Assessment of the impact of traditional septic tank soakaway systems on water quality in Ireland

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ABSTRACT

One of the key threats to groundwater and surface water quality in Ireland is the impact of poorly designed, constructed or maintained on-site wastewater treatment systems. An extensive study was carried out to quantify the impact of existing sites on water quality. Six existing sites, consisting of a traditional septic tank and soakaway system, located in various ranges of subsoil permeabilities were identified and monitored to determine how well they function under varying subsoil and weather conditions. The preliminary results of the chemical and microbiological pollutant attenuation in the subsoil of the systems have been assessed and treatment performance evaluated, as well as impact on local surface water and groundwater quality. The source of any faecal contamination detected in groundwater, nearby surface water and effluent samples was confirmed by microbial source tracking. From this, it can be seen that the transport and treatment of percolate vary greatly depending on the permeability and composition of the subsoil.

Key words | *Escherichia coli*, microbial source tracking, pollution attenuation, septic tanks, subsoils

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INTRODUCTION

In Ireland approximately 500,000 rural households depend on on-site wastewater treatment systems for their effluent disposal (CSO 2011). It is often assumed that older (over 20 years) septic tanks discharging to soakaways are a significant source of pollution, and yet very few studies have set out to quantify the effect. One of the key drivers for this research was a recent ruling by the European Court of Justice which found Ireland did not comply with the EU Waste Directive 75/442/EEC. As such, an on-site wastewater treatment system inspection plan has been put in place to identify potential sites that might fail to meet required standards. One of the most common forms of on-site wastewater treatment systems is the combination of septic tank followed by a soakaway area. The EPA (EPA 2009) currently recommends the presence of 0.9 and 1.2 m of unsaturated subsoil below the invert of percolation trenches receiving secondary effluent and septic tank effluent, respectively. The overall depth to which existing soakpits extend varies greatly, and, so, often times the operational effluent infiltration depth is much greater than those currently recommended. The implications of this are particularly acute in subsoils of higher permeabilities. The soakpit provides a direct route to the underlying subsoil at a much greater depth than conventional systems, thus aiding the migration of nutrients and pathogens.

Through this research the performance of these traditional septic tank soakaways is being monitored across a range of subsoils: two in low permeability and a further four in moderate to high permeability subsoils. The aim of the project is to determine the chemical and microbiological pollutant attenuation in the subsoil of these existing septic tank soakaway systems with respect to groundwater and surface water pollution. Soakaways (or soakpits) are traditionally large pits dug in the ground and back-filled with stone or rubble. Effluent is gravity-fed from the septic tank to the soakaway by means of a single discharge pipe (Figure 1). If these systems are not installed and maintained correctly, or if they are installed in unsuitable subsoil conditions, sufficient effluent treatment will not occur and they may pose a significant risk to water quality. The aim of this research is to identify the subsoil conditions where these

