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Chloride, sodium, potassium and faecal bacteria levels in surface runoff and subsurface percolates from grassland plots amended with cattle slurry

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Abstract

This study investigated the effectiveness of vegetated buffer strips for removing contaminants in runoff from grassed plots (slope 15%) after application of cattle slurry. Plots (8×8 m^2 or 8×3 m^2) received slurry or inorganic fertilizer, and then simulated rainfall (1, 7 and 21 days after slurry/fertilizer application); after each event, runoff and percolates were sampled at various distances downslope (2, 4, 6, and 8 m), and analysed for Cl^-, Na^+, K^+ and faecal bacteria contents. Contaminant concentrations were markedly higher in runoff from the slurry-amended plots than in runoff from the fertiliser-amended plots. After the first rainfall event, some contaminant concentrations in runoff from the slurry-amended plots declined with distance downslope (i.e. with buffer strip width), supporting the relative efficacy of the strip for retaining pollutants. After the second and third rainfall events, by contrast, our results suggest remobilisation of contaminants retained during the first event. Faecal bacteria levels (especially streptococcus levels) remained high throughout the study, even in percolates and runoff collected 8 m downslope after the third rainfall event, and indeed even downslope of the adjacent fertilizer-amended plots (indicating lateral movement): this suggests that bacterial contamination may be the most significant risk arising from slurry application.

Keywords: Buffer strips; Cattle slurry; Mass drift; Percolates; Simulated rainfall; Surface runoff

1. Introduction

Cattle slurry can be considered a valuable resource, in view of its fertilising potential, and indeed it is widely used as a fertiliser. At the same time, however, it is important to bear in mind the risks of its application in inappropriate amounts or under inappropriate conditions, which may lead to diffuse contamination (Ackerman and Taylor, 1985; Amberger, 1987; Castilho et al., 1993; Novotny and Olen, 1994). In Galicia (Northwest Spain), the contamination of water bodies associated with agricultural land uses has increased in recent decades, most notably as a result of cattle slurry, and indeed the levels of contamination of many water bodies are now closer to those observed in the European regions traditionally considered as problematic in this respect (Carballas et al., 1990; Díaz-Fierros et al., 1990, 1993; López, 1993; Núñez-Delgado et al., 1998; Peña, 1996). Towards the end of 1980s our group performed studies of the characterisation of Galician cattle slurries (Díaz-Fierros et al., 1987). More recently, however, we have centred on the design and evaluation of strategies for the reduction of contamination risk due to diffuse-source contamination (Núñez-Delgado et al., 1995, 1996, 1997a,b; López et al., 2000). As indicated by Bahri (1999), however, control of water contamination due to agricultural practices such as slurry application remains very difficult. Best management practices such as vegetated buffer strips have been proposed and implemented; in the best cases, buffer strips of this type are low-cost and highly effective (Blackwell et al., 1999; Haycock et al., 1997; Larsen et al., 1994; Núñez-Delgado et al., 1995; Uusi-Kämppä et al., 2000).

Chloride, sodium, potassium and faecal bacteria are important contaminants present in cattle slurry. In runoff or percolates from land that has received organic fertilisers or wastewater discharge, raised chloride levels

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may be an indicator of surface and/or deep contamination (Núñez-Delgado, 1993). In addition, the APHA (1998) notes that "chloride concentration is higher in waste waters than in raw waters and may harm growing plants". Chloride is used as an inert tracer in studies of the transport of solutes in porous media, particularly in column trials (Kluitemberg and Horton, 1990; Leij and van Genuchten, 2000; van Genuchten and Wierenga, 1986).

Potassium levels are high in Galician cattle slurries, to the extent that crops fertilised with cattle slurry often show deficient absorption of magnesium (Carballas et al., 1990).

Sodium, also present at high concentrations in Galician cattle slurries (Carballas et al., 1990), requires special attention in view of its major role in soil structure destabilisation and increased salinity in soils and waters affected by the application of organic fertilisers (APHA, 1998; Page et al., 1982; WHO, 1995).

Faecal-indicator bacteria levels clearly provide information on the severity of biotic contamination episodes due to the use of slurry as fertiliser, and at the same time on the persistence of such episodes and on aspects related to the risks of these agricultural practices as regards public health (Núñez-Delgado, 1993; WHO, 1995).

In the case of fertiliser application to sloping grassland, it is clearly important to have information not only on the amounts of contaminants removed by surface runoff, but also on the amounts in subsurface percolates. The latter allows evaluation of the risk that the contamination will be transmitted by the subsurface and deep routes. Useful information in this regard can also be obtained by laboratory column studies, which provide complementary data on in situ solute and microorganism transport (Núñez-Delgado, 1993, 1996, 1997a; López et al., 2000).

