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CROSS-CORRELATING LANDFILL GAS QUALITY WITH CLIMATIC FACTORS AT THE CITY OF REGINA LANDFILL

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Abstract:

Landfill gas is a by-product of the anaerobic decomposition of organic waste, and consists mainly of CH_4 (methane) and CO_2 (carbon dioxide), both of which are important when considering discussions on climate change and global warming. Five years of landfill gas data at the Regina landfill was collected to study the impacts of selected climatic factors on landfill gas collection using cross-correlation analysis. Cross-correlation is used to estimate the degree of correlation between two sets of time-series data, and returns the lag, or delay, between each series. Cross-correlation has been used successfully in a number of different fields, including seismic refraction, finance, and climate; however, its use in the field of solid waste management is extremely limited. The objective of this study is to examine five different climatic factors (rainfall, snow cover, temperature, pressure and relative humidity) on landfill gas quality (CH_4:CO_2) and residuals (the gas collected that is not CH_4 or CO_2), of which precipitation will be discussed in this paper. Surprisingly, a consistent lag time was not observed at the Regina landfill during the study period. Results suggested that a number of reasons could be behind this phenomenon. Understanding the impact that these climatic factors may have on landfill gas collection could help to increase efficiency of collection, especially in harsh climates. As well, information on the relationships in between climatic events and increases or decreases in landfill gas quality may help landfill designers and operators to optimize the landfill system and improve environmental compliance at the landfill.

1 Introduction

Canadians are one of the largest producers of solid waste in the world, generating 965 kg/cap in 2010 (Richter et al., 2017; Bruce et al., 2016). The majority of Canadian waste is sent to landfills, due to the high availability of un-developed land (Bruce et al., 2016). Saskatchewan and western Canada have grown substantially, making efficient management of solid waste more difficult (Wang et al., 2016).

Landfills contribute a significant amount of anthropogenic greenhouse gases to the atmosphere (Park and Shin, 2001; Fourie and Morris, 2004; Di Bella et al., 2011; Spokas et al., 2005; Themelis and Ulloa, 2007). In Canada, landfills account for approximately 20% of all national methane emissions (Environment Canada, 2014); while in the United States, landfills are the third largest source of methane emissions (USEPA, 2015). Landfill gas consists primarily of methane (CH_4) and carbon dioxide (CO_2), the two most important greenhouse gases, along with other trace gases. CH_4 is 23 times more potent than CO_2 on a molar basis over a 100 year time frame (Spokas et al., 2005).

The City of Regina landfill is located in a semi-arid climate, with average precipitation of about 308.9 mm per year (Statistics Canada, 2016). The landfill has two peaks, one of which has been closed and covered with final cover. The landfill also has a landfill gas (LFG) collection system, which collects and flares LFG.

Precipitation data and LFG composition data were examined in this study to explore their inter-relationships.

In their 1973 study, Farquhar and Rovers found that moisture content of waste plays an important role in supporting maximum LFG production. The moisture content of waste entering the majority of US landfills at the time of the study was much lower than the 60-80% wet weight suggested for maximum LFG generation (1973).

Munasinghe (1997) studied how hydraulic retention time (HRT) at a landfill was related to changes in landfill gas and leachate quality. The HRT is the time that water spends suspended with the solid waste in a landfill. Munasinghe (1997) found that as the HRT reduces (from increased precipitation) CH_4 concentration is increased because of the dissolution of CO_2 into the water that enters the landfill, as well as enhanced methanogenesis because of decreased CO_2 partial pressure.

Wreford et al. (2000) measured and analyzed gas composition from 8 wells at an active municipal solid waste (MSW) landfill in Vancouver. Field evidence suggested that CH_4 production was affected by precipitation 14 days prior to sampling, and that high moisture input coincided with peak CH_4 production during the study period (Wreford et al., 2000). According to their study, this may have been due to a number of factors, including organic content (which would have been placed at the top of the landfill) leaching down as a result of precipitation to increase microbial activity in other areas in the landfill, and thus increase the amount of CH_4 being produced. As well, a reduced HRT may have caused pH to rise, which then favours methanogenesis. LFG quality (CH_4:CO_2) also increased dramatically following periods of intense rainfall (7 days prior to testing), which may have been due to dissolution of CO_2 (Wreford et al., 2000).

