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research bulletin

CL:AIRE research bulletins describe specific, practical aspects of research which have direct application to the characterisation, monitoring or remediation of contaminated soil or groundwater. This bulletin describes how continuous monitoring, rather than a periodic measurement approach, can reduce uncertainty in ground-gas risk assessment.

The Utility of Continuous Monitoring in Detection and Prediction of "Worst Case" Ground-Gas Concentration

1. INTRODUCTION

Many environmental parameters show high temporal variability, therefore, their representative measurement requires multiple measurement. In the case of ground-gas monitoring, flaws in the existing multiple measurement approach have been identified in the literature and are subject to continuing correction (e.g. Wilson *et al.*, 2009).

The two underlying causes of these flaws are that, whilst accurate quantification of risk requires accurate measurement of ground-gas concentration and of ground-gas fluxes:

1. Both are likely to be temporally variable,

2. Neither is measured directly:
- concentration of gas in the ground is inferred from periodic (weekly - monthly) sampling of gas accumulated within a borehole
- flow of gas from the ground is inferred from periodic measurement of gas flow from the same borehole. The relationships these inferences are based upon will be highly site-specific and time-dependent.

This bulletin aims to show how the impact of these can be reduced by continuous monitoring, thereby reducing uncertainties in ground-gas risk assessment. To this end, it is first necessary to understand the general principles of current ground-gas risk assessment.

The conceptual site model in ground-gas risk assessment - The latest guidance encourages a risk-based approach consistent with CLR 11 (Defra and Environment Agency, 2004) comprising a preliminary risk assessment (PRA), generic quantitative risk assessment (GQRA) and where appropriate a detailed quantitative risk assessment (DQRA).

The PRA requires the production of a well designed initial conceptual site model (ICSM), which is subsequently used to inform the needs of the intrusive site investigation. Throughout the investigation and GQRA/DQRA the ICSM is continuously calibrated, as the level of understanding increases and the need for further investigation is assessed, the importance of this iterative process is clearly set out in BS 8485 (BSI, 2007). A Conceptual Site Model (CSM) developed this way is used to determine the current ground-gas regime and to predict how this will change in the future, in the context of source-pathway-receptor linkages.

Monitoring wells are the preferred method to sample sub-surface gas, therefore, the ICSM and the sensitivity of the end use will guide:

i) the number and location of monitoring wells,
ii) the position of their response zones.

Previous guidance has suggested minimum numbers of monitoring rounds (CIRIA Report 150 (Raybould *et al.*, 1995)); however, in later guidance this is recognised as potentially dangerous, as guidance may be interpreted as prescription and thereby the main objectives of data collection may be overlooked. CIRIA Report C665 (Wilson *et al.*, 2007) states, *"However, focusing on a minimum number and period of readings can be misleading and the key should be that the monitoring period for a specific site covers the "worst case" scenario"*.

After the initial investigation is completed, the information should be reviewed in the context of the CSM and, if there is still a lack of understanding, further investigation may be needed. This approach, in which all available information is incorporated into decision making, will always be the most appropriate when prediction of the behaviour of a large complex system - typically all environmental systems - is required. The guidance provides a framework within which quantitative and qualitative data can be combined, and physically based and empirical models mixed through mutual calibration. Much of this procedure is implicit in the production of the ICSM and CSM, the requirement for which is heavily emphasised in the guidance.

In the investigation of other environmental systems for both engineering and research purposes, technological advances have been employed to allow monitoring to become more extensive and intensive. The resultant high resolution data have then been able to reduce uncertainty in prediction by providing calibration data for physically based models and enhanced datasets for empirical models. Incorporation of similar monitoring and the resultant data into the procedure for ground-gas risk prediction should also be able to reduce uncertainty.

As the price of devices for unmanned, secure (in borehole) continuous gas concentration measurement is now low enough for their extensive deployment this bulletin will:

- support the latest guidance by illustrating variability in ground-gas concentration and the influence of environmental factors on this variability,
- show how continuous gas concentration monitoring and the resultant data can be incorporated into the assessment procedure described in the latest guidance.

2. RISK ASSESSMENT AND "WORST CASE" GROUND-GAS CONCENTRATION

In order to recognise how the ability to collect gas concentration data at much increased temporal resolution can be applied within the framework of current guidance, it is first necessary to show explicitly how the guidance deals with temporal variability. As far as risk assessment is concerned the variability of ground-gas concentration/flow over time has implications for the two related tasks of:

- determining representative gas concentration,
- calculating risk posed by gas.

