Analysis of landfill gas migration by use of autonomous gas monitoring platforms

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Abstract: Autonomous gas sensing platforms have been developed to facilitate the long-term continuous monitoring of landfill gas concentrations. The analysis of a municipal landfill site in Ireland forms part of an on-going collaboration with the Environmental Protection Agency in monitoring the migration of greenhouse gases, i.e. methane and carbon dioxide, emanating from the landfill site. Target gas concentrations were automatically recorded via infrared gas sensors calibrated for the respective gases, with this data being logged remotely every six hours to a central base-station. The autonomous platform with its web-based portal interface provides a flexible alternative to the existing labor-intensive, manual monitoring routines. Frequent occurrences of 70% v/v methane and 6% v/v carbon dioxide were substantially in breach of the regulatory limits of 1.5% v/v and 1.0% v/v, respectively. These excessive levels of gas migration were analyzed with respect to SCADA flare data, on-site measurements and meteorological data.

Keywords: landfill gas; autonomous measurement; remote monitoring; gas migration factors

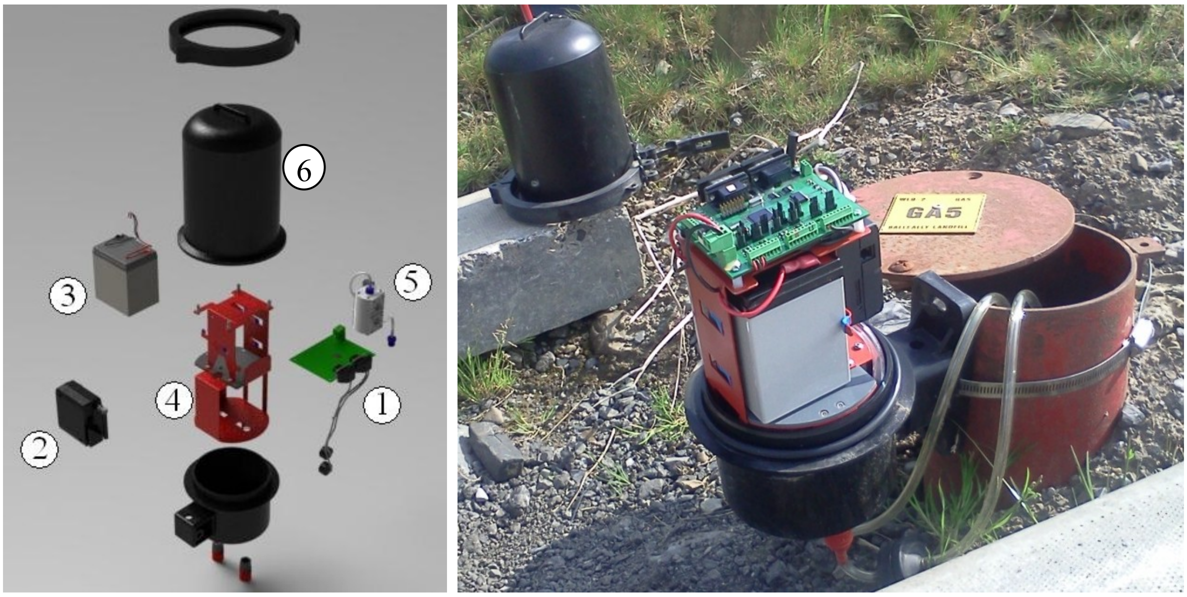
1. Introduction

The handling and utilization of landfill gas is a key feature of landfill site management. To this end, autonomous platforms enabling the real-time monitoring of gases in the environment have been developed. Such monitoring is applicable to the mandatory licensing terms of landfill sites [1], as well as being reflective of the increased awareness of environmental monitoring dictated by a recent European directive [2]. Landfill gas, predominantly comprised of methane (CH_4) and carbon dioxide (CO_2), is produced from the decomposition of biodegradable waste in an anaerobic environment. A number of complex factors can influence the rate of gas generation, including the type of waste, soil conditions, the age of landfill site, the effectiveness of gas extraction and meteorological dependencies (rainfall, barometric pressure and tidal activity) [3-4]. Weather conditions can have a substantial effect on landfill gas generation and migration. Rainfall reduces the permeability of the soil, inhibiting surface emission and thus potentially increasing gas migration. A reduction in barometric pressure can induce a differential pressure between the upper and lower layers of the waste body, and this pressure gradient can induce a flux that results in an increase in gas migration. Tidal activity may influence gas migration in coastal landfill sites where rising tide heights may induce a gas flux in the waste body. Given that meteorological effects are linked (*i.e.*, a decrease in barometric pressure is often accompanied by rainfall), the contributory effect of weather on gas migration can be complex and difficult to predict.