Park and Shin (2001) studied surface effluxes of methane from an MSW landfill in Korea, receiving 1318 mm of rain per year. During summer, the efflux rate rapidly increased compared to other seasons because of higher precipitation. This caused the pores to close off on the surface of the landfill and thus act as a barrier for the landfill gas to efflux from the landfill; however, once the sun came out, the surface would dry and surface emissions would increase. This Korean landfill experiences Regina’s yearly precipitation in a 4 month timeframe.

However, contradictory field observations were reported in literature. Farquhar and Rovers found that large infiltrations of water into the test cells disrupted CH_4 production via inhibition of methanogenic bacteria in their study (1973). Peer et al. (1992) collected data including landfill geometry, well depth, and climate variables from 21 US landfills that were either optimizing or attempting to optimize gas recovery, and found that the best predictive variables for methane emissions using a regression model were depth and waste mass. Climatic variables such as precipitation, temperature, and dew point, however, were not found to be statistically significantly related to annual methane recovery.

Relationships between climatic variables and landfill moisture content are still not clear. The environment in which the landfill is located will determine the amount of precipitation that the landfill receives, although the amount of water that physically percolates into the landfill may vary greatly depending on the physical and operational conditions at the landfill (such as the site topography, cell geometry and design, final cover and daily cover practices at the landfill). Sadek et al. (2007) found that in semi-arid climates, dessication cracks and burrowing animals along with dry periods tended to cause clay covers to meet their plastic limit quickly. Their study found that after the first wetting and drying cycle, there was a significant increase in water infiltration through the cover due to cracking.

Based on the conflicting literature, the objective of this study is to use cross-correlation to determine if precipitation has any effect on LFG quality at the City of Regina landfill. Unlike most closed landfills, the City of Regina landfill is still operating, making it more susceptible to moisture changes within the landfill. Cross-correlation studies have been used to detect the similarity of two series as a function of the lag (delay) in between the two. It has been applied successfully in a number of different fields; however, its use in the field of waste management is limited.

2 Methodology

2.1 Study Site

The City of Regina landfill is located in the northeast quadrant of the city, with a total area of 97 ha, with refuse occupying 43 ha (Lefevbre, 2006). Cut-fill waste disposal practices occurred until 1963, and since then, the site has operated as a monolithic unlined cell. The landfill serves the City of Regina and surrounding area, and accepts a variety of waste including: municipal solid waste, building demolition waste, fill dirt, recyclable concrete, asphalt and other materials (Gallant, 2011). The average typical composition of waste at the City of Regina landfill includes about 34.5% organic waste (organics and leaf and yard waste), as well as about 20% paper and cardboard waste, with plastics making up about 7.5% of waste. The remaining waste (glass, metal, and household hazardous waste) made up about 10%, and the remaining waste (26.5%) was categorized into the other category (City of Regina, 2009). It is estimated that 3.1 Mt of waste had been placed at the City of Regina landfill in between 1961 and 2011. The LFG well field consists of 27 extraction wells (Latoski, 2014), and covers approximately 38% of the total area of the landfill and was covered in 2007 with 1 m of low permeability soil with 150 mm of vegetated top soil (Lefevbre, 2006).

The LFG collection system at the City of Regina landfill is an active system, with a blower used to collect LFG from vertical wells. LFG was analyzed by a real-time SCADA (Supervisory Control and Data Acquisition) system, and data for every single minute (except during scheduled maintenance and unexpected outages) was recorded. For the purpose of this research, the per-minute readings of CH_4 and CO_2 percentages were consolidated into daily averages. During the analysis of the LFG data, it became clear that a small number of LFG measurements were considerably lower than others. An investigation of these abnormal readings was carried out. A normal distribution was used to classify anomalous data points as outliers, and for any data point that fell below three standard deviations (encompassing 99.7% of the data) from the mean, the daily SCADA files were examined. The normal distribution was used because large data sets tend towards a normal distribution, and the application of the central limit theorem, If the daily readings dropped to a negative value, the entire set of averaged values was removed. After carrying out these steps, a total of 55 data points (about 2.8% of the total) were removed. Most outliers originated from scheduled downtimes and maintenance works.