The guidance responds to the latter by treating the risk as a function of a single occurrence of the "**worst case scenario**" with respect to gas concentration/flow, pathway and receptor, rather than any sort of time-weighted function. The representative gas concentration/flow is therefore the "worst case" which is either a maximum value recorded or a record that an unacceptable level was exceeded. Much of the guidance is then concerned with ensuring determination of the maximum value or whether a value is exceeded. To this end current guidance directs that a sampling programme be designed that is likely to **detect** the "worst case" and, given the possibility of this failing, that the programme be used in conjunction with the CSM to **predict** the "worst case".

To improve the likelihood that "worst case" is detected, guidance specifies that a series of measurements should be made over a period at intervals of anything from weekly to monthly. However, it is also recognised that these sampling frequencies may not be sufficiently high to give a reasonable likelihood of observation of the "worst case" within a reasonable period. To improve the probability of measuring the "worst case" the ground-gas sampling programme is stratified by consideration of those factors known or thought likely to influence production/migration.

These factors are well documented in the NHBC guidance (Boyle & Witherington, 2007) and in summary are:

(i) meteorological conditions - atmospheric pressure, rainfall, frozen ground, temperature, wind,
(ii) ground conditions - geology, vegetation, anthropogenic activity,
(iii) hydrogeology and tidal effects.

As each of these has a different degree of control on gas production/migration and different temporal variability, the CSM must be used in determining the necessary allocation of resources for their inclusion in the sampling programme. As atmospheric pressure typically changes on a timescale of hours and is seen as a principal driver for gas migration, sampling contingent on its changes is specified quantitatively in guidance (data should be collected when the atmospheric pressure is low and falling), whilst other controls are not.

Given that both regular and stratified sampling may still fail to coincide with the "worst case", Section 10 of the NHBC guidance states, *"monitoring outside of the worst case temporal conditions may allow for a prediction of the ground-gas regime at the potential worst case temporal conditions to be made."* Such prediction relies on: recognition of a relationship between ground-gas concentration/flow and at least one other environmental variable, and the extrapolation of that relationship. The same guidance recognises that *"predicting the ground-gas regime during the possible worst case temporal conditions that a site may experience is not straightforward, as the ground-gas regime will vary significantly from site to site with copious possible responses and variations."*

Having recognised why and how guidance requires "worst case" to be established, it is now possible to describe ways in which the inclusion of continuous monitoring can reduce uncertainty in its **detection** and **prediction**. To this end continuous data have been collected from sites with different waste types, geology, hydrogeology and over varying environmental conditions in order initially to illustrate:

- the variability of ground-gas concentrations and flow (see Box 1),
- the dependence of ground-gas concentration on environmental variables.

Box 1

Representative flow measurement?

At the receptor risk from CH$_4$ will be a function of concentration (explosive limits are defined in terms of concentration), however, along the pathway concentration and flow may not be positively correlated and that there is a requirement to explicitly measure flow was identified by Wilson & Card (1999). High resolution data clearly illustrate this inadequacy of concentration measurement alone; Figure 1 shows data from a borehole beyond a landfill perimeter which had been shown in monthly sampling to have a 1-2% CH$_4$ concentration. However, automated hourly sampling and 4 hourly venting (by valve opening) of the borehole showed gas concentration fell from 1.8 to 0% within a few days, indicating that gas flow was very low. Flow and concentration are now both required to be input to the CSM in order to assess risk.

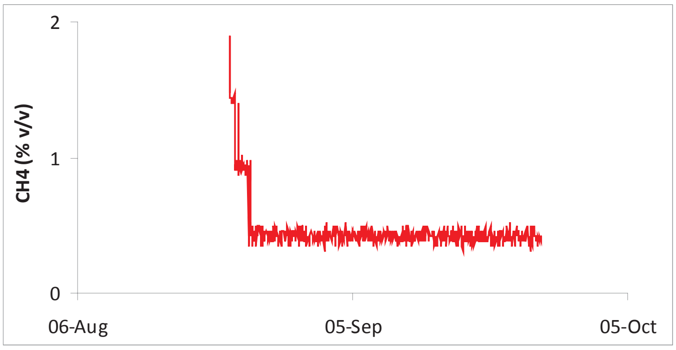

Figure 1. Declining gas concentration in a continuously monitored and periodically vented borehole.

Theoretically, flow measurement could have identified the possible false positive derived from concentration measurement at the borehole in Figure 2. However, the usual practice of measuring instantaneous flow at the same bi-weekly intervals as concentration measurement is itself subject to similar dependence on sampling interval. This concern is implicit in NHBC guidance (Boyle and Witherington, 2007) about making flow measurements in boreholes. If boreholes are left open atmospheric air may mix with the headspace and concentrations may be below detection limits, therefore, gas valves should be left open where flow rates are high and closed where flow rates are low (in this case, stratification may occur, which should be combated by recirculation of the ground-gas during sampling) (Table 10.4 in Boyle and

Witherington, 2007). However, whether a borehole is open or how often it is opened will itself cause the flow to vary.