The high greenhouse gas potencies of methane and carbon dioxide are specifically targeted in internationally-derived agreements regarding environmental sustainability [5]. Moreover, methane is extremely flammable when present in the 5–15% v/v concentration in air and carbon dioxide is a suffocation hazard for people in nearby low-lying dwellings. Therefore, these gases can have critical implications on both a global and local scale; this has been dramatically highlighted in a fire that recently raged through a dormant landfill in the Irish midlands, costing in the region of €30 million to extinguish and generating substantial national controversy [6]. In addition to the mitigation of human risk arising from gas emissions, the monitoring of the gas generation and migration is beneficial for efficient landfill site management. Regulated landfill sites are constructed with a gas extraction system consisting of a network of pipes running through the waste body [1]. To ensure thorough effectiveness of the extraction system, gas concentration levels are monitored at borehole wells located around the perimeter of the landfill site. Gas concentration levels at these locations are subjected to necessarily low threshold limits of 1.0% and 1.5% v/v for CH_4 and CO_2, respectively [1]. Current practices involve gas levels readings being submitted to the Irish Office of Environmental Enforcement (OEE) on a monthly basis. These readings are often manually acquired using a portable sensing device, such as the GA2000 Plus unit (Geotechnical Instruments Ltd, UK). Clearly this is a labor-intensive process requiring travel over difficult terrain and manual recording of gas concentration readings at that particular sampling occasion. Consequently, measurements have been taken at extended intervals, typically once per month, and with limited spatial and temporal coverage. These limitations have been addressed by the development of autonomous gas monitoring platforms. Predecessor prototype systems have been proven robust and reliable for medium- and long-term field trials [7, 8]; the monitoring platform described herein is a progression towards greater functionality and commercial-viability. Specifically, this paper presents the findings arising from the long-term continuous monitoring of a borehole well in a solid waste landfill site. Further analysis has been conducted with regard to the association of the gas migration data with factors such as gas flow properties within the landfill's extraction system and local weather conditions. The identification of factors contributing to gas generation and migration affirms the inherent value of the data from the perspectives of both landfill site management and license regulation, thus contributing to more effective gas extraction and utilization.

2. Monitoring technology

For the CLARITY autonomous gas monitoring platform, components are housed within a robust casing suitable for long-term outdoor deployment as shown in Figure 1. The compact frame and rugged nature of the platform casing, rated to IP68, permits the platform to endure long-term deployment in inhospitable environments with continual successful operation.



(i) (ii)

Figure 1. Autonomous landfill gas monitoring platform, (i) exploded view, (ii) as deployed on borehole well (with casing removed). Components: (1) control board, (2) GSM module, (3) battery, (4) extraction pump, (5) sampling chamber and sensors, (6) protective casing

The monitoring operation is controlled via a custom programmed MSP430 microcontroller (1), managing the gas extraction (4), gas sampling (5) and data communication (2). The power supply (3), a 12V 5Ah lead acid battery, currently supports deployments of of up to 10 weeks at a sampling frequency of four sample cycles per day (approximately 300 separate sample cycles). This represents a 120-fold increase in sampling capability compared to that of existing regulatory methods. A SKC Grabair pump (SKC Inc., 222-2301) extracts a sample for two minutes at 0.6 L/min from a depth of 1 meter in the borehole well. The principal components of landfill gas, carbon dioxide (CO_2) and methane (CH_4), are measured by infrared gas sensors (Dynament Ltd. IRCEL-CO2 and IRCEL-CH4). These sensors have a proven long-term reliability as demonstrated by a number of extensive deployments (up to 13 months) [8]. The data acquired from these sensors is encoded using a Huffman algorithm to enable the full dataset from the full sampling routine (40 points) to be written and sent in SMS format via GSM communication (Siemens MC35iT) to a central base-station located offsite. As a backup, all harvested data are stored locally on an onboard flash memory chip. At the central base-station, the communicated data are parsed and placed onto a database, whereupon email alerts are sent to stakeholders. In addition, all present and historical sampled data are accessible to the relevant authorities and site personnel via a web-based visualization application. Anonymized data can be publicly accessed at http://kspace.cdvp.dcu.ie/public/colum/gasMonitor/. A more comprehensive description of the platform technology has been described in a previous publication [9].