In the work reported here, we determined Cl^-, Na^+, K^+ and faecal bacteria levels in runoff from two plots to which we had applied cattle slurry (Plot A) or a commercial nitrogenous fertiliser (Plot B). Slurry or fertiliser was applied to subplots of 8 m downslope length (A1 and B1) or 3 m downslope length (A2 or B2). Vegetated buffer strips were placed immediately downslope of both plots. We monitored contaminant levels in runoff collected after 2, 4, 6 or 8 m passage downslope over the buffer strip. We also evaluated contaminant levels in percolates collected in the buffer strip downslope of Plot B.

2. Methods

The experimental plots were located on a *Lolium perenne* meadow in Boqueixón (A Coruña, Spain) with a Manning *n* value of 0.12 and mean slope of 15%. The same slope had been used previously to investigate the transport of different contaminants (for example, Díaz-Fierros et al., 1990; Basanta et al., 1995; Núñez-Delgado et al., 1997b).

The soil at the study site, a Hortic Anthrosol (FAO, 1994), had been studied in laboratory column experiments designed to investigate its capacity to remove percolating chemical contaminants, and solute transport characteristics through the three horizons of the profile (Núñez-Delgado, 1993, 1997a).

Table 1 shows the principal physicochemical characteristics of the three horizons of the plot. The analyses were performed by standard methods (Guitián and Carballas, 1976; Klute, 1986; Olsen and Sommers, 1982; Tan, 1996).

Fig. 1 shows the layout of the two experimental plots, which were separated by a strip 5.6 m wide. Plot A received cattle slurry, while Plot B received a commercial nitrogenous fertiliser (NH_4NO_3 in granulate form) without Cl^-, Na^+, K^+ or faecal bacteria. Each plot comprised two subplots, one of 8×8 m^2 (Subplots A1 and B1), and one of 8×3 m^2 (Subplots A2 and B2), with the aim of investigating the effects of application area on runoff quality. In an 8 m band downslope of each plot, we installed Gerlach troughs for runoff sampling. Ditches were dug along the upper and side borders of each plot, in order to prevent entry of runoff from adjacent areas.

The slurry and fertiliser were applied on the same day. The dose was 341 m^3 ha^{-1} for the slurry (relatively high, but frequent in Galicia) and 881 kg ha^{-1} for the fertiliser. These doses were equivalent as regards ammonium + nitrate N content. To control the slurry dose, we regulated application times and maintained constant conditions (pumping pressure, etc.) throughout.

Both the slurry and the fertiliser were analysed as per APHA (1989, 1998) and Tan (1996). Table 2 shows the physicochemical characteristics of the slurry, which was extracted by pumping from a rain-protected anaerobic storage ditch on a cattle farm close to the experimental plot. These characteristics are within the ranges observed in previous studies of the characteristics of cattle slurry in this area (Carballas et al., 1990). Total N content in the commercial fertiliser was 21.4% w/w, with 50% nitrate N and 50% ammonium N (nominal values confirmed by analysis).

Surface runoff was generated using a rainfall simulator, with non-contaminated water from a stream about 12 m downslope of the lowest Gerlach troughs. The simulated rainfall intensity was 47 mm h^{-1} (relatively high, but often occurring in storm events in the study region). The characteristics of the simulator and the rainfall it produces have been described in detail by Núñez-Delgado (1993) and Núñez-Delgado et al. (1997b). Briefly, the apparatus comprised a pair of wheeled units, each fitted with four adjustable-height

Table 1
Basic physicochemical characteristics of the soil (horizon nomenclature as per FAO, 1994)

	Horizon Au1	Horizon Au2	Horizon Au3
pH in H_2O	6.1	6.3	6.4
pH in KCl	5.2	5.3	5.4
Carbon (%)	7.96	6.84	4.38
Organic matter (%)	13.72	11.88	7.54
Nitrogen (%)	0.653	0.626	0.212
Particle density (g cm^{-3})	2.5123	2.5255	2.6881
Sand (%)	30.1	30.5	33.6
Silt (%)	49.4	53.1	40.9
Clay (%)	20.5	16.4	25.5
Texture	(a)	(b)	(a)
Exchangeable Na (cmol(+) kg^{-1})	0.643	0.147	0.225
Exchangeable K (cmol(+) kg^{-1})	0.467	0.313	0.120
Exchangeable Ca (cmol(+) kg^{-1})	9.232	5.988	5.676
Exchangeable Mg (cmol(+) kg^{-1})	1.285	1.162	1.995
Total cations (cmol(+) kg^{-1})	11.627	7.610	8.016
Available P (mg kg^{-1})	0.645	0.374	0.329
Water retention (%) at:			
pF 2.5 (30.78 kPa)	33.34	34.77	27.74
pF 4.2 (1542.48 kPa)	22.42	20.11	16.11
Available water (%)	10.92	14.67	11.63

(a) – loam; (b) – silt loam.

