

Use of seasonal parameters and their effects on FOD landfill gas modeling

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Received: 13 February 2017 / Accepted: 4 April 2018 / Published online: 18 April 2018
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Abstract Temporal and spatial variations in landfill gas generations and emissions have been observed and reported by others. Real-time gas data between 2008 and 2014 from a municipal landfill located in a cold, semi-arid climate were consolidated to fit a linear-interpolated form of LandGEM. Seasonal variations in gas collection were observed in the landfill. LandGEM's default decay rate k was not applicable for this Canadian landfill due to significant overestimation (32.2% error). Optimal seasonal k and L_o collection parameters had 8.1% error compared to field data, compared to 8.3% error using optimal annual parameters. The optimal k_{winter} was 0.0118 year^{-1} and the k_{summer} was 0.0141 year^{-1} (14.7% difference), with a corresponding L_o of $100.0 \text{ m}^3/\text{Mg}$ which changed negligibly between the sets. Three pseudo-second order iterative methods were considered, and evaluated using RSS and generation parameters in the literature. A simple application study was conducted using LFGcost-Web, and found the increased precision of seasonal k 's resulted in negligible differences with annual optimized k . The default parameters overestimated the net present worth by 12–155% for three of the four common LFG energy projects.

Keywords Seasonal variability · Cold regions · LandGEM · Methane generation rate and potential · Semi-arid climate

Introduction

Canada's solid waste generation rate is among the highest in the world (Bruce et al. 2016; Chowdhury et al. 2017; Richter et al. 2018, 2017). Its per capita nonhazardous waste generation rate was 965 kg/year in 2010, 32% higher than in the USA. In 2010, a majority of all non-hazardous solid waste collected in Canada (75.6%) was disposed in landfills. This proportion was 86.8% in Saskatchewan, a province with a poor waste diversion record (Statistics Canada 2013; Wang et al. 2016). While source reduction and diversion practices are the most effective means of reducing environmental footprints, these practices are not able to mitigate the impacts of waste already disposed in landfills in Canada and throughout the world. Proper landfill design and management before, during, and after disposal operations will therefore remain a necessary field for the foreseeable future.

Due to anaerobic decomposition, landfill gas (LFG) is generated within landfills during and after operation, and continues decades after final closure. The major components of LFG are the greenhouse gases methane (CH_4) and carbon dioxide (CO_2), trace gases, air, and evaporate. LFG management systems are used primarily to prevent methane migration to neighboring sites, and mitigate emissions that pose esthetic, health, and safety (i.e., explosive nature of CH_4) threats. These systems

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can be used for heating or electricity generation projects using methane combustion as an energy source, although the most common project in North America is LFG flaring (Lindberg et al. 2005; Mohareb et al. 2008; Rajaram et al. 2011; Sanchez 2016; Tolaymat et al. 2010). Operating costs depend on geographic location, available markets, gas quality, and quantity (Ahmed et al. 2015; Albanna et al. 2007; Sanchez 2016). Flare systems convert collected methane into carbon dioxide emissions, a less harmful product due to methane's higher global warming potential (28, 100-year time horizon) (Myhre et al. 2013).

Emission mitigation techniques require a means to estimate generation, collection, and emissions to determine the optimal solutions. Due to the temporal and spatial variability of LFG emissions (Bogner et al. 1999; Borjesson and Svensson 1997; Christophersen et al. 2001; Klusman and Dick 2000; Scharff et al. 2000), numerical models have been a vital tool in LFG management, as direct measurements at the surface are more expensive. Numerous models have been developed, and many are publicly accessible such as LandGEM, Scholl Canyon, GasSim, Afvalzorg, CALMIM, IPCC, and TNO. Among these, first-order decay (FOD) or kinetic generation models are the most common type (Kamalan et al. 2011; Thompson et al. 2009; Vu et al. 2017). In most decomposition-based models, methane generation estimates are largely sensitive to the selected k (decay constant) and L_o (methane generation potential) values (Aguilar-Virgen et al. 2014; Amini et al. 2013; Atabi et al. 2014; Bruce et al. 2017; Machado et al. 2009; Peer et al. 1993).

The FOD model LandGEM, one of the most commonly used models in North America, is selected in the present study. LandGEM is designed to output annual methane generation rates:

$$Q_{\text{CH}_4} = \sum_{i=1}^n \sum_{j=0.1}^1 kL_o \frac{M_i}{10} e^{-kt_{ij}} \quad (1)$$

where Q_{CH_4} = CH_4 generation rate (m^3/year), $i = 1$ year time increment, n = (year of calculation) – (initial year of waste acceptance), $j = 0.1$ year time increment, k = decay rate (year^{-1}), L_o = potential methane generation capacity (m^3/Mg), M_i = mass of waste accepted in the i th year (Mg), t_{ij} = age of the j th section of waste mass M_i accepted in the i th year (decimal years).

Amini et al. (2012) used composition data for five landfills in Florida in order to test four different

approaches to k and L_o calculations and found that the LandGEM defaults produced reliable results ($R^2 = 0.89$, compared to the highest 0.93), although this was likely due to Florida's temperate climate fitting the default value well. Table 1 summarizes the results of other recent studies reporting k and L_o values for warm and cold climate landfills. Warm climates have consistently higher k values, partly due to the studies being located near coastlines (Amini et al. 2012; Karanjekar et al. 2015; Machado et al. 2009) and cities with high precipitation rates (Tolaymat et al. 2010). Aguilar-Virgen et al. (2014) reported a relatively low k (0.0482 year^{-1}) given their warm climate, although this may be due to Ensenada's low precipitation rate (250 mm/year). Because Thompson's formula was based only on precipitation (Thompson et al. 2009), Quebec and Ontario's reported k values are comparable to those in warm climates. For instance, Quebec's mean annual precipitation (1070 mm) was highly relative to Alberta (445 mm) and Regina (390 mm). Derivations for k vary widely between the eight studies, either indicating the lack of a recognized optimal method or varying degrees of details in available data. Ishii and Furuichi's (2013) study was included to highlight the range in k and L_o for different organic MSW components used in the more complex IPCC model.

