Stormflow-dominated loads of faecal pollution from an intensively dairy-farmed catchment

Rob Davies-Colley, Elizabeth Lydiard and John Nagels

ABSTRACT

Rainstorms can flush large amounts of faecal pollution from land sources into water bodies, threatening, particularly, contact recreation and bivalve shellfish harvest. We quantified the faecal pollution loads of stormflows in the Toenepi Stream, draining a catchment in intensive dairy-farming (Waikato Region, New Zealand). In this stream, as is typical, *E. coli* concentration peaks well ahead of flow on storm flow hydrographs, which complicates calculation of loads. However, stormflow *E. coli* concentration correlates with turbidity in the Toenepi Stream, so we used a continuously-recording turbidimeter to estimate 'continuous' *E. coli* concentrations and thence *E. coli* fluxes (cfu/s) and loads (cfu). *E. coli* was measured on 25 out of the 30 (83%) of storm events occurring in the Toenepi Stream in a 12-month period, using an automatic sampler sampling every 2 hrs over stormflow hydrographs for microbial analysis (within 48 hr). *E. coli* (cfu) yield on individual events tended to increase systematically with event size. The sum of storm-flow exports (occurring 24% of total time) amounted to 95% of the total annual *E. coli* export from the Toenepi Catchment. The stream exported about 6% of the (expected) total *E. coli* production in cattle faeces within the catchment.

Key words | cattle, dairying, diffuse, *E. coli*, faecal contamination, stormflow

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INTRODUCTION

New Zealand has about 10 million cattle and 40 million sheep, but only 4 million people, so livestock faecal contamination is of particular concern in this country (PCE 2004). There is a high incidence of some zoonotic diseases in New Zealand, notably campylobacteriosis (currently over 400 reported cases/100,000 people/year), and livestock are the single biggest compartment for this pathogen in the New Zealand environment.

Stormflows are known to flush large amounts of faecal pollution from land sources such as livestock into water bodies downstream (McDonald & Kay 1981), threatening, particularly, contact recreation, water supply, and harvesting of bivalve shellfish (Lipp *et al.* 2001). The well-known association of high faecal microbial concentrations with stormflows is usually attributed to wash-in of faecal matter with overland flow. However, recent research (overviewed by Davies-Colley 2007) suggests that faecal microbes, such as the favoured freshwater indicator bacterium, *Escherichia coli*, usually peak in concentration well *ahead* of peak flow. This timing is problematic because faecal microbes washed in with overland flow should arrive *after* the flow peak – which travels as a wave moving down the channel appreciably faster (by about 50%) than the water and its constituents. Wilkinson *et al.* (2006) have proposed that peaks of faecal bacteria arriving ahead of flow peaks reflect entrainment of sediment stores of these bacteria. Several studies have presented evidence of the existence of such stores, and Nagels *et al.* (2002) and Muirhead *et al.* (2004) used artificial flood events (in fine weather without any confounding overland flow) to quantify their magnitude.

Dairying is a major industry in New Zealand and one that is increasingly cited for its environmental impacts, including faecal microbial pollution (PCE 2004). Faecal microbial concentrations in streams draining dairy land are not

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unusually high, at least at baseflow, although elevated compared to other land uses and often exceeding guidelines for contact recreation (Wilcock *et al.* 2007). However, concentrations in these same dairy streams can be two or more orders of magnitude higher during stormflows (Donnison *et al.* 2006). We wished to better understand faecal pollution dynamics over storm events, and sought to quantify the faecal pollution yields from dairy land – as a precursor to catchment modelling efforts to assess mitigation measures. The Toenepi Stream, draining an intensively dairy-farmed catchment near Morrinsville, Waikato Region, New Zealand, was chosen for study because of its proximity to our laboratory at Hamilton and because several other research projects are underway on water quality effects of dairying and mitigation measures in this catchment (Wilcock *et al.* 2006). This paper reports (1) the stormflow faecal pollution dynamics in the Toenepi Stream as indicated by *E. coli*, and (2) the export of this bacterium in individual storm events *versus* intervening baseflows, and the total export as a proportion of catchment 'production' in livestock faeces.

METHODS

The Toenepi Catchment is one of 5 representative dairy focus catchments in New Zealand (Wilcock *et al.* 2007) which are the subject of intensive long-term monitoring to document environmental improvements as best management practices (BMPs) are increasingly adopted. The Toenepi Stream (catchment area 15.1 km^2 above the hydrometric site at 37° 42.28′ S, 175° 33.06′ E) is a tributary of the Piako River in the Waikato Region of New Zealand near Morrinsville, one of the most intensively dairy-farmed areas in New Zealand (about 3 cows/ha). The Toenepi Catchment has mostly flat (89% $< 7°$) topography with appreciable artificial drainage, and is 100% pasture, with 83% of livestock being dairy cows (Wilcock *et al.* 1999, 2006). The catchment receives about 1160 mm/yr of rainfall and streamflow export is 419 mm/yr (36% runoff) at a mean flow of 210 L/s (median flow = 73 L/s).