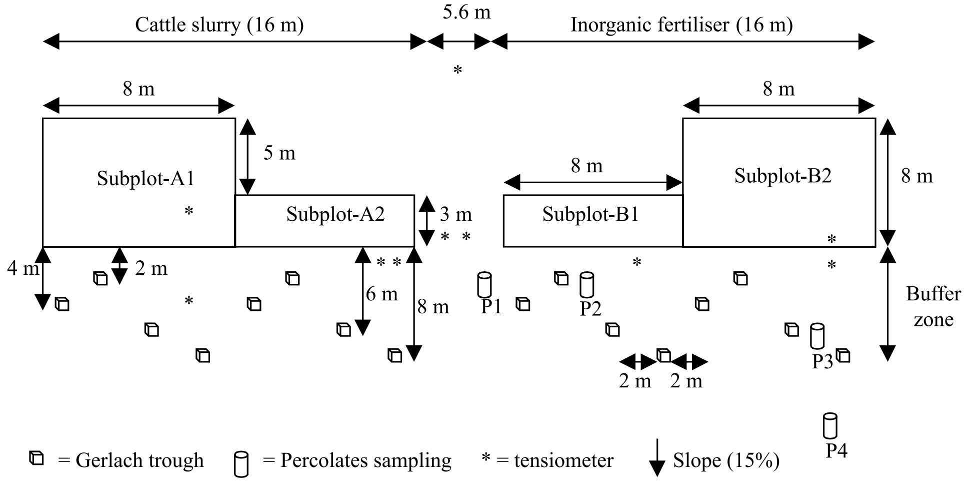

Fig. 1. Schematic drawing showing the layout of the experimental plots. Slope 15% down from top of diagram.

Table 2
Basic physicochemical characteristics of the cattle slurry

pH	7.1
EC (μS cm^{-1})	5300
Cl^- (mg l^{-1})	2494
o-P (mg P l^{-1})	156.5
COD (mgO_2 l^{-1})	17 700
Na^+ (mg l^{-1})	620
K^+ (mg l^{-1})	1695
NH_4^+ (mg l^{-1})	606.04
NO_3^- (mg l^{-1})	47.99
Dry matter (% w/w)	3.2

EC – electrical conductivity; *o*-P – ortho-phosphate; COD – chemical oxygen demand.

wide-angle square-field aspersion heads (Fulljet 1/2 HHSS40WSQ, Spraying Systems). The two units each provided simulated rainfall over an area of about 8 × 8 m^2. The water is propelled by two pumps linked in series.

A total of three rainfall events were simulated (1, 7 and 21 days after slurry or fertiliser application). After each event, surface runoff samples were taken from the Gerlach troughs located 2, 4, 6 and 8 m downslope of the lower border of the corresponding plot. Samples destined for bacteriological analysis (APHA, 1998) were taken with appropriate precautions.

In addition, subsurface percolates were also sampled after each event, using sampling devices (Núñez-Delgado, 1993) pre-installed at different depths (P1 at 45 cm, P2 at 51 cm, P3 at 49 cm, and P4 at 31 cm; see Fig. 1). One of these devices (P1, 1 m to the left and 4 m downslope of the lower border of Plot B) was located in the band separating the fertilised plots, while the remainder were located downslope of the area fertilised with commercial fertiliser (P2, 4 m downslope; P3, 6 m downslope; P4, 12 m downslope). Unfortunately, the percolate sampling devices installed downslope of Plot A did not function properly, and we have no data for this area.

All runoff and percolate samples were analysed for Cl^-, Na^+, K^+, faecal coliform and faecal streptococcus contents, by standard methods (APHA, 1989, 1998).

Finally, matrix potentials (and thus soil moisture content) were monitored with a series of tensiometers located in and downslope of the plots (Fig. 1); the tensiometers were fitted with pressure transducers, permitting real-time measurements (Klute, 1986; Núñez-Delgado, 1993).

3. Results and discussion

Simulated rainfall depths (mm) in the three rainfall events were 23.5, 43.1 and 45.4 mm, respectively, in Subplot A1, 39.2, 45.4 and 40.0 mm, respectively, in Subplot A2, 53.3, 62.7 and 92.4 mm, respectively, in Subplot B1, and 65.0, 78.3 and 69.7 mm, respectively, in Subplot B2.

Rainfall depth differed among subplots because rainfall simulation was maintained until runoff amounts sufficient for physicochemical and microbiological analyses had been collected in each of the Gerlach troughs of the subplot in question. Evidently, these differences may have had some effect on the results; however, preliminary tests in the experimental plots had shown that application of equal amounts of simulated rainfall led to up to 40-fold differences in runoff volumes between different sampling points (Núñez-Delgado, 1993), so that application of a uniform amount of rainfall would have meant choosing between (a) no runoff collection at some sampling points and (b) collector overflow at some sampling points. Note that no natural rainfall events occurred during the study period.

