Wetlands and Aquatic Processes

Fecal Contamination of Pastoral Wetlands

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ABSTRACT

Near-channel hill-country wetlands draining steep pastoral land in New Zealand exhibit high levels of fecal contamination at a range of flows. This contamination is attributed to both the transport of bacteria into a wetland from the surrounding catchment and the direct excretion of fecal material onto wetlands by grazing cattle. *E. coli* concentrations observed at low to moderate flow at 20 sites varied between 0.5×10^1 and 2×10^4 most probable number (MPN) 100 mL^{-1}. High flow concentrations measured at two wetlands ranged up to 6×10^6 MPN 100 mL^{-1} and yielded storm period bacterial loads of between 1×10^6 and 3×10^{10} MPN per event. Given the disproportionately large fraction of surface and subsurface flow from the catchment that passes through the wetlands, these yields represent a large proportion of the total loss of bacteria from steep grazed hillsides, across a range of storm events. Cattle are attracted to the smaller, shallower wetlands for grazing in both summer and winter. Excluding stock from shallow wetlands may therefore yield improvements in bacterial water quality, although accurately quantifying this improvement is difficult without long-term studies. Cattle are not attracted to larger, deeper wetlands, presumably for fear of entrapment, and fencing them is unlikely to realize significant improvements in bacterial water quality. A statistical model incorporating solar radiation and flow explains 87% of the variance in *E. coli* concentrations across five monitored rainfall events. A positive correlation was found between solar radiation and *E. coli* concentration. The study was conducted in winter when clear, sunny days are relatively cold. Solar radiation on these days appears to be too weak to promote die-off but the colder temperatures aid survival.

A number of studies (e.g., Baxter-Potter and Gilliland, 1988; Wilcock et al., 1999) have shown that grazing livestock are an important diffuse source of fecal contamination to freshwaters. This contamination can arise through the delivery of fecal material in overland (Doran and Linn, 1979) and subsurface flows (Unc and Goss, 2003) to a watercourse and, where livestock have access to a stream, direct deposition of fecal material (Gary et al., 1983; Davies-Colley et al., 2002). Hunter and McDonald (1991) showed that near-channel saturated areas, which readily generate overland flow, preferentially deliver high numbers of fecal bacteria to pastoral streams. They also suggested that these wet zones aid microbial survival. Similarly, Hunter et al. (1992) identified overland flow, generated on near-channel bog zones, to be the most important process in the delivery of fecal coliforms to an upland stream channel.

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Near-channel saturated areas are found extensively in hill-country pasture in New Zealand. These areas, hereafter termed "wetlands," are generally formed through the convergence of surface and subsurface flows on steep hillslopes. They range in size from 1 to 1000 m^2 and are well vegetated with pasture grasses, sedges, and rushes. Given the disproportionately large fraction of flow from the catchment that passes through them (Cooper, 1990) and their proximity to the stream network, these wetlands are, potentially, a critical source area with respect to the delivery of agricultural pollutants to pastoral streams.

To date, studies of such wetlands in New Zealand have focused on nitrogen, having shown that rates of denitrification can be high provided that hydrological residence times are sufficient (Burns and Nguyen, 2002; Rutherford and Nguyen, 2004). However, grazing stock have access to these wetlands and casual observation in the field has indicated that they may be preferentially attracted to them for lush grazing. Consequently, in contrast to constructed wetlands that typically act as a sink for microbes (e.g., Chendorain et al., 1998; Davies and Bavor, 2000), these natural wetlands may provide an important source of fecal contamination to pastoral streams.

This paper describes a study of wetlands in hill-country pasture in New Zealand that had two key objectives. The first objective was to determine levels of wetland fecal contamination across a range of outflows and, since most flow generated on the catchment discharges through these wetlands, thereby quantify the diffuse source of fecal contamination to hill-country pastoral streams. The lack of information in this regard currently limits accurate prediction of bacterial water quality, and imparts uncertainty to assessment of the impact of mitigation measures such as riparian buffer strips (Collins and Rutherford, 2004). The second objective was to determine whether cattle are preferentially attracted to wetlands for grazing and hence assess whether excluding stock from them is likely to improve bacterial water quality.

