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Water table: The dominant control on CH_4 and CO_2 emission from a closed landfill site

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Abstract. A time series dataset was conducted to ascertain the effect of water table on the variability in and emission of CH_4 and CO_2 concentrations at a closed landfill site. An in-situ data of methane/carbon dioxide concentrations and environmental parameters were collected by means of an in-borehole gas monitor, the Gasclam (Ion Science, UK). Linear regression analysis was used to determine the strength of the correlation between ground-gas concentration and water table. The result shows CH_4 and CO_2 concentrations to be variable with strong negative correlations of approximately 0.5 each with water table over the entire monitoring period. The R^2 was slightly improved by considering their concentration over single periods of increasing and decreasing water table, single periods of increasing water table, and single periods of decreasing water table; their correlations increased significantly at 95% confidence level. The result revealed that fluctuations in groundwater level is the key driving force on the emission of and variability in ground-gas concentration and neither barometric pressure nor temperature. This finding further validates the earlier finding that atmospheric pressure – the acclaimed major control on the variability/migration of CH_4 and CO_2 concentrations on contaminated sites, is not always so.

Keywords: asphyxiant; explosive mixture; Gasclam; greenhouse gas; risk prediction

1. Introduction

Landfill gas is produced under anaerobic conditions by microbial degradation of the organic portion (such as animal and vegetable matter, food, garden, wood and paper waste) in waste disposed of in landfill facilities (NHBC 2007, Bogner 2007). The two major components in landfill gas are CH_4 (55-60% v/v) and CO_2 (40-45% v/v) (Scheutz *et al.* 2008, Nagamori *et al.* 2016). It also consists of numerous trace gases, such as VOC, H_2S, N_2O, and CO (Xiaoli *et al.* 2010). Landfill gas production occurs in three sequential phases (that is, physical, chemical and biological reactions) before stable CH_4 and CO_2 production takes place (Christensen *et al.* 1996, Xiaoli *et al.* 2010, Njoku *et al.* 2018). It can take several decades for the production of landfill gases to end depending on the quantity and composition of waste land-filled, moisture content and

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general weather condition (Christensen *et al.* 1996, North Carolina Department of Environment and Natural Resources 2010). CH_4 and CO_2 are two main greenhouse gases because of their potential to absorb infrared radiation reflected from the earth's surface (US EPA 2017).

Landfill is recognised to accounts for a significant amount of total methane emission around the world. Globally, the overall emission of CH_4 from waste only, is estimated to be roughly 18% of the worldwide man-made CH_4 emission (Bogner *et al.* 2007, Singh *et al.* 2018). However, globally, the total amount of landfill CH_4 emitted to the atmosphere ranged between 35 and 69 Tg/year, out of a projected yearly total emission of about 600 Tg CH_4 (Denman *et al.* 2007, Bogner *et al.* 2007). In Europe, landfills were discovered to produce the second largest anthropogenic CH_4, releasing about 3373 Gg of CH_4 from waste dumps in 2006 (EEA 2008). In the US, landfill CH_4 discharge also represents the second largest anthropogenic CH_4, constituting about 23% of the total world emission. In fact, USEPA (2009) reported US CH_4 emissions to be about 6329 Gg in 2007. In UK, landfills accounted for about 46% of the total methane emission during 1996 (EA 2009). The global CO_2 release from soil respiration varies from 68 x 10^{15} gcyear^{-1} (Raich and Schlesinger 1992) to 75 x 10^{15} gcyear^{-1} (Schlesinger 1977); the scale of which is a function of the activities of subsurface microbial population and root respiration (Epron *et al.* 2006)