As can be seen, smaller amounts of rainfall were applied to Plot A (the slurry-amended plot) than to Plot B (the fertiliser-amended plot). Nevertheless, runoff percentages (100 × runoff/rainfall) were higher for Plot A than for Plot B (Table 3). This may have been due to partial saturation of soil pores by the slurry, in view of its high liquid content; however, it should be borne in mind that the simulated rainfall was applied the day after fertiliser application. Tensiometer readings indicated that, prior to the first two simulated rainfall events, soil moisture content was higher in the slurry-amended plot than in the fertiliser-amended plot; prior to the third event, however, soil moisture content was higher in the fertiliser-amended plot. Additionally, runoff depths were also probably influenced by differences in plot microtopography: 2 m upslope of the Gerlach trough in which the greatest volumes of runoff were collected there was a small hollow that channelled runoff in this direction. As noted above, we cannot rule out the possibility that the observed among-plot differences in runoff depth were partially due to differences in the amount of rainfall applied; however, it seems more likely that the plot microtopography differences (affecting hydrological characteristics not only directly, but also indirectly via effects on soil and vegetation) played a more important role. In any case, our use of runoff percentages means that values can be meaningfully

Table 3
Runoff percentages (100 × runoff/rainfall) as recorded after each rainfall event below each subplot[a]

	Slurry area			Fertiliser area		
	Subplot A1	Subplot A2	Average	Subplot B1	Subplot B2	Average
First rainfall event: buffer strip length (m)						
2	3.28	1.38	2.33	0.77	0.18	0.48
4	2.06	0.49	1.27	0.06	0.03	0.04
6	0.33	4.23	2.28	0.07	0.09	0.08
8	13.83	0.28	7.06	0.13	0.07	0.10
Second rainfall event: buffer strip length (m)						
2	0.46	0.26	0.36	0.19	0.33	0.26
4	0.37	2.11	1.24	0.29	0.01	0.15
6	0.09	0.90	0.49	0.05	0.13	0.09
8	28.51	0.55	14.53	0.06	0.19	0.13
Third rainfall event: buffer strip length (m)						
2	0.45	0.90	0.68	0.26	0.10	0.18
4	0.11	1.73	0.92	0.08	0.21	0.15
6	0.08	0.18	0.13	0.01	0.19	0.10
8	10.99	0.04	5.52	0.08	0.09	0.09

[a] Average values for each plot are also shown.

Table 4
Chloride concentrations (mg l^{-1}) in runoff, as recorded after each rainfall event below each subplot

	Slurry area		Fertiliser area	
	Subplot A1	Subplot A2	Subplot B1	Subplot B2
First rainfall event: buffer strip length (m)				
2	126	59	7	9
4	147	12	9	12
6	117	90	9	12
8	104	18	9	18
Second rainfall event: buffer strip length (m)				
2	12	9	15	nd
4	12	11	nd	nd
6	39	38	nd	nd
8	41	13	19	nd
Third rainfall event: buffer strip length (m)				
2	13	9	nd	nd
4	39	83	nd	nd
6	42	46	nd	nd
8	15	18	nd	nd

nd – not detected (<0.01 mg l^{-1}).

compared among plots, despite the between-plot differences in rainfall depth applied.

Table 3 shows runoff percentages for each rainfall event and each subplot, in each case for the four buffer-zone widths (2, 4, 6 and 8 m). Runoff percentages after the first rainfall event were clearly higher for the slurry-amended plot than for the fertiliser-amended plots, possibly because of partial obturation of soil pores by the slurry (see Barrington et al., 1987a,b; Barrington and Madramootoo, 1989; Díaz-Fierros et al., 1983), and/or because the slurry itself constitutes a significant input of liquid (as noted in the tensiometer readings before the first rainfall event), and/or because of microtopographic factors favouring confluence of runoff from the slurry-amended plot in the Gerlach trough located 8 m downslope. After the second and third rainfall events, the between-plot differences in runoff percentages were less marked, except for runoff collected in the troughs located 8 m downslope. Averaged runoff percentages for each plot (Table 3) likewise indicate that slurry application increased runoff after the first rainfall even, and that runoff as collected 8 m downslope of the slurry-amended plot was high even after the second and third rainfall events. Hydrological responses of this type may affect mobilisation of contaminants from slurry-amended plots, with a more marked effect on total masses than on concentrations, since increases in surface runoff volume will frequently be paralleled by increased contaminant load in runoff (Núñez-Delgado, 1993; Núñez-Delgado et al., 1997b).