Default L_o values in LandGEM range between 96 and $170 \text{ m}^3/\text{Mg}$ of waste in Arid and conventional locations when the U.S. Clean Air Act estimates are required. However, the United States Environmental Protection Agency (USEPA) has identified the range of reasonable US landfill L_o values lies between 56.6 and $198.2 \text{ m}^3/\text{Mg}$ (U.S. EPA 1995). Table 1 shows that only Thompson et al. (2009) calculated L_o values near LandGEM's upper boundary or high default ($170 \text{ m}^3/\text{Mg}$), and three of the four warm climate L_o values were actually closer to the reasonable lower boundary ($56.6 \text{ m}^3/\text{Mg}$). Machado et al. (2009) recognized this opposes dominant trends in the literature, and suggested that samples from their site had oversaturated water content which countered the high organic content, as the IPCC formula for L_o uses wet weight basis. This is consistent with the high L_o value reported by Aguilar-Virgen et al. (2014), as their warm climate site experienced low annual precipitation. The IPCC formula uses organic waste composition on a wet weight basis, and half of the studies in Table 1 reported composition data as such (Ishii and Furuichi 2013; Karanjekar et al. 2015; Machado et al. 2009; Tolaymat et al. 2010). There may have been bias in modeling approaches as well. Some of

Table 1 *k* and *L*_o values determined for warm and cold climates

	Location	<i>k</i> (year ⁻¹)	<i>L</i> _o (m ³ /Mg)	Data span	<i>k</i> derived from	<i>L</i> _o derived from	Reference
Warm climate	Salvador, Brazil	0.2–0.21	65.9–67	2004–2006	FOD model, curve fitting with field data	Biochemical methane potential-related equations, IPCC formula using BF values for DOC _f , curve fitting with field data	Machado et al. 2009
	Louisville, USA	0.11 (bio.) ¹ 0.06 (conv.) ²	48.4–54.8	2002–2007	Modified LandGEM and samples	Biochemical methane potential measured in lab using 3 to 11-week-old samples	Tolaymat et al. 2010
	Florida, USA	0.04–0.13	56–77	3–16 years	Linear regression fitting	Waste composition records and component-specific <i>L</i> _o from lab in literature	Amini et al. 2012
	Ensenada, Mexico	0.0482	94.457	3 months	Waste audit used to weight component-specific <i>k</i> 's in MBM 2.0 model	Waste audit and IPCC formula using DOC _f formula dependent on anaerobic zone temperature	Aguilar-Virgen et al. 2014
	Victoria, Canada	0.08	n/a	n/a	Quote from source (Hartland Landfill)	n/a	Karanjekar et al. 2015
Cold climate	Alberta	0.023	100–178	2006	<i>k</i> formula with prec. ³ as independent variable, based on USEPA defaults	Provincial composition records and IPCC formula using different DOC _f defaults 0.77 (1996), 0.50 (2006)	Thompson et al. 2009
	Ontario	0.037	90–160				
	Quebec	0.042	128–220	2008–2014	Curve fitting with field data and RSS, with constant <i>L</i> _o s	Waste records, with LandGEM inventory default as upper boundary	Wang et al. 2013
	Regina	0.023	n/a				
	Wisconsin	0.07–0.15	100	2006–2010	FOD model (IPCC) fitting using multi-age field samples	Field samples at different ages decomposed in lab batch testing	Ishii and Furuichi 2013
	W City, Japan	0.05 (paper) ⁴ 0.062 (food) ⁴	214.4 (paper) ⁴ 126.7 (food) ⁴	1988–2010	<i>k</i> formula with prec. as independent variable, based on USEPA defaults	Provincial composition records and IPCC formula where DOC _f = 0.6	Environment Canada 2014
Regina	0.011	123	1990–2007				

¹ bio. denotes “bioreactor landfill cell”

² conv. denotes “conventional landfill cell”

³ prec. denotes “precipitation”

⁴ IPCC model parameters

the studies calculated *L*_o, and then used regression or curve fitting techniques to determine *k* (Amini et al. 2012; Machado et al. 2009; Tolaymat et al. 2010). Tolaymat et al. (2010) observed higher *k* estimates when low *L*_o values were used.

Climate influences on LFG

LFG generation is dependent on waste organic content, moisture and bacteria content, temperature, nutrients,

pH, type and quantity of daily and final cover, waste density, and waste age (Ishii and Furuichi 2013; Karanjekar et al. 2015; Machado et al. 2009; Opseth 1998; Peer et al. 1993). Meanwhile, LFG emissions are dependent on generation, gas well design, cover type and thickness, moisture, ambient temperature and pressure, and operating factors such as effective extraction rates and compaction density (Borjesson and Svensson 1997; Christophersen et al. 2001; Klusman and Dick 2000; Sanchez 2016). Recent cold climate LFG

literature has been focused on cover soils and oxidation mechanisms to mitigate methane emissions (Borjesson and Svensson 1997; Chanton and Liptay 2000; Christophersen et al. 2001; Klusman and Dick 2000; Maurice and Lagerkvist 2003). Given the field evidence of seasonal variation in LFG emissions (Klusman and Dick 2000), it is reasonable to expect that seasonal variations in LFG generation may exist in cold and arid climates where key LFG generation factors are limited.

