on assessing organic stability via gas generation.

The variation in gas modeling methodologies conducted at the sites evaluated in this study suggests that additional guidance is needed as to how owners evaluate whether they are in compliance with gas production targets. The following recommendations are provided for WDNR consideration:

- Require the use of a single  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg}$ , as this is standard practice and has been shown to yield optimal fits between predicted and measured gas data (Wang et al. 2013);
- Allow owners to estimate the gas collection efficiency over time or to assume default values to differentiate between gas production and gas collection; and
- Allow the use of different decay rates for different areas of a landfill in cases where distinct gas collection rates are available for landfill areas that have been operated differently (i.e., have and have not received liquid addition).

## **Gas Management**

The aggressiveness with which site owners and operators initiate measures to enhance gas production is related to the ability to manage and use biogas. In some cases, sites had available capacity to increase energy generation and desired additional gas collection. At others, some fraction of the collected gas was flared as markets did not warrant investment in additional engines or other equipment to beneficially use the gas. Anecdotally, decreases in the price of natural gas over the past two to three years have reduced the economic feasibility for beneficial use of landfill gas.

Some sites reported gas production within 6 to 9 months following waste disposal and initiated collection via horizontal trenches within 12 months. An effective method for early gas collection noted at most sites was the installation of “belly pipes” along the leachate collection layer at the base of a landfill cell. Pulling gas from these “belly pipes” is effective in the early stages of waste placement, and some sites reported that collection was effective with only a few lifts of waste (6-10 ft each) above the pipes. Horizontal trenches were reported to be effective for the first 3 to 4 yr, after which they had a tendency to clog depending on the aggressiveness with which liquids are added to the waste. Vertical wells are the most common technique used for gas extraction throughout the long-term operation of a landfill.

At Site J, a temporary gas collection system was constructed in 2010, consisting of vertical wells and horizontal collectors to collect early gas production. Waste placement in the area with the temporary gas collection system was initiated in early 2009 and followed with liquid waste disposal and leachate recirculation in 2010. The site has a permit for ten gas engines, of which two were relocated to other sites due to a decrease in site-wide gas production. The temporary gas collection system at Site J was installed to collect gas for the remaining eight engines. Thus, the availability of on-site energy-generation infrastructure at Site J prompted the site engineer to implement aggressive actions to stimulate organic

decomposition and increase gas generation. These actions appear to have been enacted in the absence of organic stability concerns, and the decreased time for organic stability is an added benefit to the engineer's actions.

An opposite scenario is present at Site K, where waste is disposed of in a new cell initiated in 2011 and as of mid-2013, no gas collection system had been installed. A gas collection system reportedly was not required for this new cell; however, liquid addition via an RD&D permit is on-going and there likely is gas generation from enhanced waste decomposition. Wisconsin regulations require an active gas collection system for landfills conducting leachate recirculation (NR 504.095(1)(c)) and that landfills operating with an RD&D permit adhere to requirements mandated for leachate recirculation operations (NR 514.10(2)(e)). Landfill owners at Site K are aware that gas could likely be collected from this new cell, but reported that there currently are not enough incentives to support implementation of an early gas collection system. Regardless, Site K may be out of compliance with Wisconsin regulations and WDNR may need to clarify how gas regulations apply to landfills operating with an RD&D permit.

The capability to manage gas effectively was a common theme among the sites in this study, with one site owner specifically reiterating the importance of “staying ahead of the gas” to avoid gas and odor problems associated with accelerated gas production. Active gas collection systems have been installed early (i.e., before the NSPS requirement) at each of the sites visited, except Site K, so that gas could be managed effectively and, in some cases, to ensure adequate gas supply to gas-to-energy facilities.

## **IMPLICATIONS AND CONSEQUENCES**

### **Waste Management**

Most sites have experienced a decrease in the MSW fraction and overall waste tonnage for disposal in recent years (Fig. 1). A decrease in MSW tonnage at a given landfill reduces the

amount of liquid that can be absorbed. At Site M, where the average  $w_w = 44\%$  (Table 5), all recirculation was suspended in 2013. Engineers at Site M are cognizant of the amount of liquid added to the waste and target an average moisture content of 35%. They report gas wells watering out and pump freezing issues in the winter when the moisture content exceeds 35%.

The advantages associated with diversion of organic waste (e.g., food waste) are site-specific. For a site that aggressively collects gas for beneficial use, inclusion of organic waste within the landfill mass is advantageous for increasing gas generation. The opportunity to divert organic waste to an anaerobic digestion (AD) system (e.g., associated with a local POTW) can be advantageous in terms of decreasing the organic waste fraction within the landfill, providing a beneficial use for the organic waste, and using a system in which methane recovery will approach 100%. However, reducing the organic waste fraction in the landfill can adversely affect the production rate of landfill gas due to removal of the rapidly biodegradable waste fraction. Organic waste diversion will decrease the bulk waste decay coefficient and may reduce availability of landfill gas for beneficial use.

Another option is to divert organic waste to composting facilities. The environmental implications of managing organic waste by composting, AD, and landfills are complex. The benefits of composting are strongly influenced by the type of composting facility, whether the compost product is used to offset nutrient application, the extent to which landfill gas is recovered for beneficial use, and how other gas and water emissions are managed (Levis and Barlaz 2011). Life-cycle analysis (LCA) has shown that AD is a superior means for managing organic waste in consideration of green-house gas emissions (Levis and Barlaz 2011); however, the benefits of alternative strategies for managing organic wastes vary depending on site specific conditions. In this study, the predominant strategy for meeting the OSR was accelerated anaerobic decomposition of organic waste in landfills. Aggressive organic waste diversion is a relevant alternative strategy for meeting the OSR and should be evaluated via LCA as part of any waste management consideration. Although there can be environmental

benefits to organic waste diversion, the general perception among landfill owners is that organic waste diversion has not become a significant waste management strategy in Wisconsin, and has not had a measureable effect on the waste stream being managed in Wisconsin landfills.

Those sites that reported organic waste diversion to composting facilities indicated that they only accept commercial source-separated waste streams, which provides control on feedstock quality that is necessary for their end-use alternatives. Post-consumer food waste, for example, is expensive to collect and is subject to more contaminants, making this waste more difficult to manage in composting operations. Site G, for example, reported a mature yard waste composting operation and collaboration with an industrial partner to whom they sell 90% of their compost. The owner of Site G indicated that the industrial partner has strict regulations on compost composition and that they would discontinue purchasing compost if food waste was included in the composting operation. Thus, the yard waste composting facility at Site G does not contribute to organic stability of the landfill, and likely will not in the future as there are no incentives to expand the composting facility to accept other organic waste sources.

