

The Utility of Purge and Recovery Testing in Ground-Gas Flux Risk Assessment

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ABSTRACT

Purge and recovery testing is a novel method for measuring ground-gas flux. This method has been tested with Gasclam in boreholes at two landfill sites at southern Manchester, UK. The recovery rate of individual gases was used to predict when and at which concentration they would reach the unmonitored receptors. For example, at site 1 in borehole 2, CH₄ and CO₂ had concentrations of 22 % and 4 %, respectively before purging in September (2010); meanwhile in May (2011), it recorded 23 % and 4.4 %, respectively. Whereas after purging, recovery was occurred within 32 hrs and 14 hrs, respectively and 23 % of CH₄ and 4.4 % of CO₂ were recovered in 52 hrs and 27 hrs respectively after purging in summer time. This implies that CH₄ and CO₂ concentrations recovery in this borehole was faster in September 2010 than in May 2011. The recovery time of the investigated gases was varied from the length of site visit to over a day. It also varied with season and site. Soil permeability and gas production rate are suspected to be responsible for variations in gas recharge rate. In general, the recovery profiles of VOC were very different from those of CH₄ and CO₂. VOC tended to recover in no time, indicating that they could get to the receptor much faster compared to other gases, thereby posing more danger. The reproducibility of the gases was not consistent due to their low concentrations.

Keywords: Gasclam, Flux, Concentration, Local risk, Global risk, Migration rate.



INTRODUCTION

Ground-gas monitoring is an important aspect of the investigation and management of contaminated sites, as the data is critical to the process of risk assessment (Morris *et al.*, 2008; Friedrich and Trois, 2011; Ashraf *et al.*, 2014; Nagamori *et al.*, 2016; Talbot and Cards, 2019). Ground-gas concentration and its flux are the two the most important parameters in ground-gas risk assessment (Jewell and Hallam, 2012; British Standard 8576, (2013); Nwachukwu and Anonye, 2013). This is because the concentration is used to assess their local risks (explosion and asphyxiation) and flux, and their global risk (warming) (Boyle and Witherington, 2007; Katy *et al.*, 2009; Boucher *et al.*, 2009; Wilson *et al.*, 2017; Wilson *et al.*, 2018; Feuyit *et al.*, 2019).

Until 1996, only local risks of explosion and asphyxiation were assessed (Wilson and Cards, 1999), and these were done in terms of concentrations only. However, concentration is not necessarily measured at the source since it often does not constitute danger to human health there until it migrates to the receptor. Ideally, they should be measured at the receptor. Generally, there are often multiple receptors and it is rarely possible to monitor all of them. Therefore, there is a requirement to monitor the flux to determine when and at what concentration ground-gas will get to the unmonitored receptors. Boulton *et al.*, (2011) supported this hypothesis by clearly illustrating the inadequacy of concentration alone using high-resolution data of both ground-gas concentration and flux collected from the same borehole. They recommended that both variables should be incorporated into a Conceptual Site Model for effective risk assessment.

Ground-gas flux is currently inferred or generated from gas accumulated in a borehole during the inter-sampling period (Gal *et al.*, 2019); therefore, it is not instantaneous flux that is measured. If accumulation occurred without gas loss, this measurement of flux may be useful as an average over the sampling period. However, a borehole may have an unknown gas exchange (variable inflow and outflow of gas); if this is the case, the inferred flux may not always be representative of that of the accumulated gas (Boyle and Witherington, 2007; Levintal *et al.*, 2020). Also, the flux measured may be an artefact of the inter-sampling period. This is because the number of times a borehole is monitored determines the magnitude of flux that would be measured from that borehole. For example, the higher the sampling frequency, the lower the measured ground-gas fluxes since it would take sufficient time for gas pressure to recover.

The capability to make high frequency concentration measurements using the Gasclam allows for a more reliable measurement of ground-gas flux (Morris *et al.*, 2008; Boulton *et al.*, 2011; Teasdale *et al.*, 2014). The method is analogous to those used in hydrogeology. While hydrogeologists use this test in characterizing aquifer productivity in which the fluid level in a borehole is perturbed and the recovery period is monitored (Wilson *et al.*, 2006; Nwachukwu and Anonye, 2013); in our case, the fluid is ground-gas. With time-series gas concentration data, a similar approach would be adopted. By purge and recovery tests (Musbau, 2009; Acumen and Ggs, 2018), characterization of individual borehole recovery could be identified from which production and/or migration rate can be quantified.