Waste moisture content is directly related to LFG generation, and thus collection. Some studies have proposed or supported linear relations between moisture content and the decay rate k in FOD models (Environment Canada 2014; McDougall and Pyrah 1999; Thompson et al. 2009). Aside from moisture in the waste at disposal, precipitation is the main source of moisture input for landfills. However, in cold climates, infiltration is often impeded during the winter season. Frozen soil can be subject to ice formation in the pores near the surface, or else develop a thin ice layer at the surface, leading to increased runoff in spring (Arnalds 2015; Iwata 2011; Orradottir 2002). In addition, climates with deep frost lines will inhibit decay rates in waste cells closest to the surface. Thus, landfills in cold, dry climates can expect lower LFG production rates due to the combined effect of low annual precipitation, little to no infiltration during the winter, and inhibited decay in shallow cells. In addition, operating difficulties such as frozen wellheads and condensate issues are more common for landfills located in cold climates.

While some semi-arid and cold climate LFG studies have focused on field sampling for quantity (Klusman and Dick 2000; Maurice and Lagerkvist 2003; Opseth 1998), and composition (Opseth 1998), this study utilizes FOD gas modeling with real-time LFG data from a semi-arid, cold climate landfill recorded between August 2008 and December 2014. No LFG literature could be found which applies and integrates sub-annual temporal variations into FOD models. An ideal starting point is thus to compare seasonal k values to defaults and annual k values for landfills in cold climates.

COR landfill

The data used in this study were collected and processed from the City of Regina (COR). The COR landfill opened in the first quarter of 1961, and phase 1 was closed in 2011. For this study, the opening date was assumed to be January 1, 1961. The LFG collection and

flaring system was operational as of July 2008. The LFG well field consists of 27 wells at approximately 15 m depth, and covers approximately 16 ha on the north side of phase 1, a 43-ha site (Fig. 1). The final cover was constructed in 2007, and composed of 1 m of clay beneath 0.15 m of vegetated topsoil. Cells south of the well field remained uncovered until cell closure in 2011. The waste mass elevation ranges from 600 m at the base to 658 m at the summit (Conestoga-Rovers and Associates 2008). Average daily flow rates for the entire system ranged between 12,380 and 15,130 m³/day. Average methane (48%) and carbon dioxide (40%) during the study period were at the lower end of the ranges reported in literature (45–60% and 40–60%, respectively). This is likely due to atmospheric intrusion, the young age of the landfill, and that the study period included both semi-open and closed years.

Objectives

The collected gas data in this study were available in daily values (recorded per minute from 2008 to 2014), thereby enabling a study for seasonal variance in LFG generation and collection. By using the shorter time frame in each data point, the effects of temporal variability in LFG production became more significant. LandGEM is a common model used in LFG generation studies (Amini et al. 2012; Amini et al. 2013; Atabi et al. 2014; Bruce et al. 2017; Scharff and Jacobs 2006; Thompson et al. 2009), and is also widely used by engineers in North America. LandGEM was modified to output daily terms using linear interpolation, and to use different k values for different seasons. The study objectives were to (i) examine the effects of pseudo-second order iterative methods for back calculating k and L_0 , and compare them to reported values in the cold climate literature, (ii) propose seasonal k values (k_{winter} and k_{summer}) for use in LandGEM in cold semi-arid climate, and (iii) demonstrate the benefits of using seasonal sets of collection constants in LandGEM.

Materials and methods

This study required compiling, sorting, and screening of 6-year LFG and waste disposal records, as well as climate data. Gas data were used to compare and optimize a modified form of LandGEM using daily values and climate data-derived seasonal sets. Three different

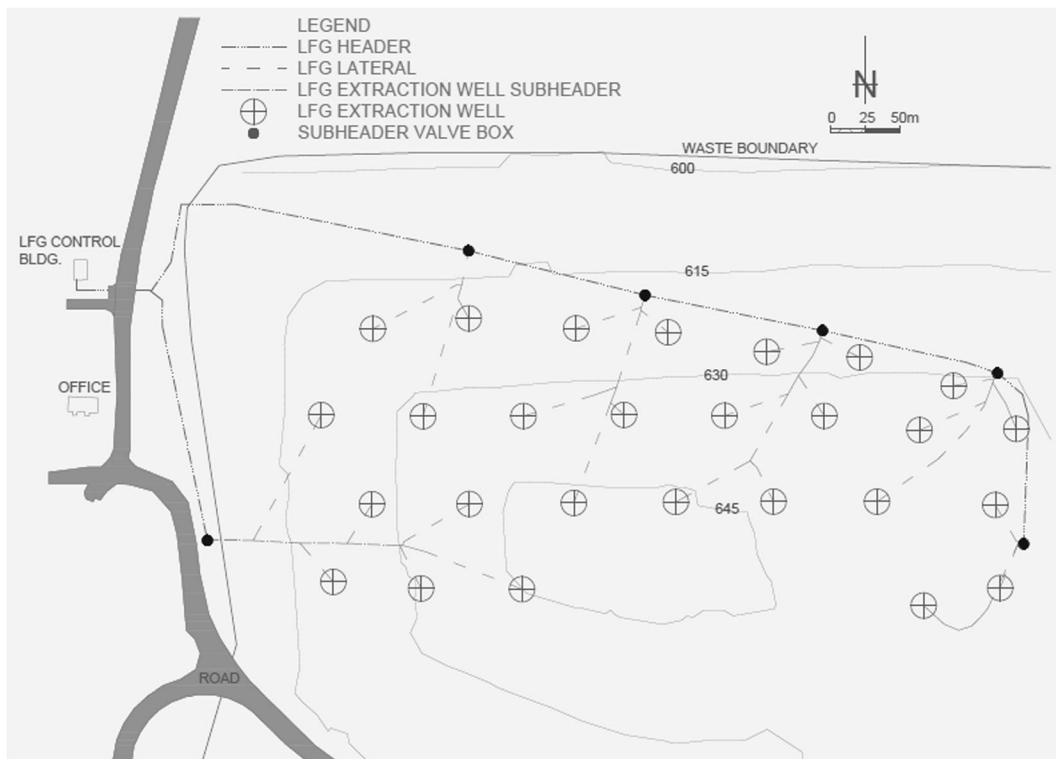


Fig. 1 LFG well field at the Regina Landfill (adapted from Conestoga-Rovers and Associates 2008)

pseudo-second order iterative methods were used for determining the site specific k and L_o values for COR.

