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Lateral migration and offsite surface emission of landfill gas at City of Montreal landfill site

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An evaluation of lateral landfill gas migration was carried out at the Saint-Michel Environmental Complex in Montreal, City of Montreal Landfill Site, Canada, between 2003 and 2005. Biogas concentration measurements and gas-pumping tests were conducted in multilevel wells installed in the backfilled overburden beside the landfill site. A migration event recorded in autumn 2004 during the maintenance shutdown of the extraction system was simulated using TOUGH-LGM software. Eleven high-density instantaneous surface monitoring (ISM) surveys of methane were conducted on the test site. Gas fluxes were calculated by geostatistical analyses of ISM data correlated to dynamic flux chamber measurements. Variograms using normal transformed data showed good structure, and kriged estimates were much better than inverse distance weighting, due to highly skewed data. Measurement-based estimates of yearly off-site surface emissions were two orders of magnitude higher than modelled advective lateral methane flux. Nucleodensimeter measurements of the porosity were abnormally high, indicating that the backfill was poorly compacted. Kriged porosity maps correlated well with emission maps and areas with vegetation damage. Pumping tests analysis revealed that vertical permeability was higher than radial permeability. All results suggest that most of the lateral migration and consequent emissions to the atmosphere were due to the existence of preferential flow paths through macropores. In December 2006, two passively vented trenches were constructed on the test site. They were successful in countering lateral migration.

Keywords: Lateral migration, biogas, methane emission, landfill, advection, macropores, wmr 1208–2

Introduction

Lateral migration review

Biogas is a mixture of methane (CH_4), carbon dioxide (CO_2) and other trace volatile organic compounds (VOC). It is produced by anaerobic decomposition of organic matter contained in the waste. Atmospheric concentrations of CH_4, a radiatively active trace gas, have increased steadily for several hundred years (Cicerone & Oremland 1988). Even if atmospheric CH_4 concentrations are not comparable with those of CO_2, the greenhouse reference gas, CH_4 still contributes significantly to climate change because its global warming potential (GWP) is 23 times higher than CO_2 over a period of 100 years (IPCC 2001). In addition to its climate change impacts, landfill operators are also concerned about the public health impacts of landfill CH_4. Populations exposed to landfill gas (LFG) run a number of health risks. CH_4 accumulated in enclosed spaces has caused significant property damage and loss of life (Drouin 1995), because the gas is explosive when concentrations in air range from 5 to 15%. Such risks

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can occur when LFG migrates laterally through neighboring soils or rock pores and infiltrates into buildings or underground structures.

Designing of landfills to control LFG surface emissions and lateral migration is a recent development. Capped landfills significantly reduce surface emissions but can pose greater risks for lateral migration if unvented. In 1983, a house adjacent to Loscoe Landfill in Derbyshire (UK) was destroyed by a LFG explosion due to lateral migration shortly after capping (Williams & Aitkenhead 1991). Saturated and frozen landfill surfaces also confine laterally migrating LGF in the same way as low permeability covers. Lateral migration was observed at a greater distance in winter than in summer due to a confining frozen surface at Ottawa Street Landfill in Kitchener, Canada (Metcalfe & Farquhar 1987). High sub-surface CH_4 concentrations due to lateral migration have been associated with high surface soil moisture content as well (Christophersen & Kjeldsen 2001).

Surface capping and LFG extraction do not completely control lateral migration. Without a lateral liner, lateral migration can still occur when an extraction system is shut down for maintenance, as a result of a power failure or conduit breech. A voluntary shutdown of the LFG migration control system at the Mississauga Landfill (Canada) allowed McOmber *et al.* (1982) to verify that advective lateral migration was occurring at this site. The LFG migration control system was installed after explosive concentrations of LFG were measured in a house next to the landfill.

Confirmation that lateral LFG migration processes were predominantly mediated by advective transport was made at the Foxhall Landfill, in Suffolk (UK) when remediation of a LFG plume was achieved after only 1 year of gas extraction (Williams *et al.* 1999). Atmospheric pressure variations can play an important role in lateral LFG migration by increasing the pressure gradients that drive gas movement. Atmospheric pressure drops in addition to saturated surface conditions explained the migration event that caused an explosion at Skellingsted Landfill in Western Sealand, Denmark (Kjeldsen & Fischer 1995).

Objectives

Because lateral migration can have serious public safety and global climate impacts, an investigation was undertaken at one study site to quantify the extent of lateral LFG migration that was occurring at the test site and to gain insight into the transport mechanisms. The study was also used to assess a surface emission evaluation method developed by Fécil *et al.* (2003). The ultimate aim of the study was to find the best solution to control LFG lateral migration occurring in this sector.

Experimental site

The Saint-Michel Environmental Complex (CESM), the City of Montreal Landfill site, is located in a densely populated residential area in Montreal. The site was a limestone quarry from 1895 to 1987, and landfilling began there in 1968. The City of Montreal acquired the site in 1984 and took control of its operation in 1988. An estimated 38 million metric tons (t) of domestic and commercial solid waste have been disposed of at the CESM.

Since 1988, the city has massively invested in LFG extraction and monitoring. A total of 361 extraction wells, 48 manual observation wells and 42 automated observation wells are used on a regular basis. As of 2000, only dry waste materials, such as demolition waste, commercial waste or lightly contaminated soil are accepted for use in shaping the landfill into a 192 ha urban park. Initially flared, the recovered LFG has fuelled an on-site power plant since 1996, and LFG production declined after the 2000 shift to dry waste. In 2005, some 27 Mt of CH_4 were destroyed. Fécil *et al.* 2003 estimated that 98% of produced LFG was collected.