Flow from a closed borehole will be zero and whilst closed gas may build up. The flow on opening the valve will depend on both the length of time for which it was closed and for how long it is open before the measurement is made. Consequently, instantaneous flow measurements are at best only useful for showing site-specific changes and only if the consistency of the sampling programme is strictly maintained.

Purge and Recovery Tests

The capability to collect high temporal resolution concentration data allows a more reliable characterisation of gas flow. The approach is that used by hydrogeologists in characterising aquifer productivity in which the fluid level in a borehole is perturbed and the recovery period is monitored.

With a continuous gas monitoring device, a small N_2 gas cylinder and a flow meter, recovery profiles are easy to collect. Ground-gas concentration is measured and then N_2 is injected into the borehole, either 3 times the volume of the borehole or until the concentration of ground-gases falls to zero. The gas concentration recovery is then monitored at an appropriate sampling frequency (every few minutes). Examples of data collected in this way (Figure 2) show the recovery profiles are:

1. *characterisable in a reasonable amount of time, i.e. a few hours - the length of a site visit,*
2. *reproducible in a borehole - the test was repeated on the same borehole and gave the same recovery profile,*
3. *distinct between boreholes, even in those otherwise identical - two boreholes with no recorded flows were both shown to contain 10% v/v CH_4, yet following purging the recovery rates are very different.*

Therefore, the method is a practical, reliable technique for characterising boreholes.

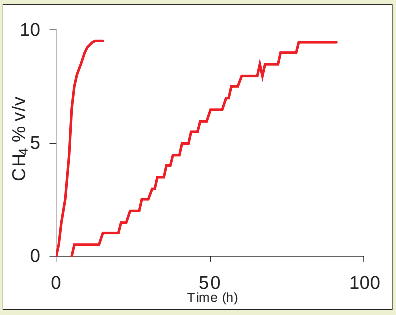

Figure 2. The recovery of gas concentration subsequent to purging to zero concentration with nitrogen; shown for two different boreholes.

Similar characterisation has been previously alluded to in guidance:

- *three full changes of the well volume was recognised (CIRIA 131, taken from Wilson and Haines, 2005) as a requirement for a representative gas sample.*
- *guidance has suggested how recovery profiles can be used to calculate ground-gas flow rates (Godson and Witherington, 1996) particularly when flow rates are low (Boyle and Witherington, 2007).*

But, this type of characterisation can now be used much more extensively.

3. DETECTION OF "WORST CASE"

To maximise the probability of detecting "worst case" concentration the sampling interval should be as short and the monitoring period as long as possible. However, resource availability requires that limits are put on both and therefore tables are provided in current guidance to help determine monitoring period and number of visits during the period (Tables 5.5a and 5.5b CIRIA Report C655 (Wilson *et al*., 2007)). Failures to detect "worst case" that arise from insufficiently short sampling interval are **interpolation errors,** and from insufficiently long monitoring periods are **extrapolation errors.**

In Figure 3 a selection of datasets, each collected at hourly intervals (see **Box 2**) from boreholes on a range of sites, shows gas concentration to be variable. This clearly supports the requirements of guidance for repeated sampling. Furthermore, the reliance on a CSM in decision making is supported, as the variability shown in this small selection is sufficient to demonstrate that detection of "worst case" will remain uncertain in typical weekly / monthly sampling programmes.

Box 2

What sampling frequency equates to continuous sampling?

Sampling is effectively continuous when at sufficiently high frequency to match that of the variability of the parameters measured. Investigations in which a 15 minute sampling was indistinguishable from hourly suggest that the latter is sufficient to fulfil this requirement. Hourly sampling is, therefore, referred to as "continuous" throughout this bulletin.

However, it should be noted that in one dataset collected at 15 minute intervals large concentration changes were detected between samples. This may only be an artefact of gas circulation within the borehole induced by rapid sampling and is subject to further investigation.

"Worst case" has been detected by hourly sampling over monitoring periods of 9-46 days in each of the datasets; in that concentration was shown to exceed 1% CH_4 at some time. Random sampling, however, is likely to fail to coincide with "worst case" concentration and thereby give a false negative. The probability of such failure is clear from the concentration duration curves which show that a 1% CH_4 concentration is exceeded for: 1, 10, 20, 60, 95% of the time in Figure 3A-E respectively. Therefore, for example, at the site for which Figure 3A is drawn there is only a 1% chance that random sampling would detect "worst case". This plotting of data in magnitude rather than time order, is commonly used in hydrology as flow duration curves for characterising rivers and making flood risk calculations.

