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Faecal contamination of watercourses from farm waste disposal for three sites in the UK with contrasting soil types

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Abstract. Despite considerable investment, some UK bathing waters fail to comply with mandatory standards as defined by the EU Bathing Water Directive (76/160/EEC). Continued non-compliance has been associated with diffuse sources of faecal indicator organism (FIO) contamination, in particular those deriving from agricultural land. This paper examines concentrations of FIOs in surface, subsurface and instream water samples at field sites considered to pose a high potential risk of FIO contamination. Quality of samples was compared with FIO standards for bathing water compliance in the UK. FIO concentrations exceeding mandatory and guideline standards were recorded frequently at all sites. In freely draining soils, FIO mobilization by rainfall was predominantly via subsurface flow, with occasional surface water flow linked to intensive rainfall events. In slowly permeable soils, surface mobilization of FIOs predominated, with the occurrence of limited subsurface samples linked to seasonal desiccation cracking within the soil, and to intense rainfall events. Watercourse FIO concentrations were significantly increased as the stream passed-by fields with freely draining soils. The data imply a generally higher risk of FIO transfer from freely draining soils and occasional increased risk from less permeable soils due to temporal changes in soil structure and rainfall intensity.

INTRODUCTION

The European Union (EU) Bathing Water Directive (76/160/EEC) was introduced in 1976 to protect human health by improving the quality of bathing waters, as defined by 18 parameters with mandatory and guideline standards. The UK interpretation of the EU Directive primarily considers compliance based on mandatory standards set for total coliforms and faecal coliforms, and guideline values for both these and faecal streptococci (Table 1), collectively termed faecal indicator organisms (FIOs). Compliance is also gauged against standards for other parameters contained in the EU Directive.

Improvements in bathing water quality in Member States of the EU have occurred since the introduction of the Directive (EEA 2004), primarily due to investment in secondary sewage treatment works. In 2003, 98.8% of UK bathing waters achieved compliance (EA 2004). However, non-compliance still occurs, even where investment in domestic sewage treatment has been made (Wyer *et al.* 1996; Kay *et al.* 1999). Also, the proportion of compliant water bodies may again fall, following the introduction of more stringent standards, which are roughly equivalent to the present guideline standards with which only 80% of UK bathing waters had complied in 2003 (EA 2004).

A need exists, therefore, to identify additional FIO sources within catchments. One potential FIO source is that originating from agricultural activity (Wyer *et al.* 1998; Hooda *et al.* 2000). For example, manure and liquid slurry are used extensively on agricultural land in the UK (DEFRA 2004), where they help to maintain good soil quality (Nicholson *et al.* 2000) and provide a rich organic source of fertilizer (Hooda *et al.* 2000). However, there are concerns about the faecal contribution that such field-applied manures are making to adjacent watercourses (Carrington *et al.* 1998).

This paper reports results from surface, subsurface and instream water samples taken within and adjacent to contrasting fields where organic manures were being applied, which were considered to be of high potential risk of causing pollution. The quality of water was compared to FIO concentrations used to define bathing water quality in the UK. The specific objectives were to assess water quality at point locations throughout the bathing season (May to September), to determine factors causing differences in water quality between locations, and to determine factors affecting variability in water quality within each field site. This study forms part of a larger project (McHugh *et al.* 2003, 2004).

MATERIALS AND METHODS

Experimental locations and sites

Field sites were selected at three locations in England: the Caerhays catchment, Cornwall; the Sandsend catchment,

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Table 1. Mandatory and guideline standards for faecal indicator organisms (FIOs) set by European Union Bathing Water Directive 76/160/EE.

Organism	Mandatory[a, b]	Guideline[a, b]
Total coliforms	95% < 10 000	80% < 500
Faecal coliforms	95% < 2000	80% < 100
Faecal streptococci	No level set	90% < 100

[a] Colony forming units (c.f.u.) 100 mL^{-1}. [b] Minimum percentage of 20 samples required to meet standard in order to achieve compliance.

North Yorkshire; and the Rowden Moor experimental plot at North Wyke Research Station, Devon. At each location, fields that posed a high risk of FIO pollution were selected. The potential risk of causing pollution was assessed in accordance with the Farm Manure Management Plans (FMMP; DEFRA 2003), whereby a field is considered to have a high risk if it is adjacent to a watercourse, has a moderate slope (>4°) and/or contains drains. Three fields each at Sandsend and Caerhays were chosen, and two hydrologically isolated field plots at Rowden. All the field sites were adjacent to either a stream or drainage ditch and some fields had pipe drainage (Table 2). Applications of organic manures at all sites (Table 2) were within acceptable Code of Good Agricultural Practice limits for England and Wales (MAFF 1998).

