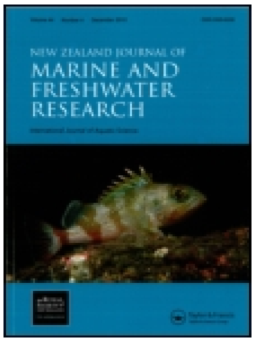

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Short communication

Water quality impact of a dairy cow herd crossing a stream

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Abstract The water quality impact of a herd of 246 dairy cows crossing a stream ford was documented. Two cow crossings produced plumes of turbid water associated with very high concentrations of faecal indicator bacteria (*Escherichia coli*) and high suspended solids (SS) and total nitrogen (TN). On the first crossing, towards the milking shed, the cows were tightly-bunched and produced a sharp spike of contamination (*E. coli* peaking at 50 000 cfu/100 ml). After milking, the cows wandered back across the stream as individuals or small groups, and contaminants were less elevated, albeit for a longer period. Light attenuation, measured continuously by beam transmissometer, correlated closely with *E. coli*, SS, and TN, permitting the total yield of these contaminants to be estimated. Contaminant yields for the two crossings were very similar, suggesting that time taken and whether or not cows are herded may not greatly influence water quality impact. The cows defecated c. 50 times more per metre of stream crossing than elsewhere on the raceway. This study has shown that cattle accessing stream channels can cause appreciable direct water contamination, suggesting that excluding cattle from streams will have major water quality benefits.

Keywords bacteria; *Escherichia coli*; environmental management; indicators; livestock; water quality

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INTRODUCTION

Pastoral agriculture has been implicated as the single largest cause of water pollution in New Zealand (Wilcock 1986; Smith et al. 1993; MfE 1997; Vant 2001). Characteristic concentrations of the favoured faecal indicator organism (*Escherichia coli*) in agricultural streams are typically c. 20 times higher than those in forested catchments, and frequently exceed guidelines (MfE 2003) for contact recreation. Direct access of livestock, particularly cattle, to stream channels is thought to be a major cause of diffuse faecal contamination of streams draining pastoral land, possibly of comparable overall importance to wash-in of faecal matter from contributing areas of pasture after rainstorms (Nagels et al. 2002; Collins & Rutherford 2004).

It is difficult to study the water quality effects of occasional and sporadic, but probably cumulatively important, entry of livestock into streams flowing, unfenced, through grazed pasture. However an opportunity to document water quality impacts, and quantify the mobilisation of contaminants, exists where dairy cattle cross and re-cross stream channels intersected by farm tracks ("raceways") linking milking shed and pastures. Previous work on cattle impacts on streams in New Zealand has demonstrated intense water contamination from dairy cows (up to 100 000 colony forming units (cfu)/100 ml of

E. coli, Adrian Meredith, Environment Canterbury pers. comm.) and appreciable faecal contamination of streambed sediments downstream of cattle access points (Keith Hamill, then of Environment Southland pers. comm.).

This short communication reports the water quality impact of a herd of dairy cows crossing a stream on a raceway connecting pasture and milking shed. We found that the crossings had a marked impact on stream water quality, particularly faecal contamination as indicated by *E. coli*. Our findings have important policy implications for livestock management in riparian zones in New Zealand.

METHODS

Study site and approach

The experimental work was conducted on the Sherry River, a tributary of the Wangapeka River, that is, in turn, a tributary of the Motueka River (Tasman District, northern South Island, New Zealand). Broad-scale water quality monitoring (October 2000–September 2001) indicated elevated faecal indicator bacteria concentrations in the lower Sherry River, with >10-fold increase in median *E. coli* compared with the upper reaches of the Sherry, which are mainly forested (Young et al. unpubl. data). This faecal contamination was hypothesised to reflect dairy farming on four properties in the lower Sherry Valley, particularly the frequent crossing of cows through the river water.

A ford on a dairy farm raceway intersecting the Sherry River (at 41°28′S, 172°43′E) was chosen for study. This ford is on the furthest upstream dairy farm in the Sherry Catchment. The ford consisted of a concrete pad c. 17 m in length constructed at river bed level to form part of the raceway system. The approaches to the ford were steep unpaved ramps cut perpendicular to the channel through bank materials by earthmoving machinery so as to drop raceway elevation from floodplain level to streambed (ford) level. Before construction of a bridge over the Sherry River at this site in April 2002, largely as a result of the findings presented below, the ford was used up to 4 times daily for crossing of the herd (246 cows, mainly Freisians with a few Jerseys) between pasture and milking shed. The herd was grazing pastures dominated by ryegrass.