Whilst it is clear that sampling at temporal resolution of 1 hour rather than weeks can prevent interpolation errors and is a useful addition to investigations, it cannot in itself prevent errors in extrapolation. To minimise such errors, the deployment period should be as long as possible; in practice this will depend on the objectives of the monitoring which may be:

- as a prelude to change of use (redevelopment, surrender of licence) and therefore time limited,
- monitoring an ongoing hazard (active landfill perimeter).

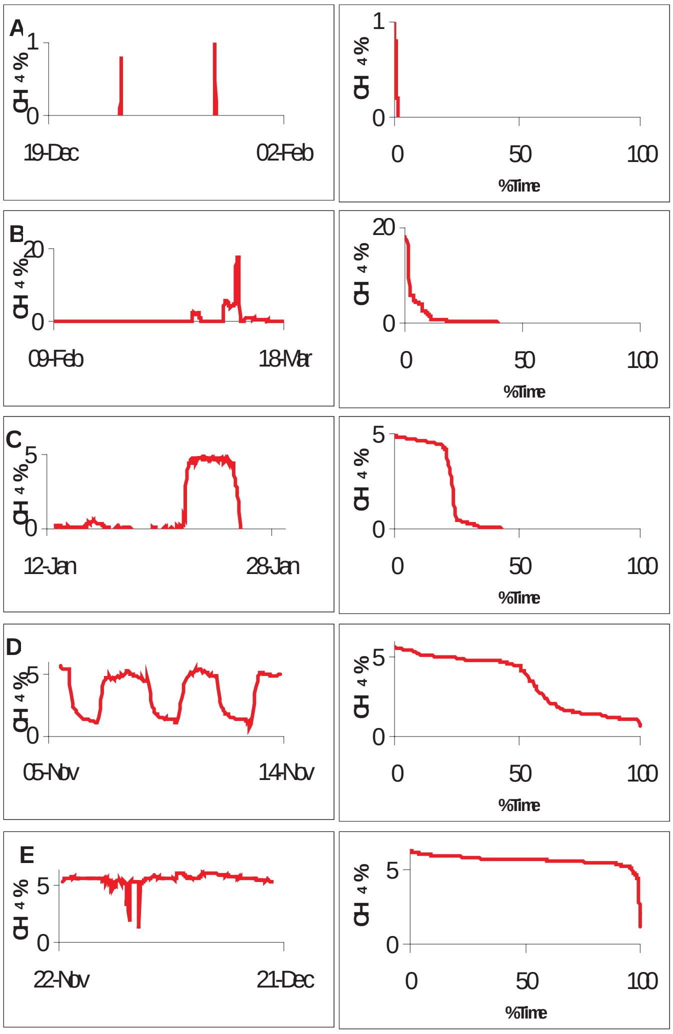

Figure 3 (A-E). Paired graphs of CH_4 concentrations in boreholes at 5 different sites, left graph shows variation of concentration with time and right graph shows the gas concentration duration. The percentage of time that concentration exceeded a 1% trigger value can easily be read from the right hand graph.

In both cases, continuous deployment would provide the highest probability of detecting "worst case", however, limited resources may preclude this. At this time insufficient data of high temporal resolution have been collected to allow relationships to be defined between the length of a continuously monitored period and the probability that an extrapolation error may occur. Consequently, it is most appropriate to use continuous monitoring as a support to, and within the context of, present guidance.

Given the existing recommendation to make multiple measurements and (therefore) multiple visits, it may be most efficient that continuous monitoring occurs for at least the period between the first two scheduled visits. The period of continuous monitoring may then curtail the need for subsequent visits. However, if unacceptable concentrations are not detected during this period and the period cannot be extended, the high resolution characterisation of the gas regime will be useful in predicting when and whether such concentrations are likely to be reached - as discussed in the next section - and thereby in designing any subsequent periodic monitoring programme.

4. PREDICTION OF "WORST CASE"

Even with continuous monitoring the site-specific gas concentration record may be too short for sufficient confidence that extrapolation errors have been avoided, therefore, "worst case" must be predicted rather than detected. The reliance on prediction and the use of the CSM for prediction are emphasised in recent guidance: *"It is of vital importance that the Conceptual Site Model is capable of predicting the worst case temporal conditions that the site may experience, so that these can then be used in the ground-gas risk assessment. This is essential, and cannot be stressed enough, as the ground-gas protection measures installed must be capable of coping with this event"* (Boyle and Witherington, 2007).

Confidence in detection may be insufficient because the site-specific gas concentration record may be short; however, larger datasets built up from many other sites, and/or longer term datasets of correlates of gas production/migration may be available and these can be used to predict "worst case". The CSM as a product of experience and generic understanding of processes of gas production and migration is effectively the use of such long term datasets.