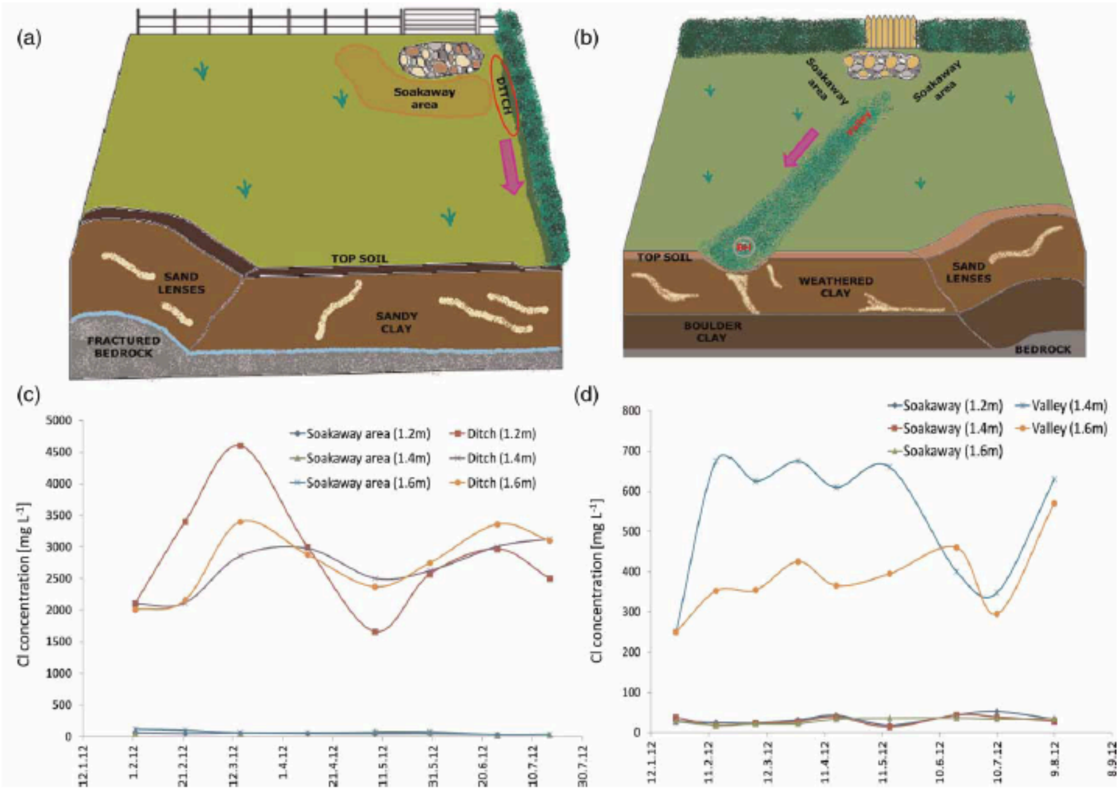

Figure 1 | Cross-sections of two low permeability sites (a) Site A and (b) Site B and mean Cl concentrations at (c) Site A and (d) Site B.

systems operate correctly as well as highlighting the areas where these systems fail to achieve adequate effluent treatment, whereby remediation solutions should be considered.

MATERIAL AND METHODS

Site selection and setup

Assessments were carried out at the six selected sites (as per the EPA Code of Practice 2009) with subsoil permeability determined by means of a falling head percolation test, known as a *T*-test, based on the average time for a 25 mm water level drop (see Mulqueen & Rodgers 2001). Sites with *T*-values of 60 < 90 were classified as low permeability whilst sites with *T*-values of 10 < 50 and <10 were classified as moderate and high permeability, respectively. The corresponding field saturated hydraulic conductivities (Elrick & Reynolds 1986) and details of selected sites are shown in Table 1.

Monitoring instrumentation was installed at each site. Clusters of three suction lysimeters (Soil Moisture Equipment

Table 1 | Summary of site characteristics

Site	Permeability	PE	K_{fs} (m/d)	Sampling duration	Subsoil classification	Groundwater vulnerability[a]
A	Low	3	0.061	11 months	Sandstone till (Devonian/Carboniferous)	Moderate
B	Low	4	0.059	12 months	Shale and sandstone till (Namurian)	Moderate
C	Moderate	3	> 0.28	4 months (ongoing)	Glaciofluvial Sands and Gravels	High
D	Moderate	3	< 0.15	4 months (ongoing)	Glaciofluvial Sands and Gravels	High
E	High	2/3	> 0.45	6 months (ongoing)	Limestone till (Carboniferous)	High
F	High	5	8	8 months (ongoing)	Sandstone till (Devonian)	Extreme/High

[a]DELG EPA GSI (2004). K_{fs}, field saturated hydraulic conductivity; PE, population equivalent.

Corporation Model 1900) were installed at the low permeability sites around the soakaway areas at nominal depths of 1.15, 1.45 and 1.75 m below ground level. At the moderate and high permeability sites suction lysimeters were installed at depths ranging from 1.2 to 3 m below ground level as effluent was expected to percolate more rapidly and to a greater depth in free-draining conditions.

Soil suction lysimeters allowed soil water analysis at different depths around the soakaway areas in order to determine the extent of the effluent plume (Figure 2) with minimal disruption to the existing site setups. In conjunction with these, upstream and downstream boreholes were installed at the low permeability sites in order to assess the impact of these systems on groundwater quality. At each of the moderate and high permeability sites existing wells were sampled to assess groundwater quality. In addition, rainfall data and other meteorological parameters have been recorded to determine the effect of recharge on the attenuation of contaminants within the soakaways.