Apart from CO_2, CH_4 is acclaimed the next largest powerhouse of climate change in the atmosphere (Environmental Agency 2008, Boucher *et al.* 2009, Cai *et al.* 2014). This is because; after CO_2, comes CH_4 in terms of the long-lived greenhouse gases with the largest radiative forcing (Forster *et al.* 2007). In spite the place of CO_2 in global warming, CH_4 is actually a more dangerous greenhouse gas given its higher molar absorption coefficient for infrared radiation and its longer occupation time in the atmosphere (Solomon *et al.* 2007). For example, within a time scale of 100 years, CH_4's global warming potential (gwp) is 25. These are the reasons CH_4 is frequently marked for climate cushioning policies (Boucher *et al.* 2009). CH_4 has an average life span of approximately 10 years (Boucher *et al.* 2009). It is a flammable gas which may give rise to a variety of hazards if it migrates to, and accumulates in, a property or confined spaces (Nwachukwu and Anonye 2012). For example, if generated in sufficient quantity the gas may form an explosive mixture with air (at approximately 5-15% by volume in air). It causes asphyxiation and can also be toxic in specific conditions (Nwachukwu and Anonye 2012).

Carbon dioxide too poses comparable risks to that of methane. It can as well operate like an asphyxiant when it collects in an enclosed space by displacing the existing air and giving rise to anaerobic environment (Agency for Toxic Substances Disease Registry 2016). CO_2 also causes adverse health effects, unconsciousness or even death at relatively low concentrations (at approximately 5% by volume in air) (Richard and Peter 2007, Permentier *et al.* 2017, Othieno 2017).

A lot of cases where fatality or serious injury has occurred from ground-gas explosions are recorded in literatures (New York Times 1984, Aitkenhead and Williams 1986, USEPA 1991, Health and Safety Executive 2003, North Carolina Department of Environment and Natural Resource 2010, Nwachukwu and Anonye 2012). The events were caused by the migration of landfill gas from landfill sites. The blasts were caused by the CH_4 inside the landfill gas.

Apart from incidents where people have been killed or injured, Nwachukwu and Anonye (2012) and Health and Safety Executive (2003) also gave numerous cases in the UK where landfill gas has migrated from landfill sites and been detected within buildings on adjacent sites.

The risks of explosion and toxicity due to landfill gas (CH_4 and CO_2) can be determined by measurement of their concentration (Feuyit *et al.* 2019); however, it is not just sufficient to measure its concentrations only. Also of importance is an understanding of their controls. A good

understanding of the controls on ground-gas concentration is important for: (i) deriving an optimum methodology for their measurement, (ii) predicting how they will change in future and (iii) managing their risks. In order to predict gas concentration from their controls, knowledge of the process is vital. To understand the process, time series data is needed. This is because, these data allow for the quantification and accounting of temporal variability. Furthermore, the relationships of ground-gas concentrations and their controls are different and can vary; in the absence of time series data, it is risky to infer gas regime.

Nwachukwu and Anonye (2012) stated the three basic controls on ground-gas concentrations as: (a) gas production rate, (b) soil permeability and (c) atmospheric pressure. They argued that while gas production rate determines gas availability, soil permeability has a major control on the gas migration, the two which have implications on the possibility of the barometric pressure to draw or force the gases. However, when Nwachukwu and Anonye (2012) discovered that atmospheric pressure (the acclaimed dominant control on gas variability) was not the major control on the variability/emission of CH_4 and CO_2 concentrations in the studied landfill site, they suggested that other possible controls such as atmospheric temperature and fluctuations in water table be investigated to determine the major control.

Just as atmospheric pressure, the effect of atmospheric temperature on the emission of CH_4 and CO_2 gases in the same landfill site has been investigated and atmospheric temperature found also not to be the dominant control (Nwachukwu 2019). It was sequel to this that we want to verify how much of control variability in groundwater may have on emission of the investigated gases. To do this successfully, there is a requirement to explain how **ground-gas production, soil permeability** and **fluctuations in water table** can influence the variability in and emission of ground-gas. Pressure differential effect was adopted from the work of Nwachukwu and Anonye (2012) on the same site to further buttress the effect of permeability.

Change in **ground-gas production** can be due to chemical and biological factors such as temperature, pH, moisture, chemical activity within the soil, micro-organisms within the soil (e.g., microbial degradation), aerobic and anaerobic conditions etc (O'Riordan and Milloy 1995, Wilson *et al.* 2007). Change in gas production can either raise or reduce the volume of the soil gas concentration and migration, resulting in their variability.