Wisconsin has had a ban on yard waste disposal in landfills since 1993. As such, there have not been changes in yard waste management as a result of the OSR. As yard waste is partially biodegradable, disposal of yard waste in a landfill would contribute to methane production. The decay rates for grass and leaves are such that they would decompose well ahead of a 40 year target (De la Cruz et al. 2010). The decay rate for branches is more variable and branches could contribute to methane generation for longer than 40 years, albeit at low rates (Wang et al. 2013).

At Site F, a large fraction of the municipal waste stream is diverted to an RDF facility, which decreases the amount of landfilled organic waste. Under the current OSR, Site F is required to submit an organic stability plan for the waste that is managed within the landfill. Considering that the majority of the organic waste is diverted to an RDF facility, the site owner believes that this diversion should be accounted for in the overall progression of Site F towards

organic stability. Although landfill gas is used beneficially at Site F (Table 5), the owners of Site F reported limited incentive for implementing leachate recirculation, as the cost to conduct leachate recirculation is approximately \$0.05/gal and the cost for leachate disposal to the local POTW is \$0.002/gal. Given the relatively low waste receipts at Site F, and the reduced organic fraction due to the RDF facility, the owner at Site F has only been complying with the OSR and recirculating leachate to enhance in-situ waste decomposition since 2012.

Site L has a 10% waste overfill policy for waste disposal based on observations that waste will settle back to allowable final grades within the regulated air-space volume. Operation of the landfill to enhance decomposition under the OSR is the basis for the overfill strategy with subsequent waste settlement and recovery of airspace. Thus, operations under the OSR also result in an opportunity at Site L to increase revenue via a higher airspace utilization factor (i.e., the volume of waste ultimately disposed per volume of permitted capacity). Acceptance of commercial liquid waste, which represents a revenue stream for many of the landfills evaluated, is another financial benefit of the OSR.

## **Liquid Management**

The availability of cost-effective strategies to comply with the OSR is important. The disposal of commercial liquids has proven to be important for both the liquid available to wet the waste and for the revenue associated with commercial liquid acceptance. The availability of commercial liquids has led to the diminished use of leachate recirculation and the increased acceptance of waste liquids under the RD&D rule. This has been a pragmatic approach that has benefitted the industry while also meeting the goals of the OSR. Site owners unanimously reported interest in continuing to accept liquid waste under their RD&D permits. In the absence of the OSR, landfill owners would likely continue accepting liquid waste under the RD&D rule if the economics remain favorable. Additionally, there were no reports of pronounced or

sustained problems (e.g., seeps, stability, elevated head on liner, etc.) related to liquid waste addition.

A challenge to landfill owners may exist if the RD&D rule expires and operations must be readjusted to continue complying with requirements of the OSR. If an operator was unable to add outside commercial liquids to the landfill, then some landfills may not have enough leachate to enhance decomposition. This would be site-specific and a function of waste receipts, landfill geometry, and leachate generation rates. WDNR should encourage the USEPA to make the provisions in the RD&D rule permanent elements in Subtitle D of the Resource Conservation and Recovery Act (RCRA).

Biochemical compatibility between MSW decomposition and liquid waste is essential to ensure that organic stability can be achieved when waste liquids are used as the compliance strategy for the OSR. WDNR should consider issuing guidance on assessing biochemical compatibility and organic loading rate, and require owners to assess compatibility to ensure that the environmental benefits attributed to enhanced waste decomposition are realized in tandem with the economic benefits of liquid waste disposal. For example, at sites where leachate treatment costs are high and liquid wastes represent a significant revenue stream, landfill owners and operators reported a desire to seek out special wastes with high moisture retention capacity (e.g., utility ash, foundry waste, shredder fluff) that can be co-disposed with liquid waste. Although many industrial solid wastes are inert, characterization and assessment of biological compatibility between special solid wastes and liquids wastes with anaerobic waste decomposition is desirable.

## **Gas Management**

Increased gas generation results from the operation of a landfill to accelerate anaerobic decomposition of organic waste. However, if gas generation is increased early in the life of a landfill and a gas collection system is not functional, then gas will be emitted to the atmosphere.

The main implication of increased gas generation in the absence of collection is an increase in greenhouse gas emissions.

At Site J, an early gas collection system was installed during waste disposal primarily to collect gas for energy generation. In absence of the OSR, the landfill engineer at Site J still would have been motivated to install a gas collection system prior to regulated-installation dates as the engines were in place and the gas was needed. In contrast, an active gas collection system was not in-place at Site K in areas where liquid waste was disposed. This site may have been out of compliance with gas collection regulations prescribed for sites operating with an RD&D permit. Regulations required for landfills operating with an RD&D permit need to be clarified to owners and operators such that landfills are in compliance and gas emissions and odors issues are mitigated to the extent possible.

The ability and desire for a given site to increase on-site energy generation from landfill gas was noted as an economic and regulatory challenge. For example, Site G currently operates four turbine generators that are near maximum capacity. Maintenance or replacement of one of the generators requires an air pollution control construction permit, which is difficult and expensive to obtain. The landfill's Clean Air Act permit does not allow for installation of a fifth generator, which means that there is no incentive to produce and recover additional landfill gas. In addition to regulatory constraints, revenue from electricity sales to local power companies is not sufficiently attractive to justify investments in gas utilization. The combination of these regulatory and economic constraints results in flaring of a substantial fraction (16%) of the gas collected at Site G (Table 6). Although from the perspective of the OSR there is no benefit to gas collection for energy generation as compared to flaring, landfill owners may have a desire to slow down gas generation to maximize economic benefits associated with landfill gas-to-energy systems.

A unique example of biogas utilization is at Site E, where gas eventually will be collected, treated, compressed, and transported via pipeline to a local POTW. The treatment

processes include H<sub>2</sub>S and siloxane removal as well as condensate removal. This gas management facility has a capacity of 2000 ft<sup>3</sup>/min. However, the facility is in a preliminary stage and not yet fully operational, which is likely the reason that the majority of the gas at Site E is flared (Table 5). As the gas pipeline becomes operational, gas utilization will likely increase to 100%. The ability for landfills to find collaborative partners that can use landfill gas beneficially will increase the beneficial gas use and may provide additional incentive for a landfill operator to further enhance waste decomposition through implementation of practices that encourage achievement of organic stability.