The specific test site for this study is located beside the landfill site along the north-east border of the landfilling area (Figure 1). As it has been known to be subject to lateral migration, it has been instrumented to monitor this phenomenon. Three monitoring wells were installed before the City took control in 1988. Between 1988 and 1992, the City installed 19 deep wells to monitor the fractured bedrock and 12 shallow wells to monitor the porous overburden. The 9 m layer of overburden is actually a backfill composed mostly of silt and a small fraction of dry waste. Originally created to hide the site, this narrow stretch of land was transformed into a walkway and offers local residents a nice view of the waste disposal operation.

In summer 2003, a complete survey of surface CH_4 concentrations along the 4 km north-east boundary, where the overburden is potentially in contact with the waste, confirmed the critical nature of the 120 m long contact that would become the test site. Damage to vegetation such as dead or dying trees and grass indicated that intensive lateral LFG migration was occurring. Furthermore, the distance between the waste and the nearest adjacent buildings is only 65 m.

Materials and methods

The present study attempted to compare two different approaches in evaluating lateral migration of LFG. A numerical model, based on field measurements in wells and permeability determined by pumping tests was compared with a field evaluation of surface emissions from the gas plume. Using the correlation between CH_4 concentration and flux, georeferenced surface sampling was statistically treated to evaluate the total CH_4 flux. The site's surface porosity was described using density tests which were useful for the numerical model and for the interpretation of measured surface emissions.

Wells and probes

In autumn 2003, five nests of shallow gas probes, identified as PSPG (Figure 1), were built using an AMS vapor probe kit (AMS Inc., American Falls, Idaho, USA) and the recommended 6-mm-diameter Teflon tubing. A 40-mm-diameter

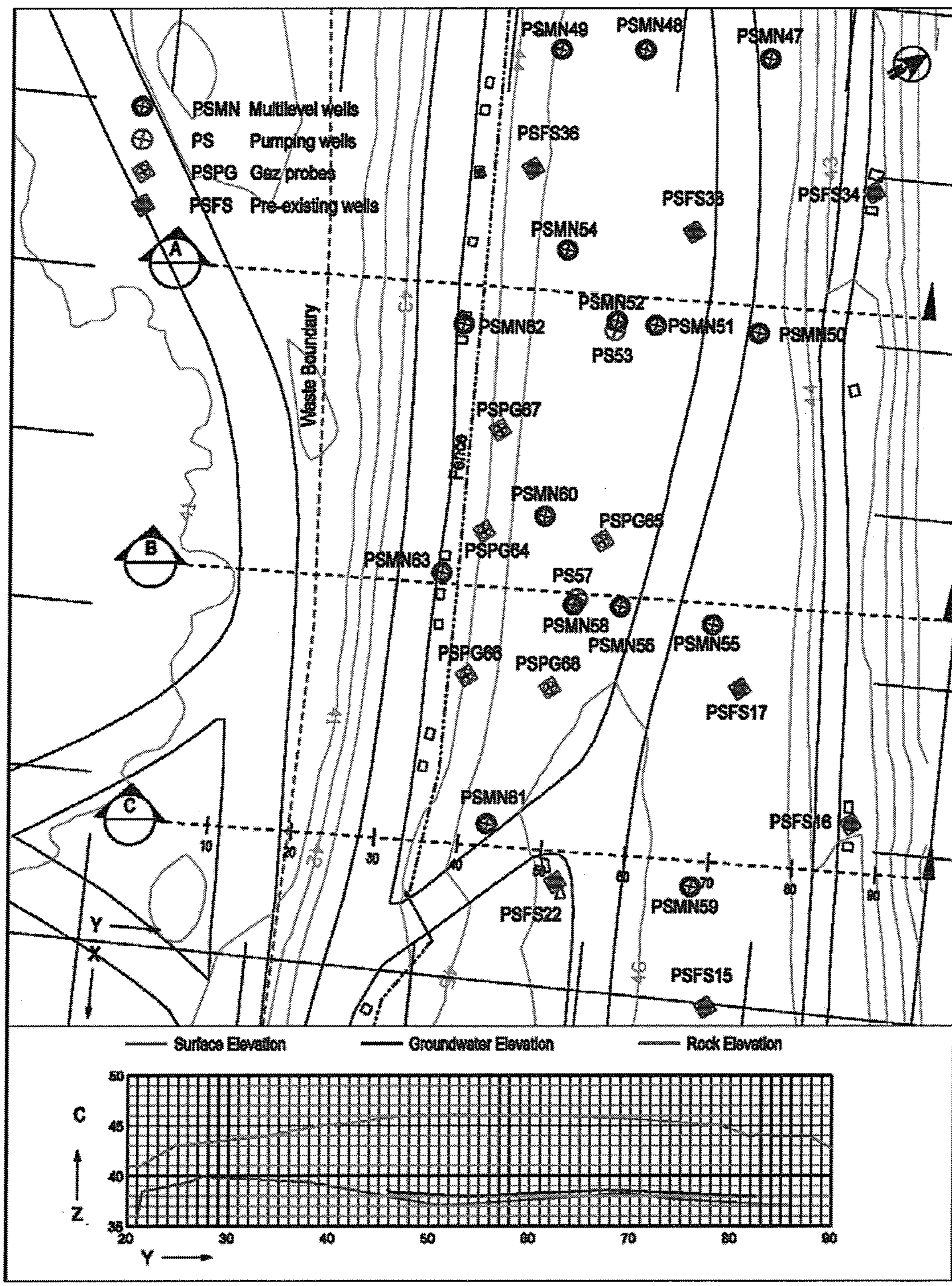

Fig. 1: Layout of experimental site.

auger fitted with a carbide tip was mounted on a hammer drill (Bosch) to create holes for installing the probes. Due to difficulties penetrating the surface, preholes varying from 0.4 to 0.8 m deep and approximately 1.0 m wide by 1.5 m long were dug using a small backhoe. The backfill was hand-mixed with bentonite powder to eliminate preferential flow paths due to excavation. A single probe was placed in each hole. Shallow vapour probes were installed in the adjacent undisturbed soil. Each nest comprised three to four probes with depths ranging from 0.10 to 1.85 m.