Data was collected in between August 2008 and January 31st, 2014, with the exception of CO_2 percentages, which were only recorded for the period of August 2008 to January 31st, 2013. Precipitation data (daily rainfall and total precipitation) was gathered from Environment Canada Gilmour Weather Station, 50.667°N, 104.833°W, approximately 25.4 km northwest of the landfill. Rainfall was measured by a standard Type B rain gauge, measuring in millimeters. From 1981-2010, Regina experienced an average annual rainfall of 308.9 mm per year (Statistics Canada, 2016).

2.2 Data Analysis

Unlike LFG quantity, quality or composition is less sensitive to site conditions and waste characteristics. In this study, CH_4 and CO_2 composition are analyzed as a ratio (CH_4:CO_2) along with percentage gas residuals (=100%-(CH_4%+CO_2%)). Key parameters in gas composition such as CH_4:CO_2 and percent residual were selected to facilitate comparisons with previous work (Wreford et al., 2000).

Seven study periods were chosen for this study, all of which occurred during the spring and summer (no events were considered where there was snow or freezing temperatures) of 2010, 2012, and 2013. Each study period was categorized based on the ratio of days with any amount of precipitation to the total number of days in the study period, hereafter referred to as the ‘precipitation ratio’. The precipitation ratio (PR) was chosen so that there were periods where less than, equal to, and greater than 50% of the days had precipitation. Data for the intensity (mm/hr) of each individual rainfall event was not available, but study periods were chosen so that either there was a day in the study period with a significant amount of rain (greater than 50 mm) or there were a number of concurrent days that had significant amounts of rain (multiples days with precipitation greater than 15 mm). Despite having 6 years of data available, data was only chosen for 3 years because of the long sections of complete data for both precipitation and LFG quality. These events were chosen because they are believed to reflect typical rainfall events that occur in Regina.

Cross-correlation studies have been used to detect the similarity of two series as a function of the lag (delay) in between the two. It has been applied successfully in a number of different fields, including seismic refraction, finance, physiology, climate, and genomics (Barnston, 1993; Podobnik, 2010; Mustafa and Hakan, 2014).

Cross correlation is used to estimate the degree of correlation of two series as a function of a shift of one of the curves. The cross-correlation function, for a pair of time series data can be given by the following equation:

[1] $C_{xy} = (t + \tau, t) = \frac{1}{T}\int_0^T x(t + \tau)y(t)dt$

Where τ is the lag (or delay) is between two data sets, T is the duration, and t is the time increment (Chen et al., 2007). The maximum value of the cross-correlation coefficient (y-axis in Figure 1) is ±1 (±100%) and denotes that both sets of data are exactly the same (positive) or exactly dissimilar (negative) at the same time ($\tau = 0$). If two sets of time series data are similar, but not exactly the same, the value of the cross-correlation coefficient will in between 0 and ±1 (Vorburger et al., 2011). In order to ensure fair comparison between study periods, all data was normalized. The confidence interval was set to 95% a typical value for data analysis in this field.

3 Results and Discussion

A typical cross-correlation plot developed in this study is shown in Figure 1, which corresponds to row 3 of Table 1, below. The lag in the figure is shown in units pre-determined by the software used, and is translated to days for the purpose of analysis. For a PR of 0.450, there is a strong positive correlation (+0.530) in between precipitation and an increase in CH_4:CO_2 at approximately 4.62 days after the initial rainfall occurred, shown as a lag of "-3" in Figure 1.

Please note that cross-correlation analysis can be subjective, as the researcher is required to select the study period for each precipitation event. The results that occur for lag greater than zero (on the right hand side of Figure 1) imply that first there is an increase in the LFG ratio, and then precipitation occurs, a finding that is not consistent with observations in the field. Results from the statistical analysis also support this, as most of results on the right hand side were less than the 95% confident interval. As such, data analyses and discussion will only focus on the left-hand side of the figure (lag equal to or less than 0).