The objective of this section is to show the value of continuous data to the CSM, both through improving the quality of site-specific information and because it improves understanding of generic processes. Assuming that the instrument making the gas concentration measurements has the ability to measure other environmental parameters at the same rate, then the underlying reason for these improvements is because of the increased certainty in recognising and quantifying relationships between the former and the latter because:

- for a specific site there will generally be many more pairs of gas concentration and environmental correlate data points collected than under a weekly / monthly monitoring programme,
- data are collected at sufficiently high frequency that the sampling frequency matches that of the variability of the parameters measured; the data can reasonably be regarded as a time series and the influence of prior conditions in altering relationships can be recognised, i.e. time dependence of relationships can be recognised.

4.1 Processes controlling gas production and migration

Gas concentrations can vary due to changes in gas generation and/or migration. Generation can change due to chemical and biological factors e.g., moisture, pH, temperature, (see O'Riordan *et al.*, 1995 for further information) and migration is a result of a driving force and pathway; for sustained migration, the gas has to be replaced with further generation. The three principal drivers for gas migration are:

i) pressure differential,
ii) diffusion along gas concentration gradients,
iii) transport in fluids (Wilson *et al.*, 2007).

Consequently, parameters likely to alter migration are differences in fluid pressures and in ground permeability. The former are typically manifest in the environment as atmospheric pressure and water table variation, and the latter as differences in geology, saturation, vegetation and land use.

4.2 Observing and refining relationships

More complete observation of the relationships between gas concentration and these environmental variables allows the relationships to be refined. This is illustrated below using the relationship of gas concentration to atmospheric pressure, the parameter long recognised to be a predictor for gas concentration, and therefore required by guidance to be a variable in the CSM. Subsequently, the same and further data are used to explain the process of gas migration.

The relationship of gas concentration to atmospheric pressure variation is considered in the light of continuous monitoring periods of increasing length (Figure 4).

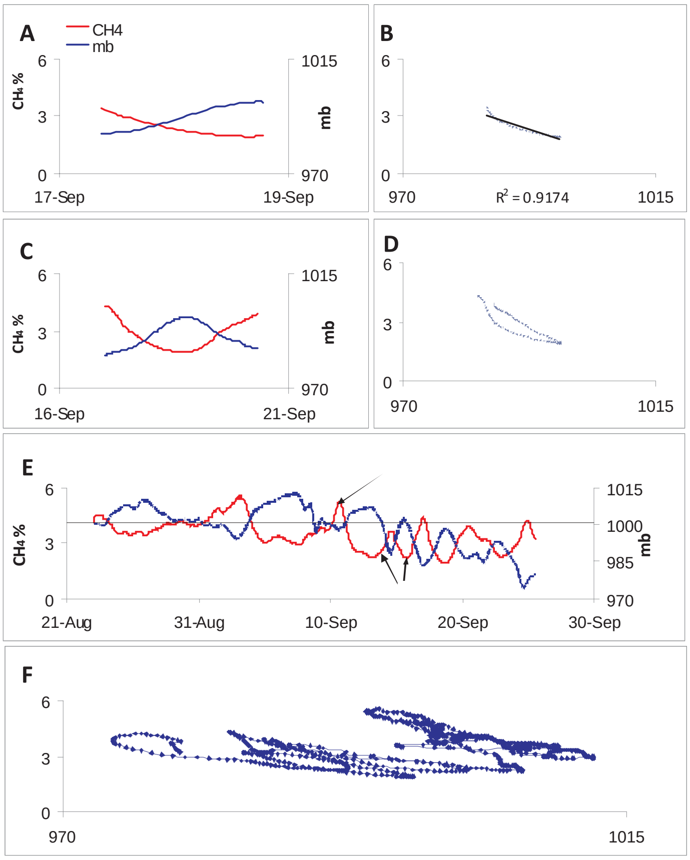

Figure 4. Gas concentration and atmospheric pressure data as time series of increasing duration (A,C,E) and plotted against each other (B, D, F). In E the arrows show different concentrations whilst pressure is 1000 mb and falling.

Single period of falling atmospheric pressure - Continuous measurement of gas concentration over a single period of falling atmospheric pressure clearly shows a negative correlation between the two parameters (Figure 4B). This negative correlation supports the guidance requirement for measurement contingent on falling pressure in order to raise the confidence in detecting "worst case". As the relationship of concentration to pressure has very little scatter it may seem possible that a minimum atmospheric pressure (taken from Meteorological Office data) could be used to allow extrapolation of "worst case" gas concentration. However, this relationship should be reconsidered in light of record of continuous data extended to include a subsequent fall in pressure.

Single period of falling and rising atmospheric pressure - There is a clear hysteresis in the response of gas concentration to atmospheric pressure (Figure 4C-D). Whilst this also supports the guidance which recognises the need to measure concentration specifically whilst pressure is falling, it also indicates the relationship is complicated by time dependence and this has implications for extrapolation which are developed below.