Descriptions of the soil in each selected field are given in Table 2. The soils at Sandsend (Brickfield2 and Dunkeswick) and at Rowden (Hallsworth1) are similar: all are surface-water gley soils, which are slowly permeable and have a horizontal saturated hydraulic conductivity of less than 0.1 m d^{-1} (Findlay *et al.* 1984). In contrast, the soils in the Caerhays catchment (Denbigh2 and Powys) belong generically to brown soils and lithomorphic soils, respectively, and are freely draining or permeable, with a horizontal saturated hydraulic conductivity greater than 0.6 m d^{-1} (Findlay *et al.* 1984). Although the surface soils are freely draining, the profile depths of Denbigh and Powys series are moderate (max. 100 cm) to shallow (max. 25 cm), respectively, overlying slate or mudstone.

At each of the three locations, rainfall data were collated to assess how representative the rainfall had been during the sample period. The data were compared to 30-year average rainfall data available from rain gauge stations at Sandsend and Rowden (Table 3). As long-term rainfall data were not available from the rain gauge station at Caerhays, rainfall was compared to the 30-year regional average (Met. Office data for England SW and Wales S [1971–2000]) and to the two preceding years (2000–01) recorded at the Caerhays rain gauge station (Table 3). The greatest discrepancy between observed rainfall and the long-term average occurred at Rowden, where August and September 2003 were much drier than the long-term average, as also was September 2002 at Caerhays.

Field installations and sample collection

All the field sites were instrumented similarly. Surface and subsurface water samples were collected at three downslope points within the field and water samples were

Table 2. Field site management and soil description for sites at Caerhays, Sandsend and Rowden.

Location	Field site	Organic manures applied	Land use during bathing season		Field drainage	Soil association	FAO[c]	Soil description[d]	Soil texture (%)[e] sand : silt : clay
Caerhays	1	None	Grassland	Animals present periodically	Pipe drained	Denbigh2	Nitisols	Well drained fine loamy soils over slate or slate rubble	30 : 43 : 27
	2	15.3 m^3 ha^{-1} slurry (late April to early May)	Arable	Maize; animal access to stream	Pipe drained	Denbigh2	Nitisols		30 : 43 : 27
	3	2.5 & 10 t ha^{-1} manure (early March, then early April)	Grassland	Animals present throughout	Undrained	Powys	Nitisols	Shallow well drained loamy soils over rock	34 : 42 : 24
Sandsend	1	18–20 m^3 ha^{-1} slurry (Apr) & 20 m^3 ha^{-1} slurry (Jul)	Grassland	Animals present periodically	Pipe drained	Brickfield2	Gleysols	Slowly permeable, seasonally waterlogged fine loamy soils	42 : 35 : 23
	2[a]	44 m^3 ha^{-1} slurry (Jun)	Grassland	Animals present periodically	Pipe drained	Dunkeswick	Gleysols	Slowly permeable, seasonally waterlogged fine loamy and fine loamy over clayey soils	41 : 32 : 27
	3[a]	44 m^3 ha^{-1} slurry (Jun)	Grassland	Animals present periodically	Pipe drained	Dunkeswick	Gleysols		41 : 32 : 27
Rowden	8[b]	34 m^3 ha^{-1} slurry (Jun, Aug & Oct)	Grassland	No animals present	Undrained	Hallsworth1	Gleysols	Slowly permeable, seasonally waterlogged clay soils	27 : 38 : 35
	11[b]	17 m^3 ha^{-1} slurry (Jun, Aug & Oct)	Grassland	No animals present	Undrained	Hallsworth1	Gleysols		27 : 38 : 35

[a]Sites 2 and 3 managed by same farmer. [b]sites 8 and 11 managed by same farmer. [c]Food and Agricultural Organization World Reference Base for Soil Resources. [d]Based on Avery (1980). [e]Average texture for 0–15 cm soil depth from National Soil Inventory, National Soil Resources Institute.

Table 3. Rainfall data (mm d^{-1}) for Caerhays, Sandsend and Rowden during the sampling period and the 30-year average rainfall.

Location	Year	Month				
		May	Jun	Jul	Aug	Sep
Caerhays	2000	2.5	1.2	2.9	2.6	5.3
	2001	0.2	1.0	3.2	1.8	1.4
	2002[a]	3.6	1.7	2.0	1.7	0.3
	1971–2000[b]	2.3	2.5	2.1	2.9	3.5
Sandsend	2003[a]	1.4	2.8	1.2	1.6	2.8
	1961–1990[c]	1.7	1.7	1.8	2.1	1.8
Rowden	2003[a]	2.0	1.4	2.0	0.7	0.8
	1966–1995[c]	2.1	2.0	1.7	2.0	2.7

[a] Year that catchment was monitored. [b] 30-year regional average. [c] 30-year average at rain gauge station.

collected from the watercourse adjacent to each field. At Sandsend, additional surface and subsurface water samples were collected from an adjacent field on the other side of the watercourse. Samples were collected monthly to achieve a baseline signature, interspersed with rainfall event sampling. Although an attempt was made on every visit to collect water samples from surface, subsurface and watercourse locations, this was not always possible during dry periods. In total, 486 samples were collected.