Sampling methodology

Monthly soil moisture, septic tank and groundwater samples were collected from each site throughout the monitoring periods. Lysimeters were put under a suction of 0.5 bar for 24 h. The resulting vacuum forces soil moisture through the porous ceramic cup, into the lysimeter for collection. Samples were extracted from each lysimeter using a vacuum-pressure hand pump, a 1000 mL conical flask and an extraction tube with a rubber stopper. Total sample volumes for each lysimeter were recorded before being transferred to the laboratory for analysis within 4 h.

Samples were analysed for the following chemical parameters: chemical oxygen demand, total nitrogen, ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N), orthophosphate (PO_4-P) and chloride (Cl). Tests were carried out using a Merck Spectroquant Nova 60® spectrophotometer and associated US Environmental Protection Agency approved reagent kits. Bacterial analysis was also carried out: Idexx Colilert®-18 was used to detect the presence of *Escherichia coli* in samples as described in *Standard Methods* (American Public Health Association. 2005).

Microbial source tracking

Microbial source tracking (MST) was also carried out at both low permeability sites during the sampling period. Samples were also retrieved in triplicate (where possible)

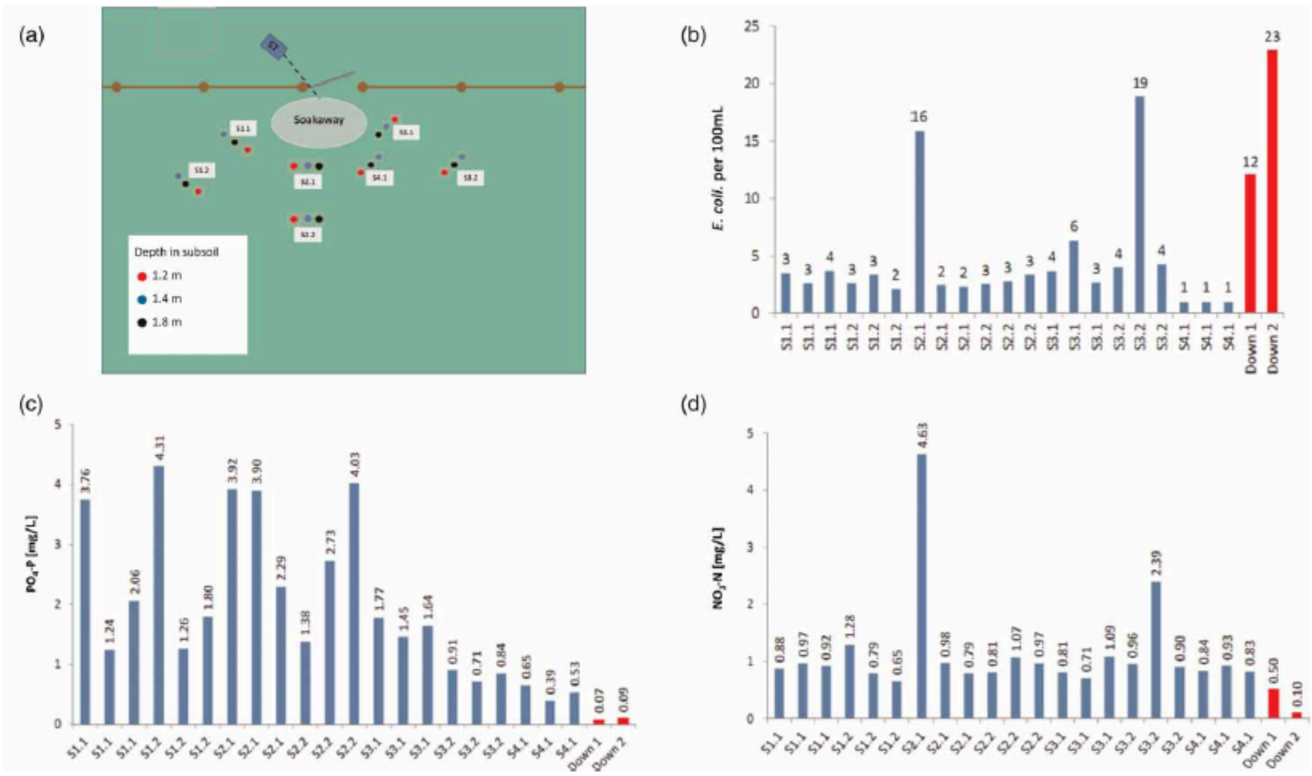

Figure 2 | Site B (a) location of lysimeter clusters and mean concentrations of (b) *E. coli*, (c) PO_4-P and (d) NO_3-N.

for library-independent molecular analysis by real-time polymerase chain reaction (PCR) for the detection of host-specific 16S rRNA gene abundance. Real-time PCR assays were designed by Kildare *et al.* (2007) targeting variable regions of the *Bacteroidales* bacteria 16S rRNA gene specific for human (BacHum) and cow (BacCow) faecal material.