Table 4 shows chloride concentrations in runoff from the slurry- and fertiliser-amended plots. Cl^- is expected to be subject to little or no retention by the soil, and indeed this ion is used as an inert tracer in laboratory column studies (van Genuchten and Wierenga, 1986; Leij and van Genuchten, 2000). This behaviour has been observed in columns containing soil from the same experimental plot (Núñez-Delgado et al., 1997a) and in other similar soils in Galicia (Núñez-Delgado et al., 1996; López et al., 2000). After the first rainfall event, the buffer strips below the slurry-amended plot did not have any clear reducing effect on Cl^- concentration (i.e. Cl^- concentration did not decline with increasing downslope distance). However, Cl^- concentrations were markedly lower in runoff from Subplot A2 than in runoff from Subplot A1, probably because Subplot A2 was smaller and thus received less slurry, not because it received a greater depth of rainfall. After the second and third rainfall events, evidence of downslope transport of Cl^- was observed (i.e., Cl^- concentration in runoff increased downslope, indicating mobilisation of Cl^- initially

Table 5
Chloride concentrations (mg l^{-1}) and mass removal (mg) in runoff, as recorded after each rainfall event below each plot

	Slurry area		Fertiliser area	
	mg l^{-1}	mg	mg l^{-1}	mg
First rainfall event: buffer strip length (m)				
2	92	301	8	11
4	79	160	10	2
6	103	626	10	3
8	61	820	13	6
Second rainfall event: buffer strip length (m)				
2	10	8	7	6
4	11	37	nd	–
6	38	59	nd	–
8	27	1353	19	7
Third rainfall event: buffer strip length (m)				
2	11	16	nd	–
4	61	136	nd	–
6	44	17	nd	–
8	16	33	nd	–

nd – not detected (< 0.01 mg l^{-1}); – = no data.

Table 6
Potassium concentrations (mg l^{-1}) in runoff, as recorded after each rainfall event below each subplot

	Slurry area		Fertiliser area	
	Subplot A1	Subplot A2	Subplot B1	Subplot B2
First rainfall event: buffer strip length (m)				
2	82.32	4.53	3.26	0.11
4	83.37	1.99	2.49	3.93
6	64.47	20.16	1.79	6.57
8	56.28	2.73	1.78	2.53
Second rainfall event: buffer strip length (m)				
2	1.52	5.31	1.26	2.02
4	3.58	2.67	0.73	8.03
6	6.26	3.93	2.36	7.31
8	15.96	7.22	2.36	3.64
Third rainfall event: buffer strip length (m)				
2	4.34	4.13	7.23	11.22
4	10.56	38.06	12.32	3.66
6	21.34	10.89	3.96	4.34
8	8.80	2.30	4.79	2.24

trapped by the vegetative filter), in agreement with the results of previous experiments performed in the same plot (e.g. Díaz-Fierros et al., 1990; Núñez-Delgado et al., 1997b), and as reported by other authors in other situations (e.g. Magette et al., 1986). In the area amended with commercial fertiliser low levels of Cl^- were detected in runoff, as expected.

Table 5 shows mean Cl^- concentrations and mass transport values in surface runoff (these latter calculated as the product of runoff volume and Cl^- concentration for each sampling point). These data confirm the above-mentioned downslope transport of Cl^- from the slurry-amended plot, particularly marked after the second and third rainfall events. By contrast, only low levels of Cl– were detected below the fertiliser-amended plot.

Table 6 shows K^+ concentrations in runoff from the slurry- and fertiliser-amended plots. After the first rainfall event, K^+ concentration in runoff from Subplot A1 declined with distance downslope, suggesting that the buffer strips effectively retained this substance. The data for Subplot A2 indicated early downslope transport of K^+ and showed lower concentrations than in Subplot A1. As with Cl^-, the latter may be attributable to the smaller area of Subplot A2, and thus the smaller total amount of slurry received. Again as expected, only low levels of K^+ were detected in runoff from the plots amended with commercial fertiliser.

Table 7 shows mean K^+ concentrations and mass transport values in surface runoff at each sampling point. These data indicate downslope transport of K^+ mass after all three rainfall events, though most notably after the second and third events. In the area treated with commercial fertiliser, K^+ mass transport values were generally low.