The surface water traps were based on a design by Gerlach (1966); see McHugh *et al.* (2004) for further details. The basic design consisted of a V-shaped trap (each arm 1 m long) orientated across the predominant slope in the field. The traps were buried flush with the soil surface. To aid transfer of surface water into the plastic pipe, a thin plastic sheet (approx. 20 cm wide) was inserted into the soil at a depth of about 1 cm and the other side inserted into a slit cut into the pipe. The collection channels converged downslope at a junction from where samples were taken over a 24-hour period.

Field drains were used to sample subsurface water. In fields having no or insufficient field drains, piezometers were installed. A standard piezometer design was used, consisting of a pre-augured hole (10 cm diameter) into which a perforated plastic pipe (5 cm diameter) was inserted above an impermeable membrane and backfilled with 10 mm pea-gravel. Water in the piezometers was evacuated 24 hours before the collection of samples for analysis. Sampling frequency was the same as for the surface water traps.

With the exception of the two Rowden fields (see below), three replicate watercourse samples were collected at the upstream and downstream borders of the field site in pre-sterilized, 150 mL, screw-top, polypropylene bottles. Samples were taken from the mid-point of the channel at approximately mid-stream depth. Care was taken to minimize disturbance of streambed sediments, and downstream samples were collected prior to upstream samples. At Rowden it was only possible to collect downstream samples from the exit points of the field drainage ditches that ran along two sides of each field plot. Because of the ephemeral nature of water in these drainage ditches, unless the drain was flowing, a sample bottle was left at the sampling point for 24 hours. If there was no rainfall in the 24-hour period, no surface drain sample could be collected.

Samples were collected at Caerhays from 16 April to 22 September 2002, at Sandsend from 8 May to 1 October 2003, and at Rowden from 1 May to 23 October 2003, which coincided with the monitoring seasons for bathing water.

FIO analysis

Water samples were stored in the dark at $<6\,^{\circ}$C and analysed within 24 hours of collection at Environment Agency laboratories. Samples were analysed for total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS) using standard UK methods based on membrane filtration (EA 2002). TC and FC were cultured using membrane lauryl sulphate broth on sterile absorbent pads, whereas FS were cultured on Slanetz and Bartley agar. Membrane filters (47 mm diameter) with a nominal pore size of 0.45 μm were placed in Petri dishes (55 mm diameter) pre-incubated for 4 h at 30 °C. Subsequently, the plates were incubated at 37 °C (TC) for 14 h, or 44 °C (FC and FS) for 14 h and 44 h, respectively. All counts were expressed as colony-forming units per 100 millilitres of sample (c.f.u. 100 mL^{-1}). The lower detection limit was 10 c.f.u. 100 mL^{-1}.

Statistical treatment of data

The geometric mean of $\log_{10}$ transformation of the concentrations in the triplicate water samples was calculated following Wyer *et al.* (1996) and Hunter *et al.* (2000). For some surface and subsurface samples it was not possible to collect triplicate samples and the reported value may therefore represent a single sample. Where a median concentration is expressed for a sampling point this refers to the median value of the geometric means. Median values were used, unless otherwise stated, because of the highly variable concentrations of FIOs observed.

Statistical comparisons of sample concentrations between sample points and field sites were performed using the non-parametric Mann–Whitney U-test. Results are expressed at 95% confidence level.

RESULTS

Quality of water samples

Table 4 highlights the percentage of samples where FIO concentrations exceeded the EU mandatory and guideline standards for bathing water (Table 1). At all three Caerhays field sites a higher percentage of downstream compared with upstream samples exceeded mandatory standards for both TC and FC. More than 70% of stream samples exceeded guideline standards and in most cases these standards were exceeded on every visit (values of 100% in Table 4). A greater proportion of surface than subsurface samples exceeded both mandatory and guideline standards.

At Sandsend the pattern between samples collected from upstream and downstream points was less clear. A greater proportion of upstream samples exceeded mandatory standards than downstream samples at field site 1 (Table 4), and similar proportions of upstream and downstream samples exceeding mandatory standards at field sites 2 and 3. Proportions of surface to subsurface samples that exceeded

Table 4. Percentage of recorded observations that exceeded UK mandatory and guideline standards for total coliforms (TC), faecal coliforms (FC) and faecal streptococci (FS) in water samples collected from Caerhays, Sandsend and Rowden.