Total genomic DNA was extracted as per Barrett *et al.* (2013). The assay conditions for MST quantitative PCR (qPCR) assays (BacHum and BacCow) were identical to those described by Kildare *et al.* (2007). *E. coli* colonies containing cloned target sequences were sent as a gift to the Microbial Ecology Laboratory (MEL) from University Davis in California. Plasmids containing cloned target sequences were used as standards in the quantitative assay. Real-time PCR quantification was performed using a Light Cycler 480 (Roche, Mannheim, Germany) in duplicate.

RESULTS AND DISCUSSION

Low permeability sites

Results from the two low permeability sites have not shown the systematic degradation of pollutants with subsoil depth as found in previous studies in more permeable subsoils (Gill *et al.* 2007). Figure 2 shows a cross sectional view of each of the low permeability sites with the assumed direction of effluent percolation indicated. Site A (Figure 1(a)) depicts a common onsite wastewater disposal scenario with a soakaway area adjacent to a drainage ditch. During the monitoring period standing effluent was observed at the surface of the ditch following heavy rainfall events, indicating that the hydraulic load was unable to percolate through the receiving subsoil and instead discharged to the draining ditch.

In order to determine the extent of the effluent plume within the subsoil, chloride was employed as a crude tracer at each site, as it does not play a significant role in geochemical reactions (Marshall *et al.* 1999). Hence, elevated chloride levels in and around a soakaway or percolation as seen at Site A in Figure 1(c) indicate the presence of effluent. Chloride levels observed in the adjacent ditch were significantly higher than those recorded in the subsoil surrounding the soakaway area. This confirmed the hypothesis that the majority of the effluent on Site A moved laterally towards the adjacent ditch rather than percolating vertically.

A similar situation was observed at Site B (Figure 1(b)), where the soakaway area was located along a valley in the centre of the field which drained away from the effluent discharge point.

Figure 1(d) shows elevated chloride levels observed in the lysimeters located along this valley, whilst those located in the subsoil immediately adjacent to the soakaway were significantly lower throughout the monitoring period. These localised high levels indicate a distinct pathway of effluent laterally along the valley rather than vertically through the subsoil.

Results from both sites suggest that the low permeability subsoil in combination with any biomat formation in the soakaway prevents the even percolation of effluent through the receiving subsoil, forcing it instead to flow upwards or laterally via distinct pathways such as sand lenses and nearby drainage routes. This affects the ability of the subsoil to sufficiently treat the percolating effluent. Results from Site B show increased levels of *E. coli* (Figure 2(b)) at lysimeter location S2.1 located along the valley and in groundwater samples from a borehole downstream of the soakaway area (Figure 1(b) indicates borehole location in relation to soakaway). Although detected levels were greatly reduced from those present in the septic tank effluent at Site B (Table 2), it highlights the risk to both surface water and groundwater bodies due to insufficient subsoil permeability resulting in the run-off of ponded effluent.

Figure 2(c) shows the reduction in PO_4-P levels between the soakaway area and the downstream boreholes. Removal of phosphorus from the percolate in the subsoil is typically due to soil adsorption and mineral precipitation

Table 2 | Particle size analysis[a]

Site	Subsoil depth (m)	Depth (m)	Clay/Silt (%) Clay (%)	Silt (%)	Sand (%)	Gravel (%)
A	5	0–2.5	20	25	33	22
B	10	0–2	24	12	31	31
C	3–10	0.5–1	39		27	34
		1–2	1	6	28	65
		2–2.4	43		35	22
D	3–10	1–1.4	16		55	30
		> 1.4	28	58	12	2
E	4	0.2	14		44	42
		1	5		22	72
		1.5	1	4	19	76
		2	5		42	53
F	2	0–1.5	3	23	39	35

