Best management practices to mitigate faecal contamination by livestock of New Zealand waters

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Abstract This paper summarises findings from the Pathogen Transmission Routes Research Program, describing pathogen pathways from farm animals to water bodies and measures that can reduce or prevent this transfer. Significant faecal contamination arises through the deposition of faeces by grazing animals directly into waterways in New Zealand. Bridging of streams intersected by farm raceways is an appropriate mitigation measure to prevent direct deposition during herd crossings, whilst fencing stream banks will prevent access from pasture into waterways by cattle that are characteristically attracted to water. Riparian buffer strips not only prevent cattle access to waterways, they also entrap microbes from cattle and other animals being washed down-slope towards the stream in surface runoff. Microbial water quality improvements can be realised by fencing stock from ephemeral streams, wetlands, seeps, and riparian paddocks that are prone to saturation. Soil type is a key factor in the transfer of faecal microbes to waterways. The avoidance of, or a reduction in, grazing and irrigation upon poorly drained soils characterised by high bypass flow and/or the generation of surface runoff, are expected to improve microbial water quality. Dairyshed wastewater should be irrigated onto land only when the water storage capacity of the soil will not be exceeded. This "deferred irrigation" can markedly reduce pollutant transfer to waterways, particularly that via subsurface drains and groundwater. Advanced pond systems provide excellent effluent quality and have particular application where soil type and/or climate are unfavourable for irrigation. Research needs are indicated to reduce faecal contamination of waters by livestock.

Keywords agriculture; best management practices; faecal contamination; mitigation; New Zealand

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INTRODUCTION

Faecal contamination of freshwaters is widespread in New Zealand (McBride et al. 2002; Parliamentary Commissioner for the Environment 2004) with concentrations of the faecal indicator *Escherichia coli* (*E. coli*) often exceeding recommended guidelines for contact recreation, and with *Campylobacter* and other pathogens often present. These findings, coupled with the high reported incidence of campylobacteriosis (Savill et al. 2001) and cryptosporidiosis (Duncanson et al. 2000) compared to other developed countries, have raised concerns over the public health risk from pathogens of faecal origin (including *Campylobacter*, *Cryptosporidium*, *Giardia*, and salmonellae) in New Zealand's freshwaters. Periodically, concentrations of faecal microbes restrict the recreational use of freshwaters (MfE 2003) and shellfish aquaculture in estuaries and lakes and increase drinking water treatment costs. Recent studies in North America by Willms et al. (2002) and Lardner et al. (2005) indicate that faecal contamination in cattle drinking water can decrease cattle productivity. Therefore, reducing faecal contamination of surface waters has potential benefits for New Zealand's animal industries as well as public health, recreational water use and aquaculture.

The potential sources of faecal contamination of freshwaters are diverse and can include point source discharges of wastewater from sewage treatment and animal processing plants, and contamination by domestic and feral animals (Ferguson et al. 2003). Grazing livestock are considered to be the dominant source of faecal contamination to New Zealand's freshwaters (Wilcock et al. 1999, 2006; Donnison et al. 2004; Parliamentary Commissioner for the Environment 2004). As a consequence, the consortium-based Pathogen Transmission Routes Research Program (PTRRP) was established with funding from the New Zealand Cross Departmental Research Programme and Ministry of Agriculture and Forestry to (i) quantify the relative significance of key pathogen transmission routes from farm animals to water bodies, and (ii) identify and evaluate on-farm measures with which to mitigate faecal contamination.

This paper describes the main findings of the PTRRP, and combines them with information from a literature review that focused upon New Zealand research, but encompassed overseas studies as well. Key faecal contamination pathways are identified together with associated best management practices (BMPs) to improve microbial water quality downstream of pastoral agriculture in New Zealand.

KEY TRANSMISSION PATHWAYS

In identifying pathogen transmission routes, a distinction is made between "direct" pathways, where faecal matter is deposited directly into waterways or so close that the potential for wash-in is very high, and "indirect" pathways such as the transmission of fresh or aged faecal matter via surface runoff and subsurface seepage or drainage. This distinction is important because direct deposition provides no opportunity for die-off of microbes in the faecal matter before reaching water. Indirect pathways, however, are dependent upon rainfall or irrigation to transport microbes, and there are opportunities for attenuation of faecal contamination via immobilisation or die-off. Indirect pathways via surface runoff and subsurface seepage or drainage also introduce the role of soil characteristics, topography and land management as factors contributing to transfer risk.