3. Monitoring results

The work described in this paper was commissioned by the OEE to monitor excessive levels of landfill gas (particularly CH_4) observed in a particular borehole well located at the perimeter of an active solid waste landfill facility. This facility has been in operation since 1971, with the current waste license dating from 2000 permitting the operation of a non-hazardous landfill. The actual name and location of this landfill sites cannot be divulged in this paper due to the socially sensitive implication of the data, though the site is in the Republic of Ireland and has a valid waste permit in compliance with EPA and OEE regulations. A mutual understanding existed between the OEE, the CLARITY team and the facility management that the data collected was intended for research and feasibility studies only.

The borehole well in question was situated at the northern boundary on Cell 4 which had commenced filling in October 2006. The autonomous gas monitoring platform was deployed on this borehole well from February 4th 2011 to October 16th 2011. Comprising of four samples per day, this deployment has spanned 253 days totaling 890 data points collected (some data points were dropped due to system downtime). The full dataset is displayed in Figure 2.

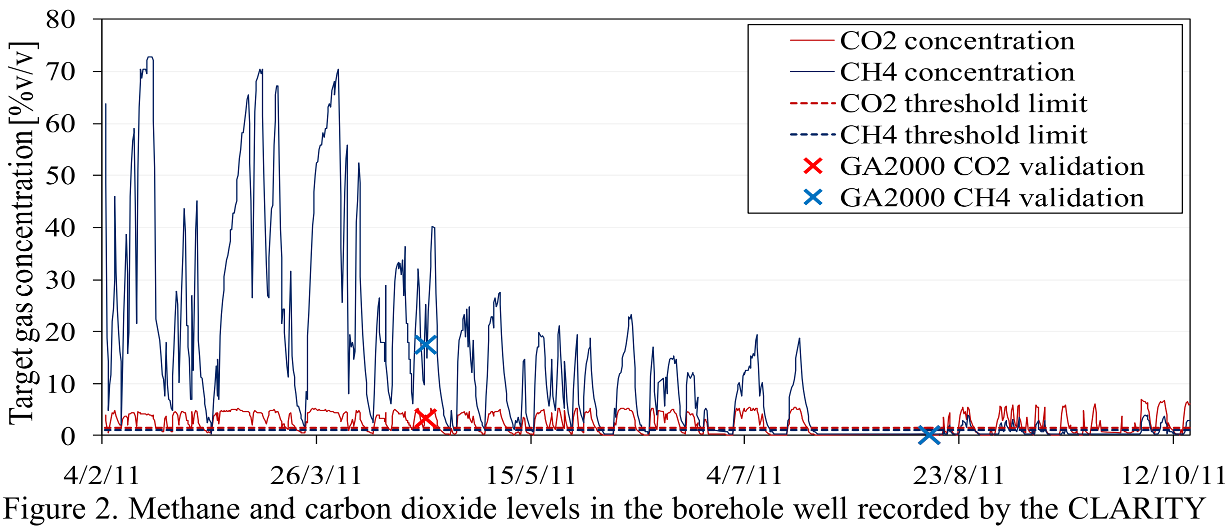


Figure 2. Methane and carbon dioxide levels in the borehole well recorded by the CLARITY autonomous monitoring platform