STUDY SITES

The study sites are located within the Whatawhata research station (175°15′ E, 37°47′ S) west of Hamilton, North Island, New Zealand. Elevation ranges between 95 and 340 m and the land is characterized by steep slopes, up to 50°. Mean annual rainfall and mean daily air temperature are 1600 mm and 13.7°C, respectively. The land was cleared of native forest in the 1920s and revegetated with clover and pasture grasses,

Abbreviations: MPN, most probable number.

although occasional remnant native trees are still present. Current land use is predominantly sheep and beef grazing with an average of 12 stock units per hectare. In addition, the headwaters have recently been retired into pine. The catchment is dominated by yellow-brown earth soils that, in places, incorporate or are overlain by volcanic ash.

The wetland chosen as the primary focus of this study (Wetland A; Fig. 1) drains a steep (10–45°) catchment (approximately 0.87 ha) grazed predominantly by cattle, and flows directly into a fourth-order (mean flow 83 L s^{-1}, channel width approximately 1.5 m) stream. Wetland A is 32 m in length and ranges between 3 and 7 m in width; its long axis lies at right angles to the stream. The slope of the wetland is 8 to 11°. The maximum depth of the wetland, defined by the depth to a firm, consolidated layer, is 1 m. Less intensive monitoring was also conducted on a smaller, shallower and ephemeral wetland (Wetland B; Fig. 1). This is 20 m long and varies between 1 and 5 m in width, with a maximum depth of 30 cm. Wetland B has a slope of 8 to 11° and drains approximately 0.48 ha of steep hillside (10–45°), also grazed predominantly by cattle. Outflow from Wetland B drains into an ephemeral channel (30 cm in width) that feeds a larger (unmonitored) wetland further downslope. Outflow from the larger wetland drains into the same fourth-order stream as Wetland A. The long axis of Wetland B also lies at right angles to the stream. Both Wetland A and B are well vegetated with floating sweet grass (*Glyceria declinata* Brébiss.), rush (*Juncus* spp.), sedge (*Carex* spp.), and lotus (*Lotus pedunculatus* Cav.).

In addition to the monitoring at Wetlands A and B, a survey was conducted, sampling 18 wetlands within the Whatawhata research station, for fecal contamination. The aim of this survey was to assess the hypothesis that fecal contamination of hill-country wetlands is widespread, and to confirm that levels of contamination in Wetlands A and B are not atypical.

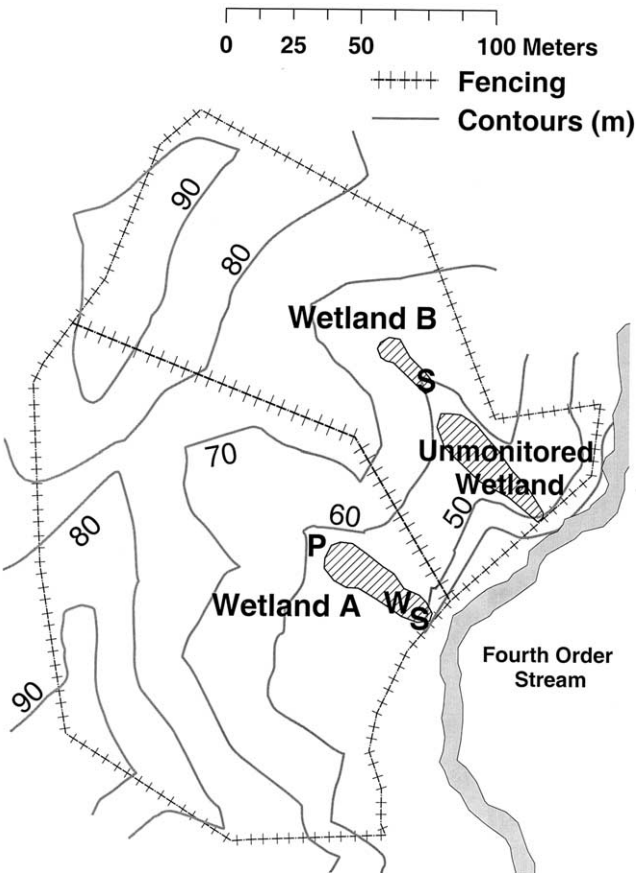

Fig. 1. Wetland map. "S" indicates that wetland outflow was sampled at this location for *E. coli*, "W" indicates the approximate location of the weir, and "P" indicates the location of the piezometer set.