[a]See BS1377–2:1990 (British Standards Institution) for method.

processes. The P-fixation capacity of a soil is dependent on a number of factors, particularly its percentage clay fraction, in this case 24% (Table 2). The presence of such a high percentage of fine particles provides a large specific surface conductive to phosphorus adsorption, and so, despite the indication of lateral movement of effluent, the subsoil promotes good PO_4-P attenuation. Figure 2(d) shows elevated levels of nitrate (NO_3-N) at the same location as Figure 2(b) (S2.1), verifying the assumption that the effluent is moving laterally along the valley. However, as with the PO_4-P, reduced levels of NO_3-N are recorded in downstream groundwater samples, suggesting that, despite the unconventional flow path, a certain level of effluent treatment was occurring. The observed elevations in average NO_3-N concentrations, illustrated in Figure 2(d) (S2.1 and S3.2), suggest the occurrence of limited nitrification within the subsoil of the septic tank effluent whose inorganic fraction is primarily in the form of ammonium (NH_4-N). As such, the potential for anammox transformations of NH_4-N to nitrogen gas exists in the low permeability subsoil where anaerobic conditions are prevalent. However, a proportion of the observed total inorganic reduction is most likely due to the dilution of percolating effluent as it moves through the subsoil. Similar reductions in PO_4-P and NO_3-N were also observed at Site A.

Microbial source tracking

The real-time PCR assay targeting human (BacHum) specific *Bacteroidales* bacteria was applied to the genomic DNA from the septic tank effluent and downstream groundwater samples. The real-time PCR results were correlated with total coliform, *E. coli* and chloride levels to assess the potential transport of sewage-borne pathogens to the groundwater downstream from the soakaway system.

Human-specific *Bacteroidales* bacteria (BacHum) were successfully detected and quantified in septic tanks from both sites with concentrations ranging from 8.23E + 03 to 5.72E + 04 GCC/50 ml. BacHum was also successfully detected in samples retrieved from the soakaway area (5.35E + 02 GCC/50 mL) and downstream borehole samples (4.95E + 02 GCC/50 mL) from Site B (Figure 3), showing a 2-log reduction of human faecal bacteria in low permeability subsoils. The real-time PCR results show a general decrease in abundance from the septic tank to the downstream boreholes. While a 1-log increase in *E. coli* was detected in the downstream sample compared to the soakaway sample, the MST was able to prove that this was coming from a non-human source (BacCow).

Moderate and high permeability sites

As detailed in the results for the low permeability sites, chloride was used as a crude tracer, to determine the extent of effluent plume development at the moderate and high permeability sites.

Figure 4(a) shows the lysimeter depth below ground level and decrease in chloride concentrations with distance from the soak-pit, with the exception of lysimeter 4, at Site E (Figure 4(b)). Low sample volumes as well as low chloride concentrations indicate that lysimeter 4 was not within the effluent plume. From the remaining sample points the plume can be said to extend horizontally to lysimeter 7 with a decrease in chloride concentrations. The deepest sampling point, excluding the well, was lysimeter 5 at 3 m below ground level, which measured an average of 95 mg/L