Only four of the ten sites evaluated mentioned gas collection efficiency in LandGEM modeling assessments. While collection efficiency is difficult to measure and cannot be accurately calculated from LandGEM, WDNR should verify that gas is being collected early and aggressively at landfills that are being operated to accelerate methane production. Early and aggressive collection was observed at several of the landfills and two of the key motivations were responsibility to minimize odors and emissions as well as a need for the gas to run engines or turbines. As indicated earlier, “staying ahead of the gas” was a common theme at most of the sites that were visited. Finally, liquid addition increases the potential for accumulation of leachate in gas wells, which decreases collection efficiency. WDNR should continue to monitor landfills to verify effective operation of gas collection and control systems and ensure that liquid addition to promote organic stability does not compromise gas collection efforts.

## **SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

This report includes an evaluation of the Wisconsin Organic Stability Rule (OSR). Ten landfills distributed throughout Wisconsin were selected for the evaluation. These ten landfills represent private and public landfill operations and manage approximately half of the MSW landfilled annually in Wisconsin. All ten landfills had implemented organic stability plans and

were reporting progress on organic stability to WDNR. Personnel at each landfill were interviewed, organic stability plans and reports for each landfill were reviewed, and data provided by the landfills were analyzed.

A general perspective shared by the landfill owners and operators interviewed for this study is that the goals of the OSR coincide with industry goals. Operating a landfill in accordance with the OSR results in enhanced gas production for energy generation, increased waste settlement for air-space recovery, and waste stabilization that will reduce long-term maintenance of the final cover. Additionally, the goals of the OSR and the economics of landfill operation currently are well aligned. For example, under the RD&D rule, a landfill can accept liquid waste for disposal, which promotes organic stability goals via enhanced in-situ anaerobic waste decomposition and is beneficial economically due to the additional revenue derived from tipping fees from the liquid waste. At eight of the ten landfills evaluated, liquid wastes were a means to enhance moisture for compliance with the OSR.

The landfills evaluated in this study appear to be in compliance with the OSR. This finding particularly is noteworthy considering the range of variability in landfill characteristics and operations. Implementation of the OSR is resulting in more rapid waste decomposition with no apparent deleterious environmental impacts; thus, the OSR should be continued. However, as waste generation and management issues are dynamic and influenced by a myriad of factors, periodic reviews of the OSR are recommended to ensure that practical organic stability actions can be implemented at all landfills to meet organic stability requirements stipulated by the WDNR.

This review has identified several issues WDNR should consider to ensure that the OSR remains successful, practical, and economical. These recommendations are described in the following.

**1. WDNR should encourage USEPA to modify RCRA Subtitle D by incorporating the provisions in the current RD&D rule.**

Wisconsin landfills currently hold the most RD&D permits of any state in the US. The relatively high number of permits granted in Wisconsin is in response to the need to comply with the OSR and the economic opportunity afforded by disposing of liquid wastes. However, the majority of Wisconsin landfills are also maintaining an active waste solidification license, whereby liquid waste can be solidified with an acceptable solid waste stream and co-disposed in a landfill in the absence of an RD&D permit (RD&D permits have maximum period of 12 yr under current federal rules). The retention of active solidification permits suggests that landfill owners are planning to retain their ability to accept liquid waste streams in the event that the RD&D rule does not become permanent. While the solidification option will ensure that accepting liquid wastes will still be possible, the current method of disposing of liquids directly into the waste is more practical and achieves the goal of increased moisture content in the OSR. This goal would not be achieved if solidification is used to manage liquid waste.

**2. WDNR should develop guidance regarding biochemical compatibility of liquid waste sources.**

The use of liquid wastes to enhance moisture content for compliance with the OSR can lead to biochemical incompatibilities that can compromise organic stability goals. Guidance on the evaluation of waste liquids for biochemical compatibility and loading should be provided.

**3. WDNR should clarify existing requirements for early and aggressive gas collection as part of organic stability plans and ensure that these requirements are followed for landfills adding liquid wastes.**

Addition of leachate and commercial liquid waste enhances early gas generation as a byproduct of enhanced organic waste decomposition. Current WDNR regulations (NR

504.095(1)(c) and NR 506.135(1)(c) require an installed gas collection system for landfill areas with active leachate recirculation. In addition, WDNR code NR 514.10(2)(e) requires RD&D projects that introduce outside liquids to the waste mass to follow code requirements applicable to leachate recirculation. This implies that landfill areas receiving liquid wastes under an RD&D permit must have an active gas collection system in place. Most of the landfills that were evaluated had installed gas collection systems early, recognizing the need to collect gas and manage odors. However, there appears to be cases where early and aggressive gas collection was not initiated with liquid waste addition under an RD&D permit. Thus, WDNR should ensure that the existing requirements for gas system installation in areas with moisture enhancement are followed for all landfills operating with an RD&D permit.

#### **4. WDNR should promote means to make beneficial use of landfill gas attractive.**

While WDNR cannot influence the value of methane on the open market, operators indicated that current (2013) natural gas prices are too low to encourage additional investment in beneficial gas use projects. Achieving organic stability without reclaiming the energy available in the gas that is generated as a result of organic stability activities negates the opportunity to recover a renewable source of energy. There will always be cases where gas volumes are too low to warrant beneficial reuse, but WDNR should consider policies that provide incentives for beneficial use of landfill gas as renewable energy. One example is the possibility to slow down gas generation if gas-to-energy infrastructure is operating at maximum capacity. The WDNR should consider allowing deviations from prescribed OSR plans if such deviations would increase the beneficial use of methane.

**5. WDNR should consider modifications to the gas generation benchmarks in the OSR and development of a standardized gas analysis procedure.**

The gas generation benchmarks in the OSR currently focus on total gas generation (CH<sub>4</sub> + CO<sub>2</sub>), and include an option to compare gas flow rates to a percentage of peak flow or to a target flow rate to support meeting OSR goals. The WDNR should consider the use of CH<sub>4</sub> in place of total gas for gas generation benchmarks as CH<sub>4</sub> production may decrease before CO<sub>2</sub> at the end of the decomposition cycle. Methane is the gas of interest from a greenhouse gas perspective, is predicted directly within LandGEM, and CH<sub>4</sub> generation can be determined at all landfills based on gas flow rate and composition.