Table 7
Potassium concentrations (mg l^{-1}) and mass removal (mg) in runoff, as recorded after each rainfall event below each plot

	Slurry area		Fertiliser area	
	mg l^{-1}	mg	mg l^{-1}	mg
First rainfall event: buffer strip length (m)				
2	43.40	142.14	1.70	2.25
4	43.70	88.49	3.20	0.48
6	42.30	256.97	4.20	1.43
8	29.60	397.82	2.20	1.00
Second rainfall event: buffer strip length (m)				
2	3.40	2.69	1.60	1.48
4	3.10	10.39	4.40	2.51
6	5.10	7.93	4.80	2.26
8	11.60	581.45	3.00	2.30
Third rainfall event: buffer strip length (m)				
2	4.20	5.92	9.20	7.08
4	24.30	54.19	8.00	5.36
6	16.10	6.12	4.20	2.12
8	5.50	11.22	3.50	1.93

Previous column studies with soil from this plot have shown clear retardation of K^+ transport (Núñez-Delgado et al., 1997a), which may contribute to reduction of K^+ levels in runoff from slurry-amended plots. The retardation of K^+ transport is probably due to interaction with illite-type clays, which are abundant in this soil (Rubio, 1993).

Table 8 shows Na^+ concentrations in runoff. Data for the slurry-amended plots indicated mobilisation of previously trapped Na^+ and downslope drift, as noted above for Cl^-, although not very clearly in the case of Subplot A1 or in general after the first rainfall event. As with Cl^- and K^+, runoff from Subplot A2 showed lower concentrations, again attributable to the smaller total amount of slurry received. Only low levels of Na^+ were

Table 8
Sodium concentrations (mg l^{-1}) in runoff, as recorded after each rainfall event below each subplot

	Slurry area		Fertiliser area	
	Subplot A1	Subplot A2	Subplot B1	Subplot B2
First rainfall event: buffer strip length (m)				
2	44.83	18.90	7.15	6.16
4	48.30	9.66	7.81	9.57
6	41.37	26.88	8.58	7.37
8	37.38	13.02	8.80	12.65
Second rainfall event: buffer strip length (m)				
2	1.52	5.31	1.26	2.02
4	6.38	5.61	5.39	10.78
6	8.82	14.52	4.51	7.26
8	14.70	6.05	7.15	5.17
Third rainfall event: buffer strip length (m)				
2	5.28	5.94	6.93	8.03
4	12.43	21.34	13.31	9.37
6	12.43	11.11	8.80	12.86
8	4.84	6.93	11.88	5.94

Table 9
Sodium concentrations (mg l^{-1}) and mass removal (mg) in runoff, as recorded after each rainfall event below each plot

	Slurry area		Fertiliser area	
	mg l^{-1}	mg	mg l^{-1}	mg
First rainfall event: buffer strip length (m)				
2	32.90	107.75	6.60	8.75
4	29.00	58.73	8.70	1.31
6	34.10	207.16	7.98	2.71
8	25.20	338.69	10.70	4.87
Second rainfall event: buffer strip length (m)				
2	3.40	2.69	1.60	1.48
4	6.00	20.10	8.10	4.62
6	11.70	18.19	5.90	2.77
8	10.40	521.30	6.20	4.74
Third rainfall event: buffer strip length (m)				
2	5.60	7.90	7.50	5.78
4	16.90	37.69	11.30	7.57
6	11.80	4.48	10.80	5.45
8	5.90	12.04	8.90	4.90

detected in runoff from the plots amended with commercial fertiliser.

Table 9 shows mean Na^+ concentrations and mass transport values in surface runoff at each sampling point. As for Cl^- and K^+, these data indicate downslope drift of Na^+ after all three simulated rainfall events. Mass transport of Na^+ from the area treated with commercial fertiliser was low.

The above-mentioned column experiments performed with soil from these plots indicated that these soils showed scant capacity to retain sodium: indeed, Na^+ concentrations were higher in the column outflow than in the feed solution (possibly because of displacement from exchange sites by other cations; Núñez-Delgado et al., 1997a). Buffer strips on these soils would, therefore, not be expected to be effective for attenuating Na^+ levels.

Table 10
Pearson product–moment correlations (r) between runoff percentage and Cl^-, K^+ and Na^+ mass removal values after each rainfall event and below each plot

	Rainfall event		
	First	Second	Third
Slurry area			
Cl^-	0.993*	0.999*	0.991*
K^+	0.987*	0.998*	0.995*
Na^+	0.998*	0.999*	0.995*
Fertiliser area			
Cl^-	0.926*	−0.108	–
K^+	0.903*	0.520	0.710
Na^+	0.970*	0.896	0.768

– no data.
* Significant for $p = 0.01$.

Table 10 shows coefficients of correlation between runoff percentages and mass transport for each rainfall event and each sampling trough. The strongest correlations were for sampling troughs below the slurry-amended plot, particularly after the second and third rainfall event. These results were as expected, since the commercial fertiliser did not contain significant amounts of Cl^-, K^+ or Na^+, so that the levels of these substances present in runoff collected downslope of this plot would be largely dependent on basal contents; equally, however, previous studies comparing the mobility of components of slurry and inorganic fertilisers have made it clear that the mobilisation of slurry components is more heavily dependent on surface runoff (Núñez-Delgado et al., 1997b).