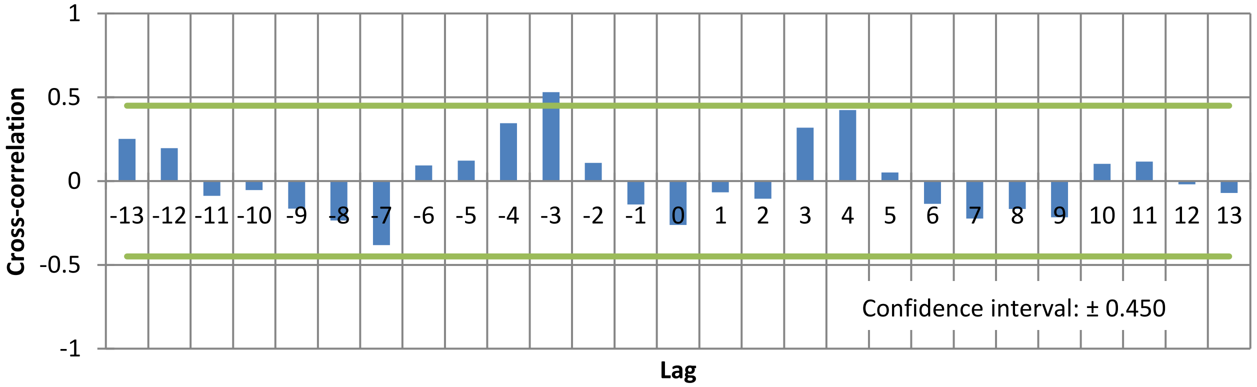

Figure 1: Example of Cross-correlation between precipitation and CH_4:CO_2 (PR of 0.450)

From Table 1, the lag varies significantly, with a minimum lag period of 0 days and a maximum lag period of 13.85 days with a mean lag period of about 4.9 days. Most cross-correlation coefficients were positive, indicating that CH_4:CO_2 increased as precipitation increased. Wreford et al. (2000) reported a dramatic increase in CH_4:CO_2 after 7 cumulative days of rainfall leading up to sampling, citing dissolution of CO_2 as a likely cause for this increase. Using a confidence interval of 95%, 3 positive correlations (PR = 0.450, 0.500, 0.563) and 1 negative correlation (PR = 0.588) were observed.

Two (PR=0.533 and PR=0.588) of the seven cross-correlation coefficients were found negative with values of -0.509 and -0.492, respectively. These negative coefficients are considered less reliable for the following reasons: (i) When compared to the averaged values in Table 1, we can see that the maximum daily rainfall and cumulative precipitation over the specific study period associated with PR=0.533 and PR=0.588 are considerably lower. Because of the lower amount of water involved in the PR=0.533 and PR=0.588 rain events, it is believed that actual infiltration rates and their effects are also lowered due to absorption of water from wetting and surface ponding, (ii) the negative coefficients are statistically less significant as the results are below (PR=0.533) or marginally above (PR=0.588) the 95% interval.

The precipitation is also lower than average for PR=0.650, but the cross-correlation coefficient is found to be positive. It should be noted that the cross-correlation coefficient is much lower than the 95% confidence threshold (=±0.450). The corresponding lag (13.9 days) is also much higher than the average value. According to our results, precipitation may or may not be a factor in the quality of collected landfill gas, as further discussed below.

Table 1: Summary of Cross-correlation between precipitation and CH_4:CO_2

Precipitation Ratio	Max Rainfall (mm) in study period	Cumulative Precipitation (mm)	Lag (days)	Cross-correlation Coefficient	95% Confidence Interval
0.450	19.6	71.8	4.62	0.530	±0.450
0.500	63.0	145.8	0.00	0.409	±0.352
0.533	15.2	40.8	1.36	-0.509	±0.524
0.563	26.1	74.7	0.00	0.523	±0.506
0.566	18.0	61.6	4.50	0.315	±0.475
0.588	12.2	54.7	9.92	-0.492	±0.490
0.650	6.8	34.0	13.85	0.287	±0.450
AVERAGE	**23.0**	**69.1**	**4.90**		

The City of Regina landfill has final cover on the closed peak, which encourages surface runoff and limits infiltration rate. However, dessication and cracking of the cover can occur in arid climates (Daniel and Wu, 1993; Sadek et al., 2007), and via thermal contraction (Andersland and Al-Moussawi, 1987), both of which would allow water to seep more easily into the covered portion of the landfill. Other areas of the landfill are still operational during the study period, and so water may be able to seep laterally through the landfill. As Farquhar and Rovers (1973) reported, a large increase in infiltrations into the landfill disrupted CH_4, a possible reason why results are inconclusive. The fact that Regina is located in a semi-arid climate and is a partially closed landfill contributes to the complexity of analysis.