Data input

The COR currently uses real-time measurement systems that record methane, carbon dioxide, oxygen (all by % volume), and total gas flow. Gas composition is measured by Hitech sensors, which use the dual wavelength infrared technique for measuring methane and carbon dioxide. Gas flow is measured using a mass-compensated Rosemount MassProBar flow meter. The real-time data set was consolidated into 2198 daily points. Data screening was carefully performed to prevent false data points from systematically altering the optimal k and L_o values, and the resulting residual sum of squares (RSS). These false data likely originated from the scheduled sampling and maintenance work performed by the landfill crew and system shutdowns. About 8.6% of the raw data set was removed when more than five readings in a day recorded negative methane and/or carbon dioxide concentrations. For example, removed methane concentration data points ranged from -100.0 to 26.8%. Excluding 2008 data, 8.2% of

unavailable or screened days were in winter, and 4.4% were in summer. To compare the results with other studies, collection efficiencies were applied to the data in order to estimate gas generation. To account for the open cells south of the well field and the final cover over the well field at Regina site, 70% efficiency was used for 2009–2011, and 80% for 2012–2014 (Bruce et al. 2017; Vu et al. 2017).

Waste mass data were compiled and processed from landfill disposal records from 1996 to 2011, a report by Reid Crowther and Partners Ltd. (1995) from 1980 to 1994, and an assumed waste disposal rate of 2.5 kg per capita together with census population data from 1961 to 1979 (Dominion Bureau of Statistics 2015). The data used were consistent with a previous study by Opseth (1998), and more recent publications (Bruce et al. 2017; Vu et al. 2017). Opseth’s estimate for total waste in place by 1997 was 6.5–7.0 Mtonnes. The data used in this study up to 1997 (6.2 Mtonnes before the 38% scale was applied) were about 4.2% different compared to Opseth’s lower estimate. The discrepancy may be explained by (i) Opseth including construction and demolition waste for all years, although stockpiling of such waste began in 1992; and (ii) Opseth’s estimates for

1961 to 1980 were based on the difference between the total estimates and known data. All raw annual mass data provided were scaled down to match the representative area covered by the well field (approximately 38%, Fig. 1), yielding a total waste mass of 3.1 Mtonnes; the respective upper and lower boundaries differed by 5.9 and 6.3% of this value (3.3 and 2.9 Mtonnes, respectively).

Seasonal sets using climate trends

Regina's cold, semi-arid climate results in low moisture infiltration into the landfill, limiting the infiltration to summer months. The cold, dry winters are thus more likely to experience insufficient moisture content to support high activity for methanogenic microbes. As per the COR development standards manual (City of Regina 2010), the effective frost depth in Regina is about 2.7 m, thus shallow cells will have inhibited LFG generation. In addition, more downtimes of the gas collection system are encountered with longer periods of sub-zero temperatures. All climate data were taken from Environment Canada's climate data archives (The Weather Network 2015). Both temperature and precipitation data trends were used in order to determine appropriate boundaries between winter and summer conditions such that the daily data could be separated into subsets for modeling. Six-month winter conditions (Maurice and Lagerkvist 2003) and 5-month winter conditions were used in the present study. Given the well field size, well depths and extraction rates, the storage lag of the LFG was assumed to be the minimum.

Ambient temperature data (Fig. 2) were used to generate two seasonal sets. The first set was denoted "5-month winter," with the subset "winter 1" using data from the 5-month span where the average temperature

was below 0 °C. Its corresponding summer period, denoted "summer 1," uses data from the remaining 7 months. The second set uses equal-length periods between the subsets, and is denoted as "6-month temp. winter." The periods and number of data points for the four seasonal sets of data are summarized in Table 2.

Precipitation data were also used to generate two seasonal sets because moisture, and thus precipitation, is the dominant factor in landfill gas generation (Albanna et al. 2007; Environment Canada 2014; Maurice and Lagerkvist 1997; Thompson et al. 2009). Fan et al. (2006) noted that in Taiwan, autumn and winter are considered the dry seasons with respect to leachate production. Thus for seasonal set "6-month prec. winter," subset "winter 3" is set between October and March because less rain and snow fall in October than in April in Regina. In order to test whether winter- and summer-based seasonal sets led to more accurate results, an opposing set was developed. The "prec. control" set, with subsets denoted "fall 4" and "spring 4," were chosen on opposing sides of the average peak rainfall month (June, Fig. 2).

LandGEM modification

This study covers 6 years of LFG collection operations, similar to the coverage in other LFG studies (Bruce et al. 2017; Machado et al. 2009; Tolaymat et al. 2010; Vu et al. 2017). Other landfill trace gases are assumed to be insignificant compared to total LFG. LandGEM's annual methane generation rates were converted into daily data points using linear interpolation to compare to the consolidated daily data records. This model assumes LandGEM's quoted annual flow occurs on December 31, similar to the triangle method (Kumar et al. 2004), wherein LFG generation continually increases to the