Field site		% Exceeding mandatory[a]		% Exceeding guideline		
		TC	FC	TC	FC	FS
Caerhays						
1	Upstream	20	70	100	100	100
	Downstream	70	80	90	100	100
	Surface	86	86	100	86	86
	Subsurface	20	24	36	52	36
2	Upstream	10	50	100	100	70
	Downstream	30	60	100	100	100
	Surface	89	44	89	78	56
	Subsurface	6	22	28	28	17
3	Upstream	20	20	100	100	80
	Downstream	50	90	100	100	100
	Surface	83	67	100	75	0
	Subsurface	0	0	22	22	11
Sandsend						
1	Upstream	100	100	100	100	100
	Downstream	67	78	100	100	100
	Surface	54	15	88	50	19
	Subsurface	No sample		No sample		
2	Upstream	25	50	75	88	88
	Downstream	22	67	78	100	78
	Surface	43	0	91	22	17
	Subsurface	17	0	67	50	50
3	Upstream	33	67	89	100	89
	Downstream	22	67	67	78	89
	Surface	40	16	53	42	16
	Subsurface	44	25	81	94	56
Rowden						
8	Downstream	57	19	81	52	81
	Surface	41	13	70	30	7
	Subsurface	0	0	57	43	57
11	Downstream	52	30	65	57	43
	Surface	36	16	71	34	9
	Subsurface	0	0	80	40	40

[a] No mandatory standard set for FS concentrations (see Table 1).

both mandatory and guideline standards were also highly variable between sites, although more subsurface than surface samples exceeded the standards at field site 3 (Table 4).

At Rowden, no subsurface samples exceeded the mandatory standards. The mandatory standard for TC was exceeded by more than 36% of surface and stream samples, although fewer samples exceeded mandatory standards for FC (Table 4). The percentage of subsurface samples that exceeded guideline standards for TC and FC was similar to the proportion of surface and downstream samples exceeding these standards. However, far fewer surface samples exceeded the guideline standards for FS compared with subsurface and downstream samples. A seasonal trend in water sample quality was observed at Rowden but not at Caerhays or Sandsend. Between June and September at Rowden, 88% of downstream samples exceeded the mandatory standards for TC, but in October this declined to less than 20% (see Figure 1c).

Comparison of FIO concentrations between field sites

The total number of samples collected at each sample point together with descriptive statistics of their FIO concentrations are presented in Table 5. Although some trends could be seen in the data, few represented statistically significant differences. The following section describes significantly different patterns only.

The greatest maximum concentrations of TC and FC were recorded at Rowden but FIO concentrations were generally greater at Caerhays and Sandsend, with field sites at Caerhays having greater surface concentrations of FIOs than Sandsend or Rowden.

At Caerhays, downstream concentrations of FS were greater than upstream concentrations at field sites 2 and 3, while at field site 1 upstream concentrations of FS were greater than downstream concentrations. Downstream FS concentrations at field site 1 were greater than those at either field site 2 or 3. Similarly, downstream TC concentrations at field site 1 were greater than those at either field sites 2 or 3. A difference was found in FS concentrations in surface samples, with field site 1 having a greater FS concentration than either field sites 2 or 3, and field site 2 having a greater FS concentration than field site 3.

At Sandsend, a difference in concentration was observed between upstream FIO concentrations, with field site 1 having a greater FC concentration than field site 2, and a greater FS concentration than field site 3. Subsurface concentrations of FC were greater at field site 3 than at field site 2.

At Rowden, the downstream FS concentration at field site 8 was greater than at field site 11.

Variability in FIO concentrations within individual fields

Concentrations of FIOs at sample points were highly variable (Table 5). For example, at Caerhays the coefficient of variation for TC for field site 3 was 461% in subsurface samples, while the smallest value for the coefficient of variation for TC concentration (surface samples of field site 2) was 66%.

Figure 1 shows representative examples of the temporal variation of TC concentrations (geometric mean) observed at sample points within a field site for Caerhays, Sandsend and Rowden. The TC concentrations presented in Figure 1 and described below are used to illustrate the observed spatial and temporal variability in FIO concentrations between sample points; the general patterns illustrated by the TC data were replicated in the FC and FS data.

At Caerhays, far fewer surface samples were collected than subsurface samples (Table 5) due to a lack of overland flow. Most surface samples were collected in August and September, whereas subsurface samples were collected throughout the season. When median concentrations were compared, surface TC concentrations at field site 1 were significantly greater than equivalent subsurface TC concentrations. There was no significant difference in concentrations between downstream and surface samples at fig site 1, but downstream samples had statistically greater concentrations than subsurface samples. On most sampling occasions, and for all three field sites, downstream TC concentrations were higher than those upstream. At field sites 2 and 3, TC concentrations were statistically greater in surface compared with subsurface samples, surface compared

Table 5. Descriptive statistics of faecal indicator organisms in water samples from Caerhays, Sandsend and Rowden.