Table 11 shows percentage reductions in contaminant concentrations in runoff sampled below the slurry-amended plot, with respect to contaminant concentrations in the slurry itself. The same data are also listed as concentration ratios. Percentage removal was in all cases

Table 11
Relationships between contaminant concentrations in runoff and in the slurry (percentage removal values and concentration ratios) after each rainfall event

	Attenuation (%)			Concentration ratio		
	Cl^-	K^+	Na^+	Cl^-	K^+	Na^+
First rainfall event: buffer strip length (m)						
2	96.3	96.6	94.7	27	29	19
4	96.8	96.6	95.3	32	29	21
6	95.9	96.7	94.5	24	30	18
8	97.6	97.7	95.9	41	43	25
Second rainfall event: buffer strip length (m)						
2	99.6	99.7	99.5	249	374	182
4	99.6	99.8	99.0	227	410	103
6	98.5	99.6	98.1	66	249	53
8	98.9	99.1	98.3	92	109	60
Third rainfall event: buffer strip length (m)						
2	99.6	99.7	99.1	227	302	111
4	97.6	98.1	97.3	41	52	37
6	98.2	98.7	98.1	57	79	53
8	99.4	99.6	99.1	156	231	105

greater than 94%. Of course, if removal had been calculated with respect to runoff collected immediately downslope of the slurry-amended area (i.e. downslope distance 0 m), values less than 94% might in some cases have been obtained, since clearly the slurry is diluted by rain. Despite this, our results clearly illustrate the variation in percentage removal with downslope transport distance (i.e. buffer strip width).

Considering all results together, buffer strip width has no clear and consistent effect on contaminant removal efficiency, though note that such effects may have been at least partially masked by the above-mentioned local variations in plot microtopography and downslope drift. Authors including Neibling and Alberts (1979) and Magette et al. (1986) have pointed out that the first metre of buffer strip is typically the most effective, regardless of the total buffer strip width. However, other authors (e.g. Young et al., 1980) have reported that buffer-strip effectiveness increases with total width, at least up to about 28 m.

Numerous factors influence the effectiveness of buffer strips (for reviews, see Núñez-Delgado et al., 1995, 1998). Detailed information on nutrient retention by plants themselves has recently been reported by Geber (2000).

Faecal coliform levels in runoff samples declined with time since slurry application (Table 12). However, bacteria of this type were still detected 21 days after slurry application, even in the plot that received commercial fertiliser: this suggests that the public health risks asso-

Table 12
Faecal coliform counts (most probable number per 100 cm^3) in runoff samples obtained after each rainfall event and below each plot

	Slurry area		Fertiliser area	
	Subplot A1	Subplot A2	Subplot B1	Subplot B2
First rainfall event: buffer strip length (m)				
2	–	–	23	23
4	400	–	–	–
6	43 000	–	–	–
8	300	–	0	–
Second rainfall event: buffer strip length (m)				
2	8	–	28	43
4	8	7	–	–
6	28	86	–	–
8	12	8	15	–
Third rainfall event: buffer strip length (m)				
2	7	4	4	4
4	4	28	–	–
6	0	4	–	–
8	150	–	4	23

– no data.

Table 13
Faecal streptocci counts (Most Probable Number per 100 cm^3) in runoff samples obtained after each rainfall event and below each plot

	Slurry area		Fertiliser area	
	Subplot A1	Subplot A2	Subplot B1	Subplot B2
First rainfall event: buffer strip length (m)				
2	24 000	1150	43	240
4	24 000	200	–	–
6	24 000	7500	–	–
8	>110 000	–	75	–
Second rainfall event: buffer strip length (m)				
2	86	32	460	210
4	186	–	–	–
6	4400	>2200	–	–
8	>4400	>830	93	–
Third rainfall event: buffer strip length (m)				
2	23	93	>1100	>1100
4	43	>1100	–	–
6	>1100	93	–	–
8	>1100	–	>1100	1100

– no data.

ciated with air or water transport of faecal bacteria may remain significant for some time after slurry application, and may affect not only the slurry-amended area but also adjacent areas (possibly as a result of atmospheric dispersion and subsequent deposition, as reported previously by Boutin et al., 1988).

Table 13 lists faecal streptococcus levels in the runoff samples. In runoff collected just downslope of the slurry-amended plot, levels of these bacteria declined with time; nevertheless, levels remained high even after the third rainfall event. Of particular interest are the high levels detected after the third rainfall event in runoff collected below the fertiliser-amended plot, which are again attributable to atmospheric dispersion and subsequent deposition of bacteria from the adjacent slurry-amended plot. In addition, the ability of streptococci to survive for long periods in the environment is well known.