The presence of **groundwater** can constrain the migration of gases within the ground. For example, a rise in groundwater level may reduce the volume of gas within the pore spaces resulting in increased gas pressure and release or lateral migration known as the "piston effect" (Katy *et al.* 2009, Davis *et al.* 2004). Heavy rainfall may also increase soil moisture content causing temporary sealing of the ground surface, particularly in fine grained soil, reducing the potential for vertical migration of VOCs in soil gas, but in some cases promoting transient lateral migration (Katy *et al.* 2009, Boult *et al.* 2011).

The **soil permeability** is a link between soil gas and the atmosphere. The relationships of gas concentration and the barometric pressure may vary due to the delay caused by change in the permeability of the soil and the rate of gas production / barometric pressure change. Permeability of the soil is dependent on ground cover and may also change with depth. Other factors which affect soil permeability include saturation, freezing, bioturbation and compaction (Wilson *et al.* 2007).

The permeability of the soil can now be determined using 'pressure differential' (that is, the difference between atmospheric and borehole pressures) obtained with the aid of the Gasclam in-borehole monitor (Boult *et al.* 2011, Nwachukwu and Anonye 2012). The lag of soil permeability to change over cycles of atmospheric pressure results in 'pressure differential' which is used to

measure the permeability of different soils. With the knowledge of permeability, soil gas availability can be determined from the amount of gas detected. Information about soil permeability and gas availability is then required for an accelerated understanding of the relationship of gas concentration and water table.

Since barometric pressure and temperature have been investigated and found not to be the major controls on ground-gas concentration in this site, the **aim** of this paper is therefore to determine if **water table** is the key driving force on the emission of and variability in landfill CH_4/CO_2 concentrations.

2. Materials and method

The dataset analysed in this work was obtained with the help of an in-borehole ground-gas monitor, Gasclam (Ion Science, UK). This instrumentation has the capability to monitor continuously and simultaneously various ground-gases (e.g., CH_4, CO_2, CO, O_2, H_2S, VOCs) alongside their environmental controls (e.g., temperature, barometric pressure, borehole pressure and water depth) on hourly sampling basis unmanned for up to three months. It logs long term, real trend information, allowing informed decision to be made on accurate, reliable data – a revolution in gas management and prediction. It measures the gases with the aid of the sensors incorporated into it. Its sampling frequency can be set and is variable from two minutes, to once daily. Data is downloaded to a PC or viewed remotely using the optional GPRS telemetry system.

The instrument was installed in a 50 mm borehole located at closed landfill site in Manchester, UK. The gas monitors were set sampling on hourly basis and left in-situ to ensure a continuous monitoring of the ground-gases and their environmental controls. The data was downloaded after 6 weeks and graphically analysed. With this type of monitoring practice, time series behaviour of the individual gases and their controls are better inferred, thereby allowing room for their risk prediction and management.

2.1 Site information

This site is same as the one investigated by Nwachukwu and Anonye (2012). It is a former 'brickworks and associated clay pits' which became a landfill site in the 1940s, for the dumping of household, commercial and industrial waste materials. It ceased to be used as landfill in about 1975. Residential properties were built on the site during the 1970s. During the late 1990s, gas was found to be leaking into some of the properties. In 1999, a 'venting trench' was built to prevent gas leaking into the houses. Although it helped, the problem was not completely resolved. But excavations within the last few months have established some of the properties are on top of tipped material and it was formally declared 'contaminated land'.

Physical site investigation works have confirmed the presence of such wastes in the eastern portion of the tip, although limited information is available for the remainder of the landfill area. A further landfill site comprising the infilled section of an abandoned railway cutting (southern strip) is situated immediately to the south of the landfill site and is reported to have been filled with inert wastes only.

The requirement to quantify the concentrations of the studied landfill gases was prompted by the complaints received from the inhabitants of the halls concerning strange odours from the site. There is also fear of potential hazards of explosion, asphyxiation and toxicity from methane,

carbon dioxide and volatile organic compounds, respectively.