Field site & sample location[a]	n[b]	Total coliform (c.f.u. 100 mL^{-1})				CV (%)	Faecal coliform (c.f.u. 100 mL^{-1})				CV (%)	Faecal streptococci (c.f.u. 100 mL^{-1})				CV (%)
		Range	Median	Mean	SD		Range	Median	Mean	SD		Range	Median	Mean	SD	
CAERHAYS																
1 Up	10	816–172 727	6147	25 214	52 617	209	313–163 636	3447	21 635	50 361	233	108–54 000	4526	8523	16 204	190
1 Down	9	289–145 455	43 812	47 604	48 576	102	318–66 000	9755	22 043	23 599	107	100–27 000	2893	8449	10 642	126
1 Surf	7	2696–1 000 000	100 000	250 178	361 424	144	21–1 000 000	39 786	229 940	372 847	162	10–101 936	9880	30 307	42 232	139
1 Sub	25	10–68 973	217	6547	15 335	234	10–17 000	156	2365	4543	192	10–5025	15	428	1164	272
2 Up	10	690–11 000	1844	3062	3184	104	490–5794	1686	2301	1956	85	36–709	180	227	202	89
2 Down	10	1666–75 452	3856	12 666	22 653	179	654–78 834	3416	10 893	23 987	220	230–4659	342	851	1374	161
2 Surf	9	264–110 000	100 000	66 434	43 759	66	10–100 000	1455	23 722	43 303	183	10–1851	222	390	602	154
2 Sub	38	10–100 000	95	6428	18 553	289	10–100 000	50	5737	18 649	325	10–44 177	10	2395	9185	383
3 Up	10	617–16 000	1954	4147	5274	127	419–9466	1116	2659	3507	132	62–1505	261	407	455	112
3 Down	10	1860–40 000	7505	13 661	14 249	104	1232–32 220	5948	12 656	12 17	97	277–61 617	736	7624	19 086	250
3 Surf	12	818–1 000 000	100 000	156 829	272 273	174	10–100 000	6318	35 541	47 720	134	10–100	23	40	36	91
3 Sub	33	10–100 000	68	3764	17 348	461	10–100 000	16	3492	17 375	498	10–9443	10	539	1956	363
Σ	183															
SANDSEND																
1 Up	9	14 928–1 000 000	261 584	385 681	345 285	90	2927–333 606	33 808	75 626	102 420	135	579–75 687	4670	16 904	26 721	158
1 Down	9	2951–606 589	50 698	152 022	207 344	136	498–86 707	3767	20 343	29 974	147	101–30 616	474	4256	9936	233
1 Surf	26	0–1 000 000	15 800	165 641	335 123	202	26–47 000	140	3380	9939	294	10–100 000	100	4027	19 576	486
1 Sub	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2 Up	8	41–100 000	3270	19 794	35 978	182	30–100 000	1939	16 708	34 622	207	32–50 147	2107	9365	17 437	186
2 Down	9	30–94 093	3298	15 776	30 660	194	179–89 225	4643	17 141	30 574	178	24–17 936	2772	4261	5893	138
2 Surf	21	90–1 000 000	10 000	73 230	219 501	300	10–2000	100	345	490	142	10–41 000	100	1887	8336	442
2 Sub	6	90–60 877	2349	11 453	24 236	212	66–483	151	232	186	80	26–7101	342	1699	2789	164
3 Up	9	359–191 340	4469	27 212	61 910	228	286–187 944	4199	27 795	60 714	218	82–23 800	320	3046	7798	256
3 Down	9	79–393 210	2912	47 627	129 668	272	46–396 636	2599	48 729	130 601	268	68–45 803	444	5507	15 119	275
3 Surf	15	282–960 000	4082	97 959	254 344	260	10–360 000	100	21 356	82 510	386	10–5100	100	408	1164	285
3 Sub	16	117–448 535	8440	74 599	138 828	186	60–20 000	673	2689	5117	190	10–4736	187	537	1184	221
Σ	137															
ROWDEN																
8 Down	21	23–24 000 000	35 000	1 216 175	5 221 660	429	10–20 000	220	1789	4441	248	81–22 000	380	2196	5220	238
8 Surf	54	10–8 181 818	5000	379 222	1 295 229	342	10–636 095	100	13 515	86 702	642	10–3200	100	182	467	257
8 Sub	7	100–1403	1000	672	554	82	100–1000	100	350	388	111	100–1000	282	458	415	90
11 Down	23	10–8 888 866	12 000	488 269	1 846 935	378	10–9 162 979	335	402 427	1 909 756	475	2–59 000	100	4071	13 212	325
11 Surf	56	10–44 000 000	2000	1 629 491	7 700 530	473	10–37 000 000	100	1031346	5 575 324	541	10–1000	100	125	180	144
11 Sub	5	100–5000	1000	1529	1976	129	100–1000	100	460	493	107	10–1000	550	528	547	104
Σ	166															

[a] Sample locations: Up (upstream), Down (downstream), Surf (surface) and Sub (subsurface). [b] n = number of samples. SD = standard deviation; CV = coefficient of variation.