Several periods of falling and rising atmospheric pressure - It is clear that the relationship between pressure and concentration varies both within and between pressure excursion events (Figure 4E-F). Consequently, the general principle of reliance on the CSM is again supported as the potential for error if periodic monitoring is treated prescriptively is exposed. Over reliance on gas concentration measurements made when atmospheric pressure is 1000 mbar and falling (Waste Management Paper No. 27 (DoE, 1989)) or even the more general suggestion of measurement at low and falling atmospheric pressure (Wilson *et al.*, 2007) may not return "worst case" concentrations. At times, marked on Figure 4E, pressure is 1000 mbar and falling but measured concentration is as low as 2% or as high as 5%.

As shown by the previous figures, the extension of sampling in collection of continuous, relative to periodic, data confirm that prediction of "worst case" will be subject to large uncertainties. However, the increase in temporal resolution is also sufficient that the data can reasonably be regarded as a time series - the sampling frequency matches that of the variability of the parameters measured. As such, data that could otherwise only produce a very wide scatter around a single relationship can be resolved into multiple sets of better correlated data. These more certain relationships and the transitions between them provide information which is useful in investigating, characterising and comparing sites. Understanding what controls these transitions or variability in the relationship between concentration and atmospheric pressure will also reduce uncertainty in prediction of "worst case". Both these benefits are illustrated through the explanation of the cause of variability developed below. This variability results from time dependence in either or both processes of gas migration and production, the former is discussed first.

4.3 Explaining processes of gas migration

Temporally stable permeability - The variability in the relationship of gas concentration and atmospheric pressure must result in part from the relative impermeability of the ground. This causes pressure changes in the subsurface to lag behind changes in atmospheric pressure and not, therefore, to be equivalent to instantaneous atmospheric pressure but also a function of its rate and direction of change. The relationship of gas concentration to atmospheric pressure will be similarly complicated. The change from one relationship to another observed in Figure 4E-F is therefore explained by the lag in subsurface response over a cycle of rising and falling pressure. Whilst the general relationship is of falling gas concentration with rising pressure, concentration at the same pressure is higher whilst pressure is rising than when falling.

The inclusion of hysteresis in a continuous relationship between atmospheric pressure and gas concentration can produce a reasonable predictor of the latter for many sites. However, continuous data also show the interaction of atmospheric pressure with the ground to result in a different type of relationship. In the time series data from a borehole on a landfill perimeter situated in sandy deposits (Figure 5), the lag in subsurface pressure response is clearly shown. However, whilst in Figures 4A-F this resulted in a series of correlations between gas concentration and atmospheric pressure, the correlation is less good in Figure 5.

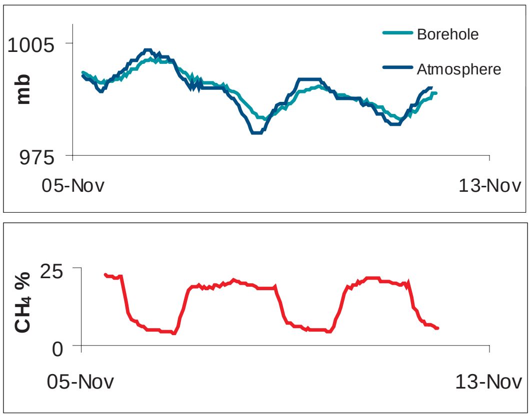

Figure 5. The delayed response of borehole pressure to atmospheric pressure and the coincidence of gas migration with the consequential differential pressure.

Periodic sampling had shown concentration to be extremely variable (Figure 5) and continuous data showed this variability to actually be bi-modal. Therefore, the poor correlation results from there being only two states of gas concentration whilst pressure varies continuously. However, although there is no continuous correlation, the switch from low to high concentration is coincident with the change from a negative to a positive differential pressure between borehole and atmosphere. An identical response is seen in a different geological setting, where 4 m of clay overlay fractured sandstone in which there was a potential ground-gas source in old mine workings (Figure 6). Whilst the borehole in the clay contained no gas indicating the impermeability of the layer, the deeper borehole showed bimodal gas concentrations. Again the switch in gas concentration is initiated and maintained by a positive pressure differential, whilst the magnitude of the differential pressure cannot be well correlated with concentration.