This work aims to investigate the potentiality of using purge and recovery tests to determine the recharge rate of the gases for effective ground-gas flux risk assessment. To verify whether such tests might be useful, there is a requirement to determine the ground-gas recovery on a reasonable timescale (relative to the length of a site visit). Also, it is essential to determine if ground-gas recovery profile is reproducible. This will be done to determine if the test would give the same recovery profile when repeated on the same borehole. Finally, a comparison between the purge and the recovery profiles of ground-gases (CH_4 and CO_2) and Volatile Organic Compounds (VOCs) will be done.

MATERIALS AND METHODS

To achieve the aim of the study, the recovery profiles of the ground-gases need to be determined. To determine the recovery profile of individual ground-gas the Gasclam was used (Nwachukwu *et al.*, 2018; Nwachukwu and Uwa, 2018), a small N_2 gas cylinder and a flow meter. The Gasclam is designed to fit into a 50 mm borehole (Nwachukwu and Ugwuanyi, 2012).

The standard headworks are 8" monitoring wells from Stuart wells and must be installed in line as the diagram below (Figure 1). It is important to have the standpipe a maximum of 3 cm above the base of the headworks as this will ensure the Gasclam will fit under the lid of the cover. The headworks must be concentric to the standpipe for the Gasclam to be housed correctly.

In this work, two southern Manchester landfill sites were investigated by monitoring two selected boreholes per site. The boreholes in site 1 are 90m deep each, while those of site 2 are 7.50m each. The initial measurement of borehole ground-gas concentrations was done using the Gasclam. The borehole volume was calculated from the borehole depth. N_2 gas which approximately equal three times (3x) the volume of the borehole, was injected into the borehole. Gas concentration was checked to be zero or close to zero. The Gasclam was then quickly installed into the borehole to measure the recovery over time (usually every 3 mins). The rate of recovery of individual gases is used to predict when and at what concentration they would get to the unmonitored receptors.

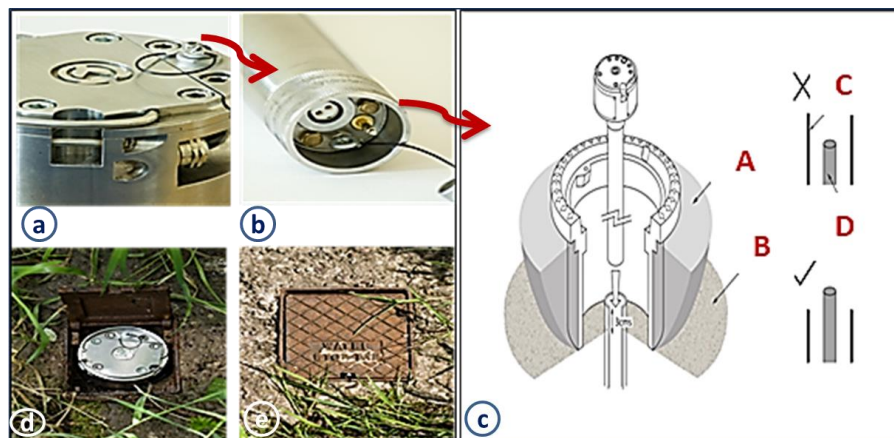


Figure 1: Gasclam In-borehole monitor (LHS) and how to install it in a borehole (RHS); a, GasClam®; b, close view of GasClam; c, dissected parts of GasClam showing A, concrete collar; B, fitting part to ground; C is protective cover and D standpipe; d-e, fit view to the ground.