We used video cameras to record the cows crossing to and from the afternoon milking. Water clarity was monitored continuously downstream of the crossing by beam transmissometry. Discrete samples taken regularly during the crossing enabled us to estimate yield of suspended solids (SS), faecal indicator bacteria (*E. coli*), and total nitrogen (TN) in the stream water. Attendant observations were made of defecation in the stream, and faecal deposits on the raceway were counted and sampled to provide an indication of *E. coli* contribution by direct deposition.

The experiment reported here was conducted on 11 October 2001, guided by the results of a pilot study 2 days earlier. At this time of year, in consideration of the seasonality of dairying, we expect that cow diet and other factors potentially affecting water quality impact would be reasonably steady. Flow in the Sherry River, measured with a Gurley pygmy current meter, was 1.14 $m^3 s^{-1}$ at 1144 h before the afternoon milking, and 1.04 $m^3 s^{-1}$ at 1754 h after milking. These flows were somewhat elevated after a fresh in response to rainfall 2–3 days earlier (53 mm at Tadmor c. 5 km north-east of the study site) that might have flushed some of the streambed stores of fine sediment and faecal bacteria. The non-toxic fluorescent dye, Rhodamine WT (100 ml of 20% solution), was used to measure travel time (2 min 13 s) from the ford to the sampling point some 60 m downstream, and to confirm full mixing across the channel.

Field instrumentation and measurement

Water quality monitoring instruments (DataSonde 4a, Hydrolab Corporation, Austin, TX, United States) were used to record water quality at 1-min intervals (pH, dissolved oxygen, temperature, conductivity, and turbidity) immediately upstream and 60 m downstream of the ford. These instruments were fixed in a submerged position in the channel, anchored to steel stakes driven into the streambed gravels. The downstream instrument was connected to a C-Star beam transmissometer (WET Labs Inc, Philomath, OR, United States) measuring light attenuation by fine suspended particles. This instrument measures transmission of a 660 nm collimated light beam over a 100 mm light path in water—from which beam attenuation coefficient, *c*, is calculated. Measurements of visual clarity (black disc visibility, Davies-Colley & Smith 2001) were used to reference the beam attenuation measurements.

Video cameras (Sony DVX 1000 and CVXV18NSP) were deployed on each side of the channel at vantage points on the floodplain above the raceway ford to provide a continuous visual record of the crossings. The videotapes were supplemented by still photography, manual recording of crossing times of cows and farm bikes, and observations of faecal deposition by the cows.

Field sampling

Water samples for *E. coli* and laboratory turbidity analysis were obtained in 100 ml sterile bottles, at intervals of 1 min during the first crossing, towards the milking shed, and every 5 min thereafter, for a total of 47 samples. Three further samples were obtained from upstream, alongside the water quality logger to provide a reference—before, between, and after the crossings. Samples for TN and SS were obtained in 1 litre acid-washed polypropylene bottles, at ½ to ⅓ the sampling rate used for *E. coli* and turbidity, with the expectation that correlation with the continuous record of light beam attenuation would permit interpolation of the former variables.

The number of fresh (i.e., <2 h old) faecal deposits was counted in a 200 m length of raceway after the cows had returned from milking. Most of these faecal deposits had been disturbed by the cow's hooves, but five intact deposits were subsampled for *E. coli* analysis and their total wet weight measured after scraping from the raceway surface.

Both water and faecal samples were stored overnight in a refrigerator before air transport (chilled, dark) to the National Institute of Water and Atmospheric Research laboratory at Hamilton, New Zealand, on the day following the experiment.

Laboratory analysis

Analysis of the favoured faecal indicator bacterium, *E. coli*, was by Colilert media using the Quanti-tray enumeration system (IDEXX laboratories, United States). The method detects *E. coli* biochemically as a subset of total coliforms (Covert et al. 1992) and has been shown to agree well with more traditional methods in several studies (e.g., Eckner 1998). This is a "most probable number" (MPN) method, but precision is high with 49 large and 48 small wells on each plate (typical standard error c. ±30%) so we report concentrations herein as cfu/100 ml. Colilert incubations of water samples were started on the day following sampling. Water samples were diluted 100-fold except for background and upstream samples which were analysed undiluted. *E. coli* was also analysed in refrigerated faecal deposit samples. A 1 g wet weight sample of faecal material was suspended in 100 ml of distilled water before being diluted 1 million-fold for the Colilert procedure.