MATERIALS AND METHODS

A 60° V-notch weir was installed approximately halfway down Wetland A, and stage height was recorded continuously every 15 min between 9 May and 7 Aug. 2003 (during the southern hemisphere winter). A flow-rating curve was established through measuring flow over the weir, by means of a graduated plastic container, during storm events. Flow was sampled twice weekly and during five storm events (A1–A5), with the 100-mL samples being analyzed for the fecal indicator bacteria *E. coli*. Four of these events were monitored using an automatic sampler at a 30- to 60-min interval. The timing of deployment of the automatic sampler reflected periods of its limited availability. Sampling during a fifth event was conducted manually at 10- to 15-min intervals, when a routine field visit coincided with a rain event. At Wetland B, two storm events (B1 and B2) were monitored with flow and sampling for microbial analysis conducted manually at the channeled outlet to the wetland. In addition, five low to moderate flow samples were collected. Sampling at Wetland B was undertaken in December 2001 as part of a preliminary study.

Subsurface soil water was collected 2 m upslope of the head of Wetland A using piezometer tubes. These were located within a narrow, grassed flowpath that feeds into Wetland A and extends about 20 m upslope. The piezometers consisted of a 2.5-cm-diameter PVC pipe, slotted over the lowest 10 cm, and covered with permeable fabric to minimize the intake of sediment. They were installed into augered holes and backfilled with quartz drilling sand, and the top of the hole was sealed with bentonite to minimize the ingress of surface water. Six piezometers were installed to depths ranging between 30 and 85 cm. The deeper piezometers lay immediately above a consolidated blue-gray clay layer. Soil water was only recovered from three of the deeper piezometers (installed at depths of 60, 80, and 85 cm, respectively) and these were sampled weekly over a 6-wk period during June and July 2003. The piezometers were emptied 1 to 2 d before sampling.

The catchments associated with Wetlands A and B are delineated by fencing, which enabled the number and duration of cattle grazing to be recorded during winter 2003 at both sites, and during summer 2001 at Wetland B. Additionally, the number of pats excreted directly onto, and within 2 m, of both wetlands was noted over the duration of each period of grazing.

On 31 July 2003 single samples were collected for *E. coli* analysis from 18 wetlands located within pastoral catchments across the Whatawhata research station. The samples were collected from the outflow of each wetland during a period of moderate flow following some rainfall the previous day. The wetlands surveyed ranged in size between 10 and 500 m^2.

E. coli were analyzed using a commercial most probable number (MPN) technique involving Colilert and Quantitray (IDEXX, Westbrook, ME). Trays were incubated at 35°C for 24 h and *E. coli* identified under UV light (366 nm). The concentration of *E. coli* was determined from MPN probability tables supplied by the manufacturer. Through necessity, on occasions both flow and piezometer samples were left more than 24 h (uncooled but shielded from sunlight) before collection for analysis. Some unquantified bacterial die-off may have occurred over this time.

RESULTS

Wetland A

Figure 2 illustrates flow and *E. coli* concentrations from the biweekly monitoring program. Baseflow is <2 L min^{-1}, but the wetland responds rapidly to rainfall, and flow often reaches in excess of 100 L min^{-1}. *E. coli* concentrations typically range between 10^1 and 10^3 MPN 100 mL^{-1} and exhibit a weak correlation with flow (Fig. 3), although large events were missed coincidentally within the biweekly monitoring. The presence of stock within the catchment (Fig. 2, Table 1) does not appear to strongly influence bacteria concentrations at low to moderate flow.

Soil water *E. coli* concentrations (Fig. 4), 2 m upslope of the head of the wetland, typically range between 10^1 and 10^3 MPN 100 mL^{-1}, broadly reflecting low to moderate flow concentrations in the wetland outlet. No clear pattern is evident in the concentrations over time, nor with depth.

Fifteen bulls were grazed within the catchment on three separate occasions for 3 to 4 d (Table 1) and their attraction to the wetland, for grazing, was not strong. This is reflected by the number of pats excreted onto the wetland (1–5) compared with the number of pats excreted throughout the catchment (>150), measured at the end of each grazing period. The cattle frequently walked around the perimeter, however, excreting between 5 and 14 pats within 2 m of the wetland edge, during each grazing period.