Investigated sites

The two investigated sites are all landfill areas. Site 1 is situated at Guide Lane Audenshaw, Tameside Metropolitan Borough Council, UK. It is a former 'brickworks and associated clay pits' which became a landfill site in the 1940s, for the dumping of domestic, commercial, and industrial waste materials. It ceased to be used as a 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 (Nwachukwu *et al.*, 2019). A 'venting trench' was installed in 1999 to prevent gas from escaping into the buildings. Though it helped, the problem was not completely resolved as gas leak was not completely abated. Excavations revealed that some of the properties are on top of tipped material and it was formally declared 'contaminated land' (Nwachukwu

et al., 2019). Physical site investigation showed the presence of such wastes in the eastern part 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. Site 2, which is located at Ruby Street, Audenshaw, Tameside Metropolitan Borough Council, also comprises of infilled brick pits, which are known to be producing landfill gas and leachate. Records show that this landfill site was infilled with inert, residential, commercial, and industrial waste products until the late 1960s (Nwachukwu and Anonye, 2013). The presence of such wastes at the site has been confirmed by physical site investigation. This landfill site is presently surrounded by council hall.

RESULTS

The recharge characteristics of ground-gas (CH₄ and CO₂) concentrations over different seasons in the studied sites are presented in Figures 2 – 5. Ground-gas recovery rates were used to measure the risk due to their fluxes as they signify the time and concentration they would get to the receptor. Higher-resolution sampling was chosen for purge and recovery testing than for longer-term continuous monitoring because ground-gases have been observed to recover over a short time scale less than 60 mins (Nwachukwu and Anonye, 2013).

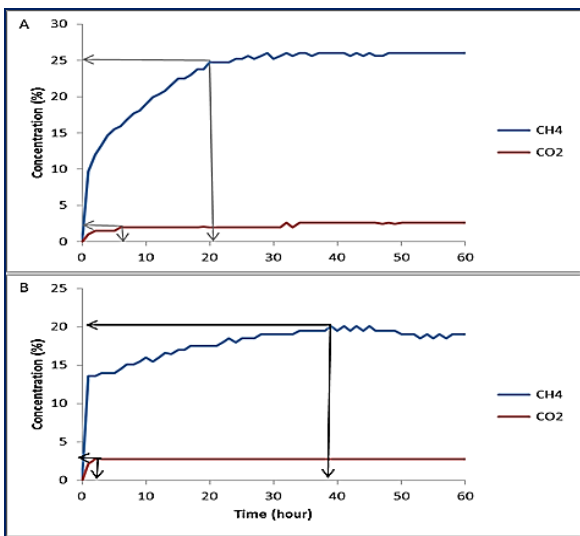


Figure (2): Recharge characteristics of CH₄/CO₂ in borehole 1 at Guide Lane on 08/09/2010 (A) and on 12/05/2011 (B).

The recovery profiles of CH₄/CO₂ concentration obtained after purging borehole 1 in September 2010 and May 2011 in Guide Lane are shown by Figures 2a and 2b respectively. Before purging, CH₄ and CO₂ had concentrations of 25 % and 2.5 % respectively in September 2010 whilst in May 2011; it is 20 % and 3 % respectively. Figure 2a shows that 25 % of CH₄ and 2.5 % of CO₂ were recovered in 22 hrs and 6 hrs respectively whilst figure 2b shows 20 % and 3 % of CH₄ and CO₂ were recovered in 38 hrs and 3 hrs respectively after purging. Both gases remained fairly constant for the remaining period of the test. The figure shows that the recharge of CH₄ was faster than that of CO₂ in September 2010 than in May 2011. The disparity in CO₂ recovery time could be due to site-related activities during the monitoring period. The concentration seemed to remain the same during the two periods as can be observed from its recovery profiles. Changes in soil permeability may have played a role on the behaviour of the gases over different seasons.

Figure 3 represents the recharge characteristics of CH₄/CO₂ concentration conducted in borehole 2 in September 2010 (Figure 3a) and May 2011 (Figure. 3b) at Guide Lane. CH₄ and CO₂ had concentrations of 22 % and 4 % respectively before purging in September 2010, and; 23 % and 4.4 % respectively in May 2011

before purging. Whilst 22 % of CH₄ and 4 % of CO₂ were recovered in 32 hrs and 14 hrs respectively after purging (Figure 3a), 23 % of CH₄ and 4.4 % of CO₂ were recovered in 52 hrs and 27 hrs respectively after purging (Figure 3b). This implies that the recovery of CH₄ and CO₂ concentrations in this borehole was faster in September 2010 than in May 2011. The variability in the permeability of the soil during the different periods is again the possible reason for faster recovery of the gases in September (autumn) than in May (spring).