In December 2003, 15 multilevel wells, identified as PSMN (Figure 1), were installed with three to four monitoring depths. The multilevel probe tubing was attached to 25 mm diameter polyvinyl chloride pipes. The different monitoring levels were filled with silica sand (Temisca #1) and isolated using granulated bentonite (Enviroplug). Sand and bentonite intervals both varied from 0.4 to 0.5 m in thickness. Premoulded cement blocks and protective metal casings were installed on top of each well and gas probe nest. Ball valves were installed on all pipes and tubings.

The thickness of the unsaturated porous media was determined by surveying the groundwater depth using a manual water level meter tape (Solinst, Georgetown, Ontario, Canada). CH_4 and CO_2 concentrations were measured using portable infrared multi-gas instruments (Eagle; RKI Instruments, Hayward, California, U.S.) with detection limits of 0.025% for CH_4 and CO_2 and precision of 3 and 2.5% of measured volume fraction, respectively. Initially, the probe's filter pack pore space was completely purged with the portable analyser (5 min at 780 mL min^{-1}). Later the sampling time was reduces to 2 min, since the measurements always stabilized within less than 1 min. Furthermore, the influence of pumping on adjacent levels in the multilevel wells was a concern.

As the measurements in probes less than 0.4 m deep were confounded by the entrance of atmospheric air, sampling at shallow depths was conducted with a peristaltic pump at a rate of 10 cm^3 s^{-1} into a 300 cm^3 bag (Tedlar) fitted with a valve and septum. For these shallow probes, the sample included the 75 mL of gas left in the probe tubing and in the filter pack pore space. Repeatability and reduced atmospheric air contamination were achieved by tolerating some probe gas residue. Gas chromatography using thermal conductivity detection (GCTCD) was used to determine CH_4 to CO_2 ratios in the shallow probe samples. Wind, atmospheric pressure and precipitation data were collected at the on-site meteorological station located less than 500 m from the test site.

A flame ionization detector (FID) (TVA 1000; Thermo Electron Corporation) used for instantaneous surface monitoring (ISM) surveys had a detection limit of 1 volumetric part per million (ppmv) of CH_4. The maximum error of the FID was 16% for measures with the three-point gas calibration used (Fécil 2003). A global position system (GPS) (Garmont 17N) antenna receiving signals from a minimum of six satellites was used for positioning.

The soil density measurements were conducted with a Troxler 501DR nucleodensimeter with a 0.3 m rod. A survey grade GPS was used for these surveys and for topography. The Leica SR530's precision was better than 1 cm.

Measurement of gas permeability of soils

Gas pumping tests to measure the gas permeability of soils were conducted by Richard Martel and Luc Trépanier (Institut National de Recherche Scientifique, Quebec City, Canada) in summer 2005 with the equipment and procedures described by Martel *et al.* (2004a, b).The well distribution was designed to cover most of the assumed LFG plume. Thus, two sets of four multilevel wells were placed at radial distances of 1, 5, 10 and 15 m from the two single-level pumping wells, identified as PS-53 and PS-57 in Figure 1. Both pumping wells were screened from 2.5 to 4 m, the borehole bottom.

Methane surface emission measurements

Although chambers have been widely used to report flux measurements, the quality of such data has been questioned. Flux chamber measurements are very time consuming and give results for a single point in a survey area. To estimate total methane flux over a surface many measurements are required. For a flux chamber data distribution that is negligibly skewed, Livingston & Hutchinson (1995) suggest more than 30 samples are needed to obtain unbiased descriptive statistics based on the arithmetic mean. Furthermore, missing a few large sources can very significantly affect the estimate of total flux (Borjesson *et al.* 2000). It is also recommended that field flux chamber campaigns do not exceed 1 or 2 days due to possible variations in barometric pressure (Bogner *et al.* 1997a), and of course other meteorological conditions that influence emission measurements and emission rates, such as rain and wind, can also change quickly and confound results.

Methane concentrations on emitting surfaces are strongly correlated to CH_4 flux consequently instantaneous surface monitoring (ISM) of CH_4, as described by (Cooper *et al.*, 1997), can be used as a surrogate measurement for flux therefore making an adequate sampling possible. The use of ISM correlated with dynamic flux chamber measurements has already been demonstrated for the City of Montreal Landfill site, where 150 flux and concentration measures were correlated (Figure 2a) (Fécil *et al.* 2003). The authors found that the correlations were valid when wind speeds were lower than 16 km h^{-1}, as suggested for ISM (Cooper *et al.* 1997).

In this study, wind conditions were restricted to 12 km h^{-1}, and a funnel with a GPS antenna was added to the FID nozzle to reduce wind effect and increase position precision for geostatistical analysis. The funnel holding the FID nozzle was waved in the air before each measurement to remove gas from the previous measurement. The displayed CH_4 concentrations were then allowed to stabilize to the background levels. The funnel was slowly placed on the surface, and the FID was triggered simultaneously. The FID was set to record values 5 s after triggering. As the concentration in the funnel may increase with time at higher fluxes, surveys were executed rigorously to avoid this source of error. Since the test site was relatively small, eleven high-density samplings of 500–1400 measurements (typically 550) were taken for each survey on the 5400 m^2 surface. On average, a survey took one individual 2.5 h.