Direct pathways

Faecal contamination of fresh waters can arise through the deposition of faeces by animals directly into waterways. Direct deposition occurs when dairy cows cross a stream on the way to or from the milking shed and through access by cattle on pasture into waterways. Other livestock, notably sheep and goats, are less attracted to water bodies. The "waterway" in this context could include the channel and riparian zone, not just the water. This is because deposition near water may, at least on occasions, be nearly as damaging as direct deposition into water because of the high potential for wash-in by surface runoff and entrainment by rising water levels.

A study of the water quality impacts of a dairy herd crossing the Sherry River in New Zealand (Davies-Colley et al. 2004) showed very high levels of faecal contamination, with concentrations of the faecal bacterial indicator *E. coli* temporarily elevated to more than 100× background levels (median around 300 per 100 ml) and greatly exceeding guidelines for contact recreation (for example, MfE (2003) propose that "A grade" swimming waters should have a 95 percentile < 130 *E. coli* per 100 ml). During one crossing (of up to four each day with twice-daily milking) the herd was estimated to have deposited about 10^{11} *E. coli* directly into the river, associated with 25 individual defecation events.

Studies of cattle behaviour in New Zealand have been conducted on both hill country (dry stock) and dairy farms to quantify direct deposition associated with cattle access. The hill country study (Bagshaw 2002) suggested that beef cattle defecate in the stream or riparian zone (defined as within 2 m of the stream bank) at an average daily rate equivalent to about 4% of the total number of defecations. Approximately half (2%) is deposited directly into the stream channel and the other half upon the riparian zone.

Dairy cattle, studied over two summers and one spring, spent on average 99.1% of their time in the paddock, 0.7% on the bank, and 0.1% in the stream (C. Bagshaw unpubl. data). On average, 98.8, 0.7, and 0.5% of defecations were in the paddock, on the bank, and in the stream, respectively, indicating a disproportionately high stream defecation rate. However, there was considerable site-to-site variation, potentially attributable to factors such as stream size, ease of access, and the characteristics of the streambed. In an associated study, access of dairy cows to the streams was shown to increase streamwater *E. coli* concentrations, often by an order of magnitude or more, compared to background levels (R. Davies-Colley unpubl. data). This increase is attributed to a combination of both the direct deposition of faecal material and the stirring up, by the cattle, of bacteria previously settled on the stream bed.

A rigorous quantification of the importance of direct deposition relative to indirect pathways is not possible from information provided by reported studies. However, a crude analysis indicates that direct deposition is about as important as some indirect pathways. For example, a dairy herd of 175 cows, each excreting 12 pats per day, 0.5% of which are deposited directly to a stream, derives an approximate average herd input of 10 pats per day, directly to stream water. Assuming (conservatively) that at least 10^9 *E. coli* are found within a fresh pat, indicates that about 10^{10} *E. coli* are deposited directly, per day, by the herd. This figure is, therefore, within the upper range of *E. coli* yields per hectare of grazed pasture, flushed via wetlands, during rain events (Collins 2004). This range also appears to be comparable to the larger yields reported for artificial drains.

Deer, like cattle, are also attracted to water. One study found that concentrations of suspended sediment, ammoniacal nitrogen, and faecal bacteria were 20–30 times higher downstream of a deer wallowing site than upstream (Environment Southland 2000). Similarly, Davies-Colley & Nagels (2002) measured concentrations of faecal bacteria that were increased 2- to 10-fold downstream of two large deer farms. Wallowing by deer is likely to enhance erosion of the stream bed and bank, and near-channel areas resulting in reduced water clarity as well as promoting faecal contamination.

Indirect pathways

In addition to the deposition of faecal material directly into waterways, a number of other transmission routes exist, referred to as "indirect", whereby faecal microbes are ultimately transferred to waterways via the flow of water over the surface of the land (surface runoff) or down through the soil horizons (subsurface flow). The nature and relative importance of each indirect pathway will vary with a range of factors including the type of farming, livestock density, management practices, magnitude of a rain event, soil type, slope angle and distance to waterways.

Hill country farmland

On hill country sheep and beef farmland in New Zealand, the generally steep topography promotes the generation of significant surface runoff under heavy and/or prolonged rainfall (Collins et al. 2005a). This provides an efficient mechanism by which faecal microbes, deposited on pasture by grazing livestock, are delivered to waterways. Paddock experiments have shown that between 2×10^9 and 5×10^{12} *E. coli*, per hectare of steep hillside (grazed by sheep), are transported to a headwater stream by the surface runoff generated by very heavy rainfall (return period of 8 years) events (Collins et al. 2005a). The yield of *E. coli* strongly correlated (negatively) with the time elapsed since the hillside was last grazed.