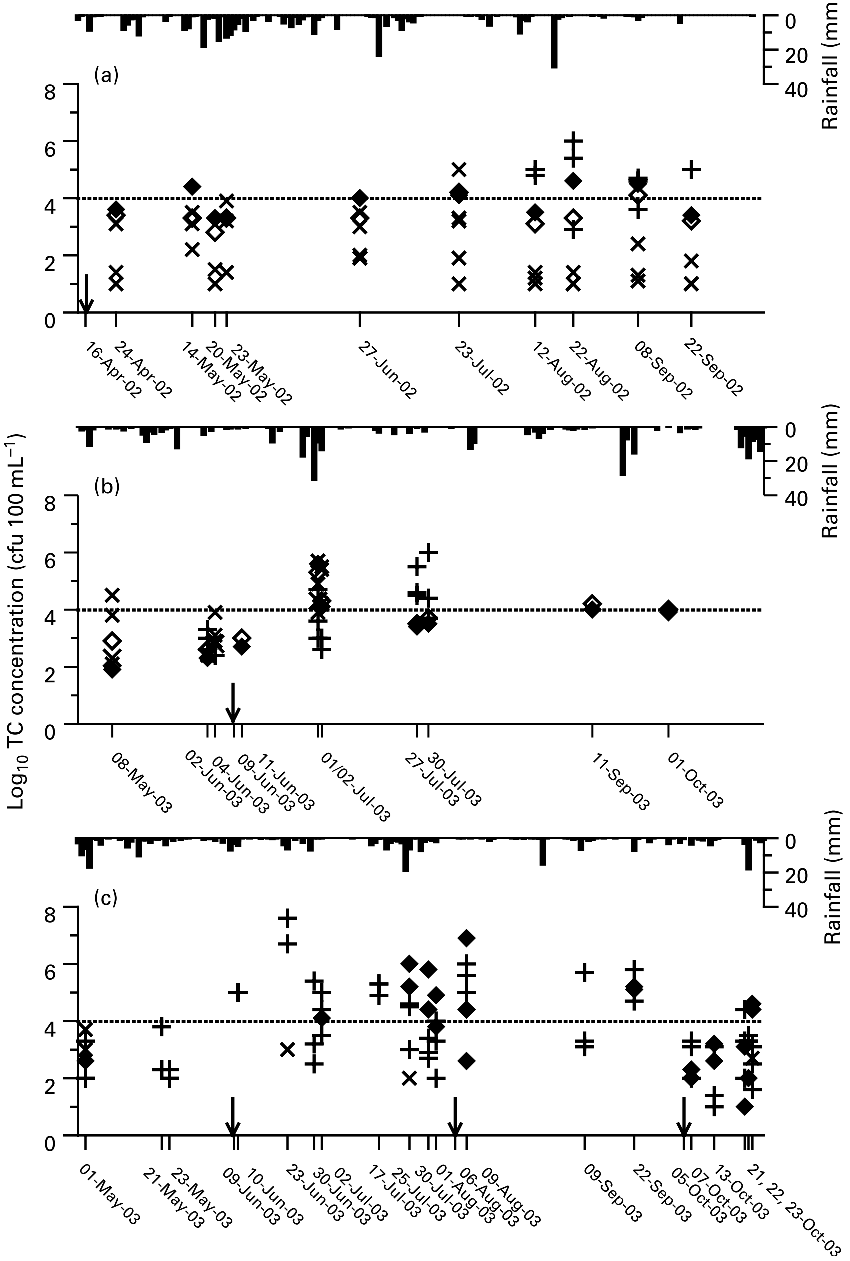

Figure 1. Differences in log$_{10}$ concentrations of total coliforms (TC) (c.f.u. 100 mL^{-1}) at surface (+), subsurface (×), upstream (◇) and downstream (◆) sample points compared to the mandatory standard (· · · ·) for TC, and daily rainfall totals throughout the bathing season for (a) field site 3 at Caerhays, (b) field site 3 at Sandsend and (c) field site 11 at Rowden. Arrows (↓) indicate when manures were applied.

with downstream samples, and downstream compared with both subsurface and upstream samples.

At Sandsend, more surface samples and fewer subsurface samples were collected than at Caerhays (Table 5; Figure 1a, b). No water samples were obtained from subsurface sample points on field site 1 and limited subsurface samples were collected from Sandsend field sites 2 and 3. TC concentrations were significantly greater upstream than downstream at field site 1, but there were no significant differences at field site 2 or 3. TC concentrations were significantly greater in surface samples compared with subsurface and downstream samples at field site 2. No significant difference was found between TC concentrations of downstream and subsurface samples in either field site 2 or 3, and there were no significant differences between surface samples and subsurface or downstream sample concentrations at field site 3. At field sites 2 and 3, TC concentrations in watercourse samples showed a tendency to increase in concentration following slurry application only when there was a significant rainfall event, as on 30 June (Figure 1b).