Fig. 2 Average monthly precipitation and temperature in Regina, 1984–2014

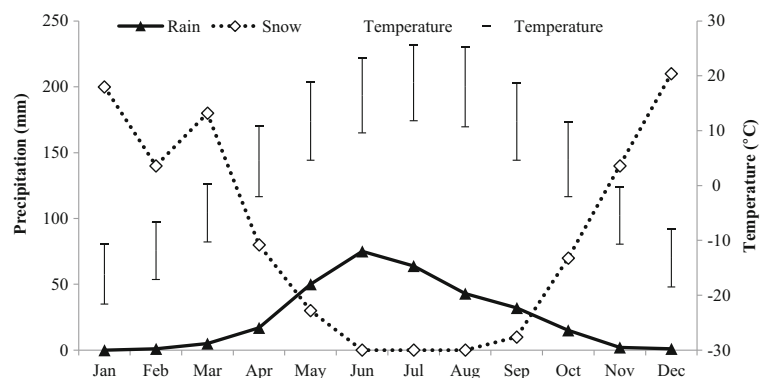


Table 2 Seasonal sets used in modified LandGEM modeling

Seasonal set	Subsets	Period starts	Period ends	Data points
5-month winter	Winter 1	November 1	March 31	745
	Summer 1	April 1	October 31	1264
6-month temp. winter	Winter 2	October 16	April 15	931
	Summer 2	April 16	October 15	1078
6-month prec. winter	Winter 3	October 1	March 31	942
	Summer 3	April 1	September 30	1067
Prec. control	Fall 4	July 1	December 31	1017
	Spring 4	January 1	June 30	992
Full set	n/a	January 1	December 31	2009

lifetime peak, then continually decreases. One benefit of this method is that flow rates are continuous at the start and end of the year, as opposed to the discontinuity which would result from applying average values each year.

Iterative method and initial values

Pseudo-second order iterative method is used in the optimization of the LandGEM parameters. The variable optimization process repeats until approximate errors are lower than 0.5% for all variables. Three pseudo-second order methods were used for each subset in this study (Fig. 3) by minimizing RSS between the modeled and collected data. Excel’s Solver function was used to minimize the RSS between the data sets. Methods and values are then evaluated relative to each other.

The initial *k* value was set to the USEPA default 0.020 year⁻¹ for arid landfills, which was also close to the value (0.023 year⁻¹) using the formula reported by Thompson et al. (2009). Based on the range of values in Table 1, a conservative initial value (100 m³/Mg) was selected for *L*_o. Historical waste records suggested waste composition in the COR was similar to national averages and other midsized Canadian cities.

Results and discussion

The five data sets are compared using resulting RSS, unless optimized *k* and *L*_o values deviated significantly from other published studies. The average methane content for the screened data set during the study period was 48%. The model results for the default *k* and *L*_o terms were not included in any graphs because their mean percent error was 32.2%, consistently overestimating the actual COR data throughout the study. For example, the model outputs 3,224,000 m³/year using LandGEM defaults in 2010, while the actual data totals 2,505,000 m³/year (28.7% higher than field data). As such, the range of USEPA default values is found not applicable for Regina’s landfill. It is hypothesized that the discrepancy is partly due to the differences in climatic condition between US landfills and the COR landfill.

Comparing pseudo-second order iterative methods

Change k and L_o

A few consistent observations occur across all the data sets (Table 3). The first is that the *k* and *L*_o results from

Fig. 3 Pseudo-second order iterative Solver methods

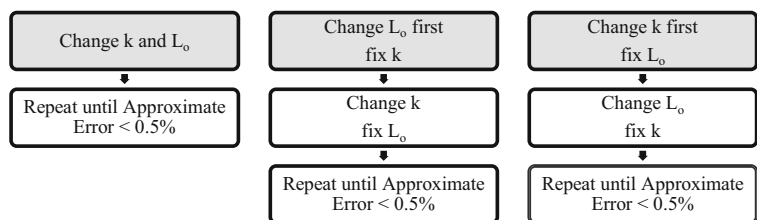


Table 3 Optimal k and L_o from minimizing RSS using the Excel Solver

Seasonal set	Sub set	Change k and L_o			Change L_o first			Change k first		
		k (year ⁻¹)	L_o (m ³ /Mg)	RSS	k (year ⁻¹)	L_o (m ³ /Mg)	RSS	k (year ⁻¹)	L_o (m ³ /Mg)	RSS
5-month winter	Winter 1	0.0068	154.0	1717	0.0200	70.4	1720	0.0118	100.0	1717
	Summer 1	0.0852	53.7	1432	0.0201	79.7	1528	0.0141		1555
	Average	0.0460	103.8	1574	0.0200	75.1	1624	0.0129		1636
6-month temp. winter	Winter 2	0.0118	101.3	2039	0.0200	71.5	2040	0.0120		2039
	Summer 2	0.0709	53.9	1166	0.0201	80.2	1241	0.0142		1264
	Average	0.0414	77.6	1602	0.0200	75.9	1641	0.0131		1652
6-month prec. winter	Winter 3	0.0051	203.5	2307	0.0200	72.0	2313	0.0121		2308
	Summer 3	0.1142	54.7	851	0.0201	80.0	983	0.0142		1011
	Average	0.0596	129.1	1579	0.0201	76.0	1648	0.0131		1660
Prec. control	Fall 4	0.0402	58.3	1972	0.0201	79.0	1985	0.0138		1996
	Spring 4	0.1872	51.8	1285	0.0201	73.4	1409	0.0125		1432
	Average	0.1137	55.0	1629	0.0201	76.2	1697	0.0132		1714
Full set		0.0583	52.1	3421	0.0201	76.2	3478	0.0132		3507

the “change k and L_o ” iterative method are more suitable to landfills in warmer, wetter climates as reported in the literature. For example, the k_{summer} for summer 3 (0.1142 year⁻¹) is 3.8% higher than the Louisville bio-reactor value (0.11 year⁻¹) reported by Tolaymat et al. (2010). Summer 3’s corresponding L_o value (54.7 m³/Mg) is lower than the EPA’s expected boundary (56.6 m³/Mg) for US landfills. Given the similar cultural trends between the two countries, lower L_o values are unexpected. Furthermore, Bruce et al. (2017) reported a L_o range for Regina between 86.2 and 132.7, depending on assumed DOC_f. The findings are consistent with Amini et al. (2012), who noted a similar result using an approach which calculated k and L_o at the same time. One of the five landfills calculated a L_o value of 3844 m³/Mg, the second highest value being 175 m³/Mg using the same method. By comparison, Ishii and Furuichi (2013) measured L_o for different wastes and reported that paper has the highest L_o (214.4 m³/Mg in their study). Subsets summer 1 (53.7 m³/Mg), summer 2 (53.9 m³/Mg), and spring 4 (51.8 m³/Mg) each had L_o values drop below the EPA’s recommended boundary, although Karanjekar et al. (2015) observed even smaller L_o in 2 of their 27 laboratory reactors.