Farm tracks in hill country readily generate surface runoff due to soil compaction and devegetation broadly similar to that occurring with livestock treading damage (e.g., Nguyen et al. 1998), and can be expected to deliver microbes and other pollutants to waterways. However, we are not aware of any quantitative information in the literature with which to assess the relative importance of track runoff.

Hill country topography also promotes the convergence of surface and subsurface flows causing near-channel saturated areas or wetlands to form. These wetlands drain into waterways and can yield high numbers of faecal microbes, particularly during heavy rainfall. For example, Collins (2004) measured storm period *E. coli* yields (across a range of rain events) of between 2×10^6 and 4×10^{10} per hectare of grazed hillside, at the outflow of a hill country wetland.

Dairy farm effluent

On dairy farms, effluent derived from the milking shed accounts for about 10% of the total daily load of faeces excreted by dairy cattle (Cameron & Trenouth 1999). The standard treatment of dairy shed effluent for many years in New Zealand has been by a two-pond system comprising an anaerobic followed by a facultative pond (Sukias et al. 2001). Such ponds efficiently remove sediment and biochemical oxygen demand, but removal of faecal indicator bacteria, although averaging about 90–99%, is inconsistent (Hickey et al. 1989), suggesting that further treatment is desirable before discharge to a waterway, for example by addition of further (maturation) ponds or constructed wetlands or upgrade of the pond system.

Land disposal of dairy effluent is increasingly favoured by most regional councils in New Zealand. Land disposal has the potential to markedly reduce the transfer of faecal microbes and nutrients to waterways, because of filtration and adsorption by soil, provided recommended guidelines are followed (Dexcel & Environment Waikato 2004). Ideally, existing two-pond systems would be used to store dairy shed wastes, providing useful disinfection prior to land application.

Artificial drains

Subsurface artificial drains commonly underlie dairy pastures where soils have some form of intrinsic drainage restriction. The presence of subsurface drains reduces saturation of the soil and the propensity for surface runoff, a process that can rapidly transfer microbes to waterways. For example, once undrained Pallic Soils have rewet in late autumn or early winter, their hydraulic conductivity falls to as low as 0.01 mm per day (Horne 1985). In these locations, virtually all winter rainfall in excess of evapotranspiration is discharged as surface runoff and shallow seepage flow. Following the installation of subsurface drains, surface runoff on Pallic Soils has been shown to reduce by 60–80% (Hedley et al. 2005).

Despite the benefits of subsurface drains in reducing soil saturation and the generation of surface runoff (which would otherwise convey faecal matter to streams) on soils with poor natural drainage, they are known to rapidly transfer both microbes and nutrients to waterbodies. This transfer can occur in response to the irrigation of effluent when the maximum depth of effluent application exceeds the soil water deficit (e.g., Houlbrooke et al. 2004a). In many soils, this permits bypass or preferential flow of water and microbes through soil cracks, large pores and worm channels rather than through the fine pores of the soil matrix. Under bypass flow, soil-water contact is minimal, providing little opportunity for the filtration or adsorption of microbes. Microbes and nutrients entrained in water can, therefore, be readily transported to subsurface drains (and hence to surface waterbodies and groundwater).

Monaghan & Smith (2004) studied the impact of effluent irrigation to land upon the generation and contamination of subsurface drain flows. They found that when the soil was wet (small soil moisture deficit) prior to application, *E. coli* concentrations in the resulting drain flows—10^5 to 10^7 per 100 ml—approached those of the applied effluent. Greater soil moisture deficits, however, led to lower *E. coli* concentrations in drain flows (c. 10^4 per 100 ml), indicating considerable mixing of the effluent with older resident soil water. The yield of *E. coli* across these reported drainage events ranged between 10^8 and 5×10^{10} from the 1080 m^2 study plot. Monaghan & Smith (2004) also found non-uniform patterns of effluent application with the outside of a small rotating irrigator receiving double the average application depth, promoting ponding and bypass flow. Hedley et al. (2005) report peak drain-flow *Campylobacter* concentrations of $>10^3$ per 100 ml, following the application of effluent at a time of negligible soil moisture deficit. Similarly, Ross & Donnison (2003) found that when preferential flow occurred, *Campylobacter* concentrations in drainage water approached those in the applied effluent.