The WDNR should develop a standard protocol for assessment of landfill gas decay rates so that every landfill owner evaluates whether they are in compliance with the OSR using the same protocol. At present, owners are assessing compliance in various ways. Some are using more than one decay rate based on landfill operations, and none are recognizing that landfill gas collection efficiency changes with time.

The WDNR should also consider clarifying that OSR gas generation benchmarks may be achieved at different elapsed times, but of critical importance is meeting all benchmarks within a period of 40-yr post closure.

**6. WDNR should consider metrics for cessation of gas collection as part of the OSR.**

Operation of a landfill to accelerate decomposition reduces the time over which methane is produced. WDNR should develop criteria for when a landfill operator may switch from active to either passive gas collection and control or no gas collection and control. For example, a metric could be based on the capacity of the landfill cover soil to attenuate or oxidize remaining methane production. Alternately, WDNR could mandate that gas be routed to a biofilter if there is not sufficient volume to run a flare.

**7. WDNR should recognize that the OSR can affect publicly- and privately-owned landfills differently.**

Although the OSR applies equally to public and private landfills, differences in their characteristics may explain why the OSR has been implemented more widely at private landfills. First, private landfills tend to be larger and more readily able to realize the economies of scale associated with accepting liquid wastes for achieving higher moisture contents needed for organic stability. In contrast, low MSW disposal rates more typical of publicly-owned landfills are associated with reduced capacity to apply commercial liquids. While a privately-owned landfill might be inclined to identify non-MSW material that could absorb liquid, there is no incentive for a publicly-owned landfill to seek alternative waste streams. Second, acceptance of waste liquids is profitable, which can motivate a privately-owned landfill, but may not be as important to a publicly-owned landfill where the primary objective may be managing waste generated within a county or region. Thus, complying with the OSR may be less economically attractive for a public landfill than a private landfill.

**8. WDNR should recognize that gas generation alone does not address post-closure care and more comprehensive criteria are needed to address functional stability.**

Functional stability must consider all landfill elements including gas, leachate, groundwater, and the final cover. While the objective of the OSR is to promote landfill stabilization, the focus is on gas generation. The WDNR needs a more comprehensive strategy to assess the stability of closed landfills.

**9. WDNR should consider a statewide life cycle analysis (LCA) to assess the effects of more aggressive organic waste diversion.**

The focus of this report has been on the manner in which the OSR has influenced landfill operations. More broadly, the OSR could have resulted in the large-scale diversion of

biodegradable organics from landfills. WDNR should evaluate whether the economics and environmental implications warrant policies to either encourage or require the diversion of biodegradable wastes from landfills to composting, anaerobic digestion, or combustion.

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## APPENDIX – LANDFILL GAS ASSESSMENTS

Appendix 1 includes a compilation of the LandGEM gas analyses conducted for each of the landfills. These analyses were adopted from landfill annual reports and were not conducted by the research team. All sites assumed waste tonnage from municipal waste (WDNR Cat. 1), pulp and papermill waste (WDNR Cat. 3), POTW sludge (WDNR Cat. 5), and all other non-hazardous solid waste (WDNR Cat. 6) contribute to methane generation. LandGEM gas analyses were not included in annual reports or other files provided for the Landfills A and G.

### Landfill D

The modeling effort at Site D was completed in 2012. Waste filling was forecasted for the remaining site capacity (2012-2018) with an equal amount of degradable waste added in each year based on an average tonnage from the previous 5 yr. An  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$  was assumed for all waste tonnage contributing to methane generation. A first-order decay rate (k) of 0.04 1/yr was assumed for older waste in-place prior to 2006 and a k of 0.08 1/yr was assumed for waste placed since 2006. The methane content was assumed 50%.

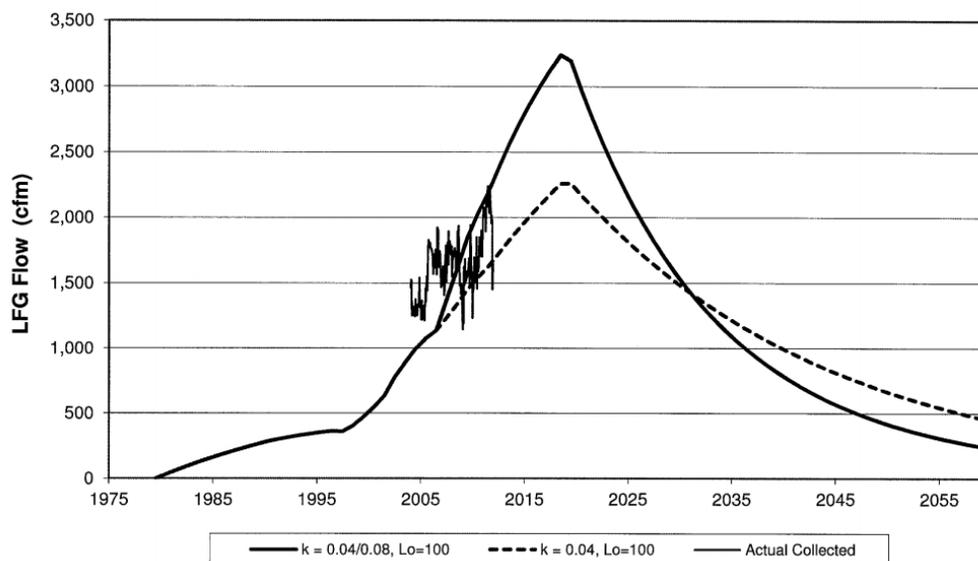


Fig. A1. Comparison between gas collected and gas predicted via LandGEM for Landfill D.

## Landfill E

The modeling effort at Site E was completed in 2010 such that waste tonnages for 1994-2009 were based on tonnage reports and waste tonnages from 2010 to 2023 (anticipated closure year) were based on estimated filling rates, remaining capacity, waste unit weight, and waste composition. Landfill gas collection was initiated in 1999 and expanded in 2002. Leachate recirculation was initiated in August 1998 and the addition of supplemental liquid wastes was initiated in 2007. The early onset of leachate recirculation at Landfill E was used as a basis for assuming a constant decay rate across the entire site. LandGEM gas curves were created for different combinations of  $L_0$  and  $k$  to compare with collection data as shown in Fig. A2. The methane content was assumed 50%.