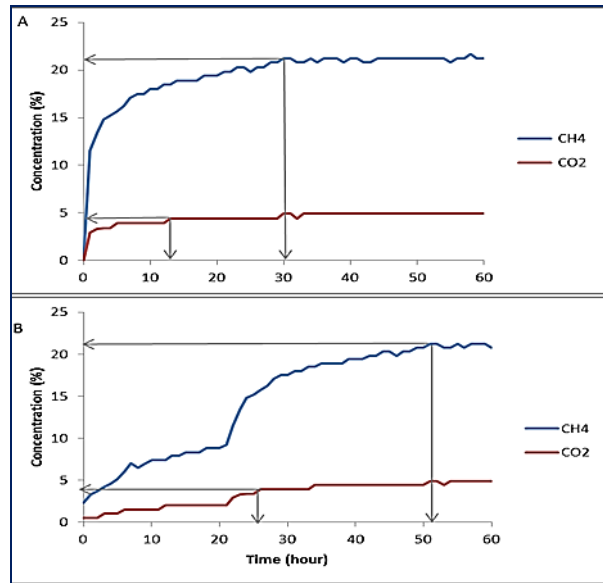


Figure (3): Recharge characteristics of CH₄/CO₂ in borehole 2 at Guide Lane on 08/09/2010 (A) and on 12/05/2011 (B).

Figure 4 represents the recharge characteristics of CH₄/CO₂ in borehole 1 at Ruby Street (site 2) from a purge and recovery test conducted in May 2011 (Figure 4a) and July 2011 (Figure 4b). The concentrations of CH₄ and CO₂ before purging were recorded in May to be 25 % and 4 % respectively, and in July as 60 % and 32 % respectively. Figure 4a shows that whilst 25 % of CH₄ was recovered in 46 hrs, 4 % of CO₂ was recovered in 18 hrs. Figure 4b, on the other hand, shows 60 % of CH₄ and 32 % of CO₂ to recover in 12 hrs and 4 hrs respectively. Just like in borehole 2 at Guide Lane, the recharge of CH₄ and CO₂ concentrations are faster in July 2011 than in May 2011. Again, the behaviour of both gases further validates our earlier finds that the gas recharge rate is often faster during periods of increased soil permeability (like in July) than other times.

The recovery profiles of CH₄/CO₂ concentration obtained after conducting purge and recovery tests in borehole 2, at Ruby Street, in May 2011 and July 2011 are shown in Figure 5; where 23 % of CH₄ was recovered in 31 hrs, whilst 17 % of CO₂ was recovered in 26 hrs in July (Figure. 5a).

In May, 22 % of CH₄ was recovered after 44 hrs whilst 3 % of CO₂ was recovered after 2 hrs (Figure. 5b). Note that 3% CO₂ concentration which was recovered in 3 hrs in May was recovered in no time in July.

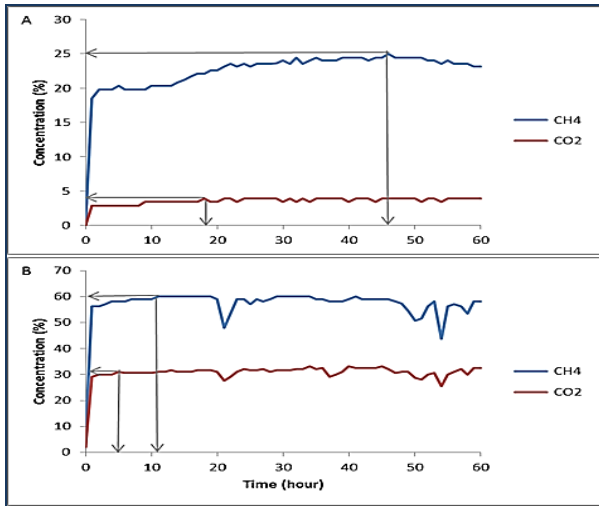


Figure (4): Recharge characteristics of CH₄/CO₂ in borehole 1 at Ruby Street on 16/07/2011 (A) and on 12/05/2011 (B).

This a major prove that CO₂ also and not only CH₄ concentrations displayed faster recovery in July than in May. This further shows that the soil was more permeable in July than in May, thereby allowing for faster recovery of the gases in July than in May.