The monitored storm events (A1–A5; Fig. 5, Table 2) show a clear increase in *E. coli* concentration with increasing flow. During small events (A3 and A4) concentrations are $<10^3$ MPN 100 mL^{-1}. During larger events (A1, A2, and A5), however, maximum concentrations are higher, typically 10^3 to 10^6 MPN 100 mL^{-1}. Bacterial loads during the five monitored events ranged between 1×10^6 and 3×10^{10} MPN (Table 2). Comparison of Events A1 and A2 illustrates a "time since grazing" effect. Peak concentration during A1 (17 d after stock were removed) was 2×10^3 MPN 100 mL^{-1} and occurred at a flow of 39 L min^{-1}. In contrast, peak concentration during A2 (1 d after stock were removed) was 1×10^4 MPN 100 mL^{-1} and occurred at a flow of 15 L min^{-1}.

Of note are the very high concentrations observed during A5, an event characterized by the joint second largest peak flow recorded during the study period. Event A5 occurred 3 d after a period of prolonged grazing. Concentrations reached 6×10^6 MPN 100 mL^{-1}, and remained between 10^3 and 10^5 MPN 100 mL^{-1} at relatively low flow some hours later. The estimated bacterial load over the 80 min of initial sampling, which began immediately following peak flow, is 3×10^{10} MPN. Surface runoff was observed during this event for 15 min in the grassed flowpath feeding the head of Wetland

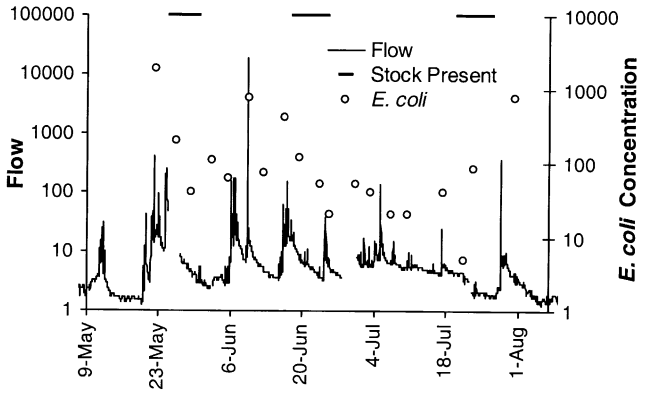

Fig. 2. Observed flow (L min^{-1}) and low to moderate flow *E. coli* concentrations (most probable number [MPN] 100 mL^{-1}) at Wetland A. The black bands at the top of the figure indicate periods of grazing. Note the *E. coli* concentration observed on 9 June was collected at a flow of 23 L min^{-1}.

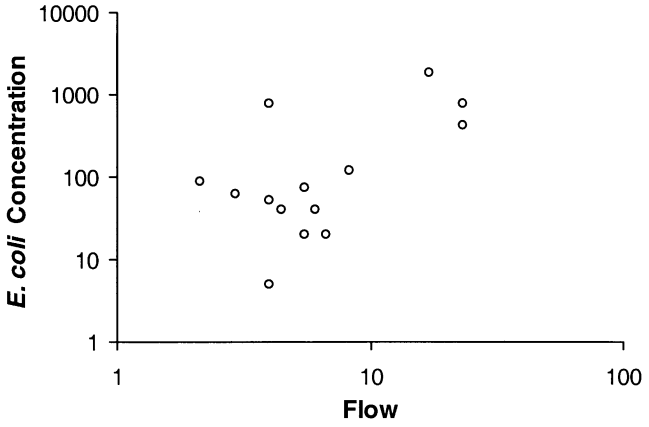

Fig. 3. Scatter plot of flow (L min^{-1}) against *E. coli* concentration (most probable number [MPN] 100 mL^{-1}) sampled at low to moderate flow from Wetland A.

Table 1. Summary of the number of cattle, dates and duration of grazing periods, and the number of pats deposited directly (Direct) onto each wetland and within 2 m of the edge of a wetland (Edge).