Turbidity was measured in the laboratory three days after sampling using a Hach 2100AN ratio nephelometer, with standards calibrated to formazin (APHA 1998, Method 2130). SS was measured on selected water samples obtained on the first crossing, and TN was measured on frozen subsamples of water samples by alkaline persulphate digestion to nitrate then determination as nitrate (automated hydrazine reduction) (APHA 1998).

RESULTS AND DISCUSSION

Field observations and videotape analysis

Figure 1A shows counts of cows standing in the water at 30-s intervals during the two crossings as determined from the video tape. During the first crossing to the milking shed, the lead cows stopped once they had reached the stream and the herd bunched up behind them. The animals lingered in the water until farm staff chased them through the channel. The whole herd of 246 cows passed through the ford in 11 min. The number of cows in the water peaked at 64 animals (at 1540 h) when we observed that a high proportion were forced off the concrete pad onto stream gravels. Because the herd was so tightly bunched we could not reliably count direct faecal depositions into the water, although frequent defecation was inferred from numerous greenish patches observed in the water immediately downstream of the ford.

The return crossing was comparatively protracted (80 min) because processing at the milking shed spread out the herd. Consequently the return crossing of the stream was by small groups of animals at a time (Fig. 1A). The cows again tended to linger in the water on the ford much longer than elsewhere on the raceway. A reliable manual count of 25 faecal deposition events into the water was obtained on the return crossing. Unfortunately, the video cameras ran out of tape after 170 cows (70% of the herd) had re-crossed (Fig. 1A).

After the return crossing, 11 fresh deposits were counted in 200 m of raceway, not including the ford. If half of these are assumed to have been deposited on return from the milking shed, we have 5.5 deposits/200 m = 0.0275 m^{-1} along the raceway. This deposition density may be compared with the 25 direct deposition events observed in the 17 m of raceway on the ford, a density of 1.43 m^{-1}. That is, the cows defecated 50 times more per unit length of their path through the stream than elsewhere on the raceway.

Five intact faecal deposits sampled from the raceway had an average weight of 920 g (Table 1) and a rather variable *E. coli* content, averaging 12

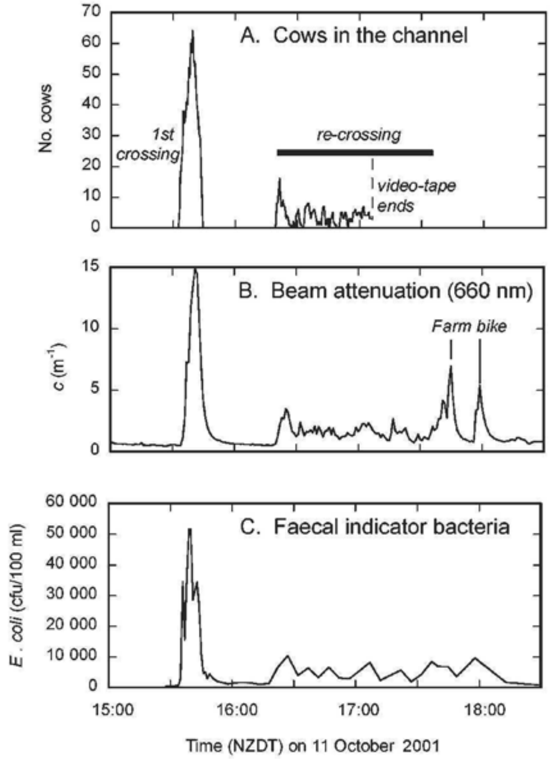

Fig. 1 Water quality of the Sherry River, New Zealand in relation to number of cows in the stream water. **A**, Count of cows in the water taken from the videotape. **B**, Water cloudiness measured as light beam attenuation, $c(660)$. **C**, Concentration of the faecal indicator bacterium, *Escherichia coli*. Two very high values measured on the return crossing (82 000 cfu/100 ml at 1702 h, and 28 000 cfu/100 ml at 1717 h) are regarded as outliers because of undispersed faecal matter (data not plotted).

million cfu per g of wet weight. Average *E. coli* content of the deposits was 9 billion cfu, but the variability between deposits suggests that the generality of these data is uncertain and better data are desirable for modelling. The bacterial indicator content of faeces of a range of animals including dairy cows is the subject of current research (Dr Lester Sinton, Environmental Science and Research pers. comm.).