Direct relationships were not observed between precipitation ratios and lag time from Table 1. In order to see how well related various outcomes (lag and cross-correlation coefficient) from the cross-correlation analysis were plotted against the precipitation factors (precipitation ratio, maximum precipitation and cumulative precipitation) over the study period. The results suggest that the lag is to a certain degree related to all precipitation factors ($p<0.15$, $0.35<R^2<0.45$), whereas the cross-correlation coefficient is not ($p>0.15$, $R^2<0.2$ in all cases). A weak positive correlation is found between precipitation ratio and lag, as shown in Figure 2. The rainfall regime and pre-existing moisture conditions at and within the landfill will also likely affect how precipitation affects LFG quality changes. As mentioned previously, Regina only receives about 308.9 mm of rainfall per year. The work done by Wreford et al. (2000) was for a coastal area in western Canada that received 1,167 mm of annual precipitation. Because Regina receives much less precipitation than Wreford et al.'s study (about 26% of precipitation), the moisture content of the buried waste in Regina may be much lower than in their study. It is hypothesized that the lower moisture saturation of waste at the Regina landfill may be partially responsible for a lack of strong correlation between the lag time and the quality of LFG, since any moisture received during drier periods may saturate the waste first, before other mechanisms help to increase production of CH_4.

The semi-arid climate at the City of Regina landfill is likely a factor in the inconsistent results observed when comparing precipitation and CH_4:CO_2. Data in the present study is taken from multiple years, and conditions at the landfill prior to the rainfall events were not considered, so it is possible that even the amount of rainwater received may not significantly affect the LFG quality. Munasinghe (1997) found that the HRT is lower when there is more precipitation. A lower HRT will result in higher CH_4 concentration (observed in our case as an increase in CH_4:CO_2) because of the dissolution of CO_2 into the water, as well as increased methanogenesis because of a decrease in CO_2 partial pressure. Blight et al. (1992) studied water storage of landfills in semi-arid climates and found that it was difficult to accurately quantify in these areas since it depended heavily on the properties and disposition of intermediate cover layers. Peer et al., (1992) also found that the best predictive variables for CH_4 production were depth and mass of waste at a landfill. Information on landfill conditions (in semi-arid climates) and other landfill properties are recommended for future studies.