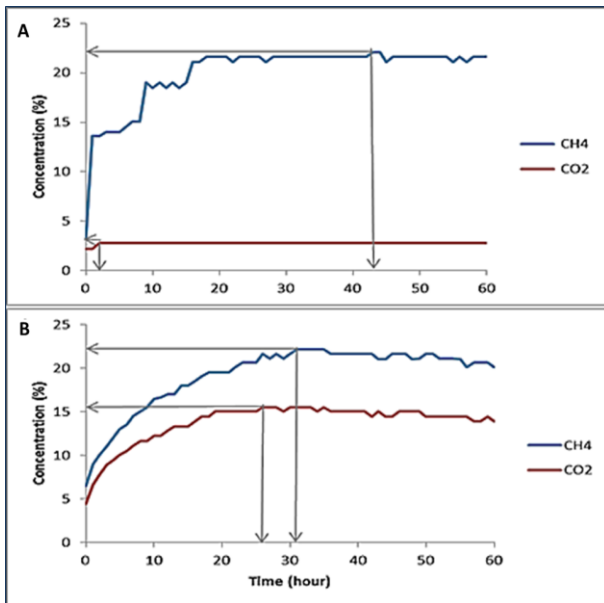


Figure (5): Recharge characteristics of CH₄/CO₂ in borehole 2 at Ruby Street on 12/05/2011 (A) and 16/07/2011 (B) in consequence.

To determine if ground-gas recovery is reproducible, the procedure was repeated 2 to 3 times in each borehole. The tests were conducted in two close boreholes at landfill site 1(Guide Lane). The recovery profiles from the purge and recovery tests conducted on 01/09/2011 in borehole 1 are represented by Figures. 6, 7 and 8 for CH₄, CO₂, and VOCs respectively; whilst those of borehole 2 conducted on same date are as shown in figures 9 and 10 for CH₄ and CO₂ only as VOCs displayed zero recoveries. Figures 11 and 12, on the other hand, represent the recovery profiles of CH₄ and VOCs in borehole 1 on 11/06/2013 during which CO₂ remained zero.

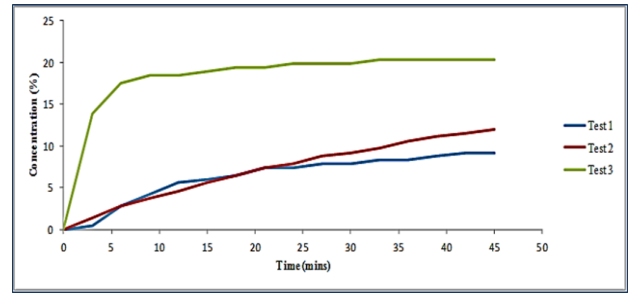


Figure (6): Recovery profiles of CH₄ (%) from three purge and recovery tests conducted in borehole 1 (1/09/2011).

As shown, Figures 6 - 8 represent the recovery profiles of CH₄, CO₂, and VOC respectively for 3 purge and recovery tests in borehole 1. For CH₄, tests 1 and 2 are reproducible and show a slower rate of recovery with the concentration much lower than in test 3 after 40 – 50 mins. The recovery profile of test 3 shows that the CH₄ concentration rapidly increases for the first 8 mins of recovery and thereafter remaining fairly constant throughout the remaining period of the test. The recovery profiles of each test for CO₂ are similar to those of CH₄ but the concentrations of CO₂ are much lower in comparison. Tests 1 and 2 are reproducible, just like that of methane. The recovery trend of VOC appears to be the opposite of those of CH₄ and CO₂. For test 1, the VOC concentration recovered to 4 ppm in no time and then increases to 7 ppm after approximately 4 mins. It then sharply decreases for about 8 mins to 1ppm and remains constant there for roughly 20 mins before dropping to 0. In test 2, VOC concentration recovered to 4 ppm as in test 1, but decreases to 1ppm after about 6 mins and remained there for roughly 8 mins before dropping to zero. The recovery profile for test 3 shows VOC concentration was dropped from 1 ppm to 0 in fewer than 5 mins.