A comparative study between this method and the method developed by Fécil *et al.* (2003) showed no significant difference under prescribed conditions (Figure 2b). At each location, measurements were repeated from six to 10 times. The observed variations between the two methods (represented by the error bars in Figure 2b), were very similar. It is important to note that this method is not as precise for detecting emission at low levels, where correlation is not as good as it

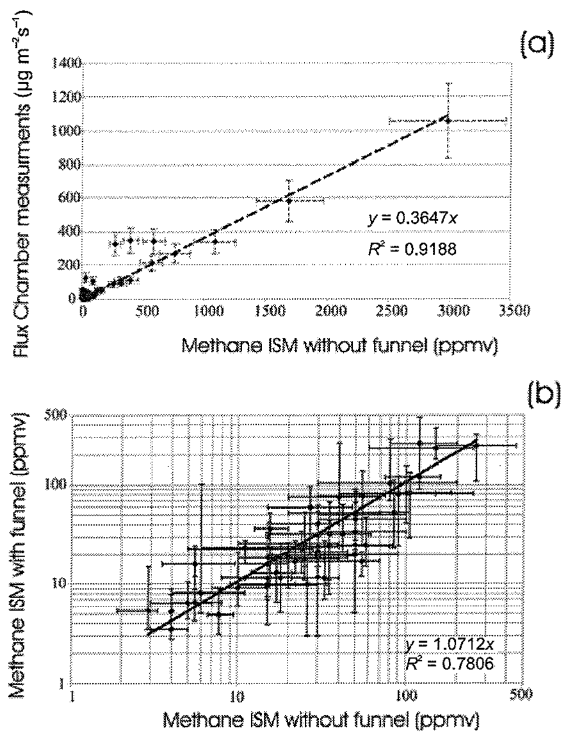

Fig. 2: (a) ISM flux correlation (Fécil 2003); (b) comparison of measurements with and without funnel.

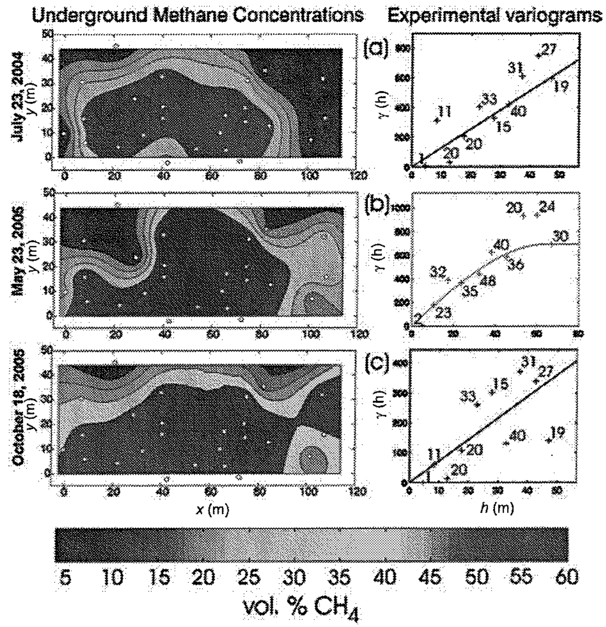

Fig. 3: Kriged maps and variograms of underground concentrations of CH_4.

is at higher emission levels. However, the major portion of total emissions occurs when and where flux is high, which contributes toward minimizing the error on the evaluation of total emissions.

When wind conditions were not respected, measurements with free ISM were lower than funnel measurements, especially for higher flux. Wind conditions were best controlled by starting measurements at sunrise. Surveys were never done under rain or on wet surfaces because of the FID's sensitivity to humidity.

Results and discussion

Characterization of the LFG plume

The CH_4 and CO_2 vertical profiles measured in the gas probe nests stabilized below depths of 0.4 m, suggesting that significant diffusion and oxidation processes were probably occurring at 0.4 m or above. Analysis of CH_4 concentrations in deeper multilevel wells revealed few cases where there was a significant variation in the vertical profile. Where concentrations varied, the CH_4-to-CO_2 ratio was uncharacteristic for LFG. Coherent levels were chosen then averaged for each multilevel well position. The resulting two-dimensional variogram was linear, and no nugget effect was evident (Figure 3). This indicates an extremely high degree of spatial correlation which validated the use of kriging for this interpolation (Chilès & Delfiner 1999). Note that for all surveys, the concentrations kriged at the upper boundary were probably exaggerated due to lack of data. This was probably also the case for the right boundary for 2005 surveys.

Nine well surveys of CH_4 and CO_2 were carried out between July 2004 and October 2005. Between summer 2004 and spring 2005, the LFG plume spread laterally, and LFG concentrations generally increased during this period. Between spring and summer 2005, the plume slowly continued its spread, but LFG concentrations diminished (Figure 3).

In addition to the complete surveys, strategic observation wells have been continually sampled since 2001. The following scenario seems to be occurring repeatedly. After CH_4 is first detected, its concentration varies according to an annual cycle, with concentration amplitudes rising from year to year. Eventually, the amplitude reaches typical LFG CH_4 levels, after which the cycle stops, and typical LFG CH_4 concentrations are maintained.

The most representative example of this pattern is provided by PS-22-FS (Figure 4). For the past 3 years, the cycle began abruptly in the days following the regular yearly maintenance shutdown of the gas collection system in October.

