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Assessing contaminant migration pathways and vertical gradients in a low-permeability aquifer using multilevel borehole systems

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Abstract

A comparison of groundwater and gas monitoring data is provided between multilevel and conventional long-screened boreholes constructed around the perimeter of a closed landfill in the English Midlands. Multilevel boreholes were constructed with up to seven separate sampling ports.

All boreholes were constructed into strata of the Triassic Mercia Mudstone Group, which proved to consist of a succession of well-bedded, weathered mudstone and clay with occasional thin beds of siltstone and sandstone to approximately 30 m depth. These are low-permeability strata which exhibit sufficient fracture permeability to allow groundwater movement. It is suspected that fractures, particularly along bedding planes, provide discrete pathways for both gas and leachate migration from the landfill.

The importance of purging channels prior to sampling both aqueous and vapour phases is emphasised in order to minimise diffusion biases.

Monitoring records for the multilevel boreholes demonstrate that there are significant vertical differences in groundwater level, and groundwater chemistry. A predominantly downward vertical hydraulic gradient is proven in all the multilevel boreholes, with a head difference of up to 5 metres over a vertical distance of 13 metres between uppermost and lowest sampling ports. Chloride concentration in groundwater varies from a background of below 50 mg/L to in excess of 700 mg/L within ports of the same multilevel borehole. Total organic carbon varies vertically from less than 10 mg/L to over 50 mg/L. None of this detail is apparent in data gathered from the adjacent long-screened monitoring boreholes, which in general recorded concentrations which were significantly below the maximum in the neighbouring multilevel.

Key words: borehole, gas, groundwater, landfill, leachate, long-screened, low permeability, methane, Mercia Mudstone, migration, monitoring, multilevel, vertical gradients

INTRODUCTION

The use of long-screened monitoring boreholes can significantly mask hydraulic and chemical variations that occur naturally over short vertical distances. These issues can be overcome by the use of multilevel sampling systems (e.g. CL:AIRE 2002*a*,*b*; Beck 2003). Hydraulic and chemical conditions within longer-screened monitoring boreholes can become averaged or biased toward the dominant condition (Martin-Hayden

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and Robbins 1997; Martin-Hayden 2000*a*,*b*; Gibs *et al.* 2000; Sevee *et al.* 2000; Britt 2005). Vertical flows induced by vertical hydraulic gradients, can cause the re-distribution of contaminants from one vertical zone to another, or can mask thin zones of contamination which become diluted, sometimes to below detection (e.g. Church and Granato 1996; Hutchins and Acree 2000; Elci *et al.* 2001; Martin-Hayden and Britt 2006). The conditions of ambient flow and contaminant dilution can occur to both groundwater in the saturated zone and soil gas in the unsaturated zone. Under these conditions, it can be difficult to identify contaminant migration pathways with any degree of confidence.

The following case history (after Fuller 2004), provides an example of how multilevel systems used in conjunction with conventional boreholes can improve the understanding of contaminant migration pathways. For the purposes of this paper, the data collected from the multilevel boreholes have been assessed separately and compared to data from the conventional long-screened boreholes. Both sets of boreholes are located on the perimeter of a closed landfill site in Worcestershire, UK.

SITE DESCRIPTION

The site was originally a clay quarry and brick works which was landfilled from approximately 1965 until 1983. The ratio of household to general industrial waste is estimated from Council records to be approximately 3:1. The depth of waste within the clay pits varies from 3 to 12 metres. The whole site was capped with between 0.75 and 1.5 metres of clay in 1983, with additional soil cover added later to offset settlement. There are no engineered barriers.

The site and surrounding area are underlain by strata of the Triassic Mercia Mudstone Group consisting of weathered red-brown laminated or massive mudstones and clay with occasional thin beds of grey to buff or pink siltstone and sandstone. The Mercia Mudstone Group is over 380 metres thick at the site, and is underlain by the Bromsgrove Sandstone Formation, which is a major aquifer. Strata dip at approximately 2° to the south-east (Figure 1).

The overall transmissivity of the Mercia Mudstone is low but there is sufficiently high hydraulic conductivity locally to allow groundwater movement along discrete bedding plane fractures, vertical discontinuities and through the more permeable siltstone and sandstone bands.

MONITORING INFRASTRUCTURE

The site has been regularly monitored by Worcestershire County Council since 1995, using boreholes located on the site perimeter. In March and April 2000, 29 new monitoring boreholes were installed including 16 long-screened gas and groundwater monitoring boreholes, three groundwater monitoring boreholes and ten multilevel monitoring boreholes. The general site layout and location of monitoring boreholes is illustrated in Figure 2 and summary construction details including screen lengths and port elevations are presented in Table 1.