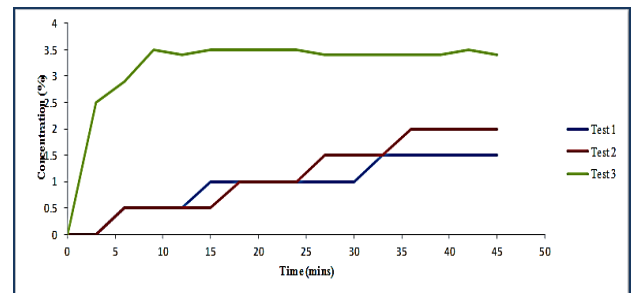


Figure (7): Recovery profiles of CO₂ (%) from three purge and recovery tests conducted in borehole 1 (1/09/2011).

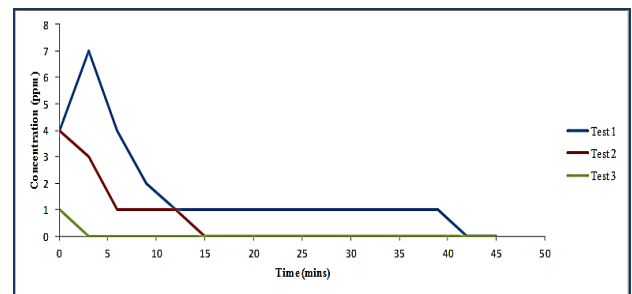


Figure (8): Recovery profiles of VOCs (ppm) from three purge and recovery tests conducted in borehole 1 (1/09/2011).

The recovery profiles of CH₄ and CO₂ for 3 purge and recovery tests conducted in borehole 2 (Ruby Street) are as shown Figures. 9 and 10, respectively. The recovery profiles of CH₄ are similar to those in borehole 1 except that in borehole 1; tests 1 and 2 are reproducible while in borehole 2, tests 2 and 3 are reproducible. In test 1, CO₂ concentration increased from 0 - 0.6% in 3 mins and remained fairly constant for 6 mins and then increased to 1.1% where it remained constant until the data was downloaded. Tests 2 and 3 displayed the same recovery profiles and therefore are reproducible. There was no recovery profile for VOC in borehole 2 as the concentration remained zero.

Figure 11 displays the recovery profiles of CH₄ for 3 purge and recovery tests conducted on 11/06/2013 in borehole 1. In test 1, CH₄ concentration recovered from 0 – 1.9% in 3 mins and then fairly increased to 33.3% and then remained fairly constant there until the end of the test. In test 2, CH₄ concentration increased from 0 – 5.7% in 3 mins and then kept increasing until it got 24.8% and remained constant there until the data was downloaded. In test 3, the concentration increased from 0 – 0.9% and remained constant for 21 mins before increasing gradually to 10.7%. Although the recovery of CH₄ concentration in test 1 is higher than that of test 2; both displayed similar behaviour as can be observed in the shape of their recovery profiles. The recovery profile decreased with an increase in the number of the test (that is, test 1 > test 2 > test 3). This behaviour of CH₄ in this borehole suggests that it is not being replenished continuously from the source and could be depleted with time.

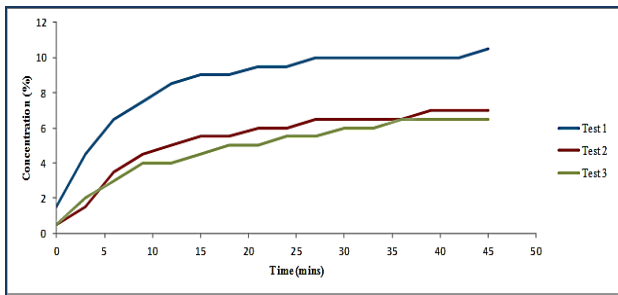


Figure (9): Recovery profiles of CH₄ (%) from three purge and recovery tests conducted in borehole 2 (1/09/2011).

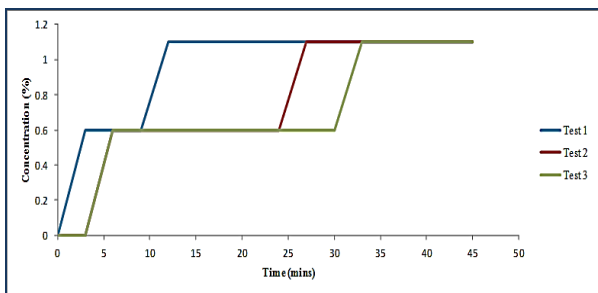


Figure (10): Recovery profiles of CO₂ (%) from three purge and recovery tests conducted in borehole 2 (1/09/2011).