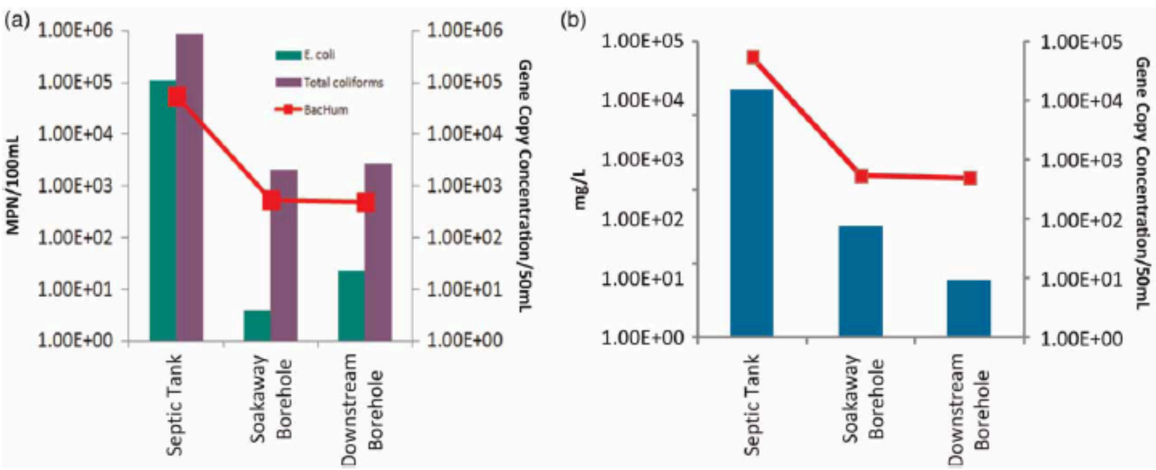

Figure 3 | BacHum gene abundance correlated with (a) total coliforms and *E. coli* counts and (b) chloride levels for the septic tank and downstream groundwater from Site B.

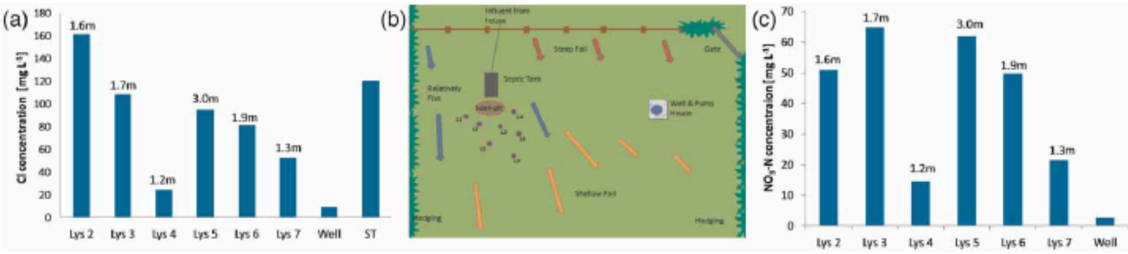

Figure 4 | Average (a) chloride levels (c) nitrate levels across sampling points shown in (b).

across the testing period, suggesting the plume extends to this depth. Overall this suggests a predominately vertical plume with some lateral dispersion due to the overall gradient of the site. Figure 4(c) confirms this with higher levels of NO_3-N at shallower depths close to the discharge point and at deeper depths further away. The high NO_3-N concentrations recorded at Site E suggest the occurrence of rapid nitrification by the 1.6 m sample depth; a slight decrease in NO_3-N values is observed by the 3.0 m depth, by which time the effluent plume is expected to have extended further in a lateral as well as vertical direction so that the overall concentration is dispersed. This gradual dispersion with depth may contribute to the reduction in impact on groundwater quality, the average concentration of which was found to be 3 mg L^{-1} over the course of the study. The dilution capacity of the groundwater may also serve to mitigate the potential impact.

Results from the higher permeability sites with a shallow depth of free-draining subsoil have shown elevated levels of *E. coli* at all sampling depths down to the bedrock under varying conditions.

Site E (Kilbeggan in County Westmeath) shows a decrease in observed *E. coli* levels during periods of heavy rainfall, presumably due to the dilution effects of rainfall recharge through the highly permeable subsoil (Figure 5(a)). Site F (Fermoy in County Cork) shows the opposite response to rainfall events, with a significant increase in *E. coli* levels during heavy rainfall events (Figure 5(b)). This is thought to be due to the reduced travel times (and therefore attenuation) of the effluent through the subsoil as a result of the temporary increase in hydraulic load and higher soil moisture conditions. Despite the elevated *E. coli* levels in the soil moisture samples, there was no adverse effect on downstream groundwater quality.

This variation in subsoil response to rainfall recharge, given both sites are in high permeability areas, may be as a result of the difference in the particle size analysis of their subsoils (Table 2). Site E has a high gravel fraction and an extremely low silt/clay fraction through which percolate can move freely with little probability of attenuation. Site F, on the other hand, has a much lower fraction of gravel and a higher fraction of silt/clay. The presence of this higher silt/clay fraction at Site F may be responsible for the attenuation of bacterial pollutant within the subsoil during periods of low or zero rainfall, as previous studies have shown bacterial attenuation is greatest in soil with high percentages of fine particles, i.e. clay and silt (Tare & Bokil 1982). Despite the increased migration of enteric pathogens recorded during these high