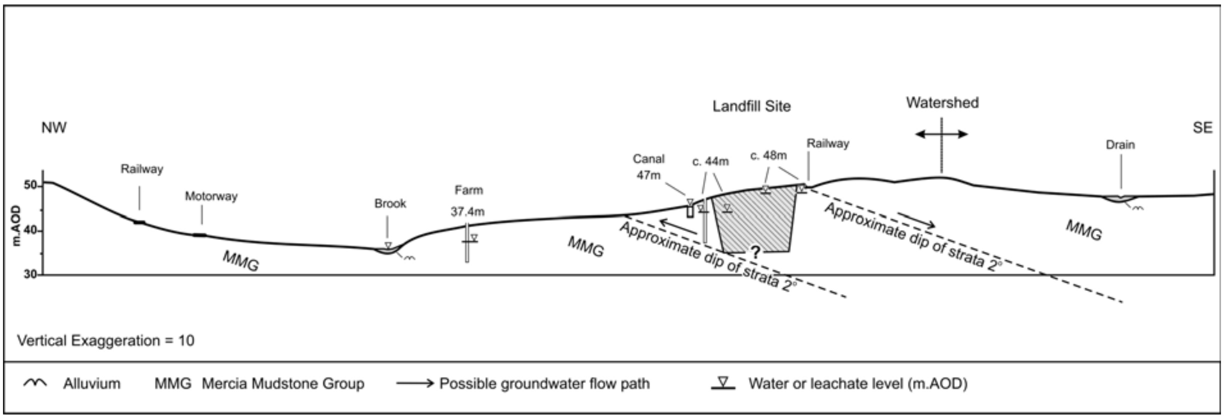

Figure 1. Simplified conceptual section

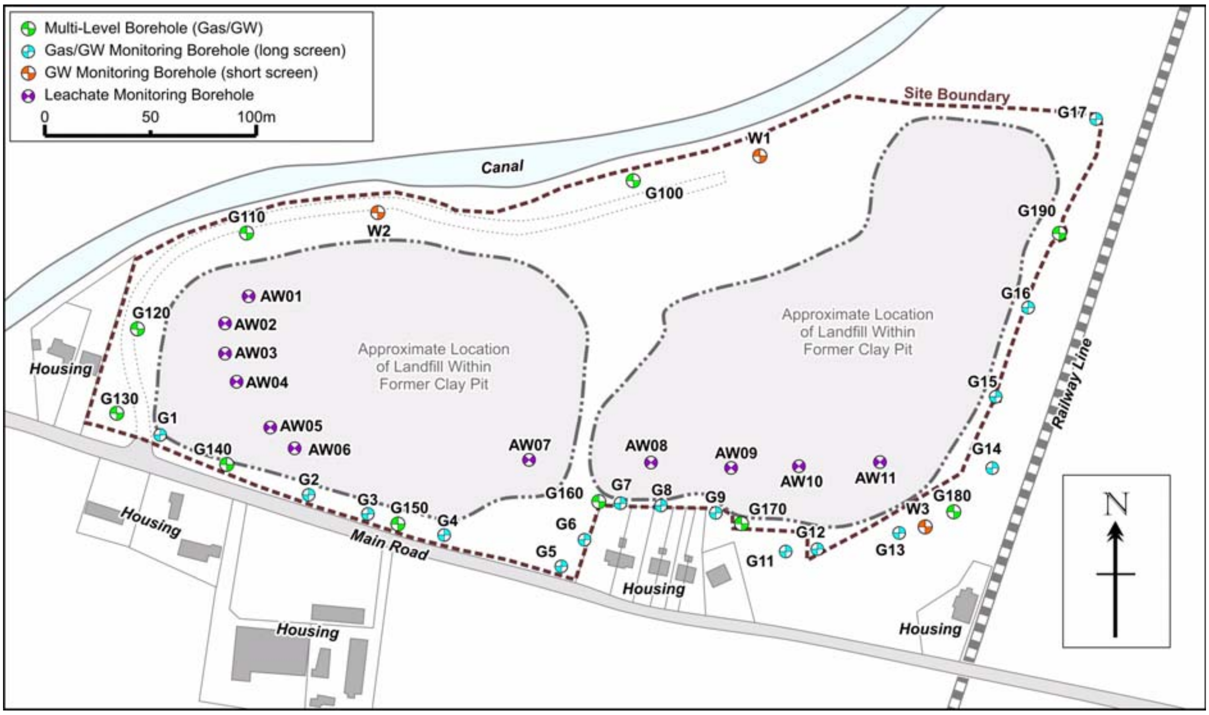

Figure 2. Site layout showing monitoring locations

The long-screened gas/groundwater monitoring boreholes were constructed from 19 mm diameter PVC flush-threaded lining to depths of between 8.5 and 14.5 metres below ground level. These were screened from the base to 1.5 metres below ground level and were finished with a gas-tight tap. The three groundwater monitoring boreholes were installed to 20 metres depth, using 50 mm diameter PVC lining including a 6 metre section of screen from 14 to 20 metres below ground level. All boreholes were completed with a filter pack around the screen and a bentonite seal to within 1 metre of ground level. All boreholes were protected with lockable steel headworks.

Multilevels were completed using the Solinst Continuous Multichannel Tubing (CMT®) system. This is a 43 mm diameter, continuously extruded, medium-density polyethylene tube consisting of seven separate channels (Figure 3). Discrete ports are constructed on site at different vertical intervals in each separate channel (Table 1). At the study site, ports were located above and below the groundwater table to allow measurements in both the saturated and unsaturated zones. Screened port intervals are 150 mm in length. Filter sand was placed around each port, typically extending the response zone to a 1 metre interval. A 1 metre response zone was chosen to ensure that during construction there was sufficient margin for error in the placement of the filter packs to accommodate any vertical movement that might occur in the CMT pipe as temporary casing was withdrawn from the borehole.

Bentonite seals were placed between response zones. Each multilevel was then fitted with a custom designed cap (Fuller 2004) to isolate gas in each channel and to allow gas sampling. A more detailed description of the multilevel system and its installation is provided by Einarson and Cherry (2002).

GROUNDWATER LEVELS AND HYDRAULIC GRADIENTS

Groundwater levels have been routinely recorded by staff from Worcestershire County Council Waste Management Team. Examples of typical time-series records of groundwater elevation in the seven ports of multilevel borehole G100 and a number of the long-screened monitoring boreholes are provided in Figures 4 and 5. The groundwater level in port G101 (Figure 4) represents a perched groundwater system within overlying

Conventional Monitoring Boreholes

					Groundwater Quality Samples			Gas Measurements			
Borehole	BH Depth	Screen Length	Groundwater Elevation		Chloride	Total Organic Carbon	Dissolved Methane	Methane in Air (% by Volume)			
	metres	metres	m.AOD		mg/l	mg/l	mg/l	No	Avg	Min	Max
G01	12.0	9.3	44.1		281	8.5	<0.005	40	0.00	0	0
G02	14.0	12.0	45.1		513	13.4	2.151	41	49.87	0	73
G03	14.0	12.0	45.4		306	23.1	1.792	40	42.26	0	73
G04	14.0	12.0	45.3		276	23	1.434	41	2.97	0	30.5
G05	14.5	12.0	46.2		39	6.7	<0.005	40	0.00	0	0.1
G06	14.5	12.0	46.8		33	6.8	<0.005	40	0.00	0	0
G07	14.5	12.0	46.9		51	7.8	<0.005	40	1.77	0	11
G08	14.5	12.0	47.1		25	5.6	<0.005	41	15.56	0	43.5
G09	14.5	12.0	48.7		54	6.9	<0.005	35	0.07	0	0.9
G11	14.0	12.0	48		-	5.4	<0.005	40	0.00	0	0.1
G12	14.5	12.0	47.4		93	5.8	<0.005	40	0.00	0	0.1
G13	8.5	6.0	49.5		20	4.8	<0.005	40	0.00	0	0.1
G14	11.5	9.0	46.8		26	5.7	<0.005	40	1.30	0	5.3
G15	11.5	7.0	46.5		-	-	-	40	36.69	0	75
G16	11.5	9.0	47.8		83	34.4	1.434	40	62.05	13.5	76
G17	11.5	9.0	46		33	14.2	<0.005	39	6.58	0.3	21
W1	20.0	6.0	45		719	31.4	<0.005	-	-	-	-
W2	20.0	6.0	40.7		269	7.9	<0.005	-	-	-	-
W3	20.0	6.0	45.6		36	5.6	<0.005	-	-	-	-