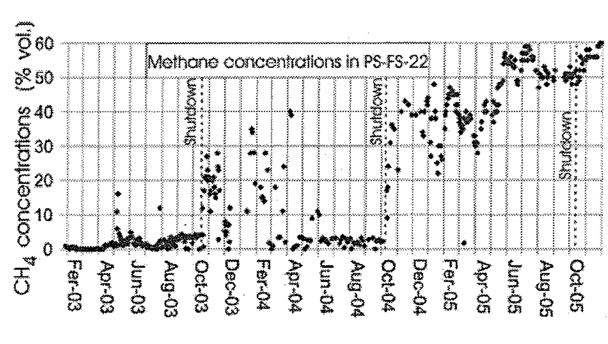

Fig. 4: Methane concentrations in PS-22-FS.

This maintenance shutdown lasted 5 days in 2004 and 2005. At this time of the year, the ground surface was saturated with water due to increased precipitation. Rapid pressure-driven flow, caused by the LFG pressure build-up, flooded the confined porous medium. When the gas collection system was reactivated, the pressure build-up was dissipated, but the gas collection was not sufficiently efficient to reverse the LFG plume progression that occurred. Surface conditions remained virtually impermeable to gas until the spring thaw. During this time, LFG concentrations measured in the multilevel wells and nested probes slowly diminished.

During the thaw, water drained to the water table, located at an approximate depth of 7 m. Vertical diffusion of LFG usually occurred only from May to August, during which time LFG concentrations drop. Eventually, the well was completely overtaken by LFG in typical concentrations. This can be explained by repeated pressure-driven lateral migration events induced by the maintenance shutdowns. More gas was being delivered to the overburden than can be dissipated by vertical diffusion. This interpretation of the reported observations is also consistent with observed variations in the methane concentration maps (Figure 3).

The PS-22-FS well was particularly important for this study, since almost all of the new multilevel wells had already been overtaken by typical LFG concentrations before the sampling began. Since CH_4 is the tracer gas, concentrations must contrast significantly in order to detect any gas movement. Very low or very high CH_4 concentrations do not allow such detection.

Gas-pumping test analysis and results

Surface conditions and saturation of the porous media were assumed to be at residual saturation during the pumping tests conducted in June 2005. Shan *et al.* (1992) and Baehr & Hult (1991) describe analytical solutions that were applicable to these field conditions. Inversion of the Baehr & Hult (1991) solution was done with AIR2D software (Joss & Baehr 1997).

Isotropic analysis of the pumping tests conducted in PS-53 and PS-57 indicated that the gas permeability (k) at these locations was 8.8×10^{-11} m^2 and 8.1×10^{-12} m^2, respectively. Anisotropic analysis, however, indicated that the radial k (k_r) values at these locations were 2.3×10^{-11} and 2.4×10^{-11} m^2, respectively. This k represents an average effective k. It integrates both variations in k produced by the water retention curve and the effect of residual saturation on k, eliminating the need for a precise determination of the relative permeability function's parameters for use in the gas transport model.

Interpretation of both pumping tests showed a strong anisotropy in the test site overburden. The k_r to vertical k (k_z) ratios at PS-53 and PS-57 were 0.123 and 0.119, respectively. Such ratios indicate that preferential paths existed in the vertical direction at the time of testing, which was likely, since the medium was backfilled and compacting conditions were unknown. In naturally deposited soils, k_r is usually an order of magnitude higher than k_z.

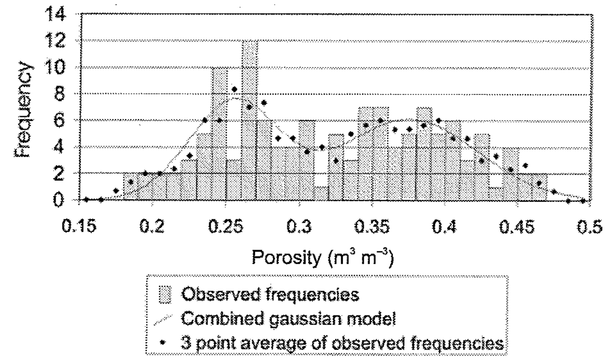

Fig. 5: Histogram of porosity.

Numerical modelling of advective lateral migration

The numeric simulation of the lateral LFG migration was conducted using TOUGH-LGM software, which was derived from the TOUGH2 simulator (Pruess 1991). The program models multiphase transport of water, air, CO_2 and CH_4 mass components, concomitant heat transport, and LFG production (Nastev 1998), and detailed geometry, input and output files, as well as a user's manual for a PC-based version of the model are available in Franzidis (2006).

The water table and the ground surface were no-flow boundary conditions (BC). On 31 July 2004, the surface was saturated after receiving 68 mm of rainfall. After this rainfall event, CH_4 concentrations at the ground surface never exceeded background levels, and all gas probes were flooded with water to a depth of 0.40 m.

Porosity (n) obtained from 128 nucleodensimeter tests showed two statistical populations: one with an average of 0.375 and a standard deviation of 0.047, and one with an average of 0.255 and a standard deviation of 0.03 (Figure 5). The lower values of n were dominant in the sector associated with transect C used for calibration (Figure 1) and so it was used in all the simulations. Porosity is important for calibration of the model, since with known LFG flow velocity through the pores, porosity controls the flux magnitude. Therefore, the relatively low standard deviation of n, combined with the fact that gas velocity in porous media was itself an average, eliminated the need for a sensitivity analysis. Flux for the other transects was determined by permeability alone.

The two-dimensional, finite difference grid was modelled with rectangular elements 0.4 m high and 0.4 m wide, with unit thickness; thus the simulated LFG migration was calculated in units of kg(CH_4) m^{-1} length along the waste boundary.