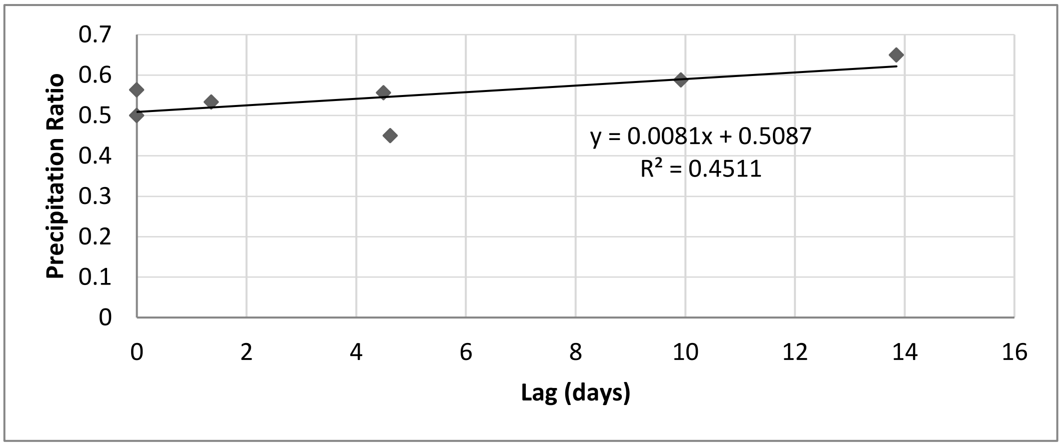

Figure 2: Relationship between precipitation ratio and lag period for CH_4:CO_2

From Table 2, the average lag observed in between precipitation and changes in LFG residual was about 5.3 days, with a minimum lag of 0 days and a maximum lag of 12.31 days observed. In 4 cases (PR=0.500, 0.533, 0.563, 0.588) the cross-correlation coefficient was positive, implying that precipitation caused an increase in the amount of residuals present. In the other cases (PR=0.450, 0.566, 0.650) the relationship was negative, meaning that precipitation caused a decrease in LFG residuals. Using a 95% confidence interval, results suggested that there is a positive relationship between PR and lag (see, for example PR = 0.500, 0.533, 0.563). Direct relationships were not observed between precipitation ratios and lag time for residual gas.

It is hypothesized that precipitation may adversely impact the operation of the landfill gas collection system, and thus cause an increase in residuals. For example, the readily degradable organics located at the top of the landfill may leach out during heavy precipitation. The LFG collection pipes placed in the landfill have a porous filter, which could be clogged by microbes and fines due to this washing action. This phenomenon has been well reported in the literature with regards to leachate collection systems (LCS). Microbial activity including the formation of multiple types of slime, or biologically induced precipitation of minerals may form 'biorock', which reduces void spaces in filter media in LCS systems (Fleming and Rowe, 2004). Although there is no research showing that this phenomenon might also occur for LFG collection systems, water infiltration after precipitation may cut the vacuum from the gas management system., This likely will lead to air intrusion and an increase of residual gases (mostly air, in this case). More research is required before definite conclusions can be made.

Table 2: Summary of Cross-correlation between precipitation and LFG residuals

Precipitation Ratio	Max Rainfall (mm) in study period	Cumulative Precipitation (mm)	Lag (days)	Cross-correlation Coefficient	95% Confidence Interval
0.450	19.6	71.8	4.62	-0.373	±0.450
0.500	63.0	145.8	5.83	0.500	±0.352
0.533	15.2	40.8	0.00	0.889	±0.524
0.563	26.1	74.7	2.67	0.621	±0.506
0.566	18.0	61.6	4.50	-0.380	±0.475
0.588	12.2	54.7	7.08	0.482	±0.490
0.650	6.8	34.0	12.31	-0.355	±0.450
AVERAGE	**23.0**	**69.1**	**5.3**		

Again, the various outcomes from the cross-correlation analysis (lag and cross-correlation coefficient) were plotted against the precipitation factors (precipitation ratio, maximum precipitation, and cumulative precipitation) over the study period. Results shows that lag is poorly related to precipitation ratio ($p=0.29$, $R^2=0.22$), as seen in Figure 3. The relationship in between the other precipitation factors (maximum and cumulative precipitation) had non-existent relationships ($p>0.8$ and $R^2<0.02$ in both cases).

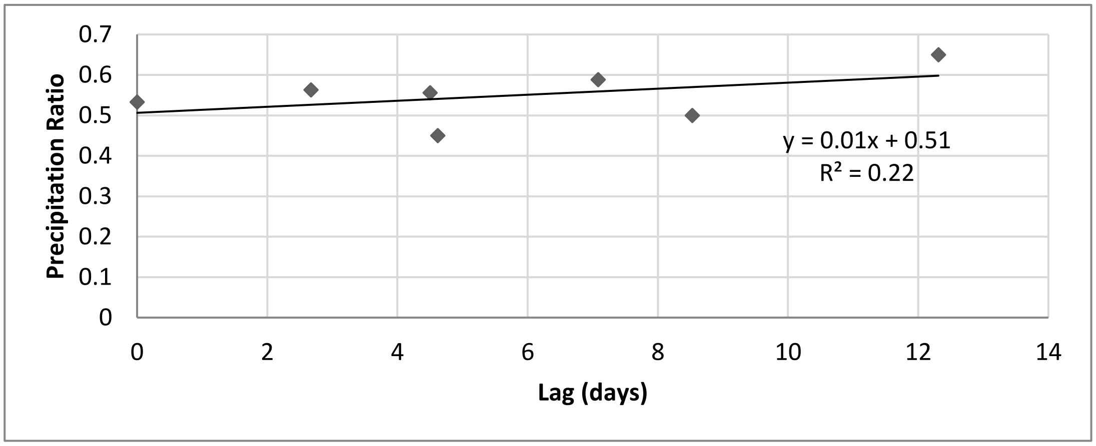

Figure 3: Relationship between precipitation ratio and lag period for residual gases