The balancing effect of k and L_o produced worse k and L_o estimates prior to applying gas collection efficiencies (data not shown). For example, winter 1 resulted in k (0.0006 year⁻¹) nine times lower than Karanjekar’s lowest reported value (0.0054 year⁻¹),

and a corresponding L_o value (1226 m³/Mg) five times higher than the EPA’s upper boundary for US landfills. The method is less reliable, and the resulting optimal values are thus considered invalid, in spite of this method consistently producing the lowest RSS values. The total RSS for this method ranged between 3149 for the 5-month winter set and 3421 for the full set (about 8.0% higher).

L_o first method

The L_o first method leads to reasonable k values compared to Thompson et al. (2009), although they did not deviate from the starting value by more than 0.4% in any subset. There is a lack of cold, semi-arid climate field and modeling studies to compare k values with; Thompson et al. (2009) and Environment Canada (2014) both use an empirical formula to determine k .

Unlike the “change k and L_o ” method, the L_o first method tended to calculate L_o values within the recommended range set by the USEPA. Tolaymat et al. (2010) calculated values below the recommended range, although they used waste sampling to determine L_o rather than numerical modeling. The range of calculated L_o values in other studies (Amini et al. 2012; Karanjekar et al. 2015; Tolaymat et al. 2010) were within 5 m³/Mg of the average L_o in this set, suggesting the USEPA’s recommended range is not reliable under certain conditions.

RSS for the “ L_o first method” tended to be lower than the “ k first method” (average 0.8% lower). However, L_o by definition is a function of the disposed waste mass composition, and thus will not change in a seasonal (or periodic) pattern, and tends instead to steadily decrease as the waste mass decomposes as shown by Ishii and Furuichi (2013). The results of the L_o first method are thus not applicable due to the method itself; additional steps and complexity are required to account for L_o 's theoretical basis, thus decreasing the method's ease of use.

The total RSS ranged from 3248 for the 5-month winter set to 3478 for the full set (about 6.6% higher). The results from changing L_o first are thus considered less reliable than the results of changing k first. L_o depends primarily on waste composition, which is not subject to change nearly as much as precipitation and weather conditions during the year.

k first method

The starting default values overestimated the methane generation, leading the first changed variable to scale down to approximate the recorded data. For the “ L_o first method,” L_o decreased by an average of 24.2%, while the “ k first method” decreased k by an average 34.5% from the starting value. The RSS range for the “ k first method” is less statistically significant, but more reasonable from a theoretical basis than the results of both other methods. In Table 3, all k_{winter} values are lower than their corresponding k_{summer} . On average, k_{winter} values were about 15.3% less than their counterparts. The k_{winter} values tend to be smaller than the full set's k values as well. This is probably due to (i) higher downtimes and lower collection efficiency during winter due to frozen wellheads and other condensate issues; (ii) reduced moisture infiltration during the winter, resulting in less LFG generation, and (iii) inhibited waste cells above the frost line during winter. The summer values (k_{summer}) were higher than the full set because they were not weighted down by low LFG output in winter months. Results suggest the use of seasonal values k_{winter} and k_{summer} may provide more accurate results by better representing the field conditions in cold, semi-arid climates.

None of the resulting k values from “ k first method” sets were close to estimates by Thompson et al. (2009) at about 0.023 year^{-1} based on the precipitation data alone. However, the values reported by Environment

Canada (2014) and Opseth (1998) were comparable ($0.006\text{--}0.011 \text{ year}^{-1}$). Other k values in Table 1 were from more temperate or wet climates, so it was expected that they would be higher than the results in the present study.

The optimal L_o values remained close to the starting default ($100 \text{ m}^3/\text{Mg}$) for all five sets, indicating the significant impact the first changed variable has on the second using this iterative method. L_o was selected as a conservative estimate from literature. The L_o from all five sets was comparable to Alberta ($100\text{--}178 \text{ m}^3/\text{Mg}$) and Ontario ($90\text{--}160 \text{ m}^3/\text{Mg}$) (Thompson et al. 2009), and within the range ($86.2\text{--}132.7 \text{ m}^3/\text{Mg}$) reported by Bruce et al. (2017) for the same landfill. The algorithm produced L_o values with at most 0.2% changes from the starting values. The results from changing k alone have been reported in Table 3 in order to represent the non-seasonal characteristic of L_o . RSS decreased minimally (at most 0.2) after the first step in all sets, meaning subsequent steps were useful only to ensure approximate errors were low and convergent.

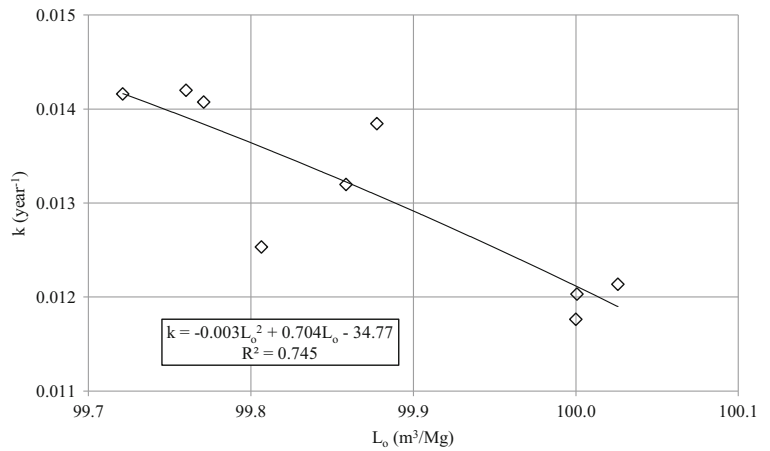
The optimized results for each seasonal subset and iterative method yield determined high k values paired with lower L_o values, and vice versa. This is consistent with the results in Tolaymat et al. (2010). Figure 4 shows the slightly negative second order polynomial relationship between optimized k and L_o for the COR landfill using k first method. Tolaymat et al. (2010) instead generated an inverse relationship between k and L_o for a larger range of L_o values ($25\text{--}100 \text{ m}^3/\text{Mg}$). The difference in observed ranges is due to using k first optimized values in Fig. 4, while Tolaymat et al. (2010) fit k values based on several different starting L_o values.