An 8-month diffusive transport model with saturated soil surface successfully reproduced the concentrations in observation wells along transect C before the gas collection system shutdown (Figure 6a). The simulation results were used as initial conditions for the advective transport model. Diffusive migration of LFG to the atmosphere during summer was neglected in determining initial conditions due to lack of ver-

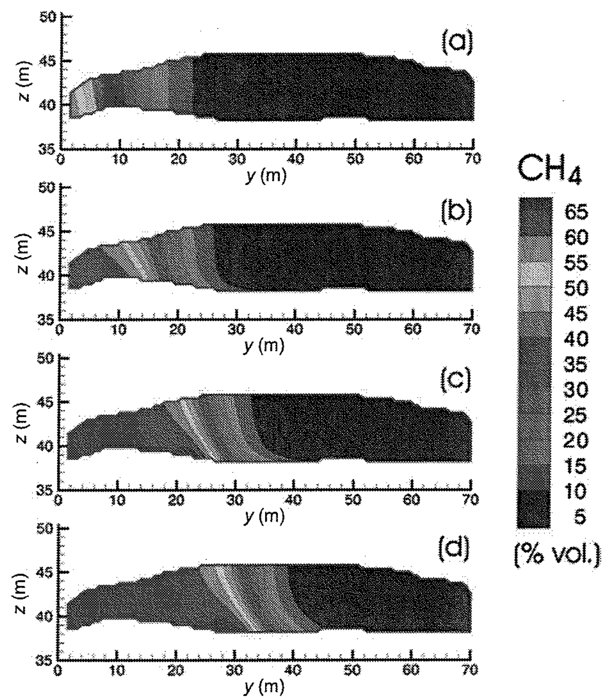

Fig. 6: (a) Initial conditions for methane concentrations; (b) concentrations of methane after 1 day; (c) concentrations of methane after 3 days; (d) concentrations of methane after 5 days.

tical gas profiles at multilevel well depths. As this only had an influence on the initial conditions in a position where no calibrating data was available, this had no impact on flux calculated by the advective transport model.

The pressure-driven model was calibrated along transect C for the autumn 2004 migration event using data from PS-22-FS and permeability measured during the pumping test conducted in PS-57.

The lateral BCs were described as a constant and uniform pressure profile. Outer lateral BCs were set to atmospheric pressure and CH_4 and CO_2 concentrations. The calibrating model on transect C determined that an increase of 400 Pa in LFG pressure at the lateral waste boundary induced a simulated LFG migration that would result in the dynamic CH_4 concentration observed in PS-22FS for the 5-day shutdown period.

Pressure was assumed to be uniform along the waste boundary, so the calibrated pressure was applied to all three transects. Transects B and C (Figure 1) were assigned k values from the PS-57 pumping test, whereas transect A was assigned results from the PS-53 test. Total migration of CH_4 for the 5 days was 24, 11 and 15 kg m^{-1} for transects A, B and C, respectively. The average of the simulated total migration for the shut-down period applied to the 120 m boundary gave approximately 2 t of CH_4. This can certainly be considered an extreme event, as the gas recovery system is shut-down only once per year. It is the authors' opinion that the total yearly advective CH_4 migration should be considered in the same order of magnitude as this migration event.

Geostatistical analysis

Methane fluxes at a single landfill are highly skewed and can vary over seven orders of magnitude (Czepiel *et al.* 1996a, Bogner *et al.* 1997b). At the site investigated here, ISM measurements of CH_4 varied from 1 to 16 000 ppmv. Only one of eleven survey sites showed good structure with untransformed ISM data, and it indicated that very high emissions were coming from a single hot spot. Although a variogram generated using log-transformed ISM data yielded good structure for all surveys, it failed to produce a normal distribution.

The variogram range here was similar to that of Borjesson *et al.* (2000), who also used this transformation with static chamber measurements, but the nugget-to-sill ratio, which reflects the degree of spatial correlation, was much better with dense ISM than in Borjesson *et al.* (2000) (Figure 7d). Czepiel *et al.* (1996b) also attempted log-transformation but reverted to a normal transformation due to poor variogram structure. Normal transformed variograms of data from this study gave almost identical structure in comparison with log-transformed data but forced a normal distribution. Nugget effect usually varied from one-third to one-half of the sill value. Two surveys had a poorer structure with a nugget-to-sill ratio of 0.6. The range was typically 20 m and varied from 15 to 35 m in the omni-directional variogram. Cross-validation removes each data point and estimates interpolation error from the remaining data. This procedure defined the number of interpolation points for each survey, which ranged from 5 to 11 points.

Kriged estimates were compared with estimates derived using inverse distance weighting (IDW), since the latter method is often used as a substitute when variograms produce poor structure (Spokas *et al.* 2003a, b). For all surveys, cross-validation of interpolation distance and the value of the exponent showed that the best compromise between mean square of error and mean absolute error was reached for a radius of 7.7 m and an exponent of 1.83. For comparison, IDW parameters for the Lapouyade study were a 6 m radius and exponent of 2 (Spokas *et al.* 2003a, b).

In order to compare identical surfaces, the field was reduced to a common area of 110 m by 45 m, which excluded from analysis one set of survey data from this study. The results were quite different depending on the interpolation method used. The IDW total flux was 1.5–4.7 times higher than that obtained with kriging. Differences between the two methods were larger when emission rates were higher because data were more skewed (Figure 7c).

IDW estimates were always close to the arithmetic average, which can serve as an appropriate estimation only if data appear normally distributed or slightly skewed (Livingston & Hutchinson 1995). The geometric mean (GM) is an appropriate estimator of log-normally distributed data when sample size is sufficiently large because positive bias decreases as the number of observations increases (Parkin & Robinson 1993). The estimations based on GM were all very close to the kriged estimates.