Water quality monitoring has been conducted in the Toenepi Stream for a decade (Wilcock *et al.* 2006, 2007), mainly at monthly intervals. This on-going 'pseudo-random' monitoring of water quality (in which most samples are inevitably taken at baseflow conditions) was augmented by a 12-month campaign of targeted storm-flow sampling of *E. coli* using an automatic sampler (Mannings VST, Texas, USA). The auto-sampler intake was located in the pond formed by the shallow V-notch weir that provides hydrological control at the hydrometric station. The auto-sampler was turned on by cell-phone-operated switch (SMITCH, Timaru, New Zealand) whenever appreciable rainfall was forecast, and thereafter obtained samples every 2 hr for up to 48 hours (24 samples). Auto-samples were collected during or soon after storm events and assayed (within 48 hrs of collection) for total coliform bacteria and *E. coli* (quantifying faecal contamination) by the Colilert Quanti-tray enumeration system (IDEXX laboratories, Maine, USA). Laboratory turbidity (Hach 2100AN nephelometer) was also measured on auto-samples as a guide to *E. coli* concentrations and as a check on drift of a field turbidimeter (described below).

The concentration of *E. coli* in the Toenepi Stream does not correlate well with flow over stormflow hydrographs because the bacterial peak always precedes the flow peak (Results – below). However, *E. coli* correlated fairly closely with turbidity over events, so we used a continuously-recording turbidimeter (Greenspan TS100, Stevens, Queensland, Australia) to estimate 'continuous' *E. coli* concentrations from which loads were calculated for individual storm events. The turbidity sensor was installed in the weir pond at the hydrometric station and connected to the logger (Unidata Starlogger, Perth, Australia) recording water level at 15 minute intervals for flow estimation. The turbidity sensor was cleaned of biofouling at monthly intervals during visits for water quality sampling. Both flow and turbidity were telemetered (daily or on demand – as during storm events) to the NIWA laboratory at Hamilton 40 km to the west. Turbidity was 'calibrated' to *E. coli* measured on autosamples on 25 (83%) of the 30 storm events occurring in a 12-month period (March 2005 – February 2006). For the five events for which few or no samples were obtained for *E. coli* measurements (owing to human error or mechanical failure), the mean relationship of *E. coli* to turbidity was assumed.

Storm loads of *E. coli* were estimated on 30 individual storm events in a twelve-month period from the 'continuous' flow and simulated *E. coli* concentrations. Flux of *E. coli* (units: cfu/s) was calculated by multiplying concentration (cfu/100 mL) by flow (L/s) (with account taken of the 'unusual' volume units that are traditional in microbiology), and flux was then integrated over time to calculate storm load (cfu).

RESULTS

Figure 1 shows the typical pattern of *E. coli* dynamics over storm-flow hydrographs in the Toenepi Stream. *E. coli* peaked well ahead of the flow peak and close to the time of maximum rate-of-change of flow. This out-of-phase relationship of concentration and flow, quite aside from its importance as an indication of faecal pollution sources, means that flow can not easily be used as a surrogate for concentration for the purpose of estimating fluxes and loads. Instead, the closely-correlated field turbidity ($r = 0.98$ in this case) was used to simulate an *E. coli* time series from the turbidity record (Figure 1).

Load of *E. coli* in storm events increased with water yield (Figure 2), although with appreciable scatter. For example, the largest *E. coli* load (indicated on Figure 2) occurred on only the fifth largest storm. The regression line (power law) fit of the data in Figure 2 has an exponent appreciably greater than 1, showing that *E. coli* load increased disproportionately with event size (water yield).

The annual yield of faecal pollution in stormflow conditions was estimated by summing the yield of the 30 events illustrated in Figure 2. The baseflow yield was estimated with sufficient accuracy by simply multiplying average baseflow concentration (276 cfu/100 mL) by flow since the (relatively low) *E. coli* concentrations during baseflows, were almost uncorrelated with flow. Table 1 summarises the loads measured over a 12-month period. Not surprisingly, given much higher concentrations in stormflow (*E. coli* up to 100,000 cfu/100 mL), the great majority (95%) of the total annual *E. coli* export from the Toenepi Catchment was in stormflows (occurring 24% of the time), with only 5% delivered in baseflows (occurring 76% of the time).