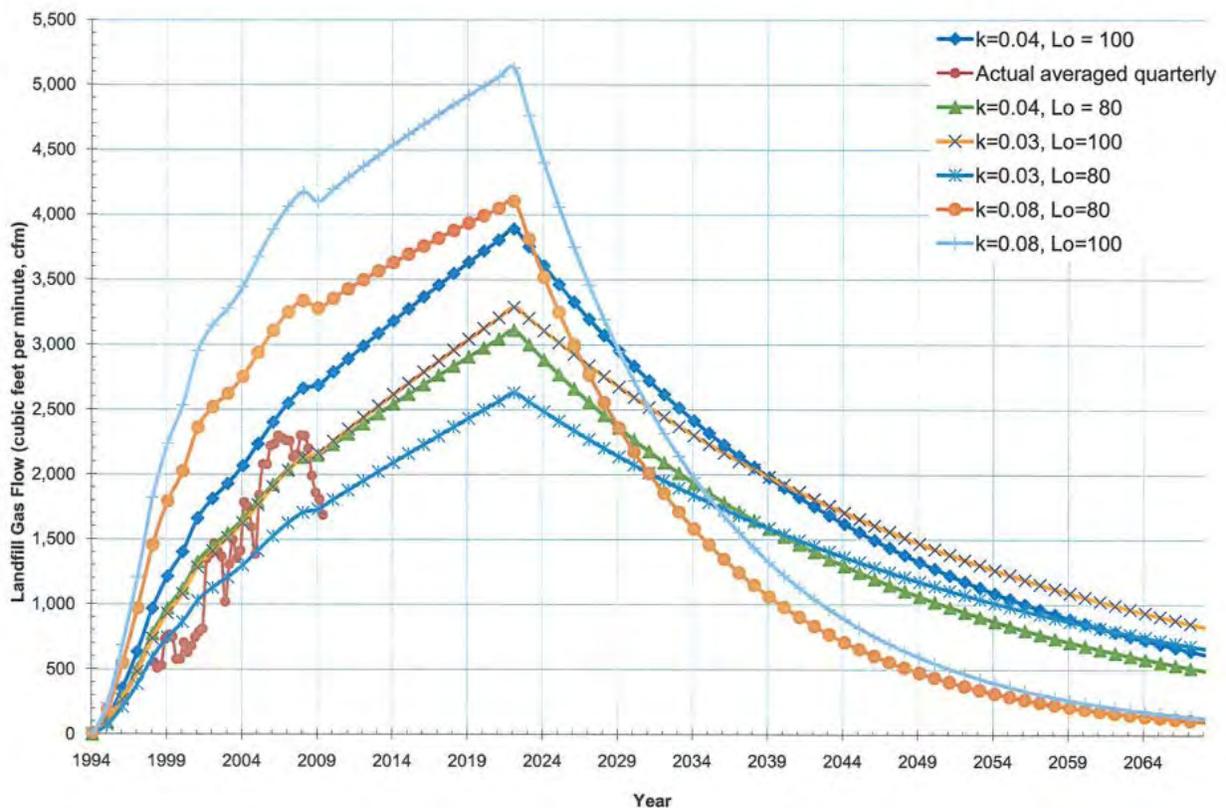


Fig. A2. Comparison between gas collected and gas predicted via LandGEM for Landfill E.

## Landfill F

In addition to the previously mentioned solid wastes contributing to methane generation, construction and demolition (C&D) waste was also considered to contribute to methane generation at Site F. Prior to 2009, C&D waste was disposed in a separate landfill and was not included in waste tonnages for gas modeling. Gas modeling at Landfill F was completed assuming that only waste placed since 1991 is contributing to gas collected on site. Waste placed beginning in 1991 was all placed within a modern Subtitle D landfill for which there is an active gas system. Predicted gas generation for Landfill F is shown in Fig. A3. The prediction is based on  $L_0 = 80 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$ ,  $k = 0.08 \text{ 1/yr}$ , and methane content = 50%. Gas collection measurements were not compared with predicted gas flows.

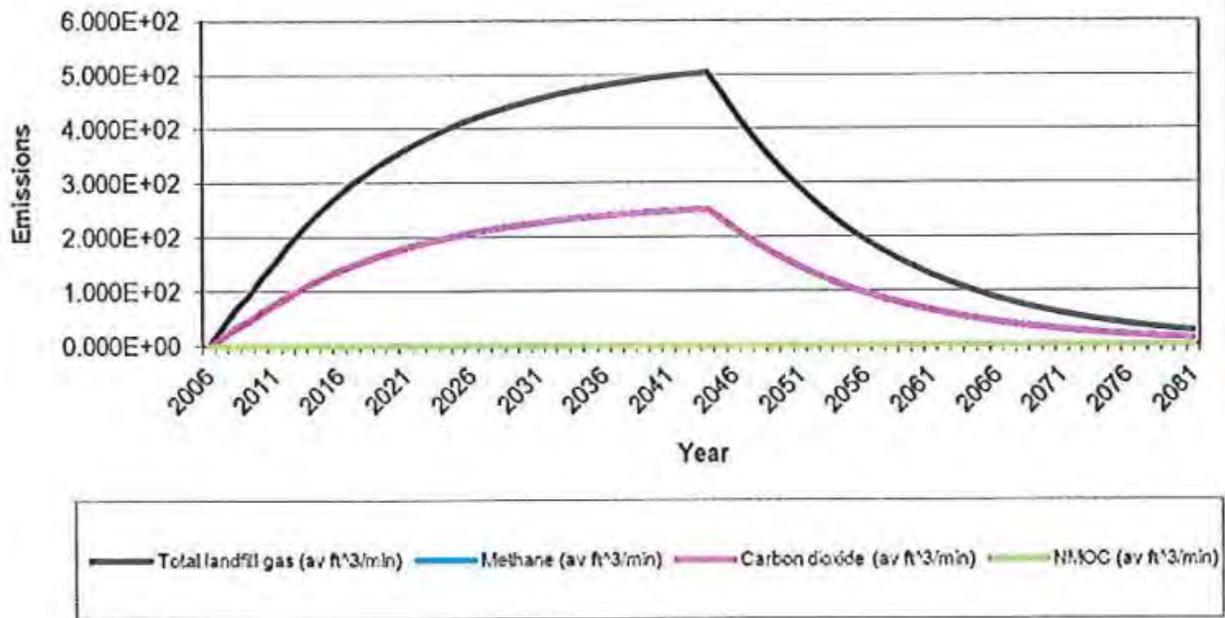


Fig. A3. Predicted gas generation via LandGEM for Landfill F.