Multi-Level Monitoring Boreholes

						Groundwater Quality Samples			Gas Measurements			
(Borehole) Multilevel Port		BH Depth	Port Elevation	Groundwater Elevation	Average Hydraulic Gradient	Chloride	Total Organic Carbon	Dissolved Methane	Methane in Air (% by Volume)			
		metres	m.AOD	m.AOD	m / m	mg/l	mg/l	mg/l	No	Avg	Min	Max
(G100)	G101	19.0	46.1	46.9	P	-	-	-	37	0.1	0	0.9
	G102		43.7	45.1	-0.36	-	-	-	37	0.4	0	7.3
	G103		41.4	44.2		47	11.6	0.108	38	0.2	0	2.9
	G104		38.9	44.1		232	47.2	0.717	39	0.2	0	1.6
	G105		36.4	42.9		311	39.2	0.065	39	0.1	0	0.9
	G106		33.9	40.6		351	44.6	0.05	39	0.2	0	1.1
	G107		30.7	40.4		363	31.9	<0.005	37	0.1	0	0.7
(G110)	G111	19.5	45.8	Dry	-	-	-	-	40	28.1	0	66
	G112		42.8	44.9	-0.77	-	-	-	35	5.8	0	34
	G113		40.3	44.8		80	11.8	<0.005	36	4.3	0	29.5
	G114		38.1	42.8		206	14.8	0.006	39	3.2	0	21.5
	G115		34.8	38.8		577	52.5	<0.005	39	2.4	0	19.5
	G116		32.5	44.6	1.09	389	20	0.036	36	4.2	0	20
	G117		29.4	44.7		85	11.6	0.143	37	3.4	0	23
(G120)	G121	19.6	47.0	Dry	Dry	-	-	-	40	0	0	0.3
	G122		44.0	45	-0.50	-	-	-	37	0	0	0.3
	G123		41.5	44.1		254	30	1.434	35	0	0	0.3
	G124		39.0	44.1		334	37.2	1.792	36	0	0	0.3
	G125		36.5	43.8		344	34.9	1.075	39	0.3	0	0.8
	G126		34.0	39.3		518	11.2	<0.005	39	0.5	0	0.9
	G127		30.5	38.3		646	9.3	<0.005	39	0.7	0.2	1.3
(G130)	G131	19.6	48.0	Dry	Dry	-	-	-	40	0	0	0
	G136		45.0	Dry	Dry	-	-	-	39	0	0	0
	G135		42.5	44.4	-0.57	-	-	-	37	0	0	0.1
	G137		32.5	38.7		-	-	-	38	0	0	0.2
(G140)	G141	19.7	50.2	Dry	Dry	-	-	-	40	0	0	0.7
	G146		47.6	Dry	Dry	-	-	-	39	0	0	0.1
	G143		44.8	44.9	-0.14	-	-	-	38	0	0	0.1
	G144		42.0	45		538	10	<0.005	39	0	0	0.1
	G145		39.3	44.4		447	11.1	<0.005	39	0	0	0.1
	G142		36.6	44.4		459	9.3	<0.005	36	0	0	0.1
	G147		33.1	44.5		471	8.6	<0.005	37	0	0	0.1
(G150)	G151	19.7	51.5	Dry	-	-	-	-	39	32.9	0	65
	G152		47.8	Dry	-	-	-	-	40	47.5	0	68
	G153		44.8	45.4	-0.02	-	-	-	39	22.6	0	60
	G154		42.5	45.4		311	21.4	1.434	37	23.9	0	60
	G155		40.4	45.3		331	21.4	2.151	39	20.2	0.2	52.3
	G156		38.2	45.2		165	13.5	<0.005	38	25.6	1.6	64
	G157		35.8	45.2		204	16.4	0.358	40	25.6	0.2	60
(G160)	G161	19.9	53.1	Dry	-	-	-	-	40	0	0	0
	G162		50.7	Dry	-	-	-	-	39	0.3	0	4.6
	G164		48.3	Dry	-	-	-	-	39	0	0	0.1
	G165		42.8	46.8	-0.89	69	9	<0.005	40	0	0	0.6
	G166		40.0	46.7		110	10.5	<0.005	36	0	0	0.7
	G167		37.1	41.7		305	19.5	<0.005	39	0	0	0.6
(G170)	G171	19.6	52.8	Dry	Dry	-	-	-	40	0	0	0.1
	G172		49.9	Dry	Dry	-	-	-	39	0	0	0.1
	G173		47.4	48.1	-0.48	-	-	-	39	0	0	0
	G174		44.9	47.9		61	4.8	<0.005	39	0	0	0
	G175		42.4	47.3		60	6.2	<0.005	39	0	0	0.1
	G176		39.8	47.3		142	8	<0.005	39	0	0	0
	G177		36.2	42.7		-	-	-	38	0	0	0.1
(G180)	G181	20.4	49.1	49	P	-	-	-	40	0	0	0
	G182		46.4	48.4	-0.19	-	-	-	36	0	0	0
	G183		43.6	47.3		-	-	-	39	0	0	0
	G184		40.9	46.4		68	6.9	<0.005	39	0	0	0
	G185		38.4	46		53	9.8	<0.005	37	0	0	0
	G186		35.6	45.9		57	11	<0.005	39	0	0	0
	G187		32.7	45.8		67	6.6	<0.005	39	0	0	0.1
(G190)	G191	20.4	46.2	Dry	Dry	-	-	-	40	38.6	0	77
	G192		43.2	46.4	-0.06	38	11.5	2.151	37	19.8	0	74
	G193		40.7	46.3		227	38.7	4.301	38	13.5	0	71
	G194		38.2	46.3		289	47.6	5.018	39	14.2	0	66
	G195		35.7	46.3		386	52.9	2.151	39	11.8	0	72
	G196		33.2	45.6		608	42.5	2.867	39	13.9	0	73
	G197		29.7	45.6		746	24.6	0.502	39	9.7	0	52

Groundwater levels recorded in December 2000
P - Perched groundwater
"-" No measurement

All groundwater samples taken in June / July 2000.
Gas results are average of weekly measurements between April 2000 and January 2001
Detection limit of portable gas analyser is 0.1% - reported as 0 for statistical purposes.

Table 1. Summary of monitoring data

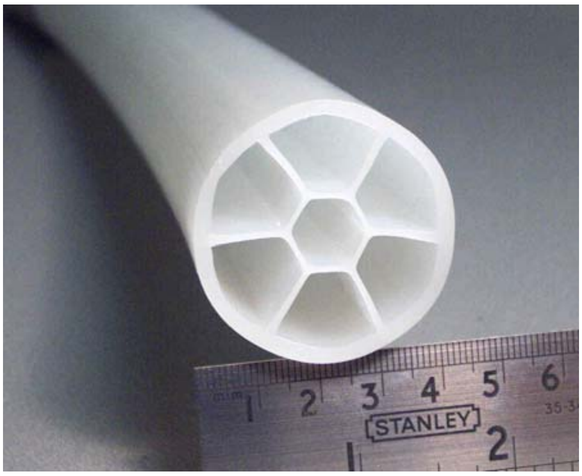

Figure 3. Cross-section of CMT multilevel tubing

superficial deposits. Ports G102 to G107 are all within the Mercia Mudstone. The data demonstrate a consistent seasonal pattern of variation and, apart from in one section of borehole G110, a consistent downward hydraulic gradient sustained throughout the five-year monitoring period. The significant vertical variation in head within each multilevel provides confidence that the ports are hydraulically isolated from each other within the borehole.