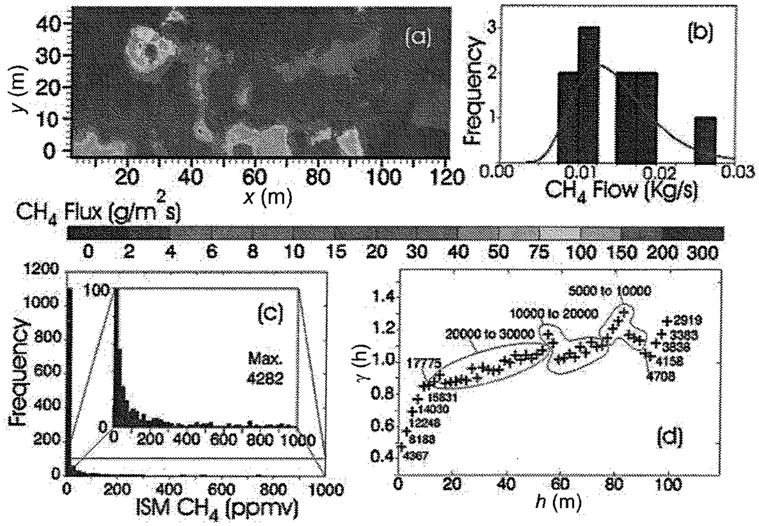

Fig. 7: (a) Map of CH_4 flux using normal transformed kriging (10 June 2004); (b) distribution of total methane flux for all surveys; (c) distribution of methane concentrations (10 June 2004); (d) variogram of normal transformed data (10 June 2004).

The ten total emission estimates were themselves log-normally distributed (Figure 7b). Bias corrected GM (BCGM) (1) was used in this case as suggested by Parkin & Robinson (1993) for small sample sizes.

$$\mathrm{BCGM} = \exp^{(y - \sigma^2/2n)}$$

where y and σ^2 are the average and the variance of log-transformed data respectively, and n is the sample size. The average and variance of log-transformed data were –4.4632 and 0.1326, respectively, so the BCGM of the total CH_4 emission rate is 0.0114 kg s^{-1}. The GM was 0.0115 kg s^{-1}, so positive bias was small.

Meteorological considerations in data

During summer 2005, there were 43 days of rain occurrences. In total, 15 rainfall events exceeded 5 mm and four exceeded 20 mm. Rain or recent rain will hinder both ISM surveying and LFG emission, so a positive bias is unavoidable. Héroux & Guy (2005) studied the effects of temperature, atmospheric pressure and precipitation on total surface flux using ISM. They targeted various combinations of high and low values of these parameters and produced a statistical model in which temperature, rain, and interacting rain and temperature were significant. This model cannot be used for off-site surface emission estimation adjustments, since the experimental plan was carried out on a landfill cover, and the statistical model cannot distinguish between the effect of these variables on LFG production and their effect on vertical gas transport.

A numerical simulation of the vertical water infiltration that occurs during the spring thaw was carried out using SEEP/W software. Soil capillary function parameters, according to the van Genuchten (1980) model, were obtained using a semi-empirical relation (Aubertin *et al.* 2003) applied to median grain size distribution data from 32 soil samples obtained during well installation. The relative permeability function of water according to the Mualem (1976) model was applied to the estimated intrinsic permeability as determined from the gas pumping tests. Saturated initial conditions were imposed to the first metre of the simulated 7-m column. The simulation results predicted that the stabilized water retention curve would be restored after little over a month (Figure 8).

According to Transport Quebec (Department of Transport, Province of Quebec, Canada), the spring 2005 thaw period for Montreal was from 21 March to 15 May. Consid-

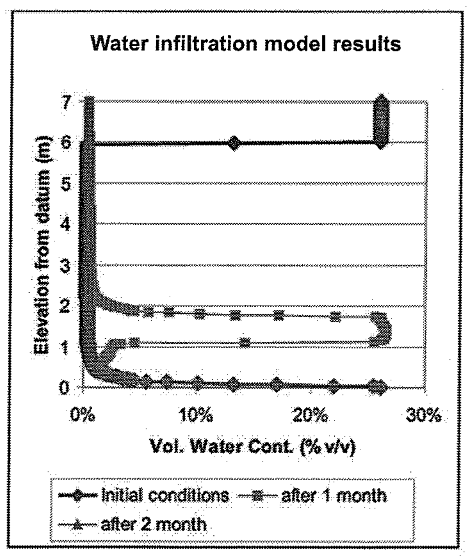

Fig. 8: Water infiltration model results (SEEP/W).

ering the vertical infiltration model results, emissions probably began after the first week of March. The first 2005 survey was done on 19 May and emissions had already started. Montreal received the tail end of Hurricane Katrina on 31 August. No LFG emissions with magnitudes exceeding background levels were measured after this event. Therefore, emissions probably lasted approximately 116 days in 2005.

Total annual emissions

Assuming an average CH_4 emission rate of 0.0114 kg s^{-1}, the total emitted CH_4 mass was 114 t. Since the simulated annual advective lateral migration was estimated at 2 t, and the estimated pore space of the overburden could contain approximately 5 t of CH_4, the vast majority of the LFG presumably passes laterally from the waste to the atmosphere through preferential flow paths.

Rapid gas flow reduces retention time for CH_4 oxidation and makes an accurate measurement of oxidation difficult. Since total lateral migration is greater than surface emissions, the gap between estimated emissions and the simulated advective transport increases if oxidation is considered.