Wetland	Cattle	Grazing dates	Duration	Pats	
				Direct	Edge
			d		
A	15	26–29 May 2003	3	5	11
A	15	19–23 June 2003	4	3	5
A	15	21–25 July 2003	4	1	14
B	15	30 Nov.–3 Dec. 2001	3	23	17
B	14	20–23 May 2003	3	22	19

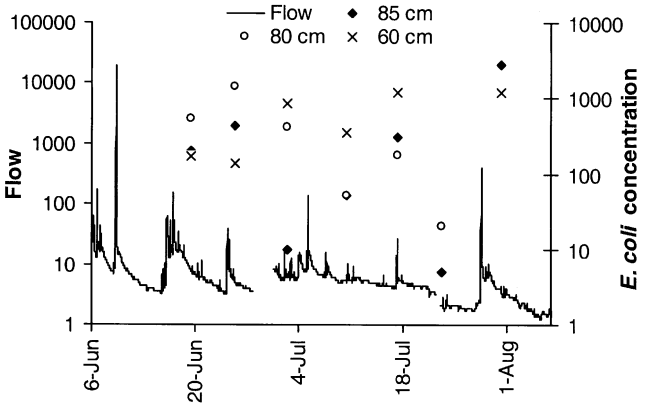

Fig. 4. Soil water *E. coli* concentrations (most probable number [MPN] 100 mL^{-1}) collected at depths of 60 to 85 cm, 2 m above the head of Wetland A.

A. A single sample of this runoff yielded an *E. coli* concentration of 3×10^5 MPN 100 mL^{-1}. That surface runoff was only observed transiently in one location during this large event indicates that this process is generally not a key delivery mechanism of microbes to wetlands.

Prediction of Storm Period *E. coli* Concentrations (Wetland A)

Pooling of the event-based data from Wetland A enabled the development of a statistical model with which to predict *E. coli* concentration in the wetland outflow. A range of independent variables (Tables 3 and 4) was examined in an interactive stepwise selection procedure and the strength of relationships assessed using the coefficient of determination (r^2) expressed as a percentage and adjusted for degrees of freedom. A predictive model was derived whereby three factors together explained 87% of the variance in *E. coli* concentrations across the five monitored events. Each factor and the partial r^2 associated with its addition to the regression model are given in Table 5. The three factors are (i) the mean