Groundwater levels in the selected long-screened and groundwater monitoring boreholes (Figure 5) show a similar seasonal variation to the multilevel records, but with more subdued short-term variations. If the groundwater head data from the conventional boreholes alone were used and no account taken of screen positions, it would probably be concluded that the overall pattern of groundwater flow was north-westerly, with the assumption made that groundwater was moving uniformly within the Mercia Mudstone. A closer examination of heads in relation to screen position in the long-screened boreholes does however highlight what appear to be anomalously low groundwater levels in boreholes W2 and W3 (Figures 5 and 6).

Figure 6 and subsequent figures are cross-sections drawn around the entire site perimeter to allow comparison of data between boreholes. Boundary sections are labelled to help with orientation.

The contoured head data from the multilevel boreholes (Figure 6) indicate flow paths which have their lowest heads at specific depths in two different locations: (i) the north-western corner of the site, focused near to the base of the landfill site (boreholes G110, G120 and G130); and (ii) along the south-western boundary of the site at the base of boreholes G160 and G170. The dominant flow path is still north-westerly. These observed hydraulic head patterns could be indicative of preferential movement of groundwater along higher-permeability zones, such as bedding plane fractures (which dip in the opposite direction to groundwater flow – see Figure 1).

The overall hydraulic gradient(s) in each of the multilevels is given in Table 1. There is considerable variation between multilevels in the magnitude of hydraulic gradients. For example in G100 (Figure 4), the gradient between port G102 and G107 in the Mercia Mudstone is 4.7 m over a distance of 13 m (downward gradient of –0.36). Larger gradients are recorded over shorter intervals (e.g. upward gradient of +1.09 between ports G117 and G115).

GROUNDWATER QUALITY

Groundwater samples were collected during June and July 2000 from all conventional boreholes and the saturated ports within the multilevel systems. Sampling methods were undertaken in accordance with best practice (e.g. early drafts of Environment Agency 2003) and all long-screened installations were purged of at least three borehole volumes prior to sampling. This particular purge procedure tends to bias the samples in the long-screened boreholes towards being a flow weighted average over the saturated screen interval of the borehole (e.g. Sevee *et al*. 2000). Regarding multilevel systems, a thorough purging of each multilevel channel is necessary to ensure that diffusion biases which could occur through the thin polyethylene walls between channels in the CMT tubing are minimized. The issue of diffusion is discussed in Einarson and Cherry (2002). Consequently in the analyses presented below there may potentially be biases arising from diffusion.

In order to assess how purging might affect sample concentrations, a simple purging trial was conducted in one of the channels of multilevel borehole G190 (port G195). Samples were taken after removing 0, 1, 3, 5 and 7 channel volumes. Chloride analysis revealed that the analyte concentration changed less than 6% with continued purging after the removal of one borehole

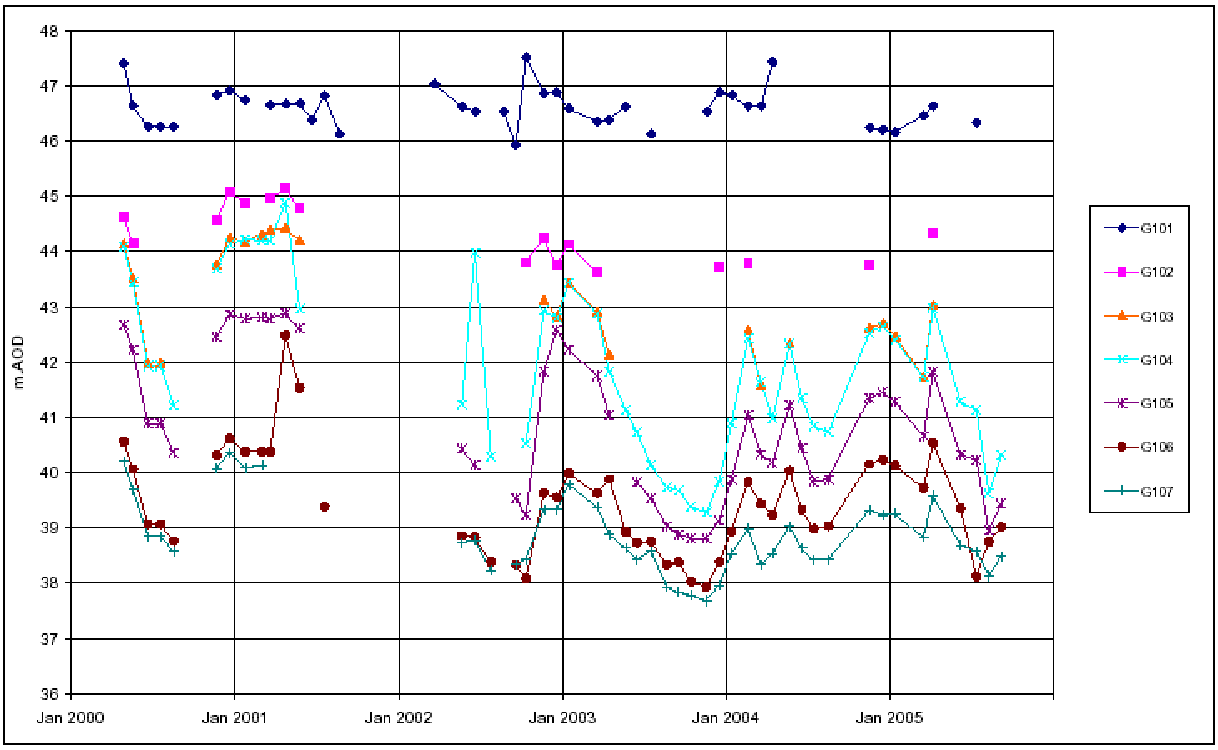

Figure 4. Multilevel G100: groundwater levels recorded in ports G101 to G107 (April 2000 to September 2005)