Porosity and macropores

A total of 128 nucleodensimeter measures were taken and georeferenced during five surveys. Occasionally, very soft and abnormally porous soil was encountered. Particularly high porosity was measured on slopes (Figures 9a and 9b) seemingly due to poor compaction. During one of the measurements, the rod actually fell into a gap between clods of soil. The soil must have been simply pushed over the edge of the slope situated in the top part of the test site. High emissions have been associated with slopes (Borjesson *et al.* 2000, Spokas & Graff 2002).

Porosity was calculated using dry density values and a grain density of 2650 kg m^{-3}. Variograms from this data gave good structure so ordinary kriging was used to create a porosity map (Figure 9a). Although kriging overly smoothed certain areas, such as the difference between plan and slope, the surfaces showing high porosity were associated with high emissions where underground CH_4 concentrations (Figure 3) were also high. The IDW method smoothed data less than kriging (Figure 9c), so values from this method showed more contrast, and this spatial relationship was more apparent. High emissions also contributed to this effect. Porosity of this magnitude likely resulted from the presence of macropores, which may be channelling LFG flow through preferential paths along the lines drawn by the porosity map.

Furthermore, by sorting interpolated points for surface emissions and comparing their cumulated CH_4 flux to the cumulated surface that these points describe, and then repeating this operation for all surveys, a clear site signature can be drawn (Figure 9d). A large fraction of the total emissions was coming from a small surface area on the study site; a phenomenon that has been widely reported at other sites (Borjesson *et al.* 2000, Spokas *et al.* 2003b). Map patterns

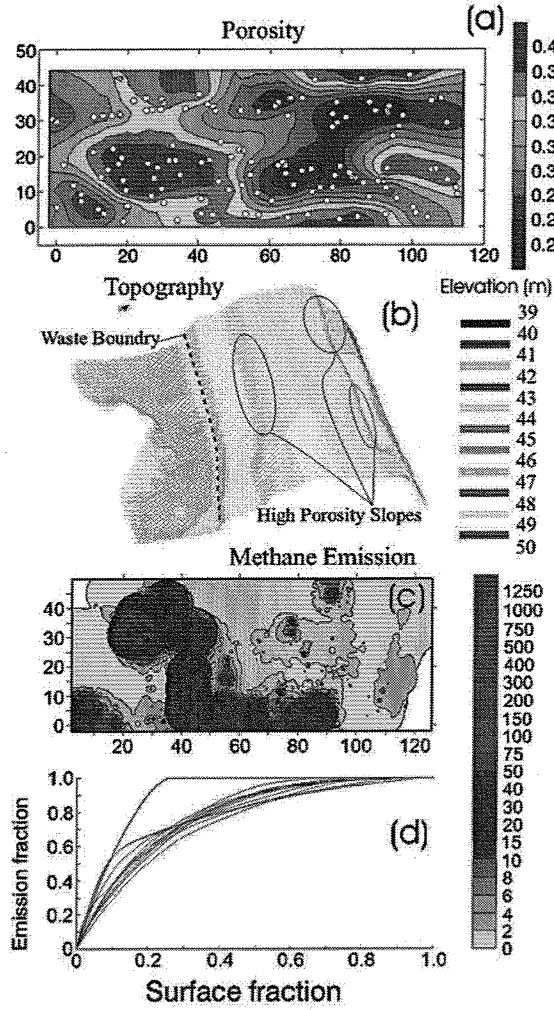

Fig. 9: (a) Kriged map of porosity; (b) topography; (c) CH_4 emission interpolated with IDW; (d) surface versus sorted emissions.

remained similar from one survey to another, while levels of emissions changed.

Conclusion

Landfill gas emissions and lateral migration were studied at a 120-m-long section of a landfill site where off-site CH_4 concentrations were frequently reported. An annual cyclical pattern in emissions was discerned from monitoring well data collected over 3 years. From September to May, the test site surface was impermeable to gas due to saturation and freezing of the top soil. Strong migration events were associated with the annual maintenance shutdown of the LFG collection system. Following an initial build-up of gas, CH_4 concentrations diminished slowly while the overburden's gas phase remained confined from the atmosphere. Dry surface conditions during summer months allowed surface emissions, thereby reducing the extent of the lateral gas plumes. Nevertheless, the overall size of the lateral gas plume increased each year.

CH_4 emissions were evaluated using ISM and flux correlation to dynamic flux chamber measurements. Due to highly skewed data, normal transformed kriging provided better emission estimates than non-transformed IDW data. Normal transformed data gave good variogram structure and estimates that closely matched the GM of the data sets.

Abnormally high porosity was found on the site, particularly on slopes and where there was evidence of vegetation damage. At the same time, a high proportion of flux came from a small surface area. Surface emission maps were usually very similar in shape to each other and very similar to the porosity maps.

The magnitude of the total LFG surface emission during the summer was inconsistent with that predicted from modelling lateral advective migration, which has been widely reported to be the dominant escape mode for LFG through naturally deposited soil. Preferential flow in macropores, due to poor compaction of backfill, was identified as the dominant mechanism for transport of LFG to the atmosphere.

The annual maintenance shutdown of the LFG migration control system should not be done during autumn or winter, as impermeable ground surface conditions and the resulting confined flow serve to enhance lateral migration.

Clearly, lateral migration posed an unacceptable risk at the study site and had to be promptly addressed. In December 2006, while awaiting publication of this article, two passively vented trenches with an average depth of 7 m and each measuring 120 m were constructed on the test site some 5 to 10 m from the waste. These trenchers were very successful in eliminating lateral migration. Several other trenches are currently under construction around the landfill.

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