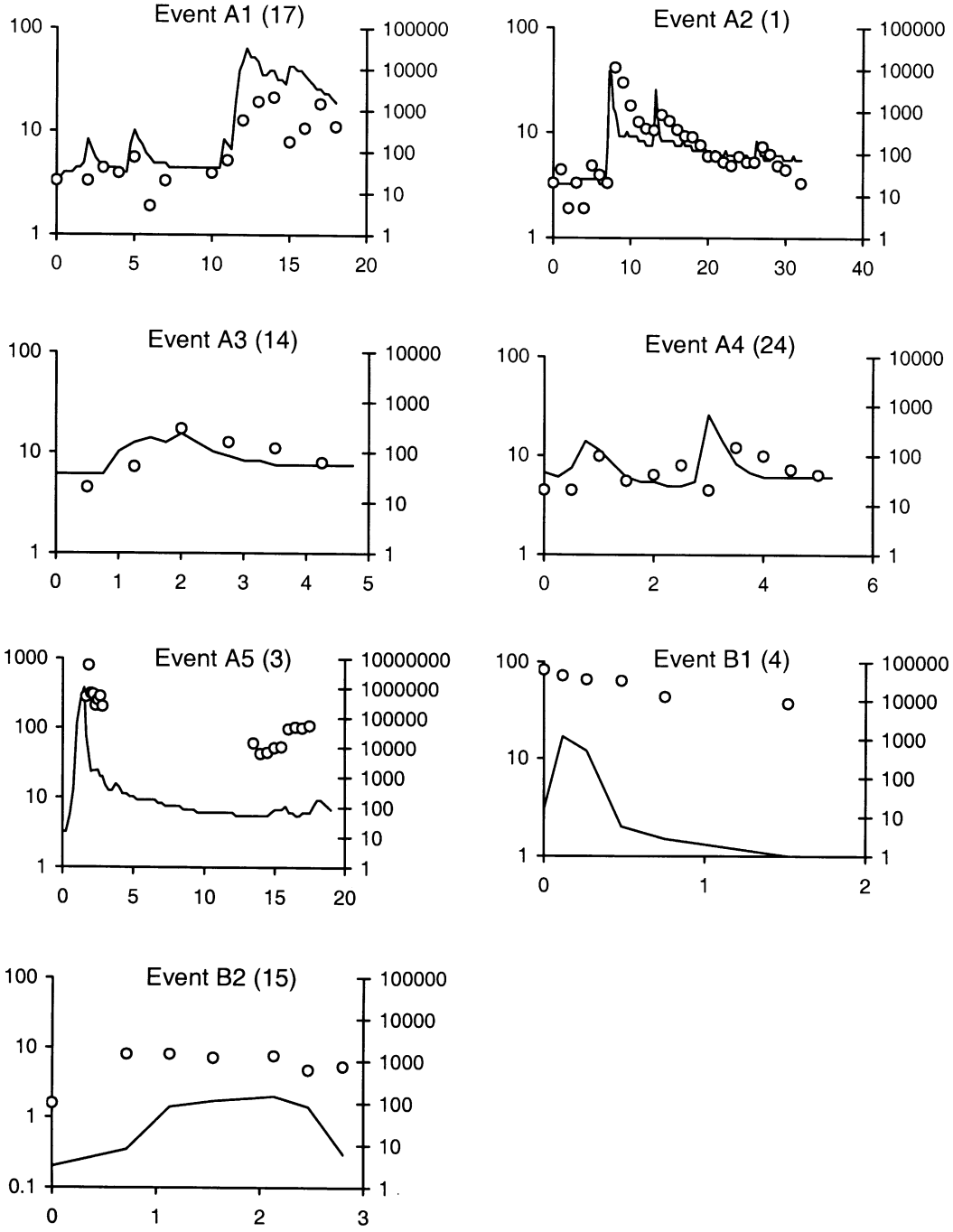

Fig. 5. Storm period flow (L min^{-1}; *y* axis) and *E. coli* concentration (most probable number [MPN] 100 mL^{-1}; second *y* axis) for five events at Wetland A (A1–A5) and two events at Wetland B (B1 and B2). Storm duration (h) is shown on the *x* axis. Note the change in scale for flow and *E. coli* concentration for Event A5, and for flow for Event B2. Time since the catchment was last grazed (d) is shown in parentheses.

Table 2. Summary of storm events sampled for *E. coli* analysis.

Event	Date	Days since stock removed	Peak concentration	Load
		d	MPN† 100 mL^{-1}	MPN
A1	15–16 June 2003	17	2.1×10^3	1.3×10^8
A2	24–25 June 2003	1	1.1×10^4	1.9×10^8
A3	7 July 2003	14	3.0×10^2	3.3×10^6
A4	17 July 2003	24	1.5×10^2	1.4×10^6
A5	28–29 July 2003	3	5.8×10^6	3.4×10^{10}‡
B1	7 Dec. 2001	4	6.1×10^4	1.3×10^8
B2	18 Dec. 2001	15	1.5×10^3	2.2×10^6

† Most probable number.
‡ Load estimation for Event A5 was based on sampling over the 80-min period following peak flow.

daily radiation before each event, since the last period of grazing (Rad); (ii) $\log_{10}$–transformed flow recorded at the time of sampling ($\log Q$); and (iii) the total volume of flow discharged across the weir before each event, since the last period of grazing ($\log Q_{ante}$), providing the following relationship:

$$\log_{10} E.\ coli = -0.33 + (0.45\ \text{Rad}) + (2.13 \log Q) - (0.54 \log Q_{ante}) \quad [1]$$

Colinearity (Table 4) was not strong ($r \leq 0.31$) between the three independent variables within the model.

Wetland B

Cattle were relatively strongly attracted to Wetland B for grazing with 22 pats excreted onto the wetland surface over a 3-d period during winter (May) 2003 (Table 1). Additionally, 19 pats were excreted within 2 m of the wetland edge and, together with those on the wetland, contributed 15% of pats excreted throughout the catchment. A similar number of pats deposited directly onto and nearby this wetland was noted during the summer (November–December) of 2001 (Table 1).