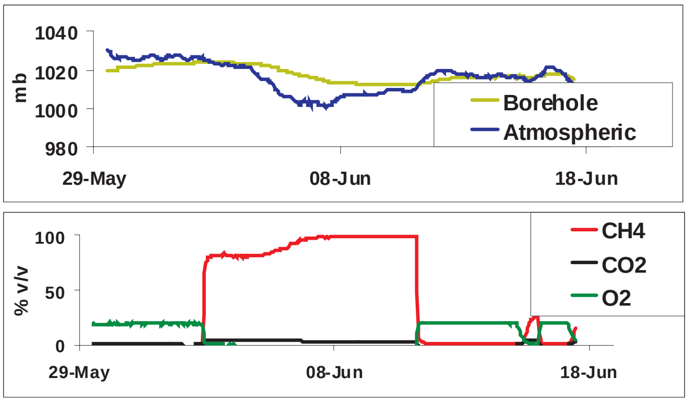

Figure 6. Effect of differential pressure on a borehole penetrating into fractured sandstone containing coal mines gas.

Temporal variability in permeability - The relationship of gas concentration and atmospheric pressure may vary because of the delay induced by the relative impermeability of the ground, but also because the permeability of the ground itself may change. Permeability varies temporally at several timescales, from saturation changes resulting from rainfall events (Wilson *et al.*, 2007) to seasonal saturation and vegetation changes. Change on an intermediate scale is shown in a borehole monitored over a UK winter period (Figure 7). During the spring there was a negative correlation between atmospheric pressure and CO_2 concentration, however, during winter there was no correlation. This is a consequence of the ground freezing, making it impermeable with subsurface pressure and gas concentration no longer driven by atmospheric changes. When temperature rises the ground thaws and connection with atmosphere is re-established; when pressure increases CO_2 concentration decreases.

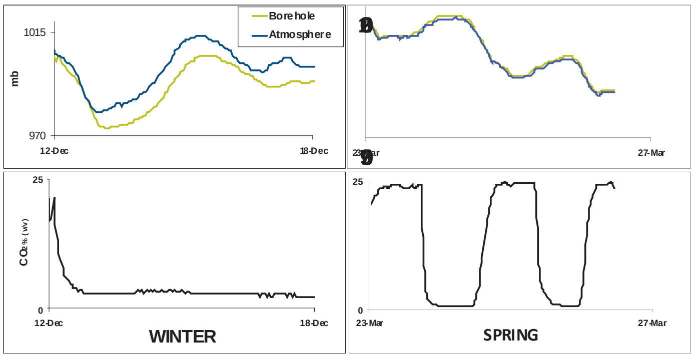

Figure 7. Frozen ground in winter decouples atmosphere and soil gases causing pressure differential and limiting gas migration. After spring thaw atmospheric pressure is again able to drive gas migration.

Quantifying permeability - Permeability has always been a necessary parameter in CSM development because of the limitations it imposes on gas migration, and continuous data show it to be essential in reducing error in prediction of "worst case". At present, permeability is largely derived from knowledge of the site geology, however, it is affected by many site-specific parameters and, therefore, requires a site-specific measurement rather than an estimate based on generic information.

The capability to make continuous measurement allows more direct site-specific quantification by recording the response of borehole pressure to rate and direction of change of atmospheric pressure. In impermeable ground there may be no correlation between borehole and atmospheric pressure, whilst in very permeable ground there should be a clear positive correlation. In most cases, which lie between these extremes, the strength of the positive correlation will be moderated by the delay in response of borehole to atmospheric pressure. This delay, or the hysteresis it produces over a cycle of atmospheric pressure change, can then be used as an index to compare permeability from site to site.

Continuous data collection is essential to the determination of relative values for this critical parameter, as contingent sampling is required in order to coincide with a change in atmospheric pressure. Further selectivity is required to sample over the period when the borehole and atmospheric pressures may be mismatched. Given the opportunity to make continuous measurements for longer periods, the variability in the relationship between rainfall events and seasonality can provide increasingly reliable permeability measurements for the CSM.

Migration, production and flow - In the same way that the ability to observe time series data allows the variability in gas concentration to be understood, it also reveals the controls on variability in the other site-specific measurement often required by guidance: flow.

The lag between changing atmospheric and subsurface pressure which complicates the relationship of the former to gas concentration also results in a pressure differential which generates flow. The borehole shown in Figure 5 had been characterised by periodic sampling as having variable flow, the time series data show this to be caused by this type of pressure differential. This has previously been recognised as "barometric pumping" (Wyatt *et al.*, 1995) and is widely seen in continuous data, suggesting flow is often unrelated to gas production. This decoupling of flow from gas production was confirmed at the same site, where a nearby borehole was shown to maintain the same borehole pressure regime and therefore identical flow, but had much lower gas concentrations; the flow was not caused by gas production.

Controls other than atmospheric pressure - Continuous data allows the effects of a major control on gas concentration - atmospheric pressure - to be more fully understood by including the effects of ground permeability and gas production. However, fluid movements other than the atmosphere can also drive gas concentration change.