## Landfill I

A gas modeling assessment at Landfill I was completed in 2007 to support the proposed organic stability plan. Annual reports since 2007 have not included comparisons of measured

gas generation to predicted gas generation via LandGEM. Gas modeling was completed on a site-wide basis with  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$  for all waste. For the closed and active sites of the older landfill, the gas collection efficiency was assumed as 85% and  $k$  as 0.03 1/yr. For the expansion area where liquid addition is implemented, two models were completed with  $k = 0.03$  1/yr and  $k = 0.077$  1/yr. The latter  $k$  was used to estimate the anticipated increase in gas generation due to moisture enhancement proposed for achieving organic stability. A comparison of gas prediction models is shown in Fig. A4. Waste tonnage used in LandGEM for the expansion area was based on the percent organic waste content reported in 2005 and an anticipated filling rate for site operation through 2021. The methane content was assumed 50%.

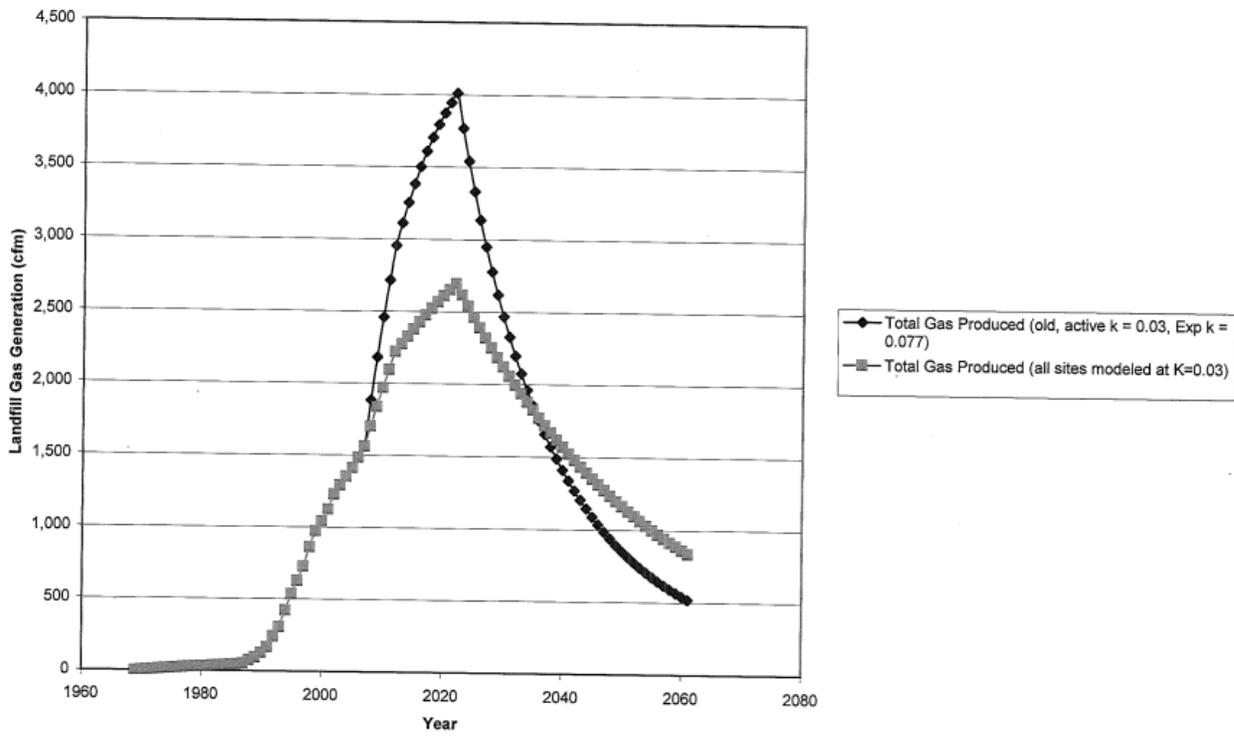


Fig. A4. Gas generation predictions for Landfill I considering (1)  $k = 0.03$  1/yr for the entire site and (2)  $k = 0.03$  1/yr for the old and active areas and  $k = 0.077$  1/yr for the expansion area where moisture enhancement actions will be implemented.

## Landfill J

A gas modeling assessment at Landfill J was completed in 2007 to support the proposed organic stability plan actions for the expansion area. Annual reports since 2007 have not included comparisons of measured gas generation to predicted gas generation via LandGEM. Waste tonnage and organic waste content (58.6%) used in LandGEM for the expansion area were assumed to remain similar to 2005. Gas modeling was completed with an  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$  and  $k = 0.03 \text{ 1/yr}$  and  $0.077 \text{ 1/yr}$ . The latter  $k$  was back-calculated to yield the minimum  $k$  required to meet organic stability goals. A comparison of gas prediction models is shown in Fig. A4. The methane content was assumed 50%.