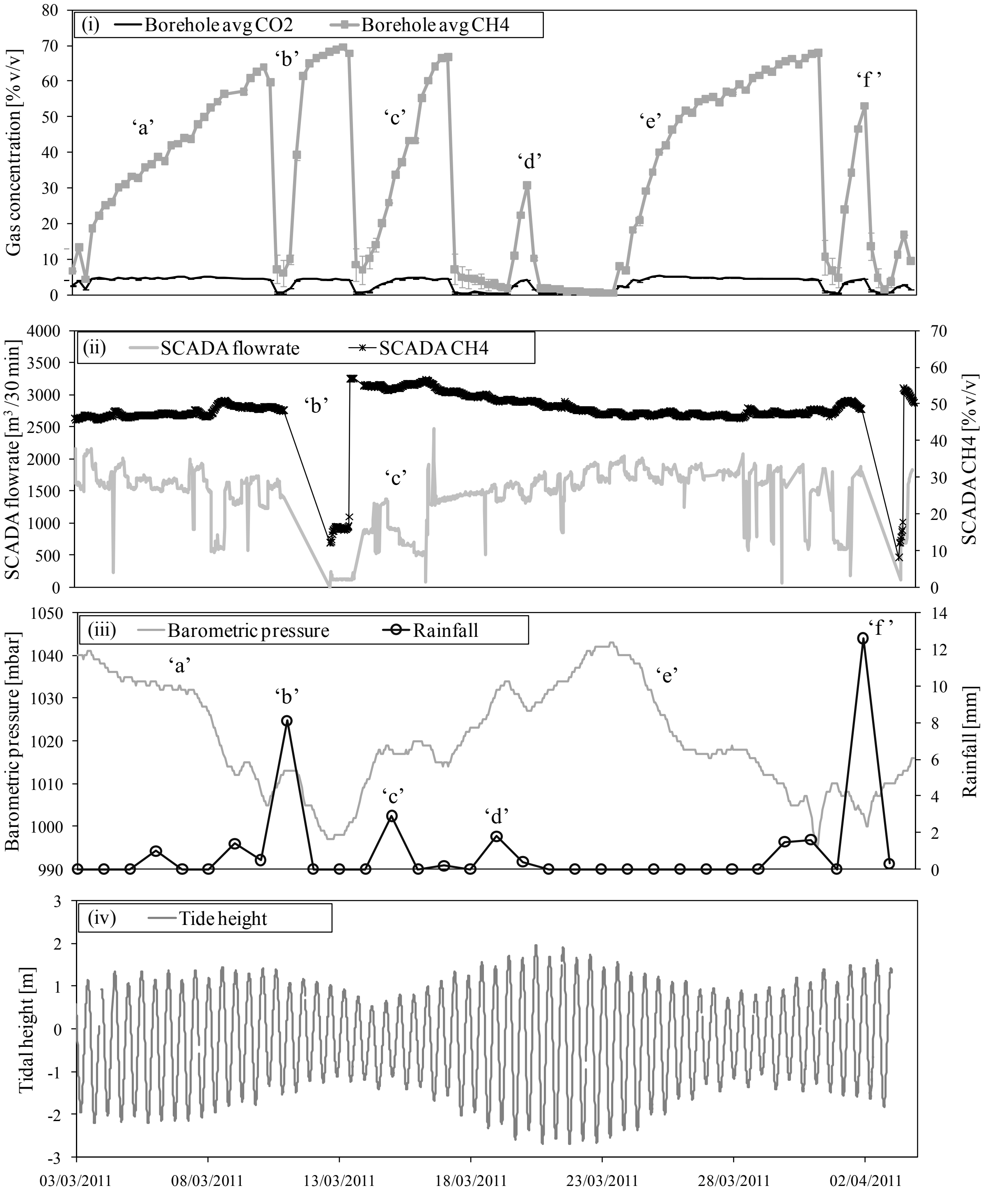


Figure 3. Subset of monitored data for investigation of contributory factors, (i) borehole gas CH_4 and CO_2 levels as measured by the CLARITY autonomous platform, (ii) engine inlet flow-rate and CH_4 levels as measured by the SCADA system, (iii) barometric pressure and rainfall levels as measured at local weather stations, (iv) tidal conditions as measured at a nearby coastal station

In order to investigate the contributory factors that influence landfill gas behavior in order to explain such high levels of gas concentration, the CLARITY team acquired information pertaining to the landfill gas field, local weather conditions and tidal activity.