Time series of water quality

Turbidity and conductivity recorded by the DataSonde upstream of the ford remained low and very nearly constant over the duration of the study, so background concentrations of other variables of interest (SS, *E. coli*, TN) are assumed to have remained constant too. These variables were measured on three upstream samples, obtained before, between, and after the two crossings (Table 2).

Figure 1B shows the continuous time series for light beam attenuation recorded 60 m downstream of the ford (data logged every minute). The beam attenuation at 660 nm peaked strongly at 15 m^{-1}, corresponding to c. 0.25 m visual clarity, during the first crossing of the dairy herd over the Sherry River on the way to milking. The beam attenuation then declined exponentially almost to background levels (c. 0.45 m^{-1}, Table 2, with a corresponding visual clarity of c. 3.5 m) until further disturbance occurred when re-crossing of the herd commenced after milking (Fig. 1B).

Light beam attenuation recorded on the return crossing was much lower and rather variable—consistent with the videotape record of the crossing (compare Fig. 1B versus 1A). Spikes of fairly high beam attenuation (Fig. 1B), **after** the herd re-crossing, record the passage of a 4-wheel motorbike ridden by a farm worker. A small peak at 1739 h records the slow herding of the last cows by motorbike (at c. 1737 h), the 1745 h peak records the (rapid) re-crossing of the ford (at c. 1742 h) when the farm worker returned for clean-up at the milking shed, and the 1757 h peak records a final crossing (at c. 1755 h) after this clean-up.

Peak *E. coli* concentrations of 52 000 cfu/100 ml (Fig. 1C) were measured coincident with the peak of beam attenuation (Fig. 1B), and the general pattern of *E. coli* mirrored that of beam attenuation. Two very high *E. coli* counts were measured on the return crossing (81 600 at 1702 h and 27 600 at 1717 h), but were unrelated to spikes in beam attenuation. In view of the otherwise close correlation with beam attenuation, these counts are regarded as outliers (not plotted) probably owing to aggregates of faecal matter reaching the sampling point undispersed. The motorbike crossings appeared to cause spikes in faecal contamination, presumably because of wash-off of faecal matter picked up by the wheels from the raceway as well as mobilisation of faecal bacteria from streambed sediment on the ford.

SS and TN also peaked coincident with the peak of beam attenuation on the first crossing (data not shown).

Mutual relationships between water quality variables

The water quality variables: beam attenuation, turbidity, SS, *E. coli*, and TN were all closely interrelated (Table 3). All of these variables correlated closely to cow count (No. cows, Table 3), allowing for the approximately 2-min travel time of the water from the ford to the monitoring point 60 m downstream. The correlations were particularly strong over the first crossing. This strong association of water quality with the number of cows present in the stream water shows that the cows caused the observed water quality degradation—by depositing and mobilising fine suspended matter, nitrogen, and faecal indicator bacteria.

The close correlation of the water quality variables with the continuously monitored beam attenuation coefficient (c), permits simulation of water quality time series, and estimation of the yield of SS, *E. coli*, and TN.

Yields of contaminants

The two crossings of the herd appeared to mobilise similar amounts of contaminants (Table 4). The light beam attenuation (optical cross-section) was particularly close on the two crossings (6140 versus 6070 m^2—these quantities are related to the surface area of light-blocking particles.) The yield of *E. coli* on the return crossing may be compared with the observation of 25 individual defecation events, which, assuming 9.3 billion cfu/deposit (Table 1), is expected to have delivered about 230 billion cfu. This is similar to the observed yield (Table 4) of 240 billion cfu, suggesting that direct deposition accounts for a large proportion of the total faecal

Table 1 Wet weight and *Escherichia coli* concentration of cow faecal deposits. (cfu, colony forming units.)