Contaminated drain flows also occur in response to rainfall during or following grazing episodes. Hedley et al. (2005) report drain flow *Campylobacter* concentrations of c. 10^2 per 100 ml following overnight grazing (80–100 cows per ha) and c. 10^1 per 100 ml following grazing 19 days earlier.

On some soil types, appreciable surface runoff, contaminated by faecal microbes, can be generated on flat to rolling dairy land underlain by artificial drainage. For example, Hedley et al. (2005) report that 46 mm and 179 mm of surface runoff were generated upon a study plot underlain by a Tokomaru silt loam soil, during 2003 and 2004, respectively. This compared with 258 mm and 388 mm of subsurface drainage from the same plots over the same periods. Furthermore, the surface runoff generated was heavily contaminated by faecal microbes, with concentrations of *E. coli* and *Campylobacter* peaking at $>10^5$ per 100 ml and $>10^3$ per 100 ml, respectively, immediately following grazing. Peak *Campylobacter* concentrations in surface runoff, generated following the application of effluent, were also $>10^3$ per 100 ml.

Groundwater contamination

The irrigation of water to encourage pasture growth can promote the flushing of faecal microbes, from faeces deposited on pasture by livestock, down through the soil horizons (particularly via bypass flow) with the potential to cause contamination of groundwater. Border-strip irrigation, in particular, has led to the faecal contamination of wells up to 11 m below ground level (Close et al. 2005). *Campylobacter* were identified in 12% of groundwater samples with concentrations ranging between <0.6 and >3.1 per 100 litre. As groundwater is often used directly for drinking purposes without treatment, these concentrations raise implications for public and animal health. Generally, the highest *Campylobacter* and *E. coli* concentrations found in the wells occurred approximately 20–30 days after a period of grazing had coincided with a border strip irrigation event or a large rainfall event.

A risk assessment of drinking this water was undertaken by Close et al. (in press) using @RISK software with the observed distribution of *Campylobacter* and assuming consumption of 1 litre per person per day. The daily probability of infection was estimated at 0.50–0.76%, giving a probability of infection during the irrigation season of 60–75%. Actual illness rates will be lower for various reasons including immunity. Close et al. (in press) also conducted an epidemiological assessment of people living in areas encompassing dairying within major irrigation schemes (c. 55% border-strip irrigation), and demonstrated a statistically significant increase in incidence of campylobacteriosis, cryptosporidiosis, and salmonellosis compared to control groups elsewhere in Canterbury.

Fine-grained aquifers (e.g., sand, sandstone and pumice) are efficient at retarding microbes through filtration. However, some large-pore heterogeneous aquifers (e.g., gravel, karst, fractured rocks) are susceptible to microbial contamination because of their high permeability, low filtration capacity, and presence of preferential flow paths (Davies-Colley et al. 2003). Protozoa are assumed to be more efficiently filtered by aquifer media than are bacteria and viruses, due to physico-chemical interactions and their generally larger particle size.

MITIGATION

Direct pathways

The study of Davies-Colley et al. (2004) shows that herd crossings in streams are a key faecal microbe transmission route. Clearly, therefore, such stream crossings by dairy herds should be avoided by use of bridges or culverts. Continued monitoring of the Sherry River, site of the crossing study by Davies-Colley et al. (2004), shows that bridging of crossings along that waterway has appreciably improved water quality. However, guidelines for contact recreation are still often exceeded there, presumably because of continuing pollution via indirect pathways and direct deposition where dairy cattle have access to unfenced tributary streams and drains (R. Davies-Colley unpubl. data.).

Permanent fencing is the most stringent and "absolute" measure with which to prevent cattle access into waterways. This has three effects: (i) the source of direct faecal deposition is removed from water and channels, and from riparian areas proximal to the stream from which surface runoff can deliver pathogens, (ii) a riparian buffer can be created (provided the fencing is set back from the bank) that can entrap microbes washed in from upslope, reducing transport to the water, and (iii) the source of soil and vegetation damage (devegetation, soil compaction, creation of cattle "ramps" (Trimble & Mendel 1995)) is removed, so that riparian functioning is restored over time, particularly a high infiltration capacity that reduces mobilisation of faecal microbes by surface runoff. Askey-Doran (1999) gives a number of suggestions for permanent and electric fencing near and across streams, including methods to avoid flood damage to fencing infrastructure. Some guidelines on fencing are also provided by Collier et al. (1995).