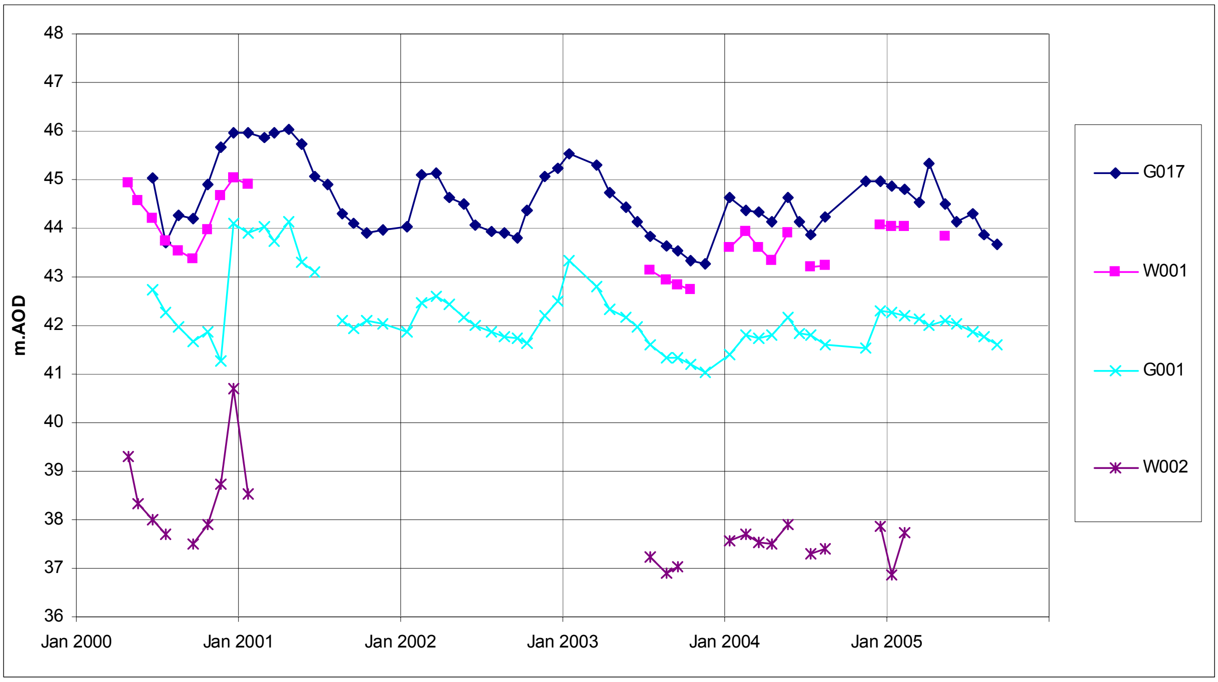

Figure 5. Groundwater levels recorded in long-screened monitoring boreholes (April 2000 to September 2005)

volume (Table 2). Subsequently a '3× channel volume' purge standard was adopted for these prior to sampling.

Table 2. Comparison of chloride analysis during purging in multilevel borehole G190 (Port G195)

No. of channel volumes purged	Chloride concentration (mg/L)	% Change in chloride concentration
0	175	
1	402	129
3	385	–4
5	407	6
7	408	<1

Following purging using inertial pumps, samples were collected at a low pumping rate and stored in laboratory-supplied containers. Samples were kept at approximately 4°C using ice packs, and were transported the same day to an accredited laboratory. Particular precautions were taken when obtaining groundwater samples for dissolved methane analysis. Channels were first thoroughly purged and pumping rates reduced as much as possible during sampling, to provide a discharge with laminar flow. Sample containers were filled to overflow and capped immediately to minimise degassing and volatilisation.

Analytical results for three selected determinants: chloride; total organic carbon (TOC); and dissolved methane; are summarised in Table 1 and discussed below.

Chloride distribution

The distribution of chloride within the multilevel boreholes (Figure 7) illustrates significant vertical variation in concentration. For example in multilevel G190 the chloride concentration varies from 38 mg/L in the highest saturated port, increasing vertically port by port to a maximum of 746 mg/L in the lowest. Concentrations in the nearest conventional boreholes, G16 and G17, are 83 and 33 mg/L respectively. Both are completed to half the depth of the multilevel, and partly because of this they produce analytical results which are biased towards groundwater quality nearer to the top of the saturated zone. Similar biases are evident between other multilevel and conventional boreholes (Figure 7). Bias in water quality samples from long-screen wells is primarily caused by water entering the borehole from

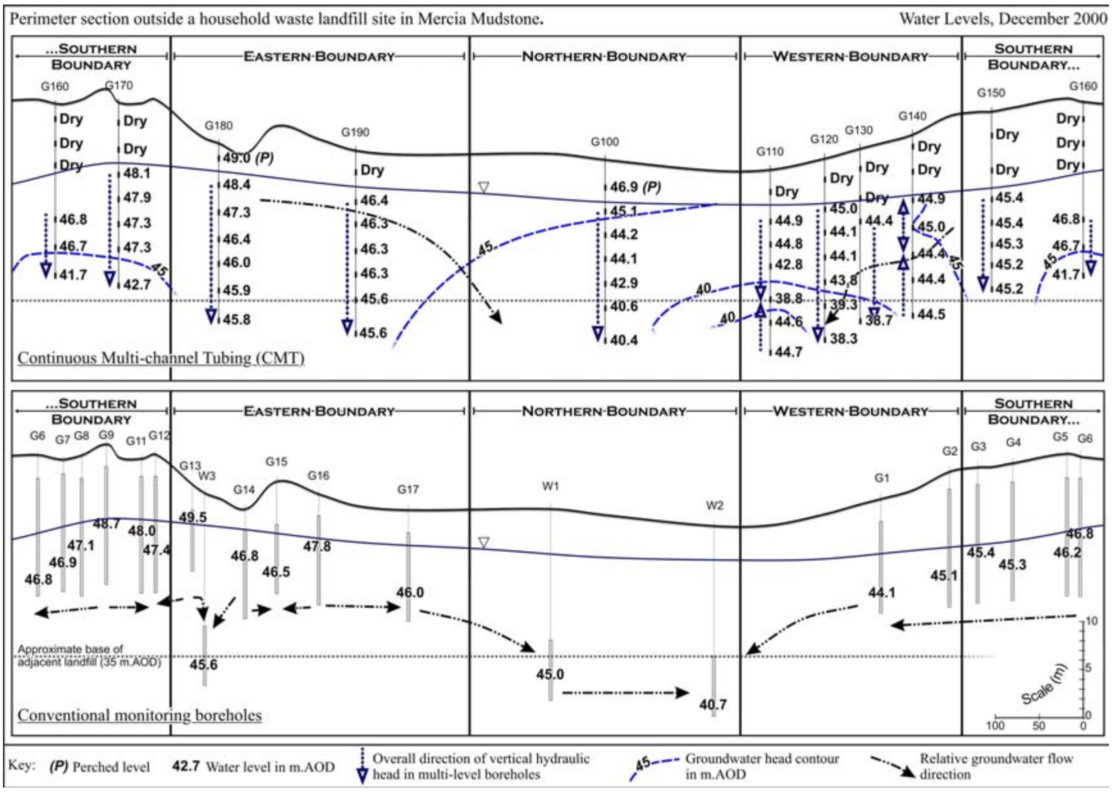

Figure 6. Groundwater levels demonstrating vertical hydraulic gradients

higher inflow zones. At this site these could be the result of a combination of factors, which will vary from borehole to borehole, including the presence of more permeable strata, the effects of ground disturbance immediately adjacent to the landfill areas, and the presence of fewer fractures at depth.