The values from “change k first” method stayed within ranges consistent with the literature for both k and L_o for all subsets. The range between the k first method's summer and winter k values has a greater theoretical basis than that of the other iterative methods. Preliminary results suggest that the k first method is the most appropriate, and is selected for further analysis.

Optimal seasonal set and k

The RSS results in Table 3 and Fig. 5 indicate that the winter periods were systematically responsible for more than half of the total RSS throughout the study. For comparison, using Environment Canada's (2014) calculated parameters and the LandGEM default parameters

Fig. 4 Relationship between optimized k and L_o using k first method



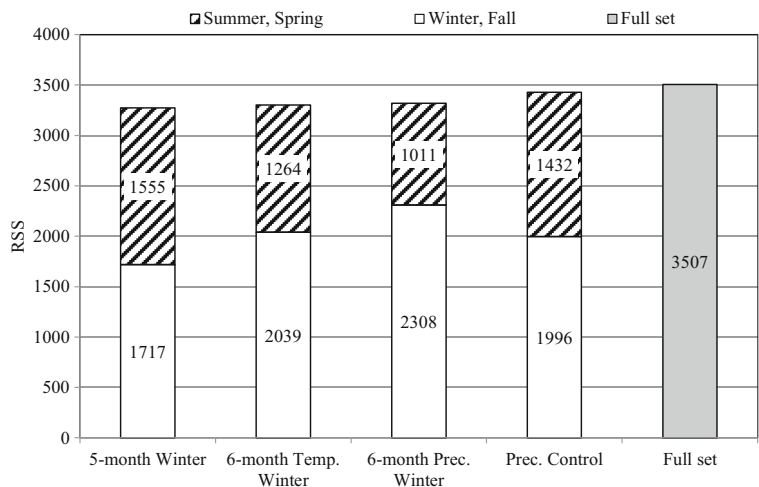
result in higher RSS values (3801 for Environment Canada values and 9070 for LandGEM default values).

For every optimized seasonal set and iteration method, the winter RSSs were greater than the summer RSSs. First, lingering low values in the data set remained, resulting in large residuals in common winter months such as November and December. For example, the summer 3 RSS from the “6-month prec. winter” set has the lowest subset RSS by 20% compared to second best (summer 2), yet it only has 1% fewer data points (Table 2), suggesting the significant effect that sub-standard operating methane flow rate data can have on seasonal subsets. Second, annual maintenance shut-downs and equipment freezing may have contributed to the gradual declines in LFG collection during certain winters. For instance, 8.4 m³/min of LFG was collected on November 23, 2009, which fell below 0.2 m³/min by November 26, and remained low throughout December.

The optimized “6-month prec. control” seasonal set RSS was 2.2% lower than the full set. This suggests that subdividing k regardless of seasonal precipitation trends still leads to minor increases in accuracy; however, it is possible that the winter data were more prone to abrupt drops in LFG flow rates, thus increasing RSS in both “prec. control” subsets. Operational reasons could include scheduled shut-downs, or freezing in the collection system as reported by Hettiarachchi et al. (2013). Time lags between LFG generation and collection may contribute to the uncertainties; however, direct evidences were not observed in the present study.

The seasonal sets defined by ambient temperature and precipitation were unable to support seasonal variation in LFG generation due to the data’s greater sensitivity to inhibited collection. Thus, this study’s seasonal k values are limited to seasonal “collection”

Fig. 5 Seasonal RSSs minimized using k first method



applications, as evidence for seasonal variations were limited primarily to operational factors affecting collection.

Ambient temperature effects on LFG generation were calculated separately, due to the lacking evidence of seasonal subset period biases, in the form of frost depth influences. An estimate for affected waste mass was calculated using available geometric data, an assumed density of 1 Mg/m³, and assumed 15% contribution of daily cover to waste mass. Approximately 3.7% of the waste mass lies above the frost line, and would not generate LFG during the 4–6 months of winter. Although this is a low proportion, the affected layers may require greater time to degrade, extending the post-closure monitoring period. Strong evidence for seasonal generation trends could be provided in future studies via field-measured temperature gradients, and moisture content sampling.

The results show that the sum of RSSs for each seasonal set is lower than the RSS for the full set. This suggests that methane estimates may have higher accuracy when seasonal collection *k* values are used. Using field data from a cold and semi-arid landfill, the optimal *k*_{winter} (0.0118 year⁻¹) and *k*_{summer} (0.0141 year⁻¹) are obtained with about 18% difference. The optimized “5-month winter” set results in the lowest total RSS value (6.7% lower than full set RSS).