Event B1 (Fig. 5, Table 2) occurred 4 d after cattle were removed. *E. coli* concentrations peaked at 6×10^4 MPN 100 mL^{-1} soon after the initial rise in flow, before peak flow. Event B2 (Fig. 5, Table 2) occurred 15 d after stock were removed, and concentrations peaked at 10^3 MPN 100 mL^{-1} at a peak flow of 2 L min^{-1}. Low to moderate flow *E. coli* concentrations ranged from 2×10^3 to 2×10^4 MPN 100 mL^{-1} from the five samples collected.

Table 4. Correlation (r) between the independent variables. See Table 3 for abbreviations.

	Log Q	Log Q_{ante}	Days	Max T	Mean T	Rad	Dur	Dpat
Log Q_{ante}	0.20							
Days	0.12	0.93						
Max T	−0.22	−0.26	−0.38					
Mean T	−0.19	0.20	0.10	0.87				
Rad	0.31	−0.09	−0.21	−0.59	−0.77			
Dur	−0.17	−0.73	−0.50	−0.33	−0.58	0.09		
Dpat	−0.06	0.62	0.53	0.58	0.89	−0.66	−0.81	
Tpat	0.35	0.50	0.19	−0.16	−0.11	0.66	−0.69	0.13

Survey

E. coli concentrations from the one-off wetland survey ranged from 0.5×10^1 to 2×10^4 MPN 100 mL^{-1}, with a median of 5×10^2 MPN 100 mL^{-1}. Concentrations at three small, shallow wetlands exceeded 10^3 MPN 100 mL^{-1}; all three had a number (>10) of recently deposited pats on them.

DISCUSSION

Hill-country wetlands draining steep pastoral land exhibit high levels of fecal contamination at a range of flows. *E. coli* concentrations observed at low to moderate flow at 20 sites varied between 0.5×10^1 and 2×10^4 MPN 100 mL^{-1}. Soil water *E. coli* concentrations above the head of one wetland broadly matched concentrations at low to moderate flow in the wetland outlet. This suggests that subsurface flows from the surrounding catchment, which maintain wetland baseflow, also provide a source of fecal contamination. High flow concentrations measured at two wetlands ranged up to 6×10^6 MPN 100 mL^{-1} and yielded storm period bacterial loads of between 1×10^6 and 3×10^{10} MPN. While this study did not quantify the proportion of flow from the catchment that passes through the wetlands, field survey of the steeper hillslopes revealed no other significant hydrological source areas. While a deep ground

Table 3. Pearson (r) and Spearman rank (r_s) correlation coefficients for relationships between independent variables and $\log_{10}$ *E. coli* concentrations across the five monitored events at Wetland A.

Independent variable	Abbreviation	Units	r	r_s
Flow recorded at the time of sampling	log Q	L min^{-1}†	0.58***	0.61***
Total flow discharged before each event since the last period of grazing	log Q_{ante}	m^3†	−0.30**	−0.16
Days elapsed since the last period of grazing	Days	d	−0.38***	−0.18
Mean maximum daily temperature before each event since the last period of grazing	Max T	°C	−0.45***	−0.21*
Mean daily temperature before each event since the last period of grazing	Mean T	°C	−0.69***	−0.49***
Mean daily radiation before each event since the last period of grazing	Rad	MJ m^{-2}	0.81***	0.41***
Duration of the last period of grazing	Dur	d	0.29**	0.25*
Number of pats deposited directly onto the wetland during the last period of grazing	Dpat	–	−0.70***	−0.58***
Total number of pats deposited on or within 2 m of the wetland during the last period of grazing	Tpat	–	0.37***	0.17

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Data were $\log_{10}$–transformed.

Table 5. The statistical model for *E. coli* concentration. See Table 3 for abbreviations.

Variable	Coefficient	Partial r^2	Significance level (p)
Constant	−0.33		
Rad	0.45	65.0	<0.001
Log Q	2.13	77.0	<0.001
Log Q_{ante}	−0.54	87.0	<0.001

water pathway cannot be ruled out, it seems reasonable to assume that a disproportionately large fraction of surface and subsurface flow from the catchment passes through these wetlands. That being the case, these yields represent a large proportion of the total loss of bacteria from steep, grazed hillsides, across a range of storm events. The yields equate to a loss of 2×10^6 to 4×10^{10} MPN per hectare of grazed hillside.