Data from the SCADA (system control and data acquisition) system monitoring the gas extraction/flaring included CH_4 concentration (in % v/v) and volumetric flow rate (m^3 per 30 min) at the inlet to the on-site engine. Unfortunately, a suspected transducer error resulted in no SCADA CO_2 measurements within this time period. An inversely proportional relationship is evident between SCADA flow-rate and SCADA CH_4. This is to be expected: a greater flow rate implies that the landfill gas volume is more rapidly extracted, thus resulting in a decrease in CH_4 concentration. Daily high-low levels are evident (typically low from 23:00 to 9:00) that related to shift work hours. Abrupt variations observed in the flow-rate correspond to extraction system downtime.

Weather data was acquired from the on-site weather station (provided by landfill management) and from a nearby weather station (provided by the national weather forecaster Met Éireann via www.met.ie/climate/daily-data.asp). Tidal data was obtained from the Irish Tides Observations archives (http://www.marine.ie/home/publicationsdata/data/imos/imositobservations.htm).

For the purpose of this paper, one month's duration (corresponding to March 3rd to April 3rd) of data from the aforementioned sources is displayed in Figure 3. This subset of the data was selected based on the multitude of events that occurred within its duration. These events are annotated for discussion as follows:

a) Steady increase in borehole CH_4 up to 65 % v/v while CO_2 remains steady at 5 % v/v.
   No significant change in SCADA data.
   Initially gradual then more rapid decrease in barometric pressure. The peak in borehole CH_4 coincides with trough in barometric pressure.
b) Rapid decrease followed by rapid increase in both borehole gases CH_4 and CO_2.
   Reduction in SCADA values reflecting extraction system downtime.
   Fluctuations in barometric pressure with an occurrence of heavy rainfall.
c) Rapid decrease followed by more moderate increase in both borehole gases.
   Fluctuations in SCADA data indicating abrupt changes in operation of the extraction system.
   Overall increase in barometric pressure with more moderate rainfall.
d) Transient peak in borehole gases up to 30 % v/v CH_4 and 5 % v/v CO_2.
   Small periodic fluctuations in SCADA data with slight increase/decrease in flow-rate/engine CH_4, respectively.
   Overall increase in barometric pressure with more moderate rainfall.
e) Substantial increase in borehole gases, initially at a rapid rate then at a lesser rate.
   Continued fluctuations in SCADA data, particularly flow-rate with abrupt changes being observed.
   Substantial decrease in barometric pressure, initially at a rapid rate then at a lesser rate.
f) Rapid decrease followed by rapid increase in both borehole gases.

Intermittent SCADA values indicating extraction system downtime.
Net increase in barometric pressure, moderate to heavy rainfall occurred.

4. Discussion

To observe the full monitoring duration as a whole, as shown in Figure 2, it is evident that the high gas concentration levels (> 50 % v/v CH_4) in the early stages of the deployment (February to April) disappears towards the latter half of monitoring. Similar behavior, where substantially high levels of landfill gas had appeared and subsequently disappeared, had been noted by regulatory checks on this borehole well in previous years. This led to this study being commissioned on behalf of the OEE, with particular interest in indentifying the environmental conditions that induce landfill gas fluctuations. These environmental conditions included general information on the landfill gas field (as obtained from SCADA), weather conditions (barometric pressure and rainfall) and tidal conditions (a concern raised by the OEE as the landfill site lay close to an estuary).