At Rowden, limited subsurface drainage restricted the number of subsurface samples collected. As at Sandsend, the samples collected at Rowden were predominantly surface samples (Table 5; Figure 1c). For field site 8, surface TC concentrations were significantly greater than those of subsurface samples. Concentrations of TC were significantly greater in downstream samples than in subsurface samples. There were significant differences in TC concentrations in downstream samples at both field sites between samples collected before October 2003 and those collected during October 2003 (Figure 1c).

Rainfall and FIO mobilization

At Caerhays, no significant correlation was found between daily rainfall totals and sample TC concentrations. However, a trend was evident (Figure 1a); in August and September TC concentrations in surface samples exceeded the mandatory EU Bathing Water standard. Greater TC concentrations were measured in surface and stream samples on 22 August 2002 than at any other sampling time. This was the first sampling to take place after the largest rainfall event recorded during the sampling period (30 mm on 17 August 2002).

At Sandsend, again, no general correlation was found between daily rainfall amounts and sample FIO concentration, although elevated TC concentrations were observed in surface and subsurface samples on 1 and 2 July 2003 following a rainfall event of 38 mm on 30 June (Figure 1b). Elevated TC concentrations were also observed in surface samples on the 27 and 30 July at a time when there was little rainfall (Figure 1b).

At Rowden, no correlation was found between rainfall and sample concentration. From Figure 1, it can be seen that the intense periods of rainfall recorded at Caerhays and Sandsend (i.e. 30 mm in 24 hours) did not occur at Rowden.

DISCUSSION

Water quality and FIO concentrations

The quality of the water samples at all field sites indicated that a high proportion of the samples did not achieve present EU standards; if more stringent standards were introduced the proportion of samples failing compliance would increase substantially. In order to improve water quality there is a need to identify sources of contamination, which can be difficult. Hunter *et al.* (2000) and others have suggested that differences in FC/FS ratio can be used to infer sources of pollution – samples contaminated by human sewage having a higher proportion of FC and those contaminated by animal sewage having a higher proportion of FS. However, this pattern can be complicated by other factors including differential die-off rates between the two indicator groups. Hunter *et al.* (2000) found that concentrations of FC and FS differed by an order of magnitude; this was found not to be true for all points in this study, based on median concentration. At Caerhays, 67% of sample FC concentrations were an order of magnitude greater than FS concentrations, particularly in surface samples. As no human sewage sludge was applied to the land, and sewage treatment works did not impact on the watercourse at the field sites, it is surmised that the enhanced FC content was likely due to differential die-off. On the other hand at Sandsend, 36% of sample FC concentrations were an order of magnitude greater than those of FS, particularly in watercourse samples, which implies contamination of the watercourse by human sewage and is plausible. At Rowden, differences between FC and FS sample concentrations were all less than an order of magnitude, which is consistent with a site where animal manure is applied. In this instance the FC/FS ratio was useful in highlighting inter-site differences; however, the full implication of these differences still requires validation.

Factors affecting FIO concentrations

More subsurface samples were obtained from sample points at Caerhays than either Sandsend or Rowden (Table 5). This was consistent with the more freely draining soils at Caerhays, which would be expected to permit subsurface seepage of water and therefore transport of FIOs into the soil (Bolton *et al.* 1999). The less permeable soils at Sandsend and Rowden, as expected, impeded the movement of surface water into the soil (Mawdsley *et al.* 1995; McHugh *et al.* 2003), allowing collection of a greater proportion of surface samples.

The most noticeable difference between data collected at Caerhays and Sandsend was the observed FIO concentrations in watercourse samples (Figure 1a, b). Downstream samples from Caerhays had greater FIO concentrations than upstream samples, implying that the field systems were contributing to FIO loading in the watercourse. In the well-drained soils at Caerhays this contribution of FIOs was from a subsurface source. Water and associated FIOs infiltrating the soil would have flowed vertically and laterally downslope, but where water reached less permeable layers at moderate to shallow depths, lateral flow would have increased, diverting more of the subsurface water towards the stream (Selby 1982).

At Sandsend, the relationship was less clear; in some instances a downstream reduction in watercourse FIO concentration implied either a loss (i.e. due to instream processes) or dilution of FIOs as the water passed by the field system. A higher proportion of rainfall would be expected to reach the watercourse from field sites at Sandsend than at Caerhays, because of the differences in permeability of the soil surface. While more surface runoff may carry greater quantities of FIOs it would also be offset by a dilution factor (Hunter & McDonald 1991).

At Sandsend, the occasions when downstream concentrations of FIOs were greater than upstream concentrations were associated with the presence of preferential flow paths through the soil, for example, the desiccation cracks which were observed between June and September, which were not observed at Caerhays or Rowden.