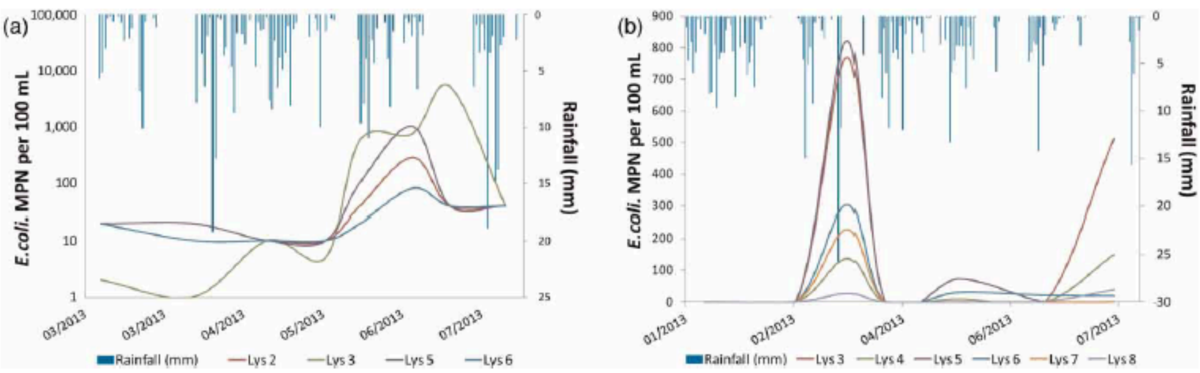

Figure 5 | Effect of rainfall recharge on *E. coli*. Concentrations at site E (a) and F (b).

rainfall events, the overall bacterial attenuation of the subsoil was high, presumably as a result of the development of a mature biomat or soil clogging layer. As highlighted by previous studies under similar conditions (Gill *et al.* 2007), the formation of this clogging layer is crucial in free-draining subsoil such as those present at Site E and Site F, as the clogged interstitial pore spaces act to prevent significant transport of bacteria through physical straining.

Similar trends were also observed at Site C and D, both of moderate subsoil permeability. This suggests the attenuation capacity of soakaways in freely moderate to high permeability subsoils varies under changing climatic conditions. Although the receiving subsoil may deal well with the effluent hydraulic load under dry conditions, heavy rainfall may cause contaminants to move quickly through the subsoil, resulting in reduced attenuation.

CONCLUSION

Results from this study show the treatment performance of these systems is directly linked to the subsoil characteristics within which they are located. Preliminary results highlight the importance of the depth, permeability and structure of subsoil in ensuring the adequate treatment of the percolating effluent.

The soakpits monitored in slow-draining low permeability conditions indicated that the low hydraulic conductivity of the surrounding subsoil forced effluent from within the soakpit to the surface. From here it moved by means of preferential pathways through the more permeable lenses present in the upper subsoil horizon or, on occasion, as surface water run-off. The health risk posed by standing effluent cannot be overemphasised. The risk to both groundwater and surface water quality was also evident, with the potential presence of enteric bacteria detected in downstream boreholes at Site A, located approximately 50 m from the site soakpit, as a result of the migration of effluent along upper horizon at the site. The transport of contaminants through higher permeability lenses (such as sand lenses) located within such glacially derived heterogeneous subsoil may also pose a risk to groundwater quality. The importance of faecal source tracking methods in circumstances where microbial contamination is detected has also been shown to be useful in aiding the identification and resulting remediation of problem sites.

As expected, in high to moderate permeability areas soakaway systems were found to pose the greatest risk to groundwater. Within these moderate/high permeability subsoils the effluent plume was found to develop primarily in a lateral direction, lateral development dependent on the gradient of the site. The formation of a biomat layer at the infiltrative surface was critical in the performance of soakpits in higher permeability soils, as it acted to increase the effluent retention time in the upper regions of the subsoil, thus enhancing the treatment potential. The absence of any significant fraction of fines (clay and silt particles) within these free-draining subsoils resulted in an increased risk of pollutant migration as a result of the increase in hydraulic conductivity following high rainfall events.

Monitoring of moderate and high permeability septic tank soakaway systems is continuing, with further results being collected across further meteorological conditions. This will provide important information needed at a strategic planning level to determine if and where remediation of existing soakaways likely will be necessary in order to protect water resources and to improve water quality.

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