Faecal deposit No.	1	2	3	4	5	Mean	SD
Wet weight of deposit (kg)	1.4	0.7	0.9	1.0	0.6	0.92	0.31
E. coli (millions of cfu/g wet)	3.1	3.0	18.7	3.1	33.6	12	14
Billions of cfu per deposit	4.3	2.1	16.8	3.1	20.2	9.3	8.5

Table 2 Water quality upstream of the ford on the Sherry River, New Zealand (c, beam attenuation coefficient; SS, total suspended solids; TN, total nitrogen). Averages of three samples collected at 1506, 1547, and 1747 h, 11 October 2001. (cfu, colony forming units.)

c(660)	SS	*E. coli*	TN
0.45 m^{-1}	1.4 g m^{-3}	300 cfu (100 ml) $^{-1}$	260 mg m^{-3}

Table 3 Spearman Rank Correlation of water quality variables with each other and with number of cows on the ford (No. cows, 60 m upstream, 2 min earlier). (c, beam attenuation coefficient; SS, total suspended solids; TN, total nitrogen; cfu, colony forming units.)

	c(660)	SS*	Turbidity	*E. coli*	TN
SS*	0.98				
Turbidity	0.83	0.95			
E. coli	0.92	0.97	0.84		
TN	0.73	0.98	0.73	0.89	
No. cows	0.73	0.94	0.75	0.83	0.89

*SS only sampled over first crossing peak.

Table 4 Yield of contaminants to the Sherry River, New Zealand from the crossing of a herd of 246 dairy cows. (c, beam attenuation coefficient; SS, total suspended solids; TN, total nitrogen; cfu, colony forming units.)

	c(660) (m^2)	SS (kg)	*Escherichia coli* (billion cfu)	TN (g)
First crossing (11 min)	6140	16.2	207	735
Return crossing (8 min)	6070	19	240	713
Total	12210	35.2	447	1448

contamination. However, the low precision of these cfu yield estimates means that such inference is uncertain.

These yields of contaminants from crossings may be put in wider perspective by considering the equivalent continuous load, expressed as a concentration, assuming two milkings (implying **four** crossings) per day. The 2×447 billion cfu of *E. coli* mobilised per day by the crossings, mixed into the daily water flow at 1.09 $m^3\ s^{-1}$ (94 000 m^3), corresponds to an average concentration of 950 cfu/100 ml over and above the background of c. 300 cfu/100 ml (Table 2), thus quadrupling concentration (to 1250 cfu/100 ml). Similar calculations show that the crossings increased SS by c. 54%, reduced visual water clarity by c. 11%, and increased TN by c. 10%.

DISCUSSION

This study has demonstrated that dairy cows walking through streams cause considerable water contamination. Of greatest concern is the high level of faecal contamination—with *E. coli* levels temporarily elevated to more than 100× background levels and more than 100× guidelines for contact recreation. The peak *E. coli* concentrations are comparable with those (tens of thousands of cfu/100 ml) measured on the rising limbs of both natural and artificial floods in another pastoral agricultural stream in New Zealand (Nagels et al. 2002; Muirhead et al. 2004). These authors found that *E. coli* correlates fairly closely with turbidity over flood events, just as *E. coli* correlated closely with light beam attenuation over the cow crossing events studied here. The rather similar behaviour of faecal indicator bacteria and fine suspended sediment (causing light attenuation) implied by their close correlation in very different types of "event", suggests use of optical measures as a surrogate for faecal indicator bacteria. Counts of faecal indicator bacteria, measured on discrete samples at considerable expense by specialist laboratories, are typically not available until the following day, whereas optical measures such as turbidity can be measured continuously and fairly cheaply.

We may distinguish three main sources of contamination by cattle accessing a stream channel: (1) direct voiding; (2) wash-off of contaminants from their hooves and lower legs; and (3) treading disturbance of streambed sediments—which are typically faecally contaminated (Muirhead et al. 2004). Potential Source (3) might have been constrained in our study because of the concrete pad at the ford, although a high proportion of the cows strayed off the concrete onto streambed gravels. Faecal indicator bacteria probably come mainly from direct faecal deposition into the water, but some could also derive from wash-off of faecal matter on the cow's legs, and from disturbance of bacteria deposited along with other fines in the streambed sediment interstices. Fine sediment particles causing light attenuation may be mobilised mainly from disturbance of interstitial fines by treading and wash-off from the cow's legs, although faecal matter itself supplies considerable fine SS and associated light attenuation. Finally, mobilisation of TN is probably dominated by direct deposition of faeces and urine, with very minor contributions washed off the animal's legs and from streambed disturbance. All of these sources of contamination are associated with the presence of cattle in the stream, but we might expect differences in their relative importance depending on behaviour of the animals; whether moving, so disturbing bed sediment, or standing in the water, which seems to encourage defecation.