Also significant is the close correlation between chloride distribution and groundwater head in the multilevel boreholes, particularly on the western site boundary. In general, high chloride concentrations are associated with zones of lowest groundwater level. These discrete zones are unrecorded within the conventional boreholes.

TOC distribution

The distribution of TOC within the multilevel boreholes (Figure 8) again illustrates significant vertical variation in concentration, but with higher concentrations recorded at shallower depths than the chloride. The variable pattern of TOC distribution provides confidence that purging of the channels prior to sampling has minimised any biases arising from diffusion.

In multilevel G190 the maximum TOC concentration of 53 mg/L is recorded in port G195, with concentrations reducing to 11.5 mg/L at the top of the saturated zone and to 24.6 mg/L in the lowest port. The nearest conventional boreholes, G16 and G17, record concentrations of 34.4 and 14.2 mg/L respectively – again values which are lower than multilevel maxima.

The overall distribution of TOC shows a less immediate correlation to head distribution in the multilevels, though there does seem to be some head relationship to concentrations on the western boundary between G120 and G110 which is not apparent in the conventional borehole data.

Dissolved methane distribution

A comparison of the distribution of dissolved methane between conventional and multilevel boreholes shows no obvious correlation to groundwater head. There are significant vertical variations in methane concentration observed within individual multilevel installations (e.g. G100, G120, G150 and G190) which give confidence that biases from diffusion have been eliminated by pre-purging. Higher dissolved concentrations are recorded at higher elevations adjacent to the body of the landfill site (Figure 9). There are however some interesting vertical differences within some of the multilevels. For example, multilevel G190 has a maximum dissolved methane concentration in port G194 of 5.0 mg/L and a minimum of 0.5 mg/L in port G197. The nearest conventional boreholes, G16 and G17, record concentrations of 1.4 and <0.005 mg/L respectively – again values which are significantly lower than the multilevel maximum.

GAS MEASUREMENTS

All gas measurements were recorded *in situ* using conventional gas-monitoring instrumentation. The gas sampling instrument with self-contained pump draws sample into the unit and gas concentrations are displayed in real time. Typically, readings gradually increase and then stabilize. The stabilized reading is recorded. In cases where the concentration increases and then decreases, the maximum gas concentration is recorded. This works well within both the conventional long-screened boreholes and the multilevel ports located in the unsaturated zone, where gas can move freely.

Volatile gases, including methane, have the potential to rapidly diffuse through the polyethylene CMT tubing and into adjacent channels. To minimize this potential bias, thorough purging of the channel followed by sampling (as described above) is recommended by the manufacturers. Methodologies are detailed in EPRI (2005).

The gas measurement methodology for multilevel ports submerged below the water table needed to be adapted. Any gases detected in the saturated multilevel channels can be derived from either volatilization of gases dissolved in groundwater or from diffusion of higher concentrations of gas in one or more channels into adjacent channels with zero or lower concentrations of gas in the multilevels. Both sources of gas will mix in the channel, though if diffusion is dominant the concentration will tend towards the highest concentration present in any one channel. The actual concentration recorded will depend on the time interval between sampling events – in this case weekly.

Each channel is sealed from air. At the time of sampling, the relatively small volume of gas contained in each channel has to be sampled without mixing with air. A 6 mm diameter drop-tube was permanently