At Rowden, FIO concentrations in watercourse samples also exceeded mandatory standards on several occasions (Figure 1c). Although the soils at Rowden and Sandsend are both described as slowly permeable, they differ in that desiccation cracks were observed at Sandsend but not at Rowden. Therefore, the primary pathway for FIO delivery to the watercourse at Rowden was by surface water flow. Factors that will have contributed to FIOs reaching the watercourse at Rowden were: availability of FIOs on the soil surface, rainfall intensity, and the absence of a physical barrier preventing surface water flow reaching the watercourse. Although manure was applied to the Rowden sites on three occasions (Table 2), rainfall intensity at Rowden was lower than at Sandsend; also at Caerhays and Sandsend, there were uncultivated grass strips averaging 3 m wide and hedges between the edge of the field and the watercourse, while at Rowden there was only an uncut grass strip less than 1 m wide between the sampling position and the drainage ditch.

The difference between watercourse FIO concentrations at upstream and downstream sampling locations may also be linked to FIO survival. At Caerhays, FIOs may survive longer because the subsoil offers some level of protection, accessible through the permeable soils (Jawson *et al.* 1982; Hunter & McDonald 1991), while at Sandsend, where surface flow dominates, FIOs may decline in number more rapidly because of exposure to UV-radiation and desiccation (Nicholson *et al.* 2000). At Rowden, where slurry was applied three times during the bathing season, surface and downstream FIO concentrations exceeding mandatory standards were recorded throughout this period (Figure 1c). This implies that repeated application of slurry throughout the bathing season maintained concentrations of FIOs at the soil surface that potentially contributed to watercourse FIO loading. A significant decrease in TC concentration in downstream samples at Rowden during October has not been explained by the data collected here. It is possible that this decrease is related to the concentration of FIOs present in the slurry in the final application made on 5 October 2003, as FIO concentration is affected by storage conditions (Nicholson *et al.* 2000).

Land management and FIO concentrations

The impact of land management (Table 2) on FIO concentrations was not conclusive. Only FS concentrations at Caerhays field site 1 (where no organic manures were applied) showed any significant difference compared with field sites 2 and 3 (where manures were applied). It has been suggested by Vinten *et al.* (2004) that greater concentrations of FIOs should be observed in water draining from fields that are grazed than from fields where only slurry has been applied, as duration and condition of slurry storage reduce the concentration of FIOs compared with fresh faeces (Nicholson *et al.* 2000). However, differences in FIO concentrations between the two grazed fields at Caerhays (field sites 1 and 3) may also be related to differences in animal age, diet and stress (Nicholson *et al.* 2000), and also how long the animals were present.

At Sandsend, greater FIO concentrations were observed in surface samples following moderate rainfall (27 and 30 July 2003; Figure 1). These events happened less than a day after animals had been grazing in the field. On these occasions the rainfall was sufficient to mobilize FIOs on the soil surface, but insufficient to deliver a significant quantity to the adjacent watercourse, as reflected in the relatively small FIO concentrations in the watercourse samples.

Differences in FIO concentrations were expected between the two field plots at Rowden because field site 8 received double the quantity of slurry. Some significant differences in FIO concentrations were observed, which suggests that increasing the quantity of slurry applied to a field can significantly increase FIO concentration in an adjacent watercourse. But these differences are limited to specific conditions, for example the slurry was from the same source and had been stored and applied similarly.

CONCLUSION

At all the high-risk field sites studied, which were managed according to recommendations of the UK Code of Good Agricultural Practice, mandatory EU quality standards were, on occasion, exceeded. The introduction of more stringent standards would see a substantial increase in the number of samples failing compliance. While other factors will also have contributed to the FIO concentrations observed in each catchment, there is evidence that soil type does impact on FIO delivery from field site to watercourse. These data suggest that field sites on permeable soils had the greater potential to contaminate watercourses because FIO concentrations increased as the stream passed-by the field. This implies that more permeable soils potentially pose a greater risk to FIO pollution of watercourses than impermeable soils. However, an increased risk of FIO pollution from impermeable soils may occur when preferential pathways, such as the development of desiccation cracks in the soil, become active. Equally, the risk of FIO contamination of watercourses was increased under conditions of greater rainfall intensity.

Diffuse FIO pollution results as a combination of increased risk due to management regimes (i.e. application rates, methods and timing) in combination with both a mechanism to mobilize and a pathway connecting soil stores of FIOs with an adjacent watercourse. The risk of faecal pollution of watercourses from impermeable soils may therefore have a specific time-frame (i.e. when cracking occurs or during intense rainfall events), while the hazard posed by permeable soils may be more constant, with occasions when greater risk of pollution results from increased rainfall intensity leading to overland flow. As greater concentrations of FIOs were observed in surface samples than subsurface samples, inhibiting the movement of surface-mobilized FIOs by placing a barrier, such as an uncropped buffer strip or raised bank, between the field and the adjacent watercourse may reduce the risk of contamination. Such options require further investigation.

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