The recovery profiles of VOC for three purges and recovery tests conducted on 11/6/2013 in borehole 1 is

shown in Figure 12. The first test shows that VOC concentration recovered to 7 ppm in no time and then increased to 21 ppm 3 mins later before dropping down to 10 ppm. It kept on going down until it got to 3 ppm and remained constant there till the end of the test. Just like the first test, the second and third tests also recovered in no time to 12 ppm and 10 ppm respectively. While tests 1 and 2 displayed the same recovery profile of VOC concentration; that of test 3 is of several other of magnitude higher than that of the first two tests.

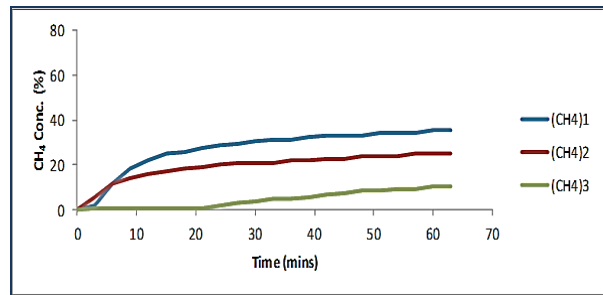


Figure (11): Recovery profiles of CH₄ (%) from three purge and recovery tests conducted in borehole 1 (11/06/2013).

Meanwhile, the behaviour of VOCs is exactly the opposite of that exhibited by CH₄ which decreased with an increase in the number of purging (Fig. 12). While it can be concluded that tests 1 and 2 were reproducible in this borehole; test 3 did not follow suit. The high concentrations of VOCs recorded after the third test could have been mobilized by the nitrogen gas injected into the borehole. Studies has also shown that the migration of CH₄ and CO₂ induces the migration of VOCs from contaminated sites (Katy *et al.*, 2009; Felice *et al.*, 2018) and therefore may be another reason.

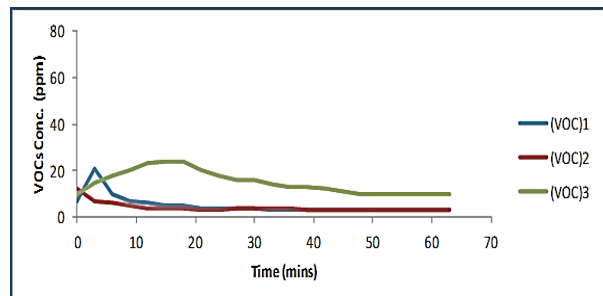


Figure (12): Recovery profiles of VOCs (ppm) from three purge and recovery tests conducted in borehole 1 (11/06/2013).

DISCUSSION

A cursory evaluation of the datasets obtained and presented in Figures 1 - 4 shows that the recovery of CH₄ concentration in Guide Lane was faster in September 2010 (autumn) than in May 2011 (spring), whilst in Ruby Street (Site 2), was faster in July 2011 (summer) than in May 2011 (spring). Generally, the CH₄ concentration recharge was fastest in July 2011 (summer) amongst all the months considered in the two sites. The rate of CH₄ recovery showed a relation with temperature where the recorded range was the highest

in summer and the lowest in spring (summer > autumn > spring). Seasonal changes in soil permeability, which is the ease at which gases, liquids, and plant roots penetrate or pass through bulk mass or a layer of the soil, could have been the reason for the observed behaviours of the gases (Sparks, 2003). This could be the reason for the observed behaviours of the gases. There is often high rainfall (water of very low salinity) in the spring season (March - May), which results in soil leaching thereby reducing soil permeability (Hillel, 2005). This is not the case with the summer (June - August) and autumn (September - November) seasons where rainfall is reduced and resulted in an increase in soil permeability. However, in the winter season, the pores of the soil are often blocked by snow that reduced soil permeability (Sparks, 2003). These imply that gas recovery should be faster in summer and autumn than in winter and spring seasons, which validates our findings. In similar studies done by Nwachukwu and Anonye (2013) and Nwachukwu and Nwachukwu (2020), they recorded the same observation in which the effects of changes in season and variations in gas production rate resulted in the variability in and emission of CH₄ and CO₂ concentration during the monitoring periods of the study.