For example, on July 13, 2012, more than 20 homes built on the site had to be evacuated because of a methane scare. Householders, including families with children, were told to leave their homes just before 8 p.m. after methane alarms sounded. The special alarms were set up after the highly flammable gas was discovered in the area leaking from the former Guide Lane landfill, nearby. About 50 residents were told they could return to their homes around midnight after tests showed the methane was at safe levels. Fire fighters were called to the scene to help the council and other agencies with the evacuation.

3. Results

The results are presented in Figs. 1-2 and Tables 1(a) and 1(b).

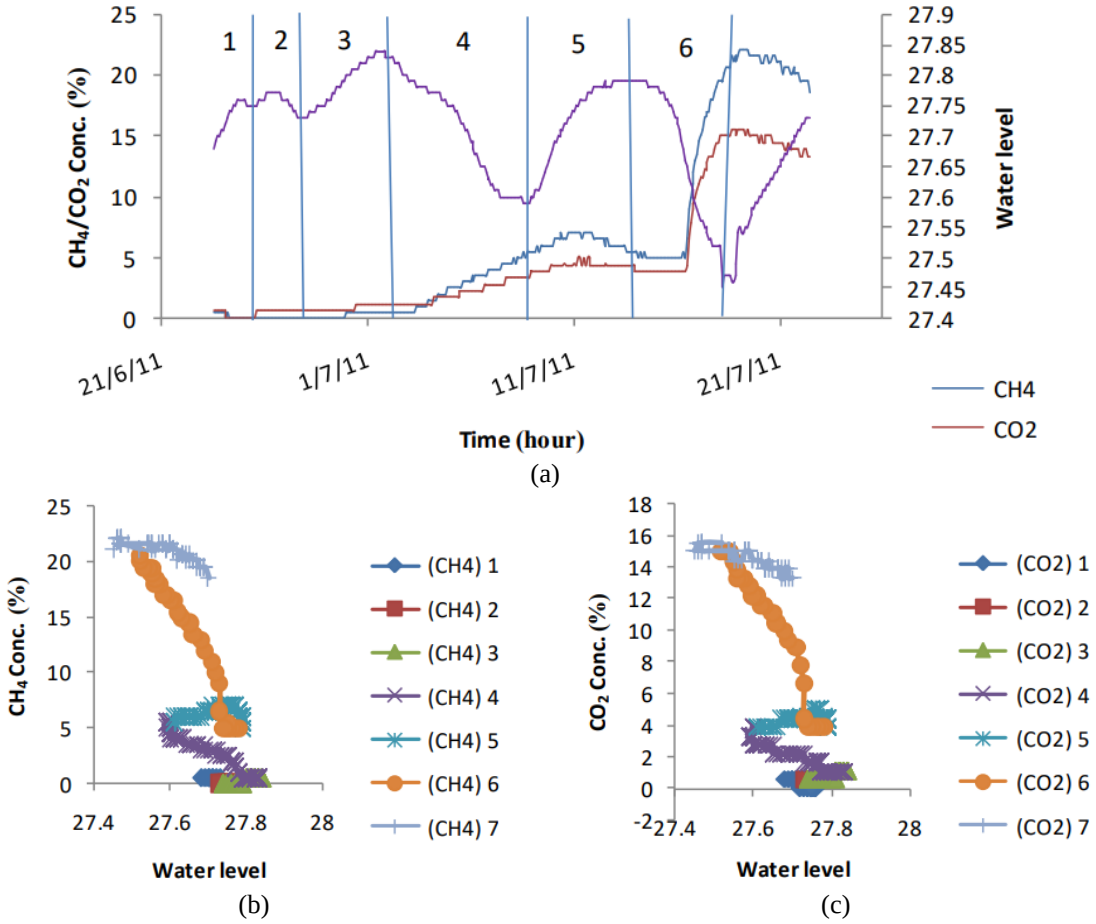

Fig. 1 (a) Methane, carbon dioxide concentration (in percent) and water level (in cm) as a function of time. The data series is split into sections 1-7. Series split is based on periods of changing water level, (b) and (c). Analysis is for the entire dataset; however, different sections of concentration changes with water level are indicated by different colours