Table 14
Physicochemical and microbiological characteristics of percolate samples obtained after each rainfall event. Cl, K$^+$ and Na$^+$ concentrations: mg l^{-1} [a]

	P1[b]	P2[b]	P3[b]	P4[b]
First rainfall event:				
Cl$^-$	7	6	6	9
K$^+$	0.22	10.01	2.53	0.13
Na$^+$	2.20	6.60	2.75	3.86
FC	–	75	–	–
FS	–	240	–	–
Second rainfall event:				
Cl$^-$	–	–	–	–
K$^+$	0.05	0.21	0.04	0.06
Na$^+$	1.98	5.41	4.73	3.85
FC	–	–	–	43
FS	–	–	–	1100
Third rainfall event:				
Cl$^-$	–	–	–	–
K$^+$	0.22	5.39	0.11	0.07
Na$^+$	1.98	4.07	1.54	3.74
FC		4		0
FS		240		>1100

– no data; FC – faecal coliforms; FS – faecal streptococci.

[a] Faecal bacteria counts: most probable number per 100 ml.

[b] See Fig 1.

Column studies performed with soils similar to those of the study plots have likewise suggested that slurry application may lead to worrying levels of streptococci in effluents deriving from slurry application (Núñez-Delgado et al., 1996). Even more worrying are viruses, which show a much greater capacity for penetration into the soil (Powelson and Gerba, 1994). Most studies have found that buffer strips and soils are not very effective for reducing contamination by faecal microorganisms, though some have reported significant contaminant-removal effects (Núñez-Delgado et al., 1995, 1998; Mallin and Wheeler, 2000).

Table 14 shows the results of physicochemical and bacteriological analyses of percolates collected after the three simulated rainfall events. K$^+$ concentrations were low after the second event but high again after the third event. Na$^+$ concentrations were similar after all three events. The most significant cause for concern was contamination by bacteria, particularly streptococci. It is important to note that the significant contaminant levels and high faecal bacteria levels were observed despite the fact that the percolate samples were taken below the fertiliser-amended plots, not below the slurry-amended plots. The possible explanations for this again include atmospheric dispersion of bacteria (Boutin et al., 1988), but also high basal levels or lateral subsurface transport (Núñez-Delgado, 1993). Whatever the original causes of the contamination, a significant risk of contamination of subsurface and deep water bodies remains, despite neutralising effects (retention of cations at ion exchange sites, reduction of microorganism levels by filtration, competition from saprophytes, or inactivation by UV).

4. Conclusions

After all three simulated rainfall events applied to the plots in the present study, runoff percentages from the slurry-amended area were markedly higher than those from the fertiliser-amended plot. This may be attributable (a) to partial saturation of the soil by the liquid component of the slurry, and to sealing of soil-surface pores by its solid components, and (b) to between-plot differences in microtopography.

Throughout the experiment, we observed downslope transport of Cl^-, K^+ and Na^+ across the vegetated buffer strips. This transport was apparent from both concentrations in runoff and mass transport values, and was particularly marked after the second and third rainfall events, suggesting that contaminants initially trapped by the buffer strip are mobilised during subsequent runoff events. This should be borne in mind in the design of sloped areas for use as vegetated buffer strips.

As expected, contaminant concentrations in runoff from Subplot A1 (which received cattle slurry over an area of 64 m^2) were higher than in runoff from Subplot A2 (which received cattle slurry over an area of only 24 m^2). This suggests that contaminant concentrations in runoff increase with increasing area of slurry application.

We did not observe any clear relationship between buffer strip width and contaminant levels in runoff. This may reflect downslope transport of contaminants across the buffer strip in each consecutive rainfall event. However, contaminant concentrations in runoff (Cl^-, K^+, Na^+) in all cases showed percentage removals of more than 94% with respect to concentrations in slurry. Of course, it is important to note that part of this removal was due to dilution by rainfall.

Correlations between surface runoff percentages and contaminant mass transport values were markedly higher for the Gerlach troughs located downslope of the slurry-treated plots. Though this result is as expected (since contaminant levels in runoff from the fertiliser-treated plots were very low), it suggests a need to pay particular attention to the application of livestock slurries during periods when there is a high probability of major high-intensity rainfall events, since runoff transport of slurry contaminants is particularly likely during such periods.

Finally, our results indicate that the slurry components most likely to give rise to significant contamination are bacteria. Downslope and close to slurry-amended plots, both surface runoff and subsurface percolates showed high levels of bacteria (especially faecal streptococci) even after the third rainfall event. Bacterial contamination of waters receiving surface runoff, subsurface drainage or deep flow, from slurry-amended land thus constitutes a significant public health risk, notably when the slurry is not pretreated to reduce bacterial contamination. These issues need to be taken into account in the control of slurry application, particularly during high-rainfall periods during which significant runoff is probable.

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