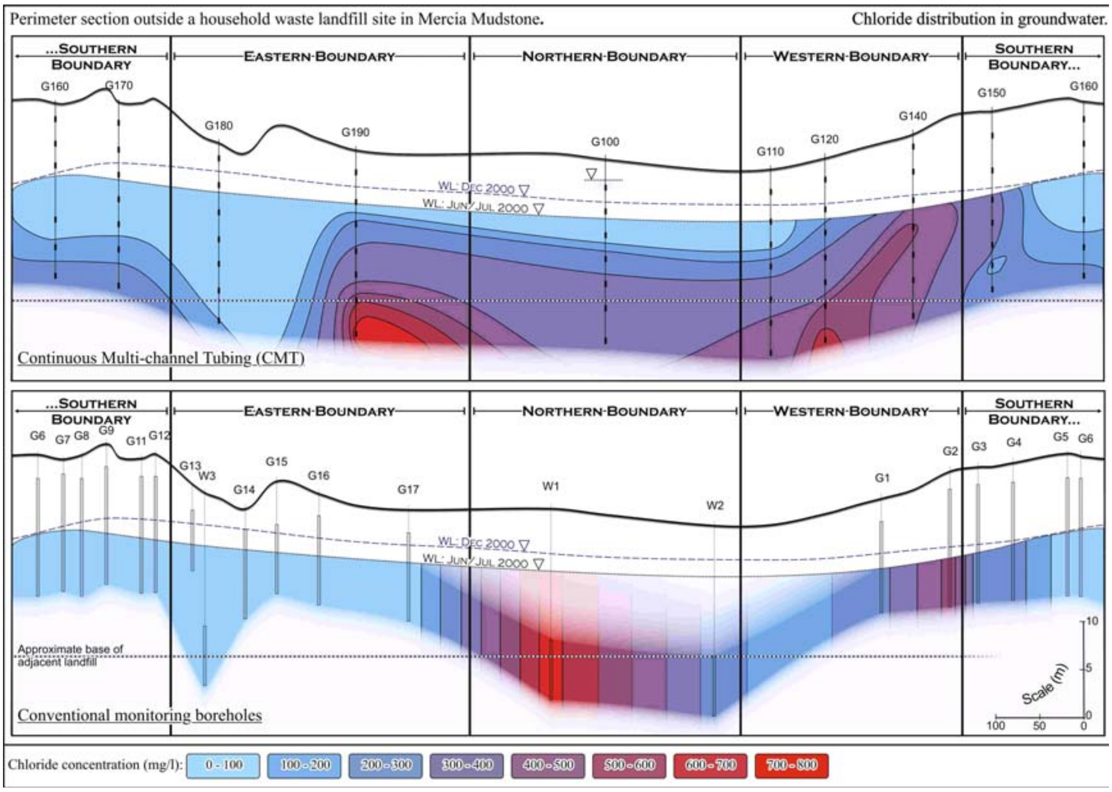

Figure 7. Chloride distribution

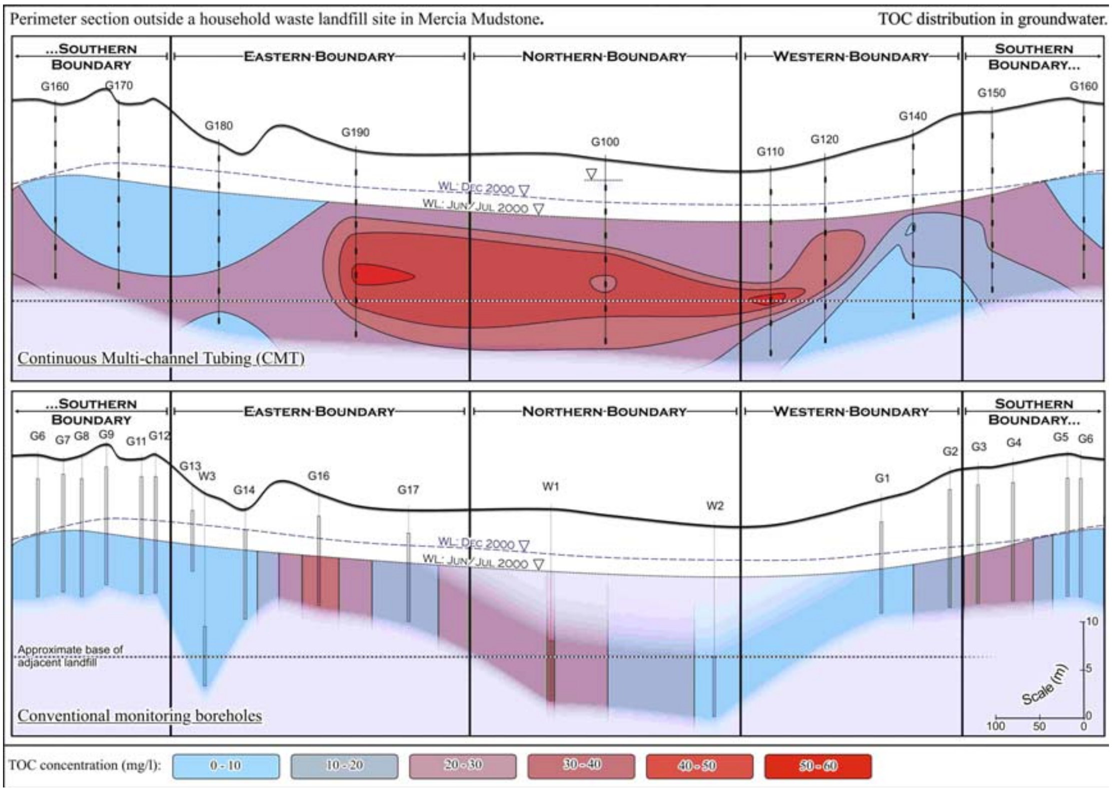

Figure 8. Total organic carbon distribution

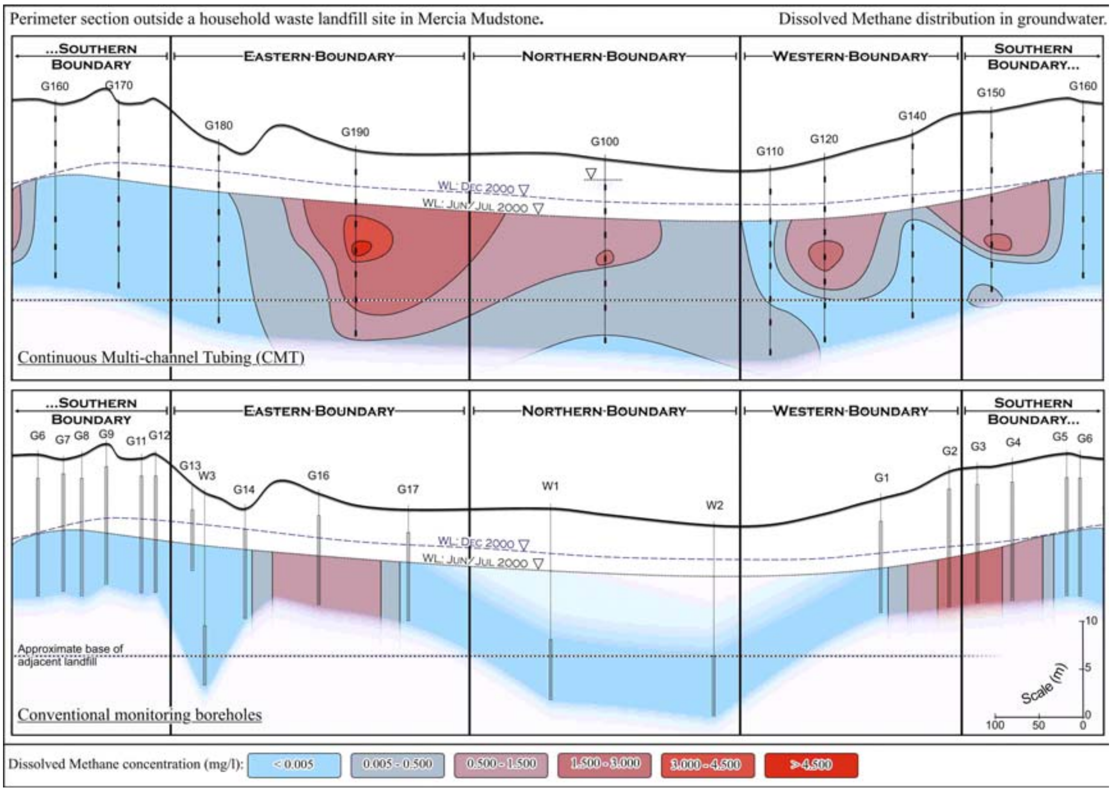

Figure 9. Dissolved methane distribution

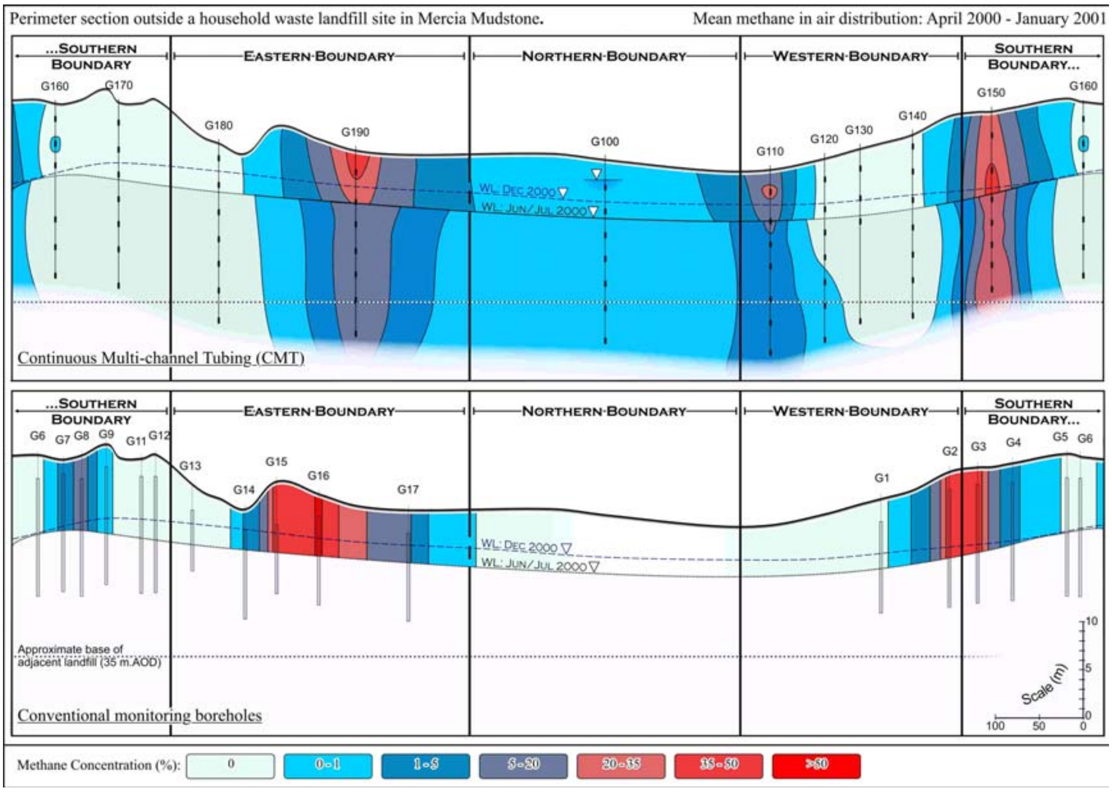

Figure 10. Hydrocarbon (methane) in air distribution

suspended from the gas tap at the wellhead to 1 m above the maximum water level expected in the channel. Immediately prior to sampling, the gas-tight seal was broken to avoid a vacuum during purging. This allowed air to enter the channel from the surface. Gas was then extracted through the drop-tube using the pump on the portable gas analyser. The maximum gas concentrations recorded on the meter were recorded immediately prior to the sample drawn through the drop-tube becoming diluted with atmospheric air.

A statistical summary of methane in air measurements recorded weekly between April 2000 and January 2001 is given in Table 1. Average values over this period are plotted in cross-sections on Figure 10.

Methane in the unsaturated zone

The pattern of methane distribution in the unsaturated zone is very similar between both sets of boreholes. However, data from the multilevels shows that despite concerns relating to diffusion, there are significant vertical differences in the unsaturated zone (e.g. multilevels G140 and G150), which are not apparent in the long-screened boreholes (Figure 10).

Methane in the saturated zone

Volatilised methane concentrations cannot be specifically identified by measurement in the conventional long-screened boreholes. In these, volatile compounds released from the groundwater surface will be mixed and diluted into the unsaturated zone gas flow. The multilevel boreholes have the advantage that the ports are completely sealed below groundwater level, so that potentially any gas accumulation within the channel between sampling events will be that volatilised from the associated groundwater. However, this advantage could be biased by diffusion from higher concentrations of methane in adjacent channels – particularly those sampling gas in the unsaturated zone. Sampling gas from the headspace in the saturated channels provides a means of evaluating this effect.

The data in Table 1, illustrated in Figure 10, show methane concentrations within the saturated multilevel channels which are, in general, lower than those in the overlying unsaturated zone (e.g. multilevels G110, G150 and G190). In the case of multilevel G150 a maximum methane concentration of 47.5% v/v was recorded in port G152 located in the unsaturated zone. A maximum methane concentration of 25.6% v/v was recorded in saturated zone ports G156 and G157, which approximates to 150 mg/L of methane in each channel. However, the dissolved methane in water concentrations in ports G156 and G157 are <0.005 and 0.358 mg/L respectively. By applying Henry's Law, even the higher aqueous concentration of 0.358 mg/L would only cause approximately 10 mg/L of methane to partition to the vapour phase in the channel – i.e. 15 times less than that actually recorded. This same relationship is evident in many of the other channels where gas is recorded, leading to the conclusion that diffusion from the unsaturated zone is causing a significant positive bias in the saturated channels.

CONCLUSIONS