No purge and recovery test was conducted in the winter; however, the range of recovery implies that it will be lowest in winter during which the ground is frozen thereby disconnecting the subsurface from atmospheric interaction. These findings also suggest ground-gas flux to constitute more risk in summer and autumn than in winter and spring (Nwachukwu and Nwachukwu, 2020).

Most of the observed irregular recovery of CO₂ concentration could majorly be due to its low concentrations in the investigated sites (Nwachukwu and Anonye, 2013). The low concentrations of CO₂ can be traced to the depths of the monitored boreholes which are mostly deep. This can be explained by the fact that the more CH₄ is produced in deep boreholes, due to their anaerobic nature, the more CO₂ is produced in shallow boreholes due to their aerobic condition (Holden, 2005; Nwachukwu *et al.*, 2019). This might be the reason for the high concentrations of CH₄. Furthermore, landfills are generally known to produce more CH₄ than CO₂ concentrations (Haro *et al.*, 2019; Zhang *et al.*, 2019).

The recovery profiles (Figures 5 - 11) of the gases for three purge and recovery tests show that the gases were reproducible; however, this was not consistent throughout the tests. Generally, unlike CO₂; CH₄ concentration was the most reproducible among the investigated gases. This further supports our earlier discovery on the effect of borehole depth on the rate of production and therefore recovery of CH₄ and CO₂ concentration. Moreover, the gases were more reproducible in June (summer) than in September (autumn) thereby validating our earlier finding that ground-gas recovery rate can vary from season to season and from

site to site.

The recovery profiles of VOC (Figures 7 and 11) show VOC concentration to recover in no time unlike that of CH₄ and CO₂. This could be due to the inherent ability of VOC to volatilize into the atmospheric conditions under normal temperature and pressure as validated by the works of Katy *et al.*, (2009) and Mentero-Mentoya *et al.*, (2018). This property of VOC makes it the most dangerous among the studied gases as it can get to the receptor faster than other gases. The concentrations of recovered VOCs were observed to be generally low and therefore validate findings in literature (Katy *et al.*, 2009; Musbau, 2009; Nwachukwu and Ugwuanyi, 2012; Nwachukwu and Uwa, 2018; Zhang *et al.*, 2019; Talbot and Card, 2019).

CONCLUSIONS

Purge and recovery tests to determine the recharge rate of ground-gases were not always completed within the length of a site visit (one day). This is because, sometimes, it took more than a day for the ground-gases to recover. Ground-gas recovery rate varied from season to season and from site to site. Apart from a change in season, another factor that could be responsible for variation in the recharge rate of the gases is the rate of gas production.

The purge and recovery test to determine whether ground-gas concentrations are reproducible were completed within the length of the site visit. The recovery profiles obtained from the tests varied enormously from borehole to borehole and in general, the VOC recovery profiles observed were very different from those of CH₄ and CO₂. For example, in borehole 1, the purge and recovery tests of CH₄ and CO₂ show similar recovery profiles to those of methane and carbon dioxide shown in the literature (Boult *et al.*, 2011). However, the reproducibility of the tests is questionable as it was observed that the recovery profiles of the two gases for tests 1 are of greater magnitude than their recovery profiles in tests 2 and 3. This, however, could be due to the flushing of a system of gas by test 1 giving lower concentrations in the recovery profile for tests 2 and 3 as was also observed by Boult *et al.*, (2011).

The recovery profiles of VOCs have no resemblance to those of CH₄ and CO₂ as VOC concentration generally recovered much faster than their sampling rate. It is, therefore, suggested that the sampling frequency of the Gasclam be increased to match the frequency of recovery of VOCs. The time it took each of the VOC's recovery tests to go down to zero is in order of test 1 > test 2 > test 3 (Fig. 1). This suggests that VOC concentration in borehole 1 is low. This also might be the reason they showed no recovery in borehole 2, given the proximity of the two boreholes (~ 2 meter apart). Therefore, the irreproducibility of VOCs in the boreholes may not be unconnected with their trace availability.

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