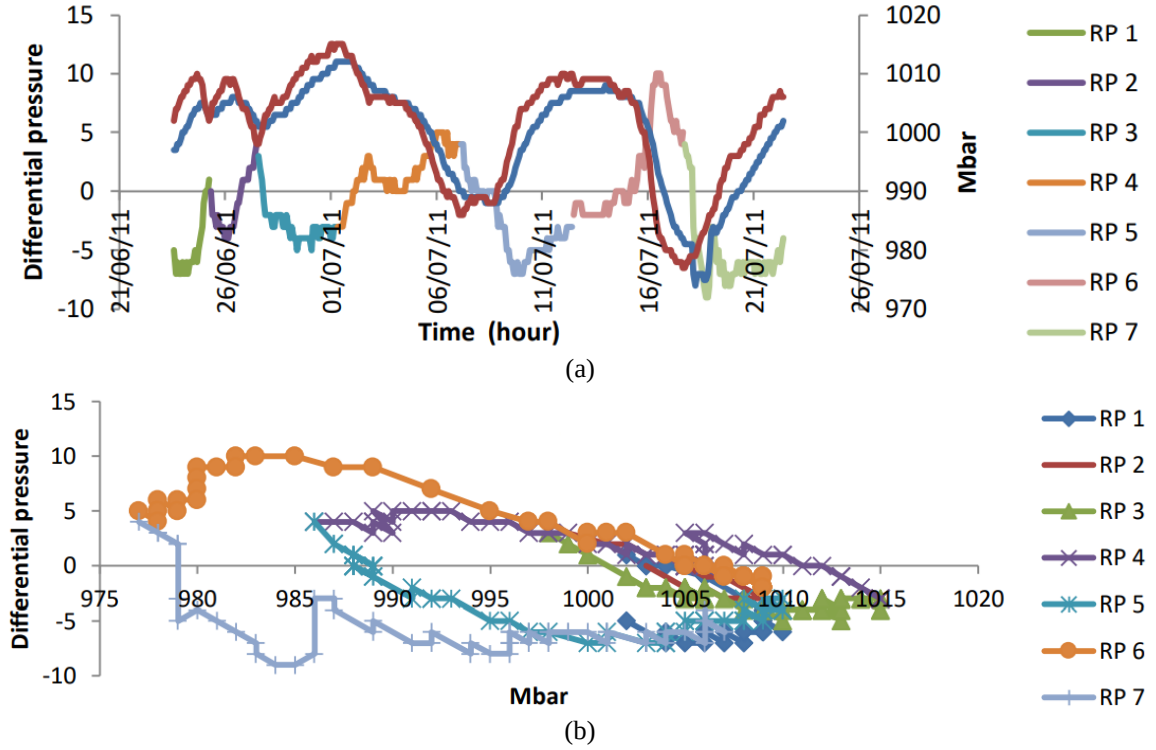

Fig. 2 (a) and (b) The relationship between atmospheric, borehole pressure and differential pressure as time Series of increasing duration (a), with (b) displaying the differential pressure as a function of atmospheric pressure (Nwachukwu and Anonye 2012)

Table 1(a) Gas correlations, (R^2) over single periods of increasing and decreasing water level

			R2	
Gas	Sections 1 and 2	Sections 3 and 4	Sections 5 and 6	Section 7
CH_4	-0.591	-0.839	- 0.784	- 0.648
CO_2	-0.014	-0.787	-0.773	- 0.823

Table 1(b) Gas concentrations over single periods of increasing water level and single periods of decreasing water level

			R2				
Gas	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
CH_4	- 0.763	n/a	-0.795	- 0.947	-0.002	-0.938	-0.648
CO_2	-0.785	-6E-0	-0.695	-0.919	-0.146	-0.959	-0.823

4. Discussions

The times series data obtained with the aid of Gasclam (Ion Science, UK) were used to examine CH_4, and CO_2 concentrations and water table as a function of time. This was in order to

determine the magnitude of control water table has on these gases, if any. The effect of hysteresis on the variability of the gases was also investigated; however, that of soil permeability was adopted from the works of Nwachukwu and Anonye (2012).