A total of 16 long-screened gas and groundwater monitoring boreholes, three groundwater monitoring boreholes and ten multilevel monitoring boreholes were installed around the perimeter of a closed landfill to monitor groundwater levels and groundwater quality, allowing comparison of data between conventional long-screened (>6 m) monitoring boreholes and multilevels which monitored seven discrete (1 m) vertical intervals within a single borehole.

Water-level data from each multilevel show significant vertical variation, indicating a good hydraulic seal between monitoring ports within each borehole.

In general, water levels from the long-screened boreholes show a similar, albeit subdued, seasonal variation to levels from the multilevel boreholes.

Interpretation of groundwater flow directions taken solely from long-screened monitoring boreholes suggests a north-westerly flow path across the site. Data from multilevels suggest a more complex flow pattern, with vertical and horizontal flow paths being concentrated toward discrete horizontal intervals within the Mercia Mudstone. The multilevel boreholes confirm predominantly downward hydraulic gradients across the site, which, while expected, cannot be determined from hydraulic data from the long-screened boreholes.

The distribution of chloride within some multilevel boreholes (e.g. G190) shows significant vertical variation in concentration and maximum values compared to nearby conventional boreholes (e.g. G16 and G17) which appear to show bias towards groundwater quality at the top of the saturated zone. High chloride concentrations in multilevels are often associated with zones of lowest groundwater head. These discrete zones are unrecorded within the conventional long-screened boreholes.

TOC in multilevels show higher maximum readings than in conventional monitoring boreholes, with the highest readings associated with mid-level groundwater heads immediately adjacent to landfill areas. This distribution cannot be determined at all from conventional borehole data.

Multilevels allow a simple means of measuring stratification of gas concentrations within the unsaturated zone, though careful attention to the process of purging and sampling is needed in order to avoid positive biases from diffusion.

Measurement of methane in the saturated channels of the multilevel systems has demonstrated that diffusion biases are probably occurring and creating significant ambiguity in the interpretation of gas concentrations in the headspace.

Multilevel boreholes provide detailed vertical distribution of hydraulic head, groundwater chemistry and unsaturated zone gas concentrations that cannot be resolved using conventional long-screened monitoring boreholes. In this case history, the use of multilevels over conventional long-screen boreholes has provided the Council with a greater degree of confidence in understanding and explaining how and why gas migration can occur in very localised zones within the Mercia Mudstone. These data will lead to better targeting of discreet migration pathways that fall outside the zone of existing gas control systems.

For the purposes of this paper, data from the multilevel boreholes have been assessed separately from data from the long-screened boreholes. In practice, data from most site investigations involving multilevels and longer-screened boreholes would be collated together. The greater vertical differentiation possible with multilevels provides an indication of the degree of uncertainty when assessing data from mixed (averaged or biased) samples taken from longer-screened boreholes, particularly in cases where significant vertical hydraulic gradients exist.

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