Alternatives to fencing can potentially reduce the input of faecal material directly to waterways. These involve the encouragement of livestock away from waterways through provision (off-stream) of resources such as water, shade and shelter. An alternative water source, in particular, has been shown experimentally to provide significant incentive for cattle to move away from channels in semi-arid areas of the United States (e.g., Miner et al. 1992; Shefpaddock et al. 1997). However, under very intensive stocking conditions in New Zealand, alternative water sources located on hilltops did not reduce the use of streams by beef cattle (Bagshaw 2000). The usefulness of alternative water sources with dairy cattle remains untested within New Zealand.

Indirect pathways

Soil characteristics

The identification of soils with high risk of transfer to waterways is a key step towards mitigating accelerated microbial pollution of waters from grazing and irrigation events (effluent and water).

The generation of surface runoff

The ability of a given soil to attenuate microbes is strongly dependent upon the degree to which water from rainfall or irrigation can infiltrate into the soil, rather than generating surface runoff, that can rapidly transport microbes downslope to waterways. Poorly drained soils with a low infiltration rate have been shown to be a relatively strong predictor of streamwater faecal contamination (Collins 2003). McLeod et al. (2005) have mapped relative soil surface runoff potential across New Zealand, based on drainage class, depth to impermeable layer, permeability above an impermeable layer (based on measurements of hydraulic conductivity) and slope angle.

In the North Island, very low relative potential for runoff is associated with soils developed in volcanic tephra in the central North Island and Taranaki regions (McLeod et al. 2005). High runoff potential is largely associated with hilly or steep land, especially where drainage is restricted, such as on clay-rich soils in Northland. Flat, poorly drained land in the greater Waikato region, however, also has a high relative potential under high rainfall. In the South Island, very low runoff potential is predominantly associated with soils developed on alluvial plains. High potential is again associated with steep land, especially where drainage is restricted.

Microbial attenuation within soil

The ability of a soil to attenuate infiltrating microbes strongly affects the transfer of faecal microbes to waterways. Soil microbial attenuation is strongly dependent upon the degree to which infiltrating water passes through the fine pores of the soil matrix, and contacts reactive internal surfaces that aid attenuation. The more water movement that bypasses these fine pores, flowing instead through macropores (cracks, large pores and worm channels), the less opportunity there is for microbial attenuation. Soils characterised by strong bypass flow should be subject to less intensive grazing and application of effluent.

Results from microbial breakthrough curves using undisturbed soil cores (Aislabie et al. 2001; McLeod et al. 2001, 2003, 2004) have been combined with the New Zealand Soil Classification (Hewitt 1998), to extrapolate the relative risk of rapid microbial transport to all soils across New Zealand (McLeod et al. 2005).

The results indicate that approximately 50% of North Island soils on flat to rolling land have a high potential for microbial bypass flow. Large areas where soils have a drainage or structural impediment occur, for example, in Northland on old, strongly weathered, strongly structured, clayey soils, and in Manawatu, Wairarapa, and Hawke's Bay. Low-lying poorly drained soils with a high potential for microbial bypass flow occur on the Hauraki Plains and in Waikato. There are large areas of Organic Soils in Waikato that are also rated as having a high potential for microbial bypass flow. Approximately 40% of North Island soils have a low potential, and large areas of these soils are associated predominantly with volcanic soils in Taranaki, central North Island and Waikato.

Approximately 50% of South Island soils have a high potential for microbial bypass flow. Large areas occur, for example, on the West Coast where soils with an iron pan or poorly drained soils have developed. A drainage impediment suggests that many of the soils in the south and east of the South Island have a high potential. In contrast to the North Island, <25% of South Island soils have a low potential. Those that do are associated predominantly with Allophanic Brown Soils developed from loess.

Irrigation management

Effluent irrigation

In addition to the identification of appropriate soil properties, timing, volume, location and technique are also key factors in the optimal irrigation of effluent, with respect to minimising pollutant loss to waterways. Robb & Barkle (2000) provide guidelines for the application of effluent to land, and Dexcel & Environment Waikato (2004) have produced a handbook to assist farmers in this respect.