Comparing Figures 2 and 3 we can see that it appears as if CH_4:CO_2 is more closely related to precipitation than residuals when comparing R^2 values ($R^2_{ratio}=0.4511$ vs. $R^2_{residual}=0.2229$) and p-values ($p_{ratio}=0.0984$ vs. $p_{residual}=0.2847$). This follows from the work of Wreford et al. (2000) and Munasinghe (1997) which discuss the role of precipitation on reduction of CO_2 due to dissolution in water. Also, by using the confidence interval as a benchmark, we can see that about 57% of the time, cross-correlation analysis of precipitation and CH_4:CO_2 yielded results that extended past the 95% confidence limits; whereas this was only the case 43% of the time for residuals. Because of this, it is suggested that CH_4:CO_2 be used in future studies.

Research in this area is still ongoing. Selection of a lower confidence interval and different durations of rain-events are also being investigated in this study, as well as using differing definitions of continuous rainfall events. Furthermore, taking into account the previous conditions of the landfill (dry or wet years, for example) may help to explain inconsistent results. Possible areas of future work including looking at other climatic factors, such as snow cover and temperature. As well, auto-correlation, a statistical tool similar to cross-correlation where time series data is compared to itself to find periodicity, could be used to see if there is any fluctuation in LFG quality from day to night. Further to this, it may be interesting to look more in depth at the actual constituents of LFG residuals, that is – their chemical composition. Without knowing the exact composition of residuals gases, it is difficult to come to any conclusions about chemical and biological activity in the landfill that may relate LFG residuals to precipitation.

4 Conclusions

The purpose of this study was to use cross-correlation to determine if there was any relationship in between precipitation and changes in LFG quality at the City of Regina landfill. Results show that there is not a consistent lag period observed in between CH_4:CO_2 and LFG residuals and precipitation. An average lag period of about 5 days was observed in between precipitation and changes in CH_4:CO_2. In five of the seven cases studied, there was an increase in CH_4:CO_2, while in 2 cases, a negative cross-correlation was observed. This could be the case for a number of reasons, including much less precipitation occurring on average in Regina (308.9 mm per year), as well as having drier and wetter years. Results showed that CH_4:CO_2 was relatively well related to all precipitation factors (precipitation ratio, maximum precipitation, and cumulative precipitation). During dry years, an increase in HRT may not be observed, simply because increased precipitation does not increase HRT as much. More research is required in order to come to a more definite conclusion.

The relationship in between precipitation and LFG residual was only somewhat relatively related to the precipitation ratio only (unlike the ratio, which was relatively related to all precipitation factors used in this study). The average lag observed for residuals and precipitation was 5.3 days. It is likely that the relationship in between precipitation and residuals is more related to operational characteristics of the landfill gas management system. For example, microbial activity, which has been reported to cause clogging of leachate collection systems, may potentially also do the same to landfill gas collection wells, due to the downward movement of highly leachable organic material during rain events. Precipitation may thus cover the pores in the gas collection filter material, and cause the blower to work harder, causing the collection of residual gases.

As mentioned previously, research using this method is ongoing, and currently work is being carried out to see if there is any relationship in between LFG quality and snow cover. Other areas of study will include temperature, relative humidity, and pressure. With respect to this work, research could be done investigating rainfall regimes and intensity, and their effect on LFG quality, especially in arid and semi-arid climates. Rainfall intensity data could not be gathered for the study periods used in this paper. The position of the landfill and wind direction were not studied in this part of the project, but may be studied as an area of future work.

The authors believe that landfill operators would benefit greatly from this work, since knowing how climatic factors affect LFG quality could help to develop more efficient maintenance schedules. As well, developing an understanding of how these climatic factors affect LFG may help to improve the design of landfill, and systems within the landfill.

5 Acknowledgement

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