Given the extensive time duration of this analysis, a subset of the data is displayed in Figure 3. Over the dataset duration, CO_2 does not exceed much over 5 % v/v while CH_4 reaches as high as 70 % v/v. The levels of both CH_4 and CO_2 had a highly fluctuant nature with rapid changes in concentration being observed. In general, both gases were approximately synchronized, i.e., they rise and fall together at approximately same time. This suggests that the variation in gas level was related to the flare extraction rate, *i.e.* the change in extraction rate reduces the volume of gas migration thus decreasing both components of CO_2 and CH_4 simultaneously. Ideally, this should not be the case; the gas content in the borehole well represents that which was not captured in the extraction system to be processed by the flare/engine. This is evident for the most part - for the majority of events, there is no correlation between borehole gases and SCADA data. However, on occasions such as events 'b' and 'c' shown in Figure 3, a link between borehole gases and abrupt changes in flow-rate becomes apparent, i.e. two rapid increases in SCADA flow-rate correspond to dramatic reductions in borehole gases before and after event 'c'. It is a reasonable assumption that the substantial increase in extraction reduces the overall volume of gas in the waste body, the flux of which could result in a reduction of gas in the borehole well. By the same reasoning, the low levels of SCADA flow-rate during event 'c' are conducive to increased borehole gas levels given that less extraction implies more gas is left in the waste body.

There is an apparent link between borehole gas and meteorological conditions, although no strong correlations can be defined given the complex interaction between weather and landfill structure (*e.g.*, water run-off, soil soakage and permeability, water table height *etc.*). There appears to be an inverse relationship between barometric pressure and borehole gas levels – as barometric pressure decrease, borehole gas levels increase at a similar rate. This is evident in events 'a' and 'e' where the trends and occurrences of peaks and troughs matched inversely to barometric pressure. However, this is not always consistent, *e.g.* increases in borehole gases in events 'c' and 'd' are observed during increasing barometric pressure although this may have been compromised by rainfall occurring at the time. The relationship between borehole gas levels and rainfall is consistent with previous findings [8] with borehole gas levels tending to increase during or shortly after heavy rainfall, see events ‘b’, ‘c’, ‘d’ and ‘f’.

Before this study was conducted, tidal conditions were initially suspected as being a cause of excessive borehole gas levels due to the landfill site’s proximity to an estuary – it was reasoned that the rising and falling water table would induce landfill gas migration. Despite these reasonable suspicions, there appears to be no clear correlation between borehole gases and tides neither in terms of the oscillating period or variation in tidal height over the course of the dataset. Therefore, tidal conditions do not seem to influence borehole gases to the same extent as observed with extraction and weather conditions in this study although this conclusion needs to be verified in further studies of this type.

5. Conclusions

An autonomous gas sensing platform was developed for long-term continuous monitoring of landfill gas. Gas migration was successfully monitored in an 8-month deployment (February to October 2011) on a perimeter borehole well in an active landfill facility. Gas levels were observed to be substantially in breach of the regulatory threshold limits; the full extent of these breaches would not have been detected using the existing monthly sampling regime. In contrast, the ability of the deployment to provide data at a much higher sampling rate (4 per day), together with the ability to remotely access real-time data through the web-interface enabled the EPA enforcement officers and landfill facility operators to more fully characterize the transient nature of landfill gas behavior.

Admittedly the associations discussed in this paper between landfill gas and extraction/weather/tides is somewhat tenuous – clear trends observed for some events are seemingly contradicted in other events. Indeed the authors are hesitant to draw any strong conclusions due to the complexities of the interrelationships between gas generation and permeation, gas extraction, general site operation, and environmental/weather conditions. In actual fact, landfill gas behavior is governed by the many factors. However, it can be stated with a substantial degree of confidence that:

- A ramp up in extraction flow-rate will tend to reduce landfill gas content in perimeter borehole wells
- An increase in borehole gas tends to be associated with an abrupt decrease in barometric pressure and/or heavy rainfall.

The identification of the factors that contribute towards variations in landfill gas is no easy task. While the contributory effect of various factors may be studied under controlled laboratory conditions, it is not practically possible to arrive at clear-cut correlations between landfill gas behavior and individual factors in a functioning high-capacity landfill facility. Instead, one must strive to annotate events occurring in landfill gas behavior with reasoned associations to on-site conditions. In this way, a greater understanding of the dynamics of landfill gas generation and migration is attained; this leads to better informed decisionmaking and operational practices in managing landfill gas. The availability of high quality, long-term data such as provided by the sensor platform in this study will play a key role in unraveling the complex interactions between site operations, weather and local environment that together influence gas permeation behavior on landfill sites.

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