Irrigation when soils are at or near saturation can generate surface runoff and bypass flow down through the soil horizons to either groundwater or subsurface drains; both processes are rapid transmission pathways for faecal microbes. Ideally, irrigation should occur only when the volume to be applied will not exceed the water storage capacity of the soil, with effluent being stored until such soil moisture conditions arise. This "deferred irrigation" has led to marked decreases in nutrient loss to waterways (Houlbrooke et al. 2004a) and is likely to be similarly successful with respect to faecal microbes. Experimental and modelling studies by Monagahan & Smith (2004) also support deferred irrigation. Measurement or prediction of soil moisture on a daily basis is a central requirement of the deferred irrigation approach. In addition, sufficient effluent storage capacity is a key requirement, particularly during winter and spring when soil moisture deficits are small or non-existent (Houlbrooke et al. 2004a). At a West Otago study site, Monaghan & Smith (2004) estimated that between 44 and 109 days of effluent storage would be required per year depending upon rainfall and the groundspeed of the irrigator. Houlbrooke et al. (2004a) recommend effluent applications at the lowest rates possible during the critical wettest times of the year.

Where possible, land application of dairy farm effluent should be restricted to those soils that have a low transfer risk from surface runoff and/or bypass flow. However, on soils with high and medium bypass flow risk, where drainage is extensive, application should be confined to paddocks remote from waterways to maximise the opportunity for microbial entrapment and die-off to occur in soils and within the network of drains and ditches (e.g., Nguyen et al. 2002) before entry to waterways.

Irrigator type and operating practice can influence microbial loss: the problems associated with a non-uniform pattern of application by rotating irrigators of typical design can be reduced by using the highest irrigator groundspeed, thereby applying less effluent more often to any given ground area (Houlbrooke et al. 2004b; Monaghan & Smith 2004). Furthermore, an assessment of travelling effluent irrigators found an oscillating irrigator to have a more uniform pattern of application (and hence less likely to generate bypass flow) than a rotating irrigator (Houlbrooke et al. 2004b).

Water irrigation

As with the irrigation of effluent, soil properties, timing, volume, location and technique are key factors in determining optimal water irrigation practices. Close et al. (2005) identified the need to avoid irrigation immediately following livestock grazing. Hedley et al. (2005) and Connolly et al. (2004) report that *Campylobacter* concentrations in drainage water fall by at least an order of magnitude if the interval between grazing and irrigation increases from 1 to 7–10 days. A delay between grazing and irrigation permits change in the physical and chemical properties of faecal material and (usually) some net microbial die-off to occur, reducing the leaching of microbes.

Accounting for the soil moisture deficit when determining the volume of water to be applied can lead to reduced drainage, and hence reduced microbial contamination of groundwater. However, the practice of border-strip irrigation involves flooding of the soil surface and hence, even if reduced water volumes are applied, the potential for preferential or bypass flow to depth remains. Results from the study by Close et al. (2005) indicate that spray irrigation results in much less bypass flow and much lower microbial contamination of groundwater than the border strip technique. An effective mitigation measure would be to convert from border strip irrigation to spray irrigation, or to limit border strip irrigation to areas where there was less potential for microbial leaching, e.g., upon soils with few macropores, and regions with a deep vadose zone and groundwater table. However, there are significant operational and financial implications in these options and they may not be feasible in some situations.

Advanced pond system for treatment of dairy shed effluent

Advanced pond systems (APS) are a pond-based upgrade option for conventional two-stage oxidation ponds that have particular application where soil and climatic conditions are unfavourable for land application of effluent. APS consist of four types of ponds arranged in series (an anaerobic pond, a high rate pond, algal settling ponds, and a maturation pond) that result in effluent of a considerably higher quality (notably, far higher microbial quality; Craggs et al. 2004b) than the traditional two-stage oxidation ponds, with opportunities for resource recovery (energy, nutrients, and water) (Craggs et al. 2004a)).

Treatment of drain flows within constructed wetlands

Recent studies using constructed wetlands have shown potential in the treatment of drain flows from grazed and irrigated dairy pasture, particularly with respect to nutrients (Tanner et al. 2005). This mitigation measure also has the potential to attenuate faecal microbes within drain flows, an aspect that is the subject of ongoing research.