The strength of the relationships of CH_4/CO_2 concentration and water table was obtained by means of Linear Regression Analysis. This was done by dividing the dataset into different periods of increasing and decreasing water table (Fig. 1(a)) and then determining their R^2 values (Tables 1a-b) for those periods. In Fig. 1(a), sections 1-3, CH_4 and CO_2 appear to increase independently of water table, however; sections 4, 5, 6 and 7 show clearer evidence of a relationship. However, since evidence of a relationship is not enough to establish the strength of the relationship, linear regression analysis was involved.

A month datasets which was collected at hourly intervals from a borehole in the studied site shows gas concentration to be variable (Fig. 1(a) and 1(b)). This evidently supports Guidance condition for continuous sampling (Wilson *et al*. 2007, Wilson *et al*. 2017, Wilson *et al*. 2018, Talbot and Cards 2019). There is also variability in the relationship of gas concentration to water table as considered in the light of continuous monitoring periods of increasing length in the same site; however, this variability does not match the hourly sampling frequency of the ground-gases. This variability in gas concentrations relative to water table (Fig. 1(a)) is in order of days. Therefore, the sampling rate should be set to follow suit.

The clear loops formed by connection of datapoints in time order suggest that gas concentration is affected by hysteresis (Fig. 1(a) and 1(c)). The loops are more evident in sections 1-4 of Fig. 1(a).

Several periods of decreasing and increasing water table showed a strong negative R^2 with CH_4 and CO_2 concentrations (Fig. 1(a)). This negative correlation supports the Guidance requirement for measurement contingent on decreasing water table in order to raise the confidence in detecting the worst case. The R^2 was slightly bettered by considering their concentrations during specific periods of increasing and decreasing water table as indicated by sections 1 and 2 combined, 3 and 4 combined, 5 and 6 combined (Table 1(a)); and also by considering separate periods of increasing and separate periods of decreasing water table (Table 1(b)), the R^2 increased significantly at the 95% confidence level. This indicates that water table is a major control on the behaviour of the gases.

Nwachukwu and Anonye have already established that the barometric pressure and borehole pressure in this site did not always overlap (Fig. 2(a)), resulting in pressure differential. This is clearly a pointer that there is variability in soil permeability. The clear loops created by linking of datapoints in time order imply that soil permeability is affected by hysteresis (Fig. 2(b)). More of these loops appeared in sections 1-4; which confirms our earlier observation.

5. Conclusions

The time series data obtained by using the Gasclam clearly showed that there is a strong negative correlation between CH_4/CO_2 concentrations and water table over the entire monitoring period. After slightly improving the R^2 by considering their concentration over single periods of increasing and decreasing water table (Fig. 1(a), Table 1); single periods of increasing water table and single periods of decreasing water table (Fig. 1(a), Table 1), the strength of the correlation increased making the correlation to remain very significant at 95% confidence level. The clear loop formed by connection of the datapoints in time order suggests that gas concentration is

strongly affected by hysteresis (Fig. 1(b) and 1(c)). Separation of the data series into individual decreasing and increasing water table makes marked improvements in the strength of the relationship. For instance, the correlations of the relationship during the second increasing and decreasing limb of the water table are -0.787 and -0.839 for CO_2 and CH_4 respectively (Table 1); this was improved by splitting the data series into individual increasing and decreasing limb water table in which CO_2 and CH_4 had negative correlations of 0.695 and 0.795 respectively for increasing limb water table, and negative R^2 of 0.919 and 0.947 for decreasing limb (Table 1b). This shows that whilst water table is the major control during both the increasing and decreasing limb, it had more control during the decreasing limb water table. Therefore, positive correlation of gas concentration and any environmental control over any entire monitoring period does not automatically mean that such parameter does not have control on the variability/emission of the gas. It can only suggest that it is not a major control. Also, very low positive correlation over the entire monitoring period could suggests presence of control as in this case.

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Conflict of interest

Note that there is no conflict of interest whatsoever.

Recommendation

This investigation focused on the major components of landfill gas (CH_4 and CO_2) and their environmental controls. There is, also, a requirement to determine the trace components of landfill gas as some of them such as volatile organic compounds (VOCs) can be very hazardous even at low concentrations. The effect of environmental factors on them may also differ and therefore needs to be investigated.

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