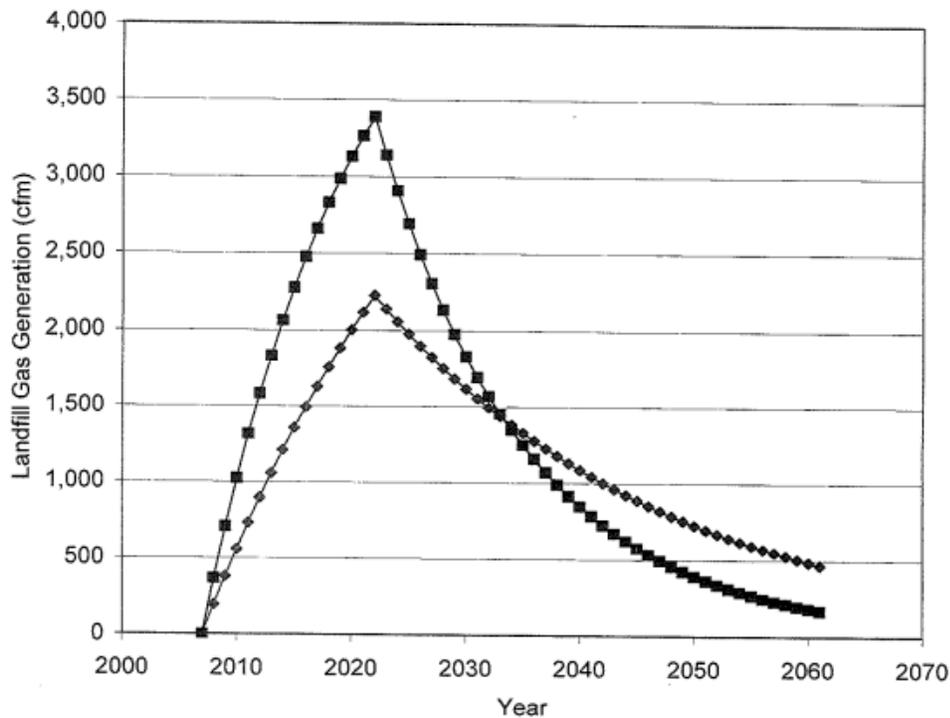


Fig. A5. Gas generation predictions for Landfill J considering (1)  $k = 0.04 \text{ 1/yr}$  for a base-case scenario and (2)  $k = 0.077 \text{ 1/yr}$  as the target  $k$ -value to achieve organic stability goals.

## Landfill K

A gas modeling assessment was completed in 2010 for the expansion area at Landfill K to support the proposed organic stability plan. Future waste disposal in the expansion area was assumed to reflect current practice. A 71% organic waste contribution recorded in 2009 was assumed for all future waste tonnage calculations input into LandGEM. Modeling was executed with  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$  and  $k = 0.068 \text{ 1/yr}$ . The 0.068 1/yr decay rate was determined by increasing the default  $k$  of 0.04 1/yr by 75% to account for enhanced gas generation due to leachate recirculation, and was reported to be the target  $k$  to meet organic stability goals. The methane content was assumed 50%. Landfill gas generation predicted for Landfill K via LandGEM is shown in Fig. A6.

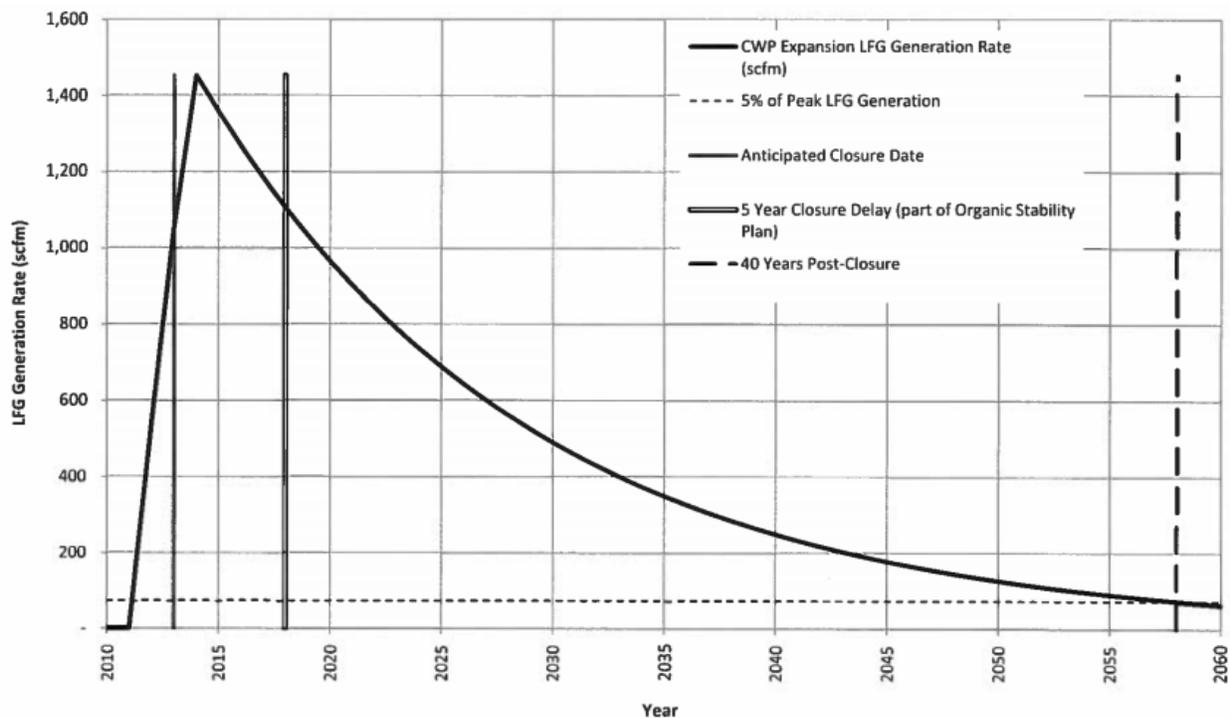


Fig. A6. Landfill gas generation prediction via LandGEM for Landfill K.

## Landfill L

The landfill gas modeling assessment at Landfill L was completed for two expansion areas (South and Southeast) that have a required organic stability plan. The modeling was conducted on a site-wide basis that also included the existing closed landfill. Thus, gas generation is predicted as the cumulative generation from the existing cell and the expansion areas. Waste tonnages between 1990 and 2011 were based on tonnage reports, and prior to 1990 were based on filled capacity and waste density estimations. Waste disposal for 2012 until site closure was based on site capacity, waste density, and composition. Comparisons of landfill gas predicted via LandGEM for Landfill L and gas collected on a site-wide basis are shown in Fig. A7. Gas predictions were completed for different pairings of  $k = 0.04$  or  $0.08$  1/yr and  $L_0 = 80$  or  $100$   $\text{m}^3\text{-CH}_4/\text{Mg-MSW}$ . An elevated  $k = 0.08$  1/yr was selected to represent an anticipated increase in gas production for the expansion area. The methane content was assumed 50%.