GRAZING LOCATION

The identification of appropriate (and conversely, inappropriate) locations for livestock grazing can lead to a reduction in faecal contamination of waterways. Aside from excluding or encouraging stock away from riparian areas, water quality improvements can be realised from fencing stock out of wetlands and seepages on pastoral land. For example, studies of hill country wetlands (Collins 2004) have shown that cattle are strongly attracted to the smaller, shallower wetlands for grazing, though not to the large, deep wetlands, presumably for fear of entrapment. Consequently, these smaller wetlands are critical source areas with respect to faecal microbes, sediment and nutrients. Such wetlands have also been shown to attenuate nitrate through the process of denitrification, provided that water moves through the wetland sufficiently slowly (Burns & Nguyen 2002; Rutherford & Nguyen 2004). Modification of wetland drainage through cattle trampling, installation of subsurface drains or artificial channels is, therefore, likely to diminish their nitrate-attenuating properties.

During wet weather, stock exclusion might be extended to those paddocks located adjacent to waterways that are characteristically prone to saturation. Such paddocks are vulnerable to pugging damage in weather conditions (i.e., rainstorms when antecedent soil moisture is already high) that are most likely to generate the surface runoff that can wash faecal matter directly to water bodies. Grazing rotations on dairy farms could be arranged such that when heavy rain is predicted, cows can be grazed on paddocks away from permanent waterways. This would involve managing pre-grazing pasture covers that allowed for alternate 12–24 h grazing of riparian versus non-riparian paddocks.

Groundwater contamination affects the quality of water used for human or stock drinking. Close et al. (2005) suggest that cows should be grazed down (groundwater) gradient, or as far away as possible from wells for at least a week prior to, and during, border strip irrigation. Permanent fencing to exclude stock around wells is also expected to be beneficial (Close et al. 2005). Further protection of wells can be achieved by sealing (concreting) an area of at least 1 m diameter around the wellhead. This prevents infiltration of microbes through the permeable, disturbed material adjacent to the well.

During prolonged wet weather, improved water quality may result through the relocation of stock from paddocks to feed or wintering pads, and herd homes (Luo et al. 2006). Appropriate disposal of effluent is, however, required to ensure that benefits to water quality are realised.

Riparian buffer strips

Fencing to exclude livestock from stream channels and a proportion of riparian land has the potential to be a particularly effective measure in reducing the faecal contamination of pastoral streams. Not only does this prevent the deposition of faecal material directly into streams and near-channel contributing areas, the dense vegetation associated with riparian buffer strips (RBS) reduces the momentum and magnitude of surface runoff, thereby aiding infiltration and promoting the entrapment of faecal material and other agricultural pollutants (Parkyn 2004). Furthermore, riparian buffers also benefit stream habitat, notably by the shading provided by shrubs and trees (Parkyn et al. 2003).

Studies under the PTRRP and elsewhere (Collins et al. 2004, 2005b; Muirhead et al. 2005) have shown that the effectiveness of RBS in attenuating faecal microbes washed in by surface runoff is influenced by: slope angle, soil type, buffer width, the type of faecal material, the degree of attachment of microbes to soil, and the rate of surface runoff. Sheep and cattle faeces differ appreciably in character which may be expected to influence mobility in surface runoff. A recent study estimated *E. coli* loading rates on sheep pasture to be appreciably higher than on cattle pasture at typical stocking densities (Wilcock 2006).

Currently it is not possible to derive quantitative RBS design guidelines that are widely applicable across pastoral land within New Zealand from the few studies that have been undertaken. To do so would require experimental work to be undertaken across a wide range of soils, slope angles, buffer types, and magnitude of rainfall events. Instead, quantitative guidelines for RBS with respect to faecal bacteria (Collins et al. 2005b) have been derived from those reported for sediment attenuation. These, in turn, were derived from a detailed sediment modelling study (Collier et al. 1995) that captured the variability of the New Zealand pastoral landscape, and simulated the effects of a permanent buffer characterised by dense vegetation. The reported RBS guidelines for faecal bacteria (Collins et al. 2005b) provide appropriate RBS width estimates, accounting for slope angle, soil drainage and the degree to which bacteria are attached to soil particles. This last factor has been shown to strongly influence the transport and deposition of faecal microbes across both bare soil and vegetated surfaces (Muirhead et al. 2005).

CONCLUSIONS

Faecal contamination of freshwaters can arise through the deposition of faeces by animals directly into waterways. Direct deposition occurs when dairy cows are herded across a stream and through access into waterways by livestock, notably cattle. Bridging streams intersected by farm raceways is an appropriate mitigation measure for herd crossings, whilst fencing stream banks will exclude livestock from channels. Water quality improvements can also be realised from fencing livestock out of ephemeral streams, wetlands, seeps, and riparian areas prone to saturation. During prolonged spells of wet weather, improved water quality is expected through the relocation of stock from paddocks to feed or wintering pads, and herd homes.