A statistical model shows that mean daily radiation since the last period of grazing, flow during each event, and total flow discharged since the last period of grazing together explain 87% of the variance in *E. coli* concentration across five monitored rainfall events. The positive coefficient for mean daily radiation (Rad; Eq. [1], Table 5) within the model (increasing mean daily radiation causes higher *E. coli* concentrations) is initially surprising given that sunlight is known to cause microbial die-off (Crane and Moore, 1986). However, clear, sunny days in winter are colder than cloudy days, as reflected by the strong negative correlation between radiation and air temperature ($r = -0.77$; Table 4). It appears, therefore, that relatively high levels of wintertime solar radiation are not sufficiently strong to cause appreciable die-off. Instead, the lower air temperatures (air temperature is used here as a surrogate for the temperature of water in the wetland) associated with this weather pattern aid microbial survival. Conversely, lower radiation associated with cloudy days leads to higher air temperatures, increasing die-off rates. Consequently, when exploring the structure of the regression model, a negative coefficient was associated with the inclusion of temperature. Given the strength of correlation between radiation and temperature, it was necessary to incorporate only one of these variables into the predictive model and radiation was the stronger predictor of the two. It is important to note, however, that the inferences drawn from the statistics with regard to radiation and temperature are speculative, and any apparent effect may instead reflect the existence of other variables not included within the model, for example, water clarity and bacterial sedimentation.

A negative correlation exists between the number of pats deposited directly on the large wetland and *E. coli* concentration (Table 3). This anomalous relationship is attributed to the very small number of pats deposited directly to the wetland (in contrast to that observed at the smaller wetland) relative to those excreted elsewhere on the hillside.

The increase of *E. coli* with increasing flow (log Q) is likely to reflect both the transport of bacteria into wetlands from the surrounding catchment and the entrainment of a proportion of those bacteria already present within a wetland before an event. The influence of antecedent flows (log Q_{ante}) reflects wash-out of bacteria during intervening events, hence the negative coefficient for this variable within the statistical model (Eq. [1], Table 5).

Their level of contamination and proximity to the stream network suggests that hill-country wetlands are an important, potentially dominant source of fecal microbes to pastoral streams. Information from this study suggests that cattle are not attracted to the larger deeper wetlands, presumably because they are wary of entrapment. Excluding stock through fencing large wetlands is unlikely, therefore, to yield significant improvements in bacterial water quality. Any small reductions in fecal contamination (realized through the prevention of the occasional pat being deposited on the shallower edges of the larger wetlands) may not be sufficient to justify the cost of fencing. In the case of Wetland A (a large, deep wetland), some reduction in fecal contamination may be realized by fencing 5 m from the edge of the wetland since a number of pats were deposited on a cattle track around the perimeter of the wetland. However, this track may be a feature of this wetland only, and not indicative of large wetlands generally.

Given the lack of cattle attraction, and limited delivery by surface runoff, subsurface transport is probably the primary mechanism for delivery of bacteria to large wetlands. If so, management options to mitigate fecal contamination of large wetlands are limited. Potential measures include the reduction of stock numbers on the land (wintering-off) and the relocation of animals to ridge tops, when soils are at or close to saturation. An improved understanding of the impact of soil type on the subsurface transport, filtration, and adsorption of microbes is desirable. This would aid identification of those soils susceptible to the rapid subsurface transport of microbes over a significant distance. Lower stocking rates may be appropriate on such soils.

In contrast to large wetlands, this study suggests that cattle are attracted to shallow wetlands both in summer and winter. Field observations showed >20 pats to be deposited directly onto a shallow wetland over a 3-d period. Assuming (conservatively) that there were 10^9 *E. coli* in each pat, then $>10^{10}$ *E. coli* were deposited directly to the wetland over this period. This estimate is, therefore, far in excess of estimated storm period bacterial loads (10^6–10^8 MPN) from the same wetland. That is, direct deposition alone can, theoretically at least, account for the level of fecal contamination observed in outflow from this shallow wetland. Fencing shallow wetlands may therefore yield improvements in bacterial water quality. The effectiveness of this mitigation measure depends on the efficiency of both surface and subsurface transport processes that deliver microbes to wetlands from the surrounding catchment. Accurately quantifying the improvement in bacterial water quality from fencing shallow wetlands is not, however, possible using information from this study alone. Instead, longer-term studies are required that capture hydrological variation and quantify levels of fecal contamination under fenced and unfenced wetlands.

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