Although the contamination caused by the crossing was only temporary it was intense, and the total yield of contaminants was high such that the equivalent continuous contamination was still appreciable, with faecal contamination being quadrupled on an equivalent continuous basis. Adrian Meredith (Environment Canterbury pers. comm.) measured similarly high faecal contamination of a stream subjected to crossing of a dairy herd (concentrations up to 100 000 cfu/100 ml), and estimated that the yield was equivalent to tripling of the average faecal contamination level of that stream.

More recently, some other cow crossing studies have been conducted, albeit with less comprehensive monitoring and sampling. For example, one of us (R. Smith) studied a 145-cow herd crossing through a small stream (Puremahia Creek, Golden Bay, northern South Island, flow = 33 litre/s on 8 March 2002). *E. coli* peaked at 78 000 cfu/100 ml and at least 11 billion cfu were released in at least 10 kg of faeces deposited on the single crossing of 2.8 min. duration. (These yields are underestimates owing to deposition of much faecal material on the streambed above the monitoring point 33 m downstream of the crossing.) The cows defecated 60 times more per unit length in the stream than on the adjacent raceway, similar to our findings on the Sherry River.

The generally similar features of these different cow crossings suggest reasonable transferability of the findings reported here—particularly as regards very high faecal contamination and appreciable mobilisation of nitrogen and fine sediment causing turbidity. The herding of cows through the channel on the first Sherry River crossing produced a very similar yield of contaminants, notably faecal bacteria, to the second crossing when the cows wandered back across the stream at their own pace. About 10% of the cows defecated in the water on the two contrasting crossings, suggesting that the kind of crossing (and the consequent stress level of the animals) has little bearing on water quality impact. The common features of different cow crossings have permitted the development (by Dr Kit Rutherford, National Institute of Water and Atmospheric Research, Hamilton pers. comm.) of a model, the "cow crossing calculator", for predicting faecal contamination and supporting environmental policy (Christina Robb, Ministry for Environment and Adrian Meredith, Environment Canterbury pers. comm.). We encourage further experimental studies of dairy cow crossings as a test of this model and the findings reported here.

Calculation of contaminant yields suggests that cow crossings account for a large proportion of the total faecal contamination of streams in dairy land, and a lower, but still appreciable, proportion of the elevated nitrogen and light attenuation. Where raceways on dairy farms intersect stream channels the "obvious" solution is to bridge the channel near the existing ford. Indeed, largely as a result of our findings, a bridge over the Sherry River was constructed near the study site in April 2002, and more recently bridges were constructed to bypass two other fords formerly used for cow crossings at farms further downstream. Ongoing monitoring is aimed at documenting the expected improvement in water quality. Of course, run-off of contaminants from bridges and associated approaches still causes some stream contamination. However, defaecation is not concentrated on bridges as it is on fords, and direct faecal deposition, washing of contaminants from the animal's legs, and disturbance of the streambed, is eliminated.

Our findings in regard to cows crossing on raceways have some implications for the water quality impact of sporadic access of cattle to unfenced stream channels, which is rather difficult to study experimentally. Modelling suggests that direct faecal deposition by cattle in channels is an important contribution to overall faecal contamination of unfenced streams, perhaps of equal or greater importance to wash-off from land (Collins & Rutherford 2004). Furthermore, damage to streambanks and disturbance of stream sediments by cattle may be important contributions to the elevated fine sediment delivery by streams draining pasture. Therefore, exclusion of cattle from streams, by riparian fencing and bridging of crossings, should yield major water quality benefits.

CONCLUSIONS

A herd of dairy cows crossing a stream on a farm raceway connecting pastures to the milking shed caused considerable water contamination. Faecal contamination, as indicated by the indicator bacterium *E. coli*, was particularly marked, but there was also appreciable mobilisation of nitrogen and fine suspended matter causing turbidity. The time patterns of contaminants mirrored that of cattle in the stream. These findings suggest that dairy cow crossings, and also sporadic cattle access to unfenced streams in grazed pasture, cause considerable water quality impact. Conversely, excluding cattle from channels, by riparian fencing and by bridging streams intersected by farm raceways, should greatly improve stream water quality.

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