By taking the sum of daily values for each year (Fig. 6) and comparing them to the recorded data, the average percent error for various sets was 8.3% for the optimized full set; 12.2% using Environment Canada inputs (Table 1); 32.2% using USEPA defaults; and 8.1% using the proposed 5-month winter. The low difference between optimized annual *k*'s and seasonal *k*'s is likely due to the screening of low flow data, which

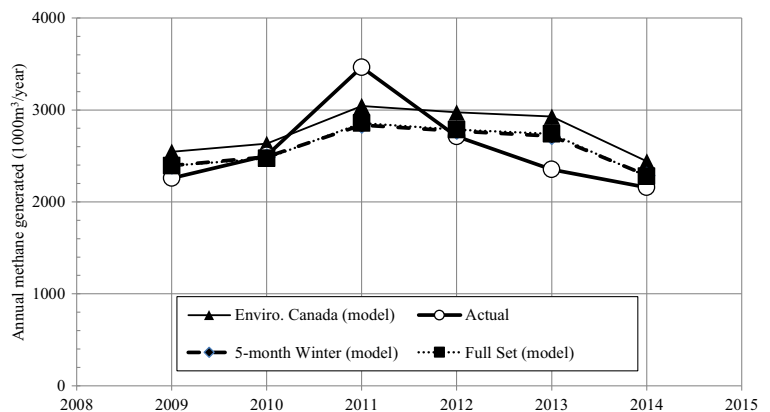
would have otherwise weighted the annual *k* estimate lower, thereby producing higher percentage error.

Sensitivity analysis was performed using different collection efficiency ranges in order to determine the effect of this commonly unmeasured variable on results. Using efficiencies of 70 and 80% resulted in 7.5% mean annual error for the full set and 7.6% for the 5-month winter, despite the usual trend of seasonal *k*'s producing lower RSS than the full set. Varying the starting *L*₀ value resulted in higher optimized *k*'s, but no significant difference on mean annual % error. In contrast, an assumed efficiency of 100%, limited to collection applications, yielded 15.5% error for the full set, and 7.3% for the 5-month winter. The varied results are likely due to the scaling of measured data, and the affected weighting of low flow data. Collection efficiencies thus have a significant effect on user results, and introduce issues for pre-design studies.

Application of seasonal *k* using LFGcost-Web

A simple application study was performed using the USEPA's LFGcost-Web 3.0 model to highlight the importance of using optimized sets compared to the suggested defaults for Regina. Optimal seasonal subset *k* and *L*₀ values were used in the model, and then weighted by the number of data points in each subset to determine the net present value for standard engine, small engine, microturbine, and compressed natural gas (CNG) projects. Other project types were not selected because the required LFG flow rates were too high for the Regina Landfill. For example, cost estimates for standard turbines (larger output than microturbines) required greater than 3 MW. Even at maximum LFG flow rates and a *k* of 0.06 year⁻¹, the Regina Landfill would output a

Fig. 6 Annual methane generated in COR using various sets



maximum of only 1.1 MW. The selected input parameters included 28 acre (11 ha) well field, average gas output, 48% methane content, no collection and flaring costs (assumed the existing network will be used), project start-up in 2017, and local government-owned project financing as outlined in the user manual (U.S. EPA 2014). A collection efficiency of 70% was used for this section, rather than the 80% value based on final cover conditions, due to the system operating 87.5% of the days between years 2009 and 2014. The net present value was overestimated between 10 and 124% (excludes small engine project) when the traditional cover-based collection efficiency (80%) was applied.

The default LFG inputs overestimated the net present value compared to the optimized sets for the standard engine (12%), microturbine (155%), and CNG projects (61%). Differences between the optimized sets, both full and seasonal, were negligible. For example, the 5-month winter and prec. control sets yielded negative net present values of \$0.1165 and \$0.1166 M, respectively, for the microturbine project, while the default set had a positive worth of \$63,500 (51.3 and 51.2% different, respectively). The two seasonal sets differed with the full set's net present value (\$0.791 M) by 0.3 and 0.6%, respectively. The higher precision produced by seasonal k 's are thus impractical to economic pre-design due to the limitations of LFGcost-Web. The default set underestimated the net present value for the small engine project (average 24%). This may have been due to an expected capacity range used in LFGcost-Web, as over supplying LFG to the engine that may have necessitated project expansions or increased maintenance. It is good practice for municipal planners to accurately estimate project costs over project lifetimes. In the case of three out of four LFG energy project alternatives, using default LFG values in LandGEM and LFGcost-Web would lead to significantly overestimated (10–124%) net present values, assuming the planners are aware of the extra downtime in winters in assessing possible projects.

Conclusions

LFG production and emission mitigation technologies require improvements in estimation and measurement techniques. Modeling is an important tool for understanding and estimating LFG production, collection, and emissions, and so increasing evaluation for various models is important. This study concluded that:

- Default LandGEM values for k and L_o were invalid for the Regina Landfill, located in a cold, semi-arid climate. The predicted methane generation was overestimated during the study period (average 32.2% error).
- The L_o first method's contradictory theoretical basis for seasonal L_o could mislead modelers, and thus are not recommended. Changing k and L_o at the same time resulted in k and L_o values inconsistent with the study climate, in addition to seasonal L_o . The most reliable method for optimizing LFG constants at Regina Landfill was the k first iterative method, determined via process of elimination.
- By summing daily data to determine annual methane generation values, the optimal seasonal set had just 8.1% error with the data compiled from available records, compared to 8.3% error with the optimized full set. Thus the use of seasonal k 's had negligible improvement over traditional curve fitting. Despite the insignificant improvement to annual estimates, using separate seasonal collection k_{winter} and k_{summer} increased the sub-annual accuracy (in terms of RSS) of LandGEM by 2.2 to 6.7%.
- From the real-time gas data, the optimal k_{winter} was 0.0118 year⁻¹, and k_{summer} was 0.0141 year⁻¹ at the Regina Landfill. 8.2% of screened or unavailable data between 2009 and 2014 were within the winter periods, compared to 4.4% in summer. The values were consistent with the other modeling studies using precipitation data alone.
- Optimized LFG constants using annual and seasonal sets produced insignificant differences between net present value estimates in LFGcost-Web 3.0 for four small LFG energy projects.

Acknowledgements Special acknowledgment goes to the team at Solid Waste Department, who supported the data collection. The views expressed herein are those of the writers and not necessarily those of our research and funding partners.

Funding information The research reported in this paper was supported by a grant (RGPIN-385815) from the Natural Sciences and Engineering Research Council of Canada.

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