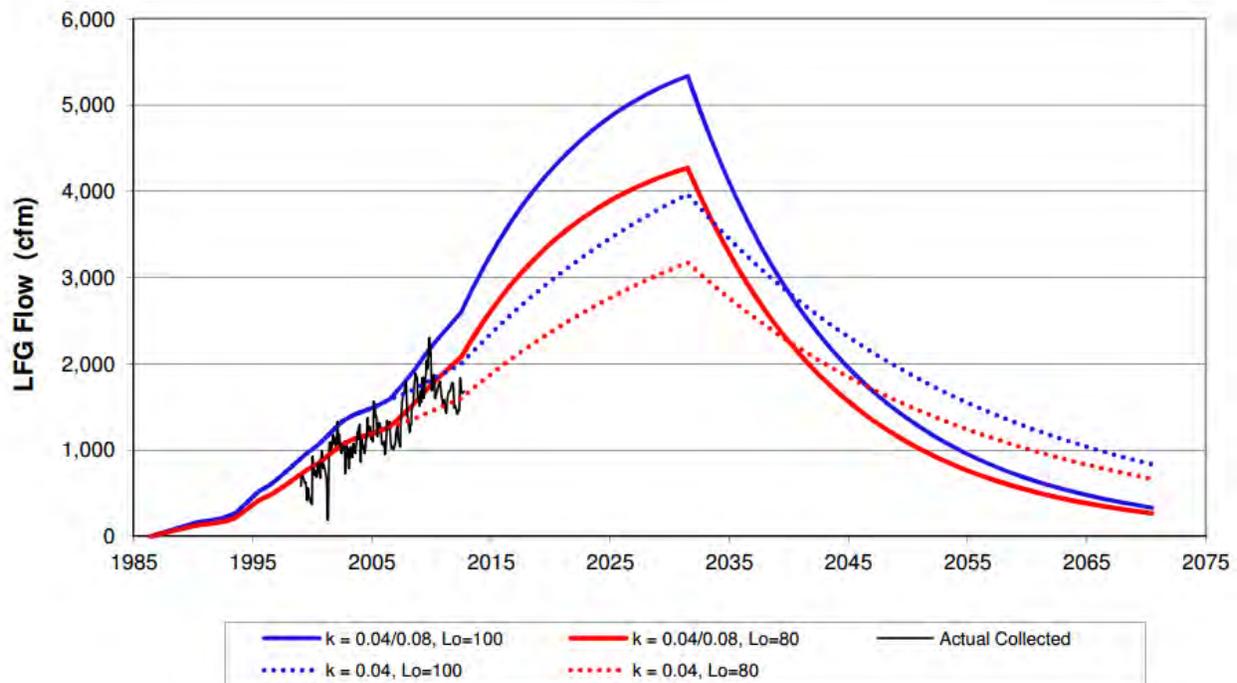


Fig. A7. Comparison of predicted landfill gas and collected landfill gas at Landfill L.

## Landfill M

A landfill gas modeling assessment was completed for the Northern Expansion at Landfill M and was included in the 2012 annual report. Two types of models were conducted: (1) constant k and (2) temporally varying k. Gas curves developed for Landfill M based on the constant k and variable k approaches are shown in Fig. A8. In the first scenario, for an  $L_0 = 100 \text{ m}^3\text{-CH}_4/\text{Mg-MSW}$ ,  $k = 0.062 \text{ 1/yr}$  for a collection efficiency of 75% and  $k = 0.050 \text{ 1/yr}$  for a collection efficiency of 85%. The variable k model was developed by site engineers and also included adjustments for  $L_0$ , percent contribution of inert waste, and collection efficiency. The following decay rate considerations were incorporated into the variable k model:

- A  $k = 0.05 \text{ 1/yr}$  was used during 1995 and 1996, which is the period of initial filling and waste was at low moisture content (~30%);
- A  $k = 0.04 \text{ 1/yr}$  was used during 1997 and 1998 due to typical conventional landfill conditions;
- A  $k = 0.17 \text{ 1/yr}$  was used during 2001 to 2006 as the site was aggressively recirculating leachate and disposing liquid wastes via solidification; and
- A  $k = 0.05 \text{ 1/yr}$  was assumed for waste placed since 2007 due to a decrease in the MSW fraction and reduced leachate recirculation.

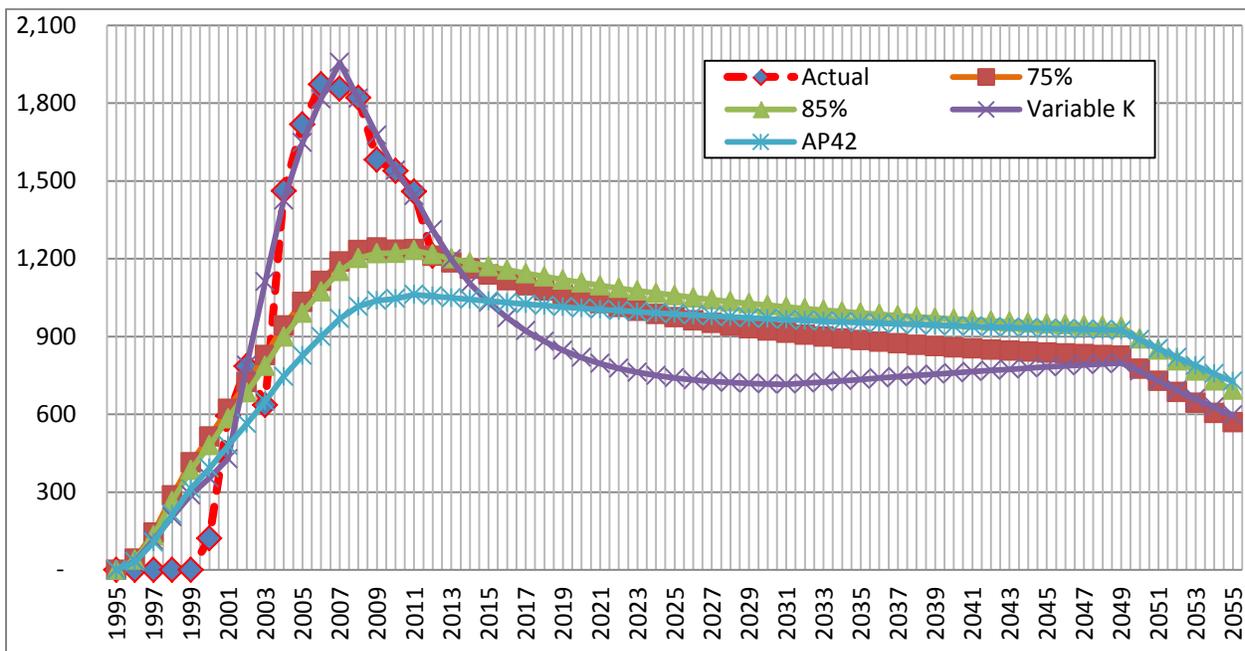


Fig. A8. Cumulative gas generation curves for Landfill M.