This is clearly shown by continuous data from a perimeter borehole of an old landfill (Figure 8) in which fortnightly sampling had shown gas concentration to vary from 2-18%. Gas concentration is not correlated with atmospheric pressure, but there is a relationship with change in groundwater level. In this case, a drop in water table has reduced gas concentration as it no longer displaces gas; however, such movements have also been seen to have the opposite effect. As with the variability in the relationship of atmospheric pressure and gas concentration, there is a requirement to collect and analyse more time series data in order to allow a more general understanding.

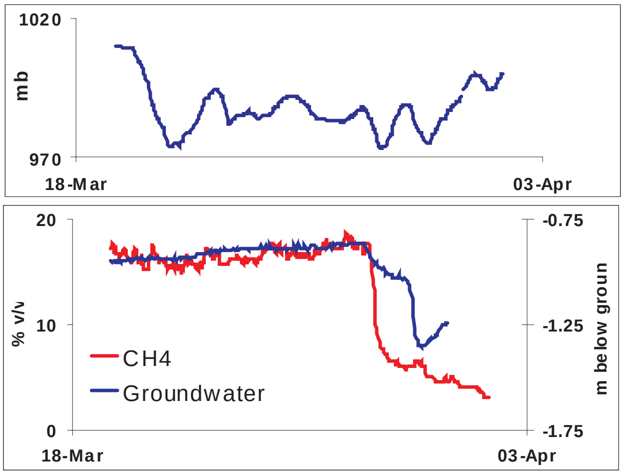

Figure 8. Monitoring well located outside former landfill where gas concentration is unaffected by changes to atmospheric pressure but is controlled by fluctuations in groundwater.

4.4 Explaining processes of gas production

Quantifying gas production - The hysteresis may not only result from delayed response of gas concentration to atmospheric pressure change because of the nature of the ground, but could in part result from limitation in gas availability. The increase in migration induced by a pressure drop may cause gas reserves to be exhausted faster than they can be replenished, therefore causing a time dependent non-linearity in the relationship between concentration and atmospheric pressure. Whilst this exhaustion merely adds variability to, and therefore uncertainty in prediction from, non-time series data, if continuous monitoring during periods of pressure change and constant permeability is possible, it can give an indication of gas production rate and its variability. This "barometric pumping" can be utilised to perturb the system in a way analogous to the "purge and recovery tests" described in Box 1; however, unlike the latter this can be done many times and without manual intervention.

The negative relationship between concentration and atmospheric pressure may break down as migration equals production, and concentration therefore remains constant despite pressure falling further. The negative relationship may even be reversed if the pressure decrease persists for long enough, and fairly complicated relationships of gas concentration to atmospheric pressure may be observed (Figure 4F). However, because the data can be assembled as a time series and if permeability can be assumed constant - primarily by deduction from rainfall records - then gas production rates can be compared between sites where pressure changes of similar magnitude and rate have been identified.

5. CONCLUSIONS

Continuous monitoring demonstrates the frequency of variability of ground-gas concentrations to be such that temporal resolution of sampling must be at least hourly in order to match it; therefore:

- For a given sampling effort (in terms of cost and time available), the inclusion of periods of hourly sampling in a monitoring programme will be effective in increasing the probability of detection of "worst case" gas concentration.
- At hourly resolution, gas concentration data and its environmental controls can be reasonably assembled as a time series. This allows otherwise non-systematic variation in relationships between concentration and its environmental drivers to be converted into an understanding of processes controlling gas concentration.
- Specifically, ground permeability and gas production can be compared between sites if time series of sufficient length is available.
- Purge and recovery tests can be a useful method of characterising a monitoring borehole along with its geography and geology; ideally, such a test should be repeated regularly.
- This improved understanding of processes will improve the confidence in prediction of "worst case concentration" and "worst case scenario".
- At present, periodic gas concentration measurements are used to calibrate a CSM derived from geology and site history; however, continuous concentration data can be of sufficiently high quality that it could be used in the design of the CSM as well as in its calibration.

More specific recommendations will develop from the experience of practitioners, as more continuous data are collected and analysed.

Beyond current guidance - Reliance on the CSM, as proposed in current guidance, is reinforced by continuous monitoring which also increases the amount of site-specific information available for the CSM.

The CSM is therefore central to future guidance; however, an improvement in the quality of gas concentration and environmental variability records (and the CSM) may change how they are related to risk assessment.

Continuous monitoring allows a step change in the confidence level for statements such as (for example) *"the concentration of CH_4 exceeded 5% for 0.02% of the time"*. It may, therefore, no longer be reasonable to make decisions based solely on "worst case" concentration when both frequency and magnitude of concentration can be stated with reasonable confidence, and realistic case concentration fluxes can be used.

Acknowledgements

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