Riparian buffer strips not only prevent cattle access to waterways, they can also entrap microbes (and other pollutants) entrained from faecal deposits of cattle and other animals being washed down-slope in surface runoff. Guidelines for optimal riparian buffer design with respect to the entrapment of faecal bacteria are referenced in this paper.

Soil type is a key factor in the transfer of faecal microbes to waterways. The avoidance of, or a reduction in, grazing and irrigation upon poorly drained soils characterised by high bypass flow and the generation of surface runoff, are appropriate management practices, and are likely to lead to improvements in microbial water quality.

Timing, volume, location and technique are also key factors in the optimal irrigation of effluent and water. Ideally, irrigation should occur when the volume to be applied does not exceed the water storage capacity of the soil, with effluent being stored until such soil moisture conditions arise. Such "deferred irrigation" can markedly reduce pollutant transfer to waterways. Spray irrigation results in less risk of soil saturation and hence less surface runoff and microbial contamination of groundwater than the border strip technique.

FURTHER RESEARCH NEEDS

Whilst the PTRRP and its associated review of information has identified a number of measures with which to mitigate the faecal contamination of New Zealand's waterways, information is still lacking with respect to several issues, outlined as follows:

(i) The provision of off-stream sources of water, shade and shelter for cattle, as an alternative to permanent fencing of streams, has had only limited testing in New Zealand. Further studies that quantify the impact of these alternative resources upon water quality would therefore be of value.

(ii) Cattle attraction to waterways and wetlands has been shown to vary with site characteristics, probably including size and depth of the water body, the accessibility, season, and stream bed substrate. An improved understanding of cattle behaviour in this respect would help to prioritise the use of fencing or other methods for protecting waterways and wetlands.

(iii) Current understanding of microbial entrapment within riparian buffer strips is limited and would be improved through further experimental studies encompassing a range of soils, slope angles and vegetation types. In particular, an improved understanding of those factors that influence microbial attachment to particulates would aid the evaluation of buffer strip effectiveness and recommendation of site-specific buffer widths.

(iv) Buffer strip experiments to date have focused upon the performance of grass buffers. However, maintenance of grass buffers will require periodic (light) grazing, preferably by sheep which do not damage soils as much as cattle and are not attracted to water. No information exists with which to evaluate the impact of periodic buffer grazing upon water quality. Furthermore, tree buffers are favoured over grass buffers for their shading and habitat benefits, and there is increasing emphasis in New Zealand on planting of native trees in riparian zones for biodiversity reasons. Again, however, there is no information available with which to determine tree buffer performance with respect to microbial entrapment.

(v) Experimental studies are required to evaluate the efficacy of measures with which to treat microbes in stormwater and effluent from farms. Constructed wetlands, vegetated ditches, and farm ponds all have potential in this respect, but little or no information is available with which to evaluate them.

(vi) Information describing the cost effectiveness of mitigation measures is scarce. Primarily, this is because the effectiveness of most measures remains difficult to quantify with certainty, e.g., entrapment efficiencies in buffer strips. However, the costs of many of the measures advocated in this paper have yet to be assessed, regardless of confidence levels in the efficacy of a particular measure.

In addition to improving our understanding of the performance of specific BMPs, two broader issues relating to faecal contamination of waterways are of significant importance and worthy of further research:

(1) The role of water in explaining reported rates of human infection in New Zealand, in particular, campylobacteriosis and cryptosporidiosis,

remains unclear. Direct exposure to water through freshwater recreation has been predicted to account for only a small proportion of reported cases of campylobacteriosis (McBride et al. 2002). However, the *indirect* impact of water due to background levels of pathogens in the pastoral landscape, upon human infection might be far more significant. Waterways, for example, may play an important role as a vector for pathogens in the environment, causing re-infection of animals in farms downstream, and maintaining a general background level of pathogens on pastoral land. Identifying causes of human infection therefore requires that water as a pathogen vector or indirect cause needs to be better understood. Furthermore, the tracing of pathogen strains that cause infection and re-infection of grazing cattle is of high priority and would help to explain the persistence of some pathogens in the pastoral landscape.

(2) Overseas, evidence is emerging to link cattle productivity with the microbial quality of cattle drinking water. Given the potential significance of this issue, New Zealand-based studies are desirable.

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