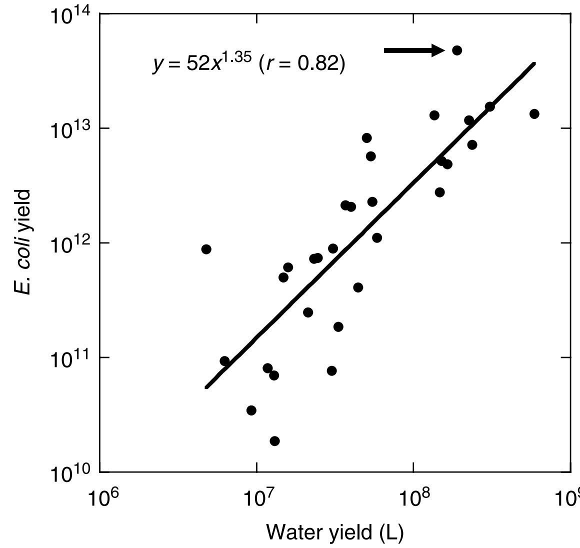

Figure 2 | *E. coli* yields versus water yields on 30 individual storm events in the Toenepi Stream over a 12-month period. (An arrow indicates the event with the highest *E. coli* yield, as discussed in the text).

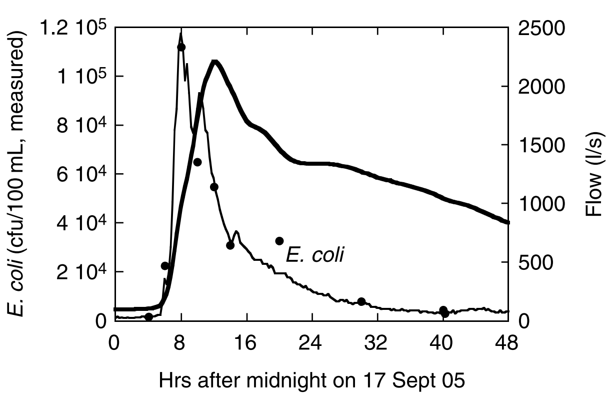

Figure 1 | Typical dynamics of *E. coli* over a stormflow hydrograph in the Toenepi Stream (18 September 2005 event). The 'continuous' *E. coli* time series (fine line) was simulated from the field turbidity record (using the relationship between *E. coli* and field turbidity; $r = 0.98$). *E. coli* measurements on automatic samples (points) are overlain for comparison, and the hydrograph is given as a thick line.

DISCUSSION

The dynamics of faecal pollution over hydrographs, with *E. coli* peaking well ahead of flow, and close to the maximum rate-of-increase of flow (e.g., Figure 1), seems to be consistent in large and small streams and almost

Table 1 | Summary of *E. coli* export from the Toenepi Catchment in 30 storm events and on intervening baseflows over a 12-month period of monitoring

	Export (cfu/y)	%
Storm events	1.5×10^{14}	95%
Base flow	8.0×10^{12}	5%
Total	1.6×10^{14}	100%

regardless of land use (Davies-Colley 2007). This timing has practical ramifications in that it complicates estimation of loads. The timing also has implications for the source of the faecal microbes, which seem most likely to come from entrainment from the stream sediments. Wash-in of faecal matter from deposits on land with overland flow, must occur of course, but cannot be responsible for stormflow peaks because such wash-in would tend to arrive much later than observed peaks of *E. coli*, and probably after flow peaks (Davies-Colley 2007). The main role of wash-in seems to be replenishment of in-channel stores on the declining limb of the hydrograph, after their flushing by flood fronts.

There is another (ultimate) source of faecal pollution from livestock besides wash-in of faecal deposits, however, namely direct deposition by livestock into streams to which the animals have access (Collins *et al.* 2007). The size of this source is compared below with the total stream annual export.

As we might have expected, export of *E. coli* in storm events in the Toenepi Stream increased systematically with size of the events (measured as water yield), but with considerable scatter (Figure 2). Much of this scatter is probably explainable considering antecedent conditions. For example, the largest *E. coli* yield (indicated on Figure 2) occurred on only the fifth largest storm event, probably because this event occurred after a sustained period (6 weeks) of baseflow recession during which time faecal pollution stores built up in the catchment to high levels. Conversely, some of the events plotting low in Figure 2 occurred soon after earlier events which probably flushed catchment stores (on land and in stream sediments).

The exponent of the power-law fitting line in Figure 2 is appreciably greater than unity at 1.35, showing that larger storm events yielded disproportionately large amounts of faecal pollution. Consistent with this, the event-averaged concentration (*E. coli* export divided by water export) tended to increase with event size – from about 1,000 cfu/100 mL in 5 megalitre events to about 50,000 cfu/100 mL in 500 megalitre events. The trend to disproportionately large exports in large events probably reflects expansion of the channel network (entraining riparian faecal deposits and causing appreciable wash-off of faecal matter), and also flushing of faecal pollution into mole drains.

The total export of *E. coli* from the Toenepi Catchment may be expressed on a catchment areal basis: 1.0×10^{13} cfu/yr/km^2. This quantity is currently difficult to put into context because such data are not yet common in the literature – in contrast to the considerable yield data for the other two main categories of diffuse pollutant: nutrients and sediment. The weighting of faecal pollution towards stormflows, and the difficulties that represents for measuring fluxes, is, of course, one major reason why faecal pollution load data are rare. However, we state the faecal pollution yield here in the expectation that such data may become more common in future – for different types of agricultural and forestry land use, and for urban land use.

The total export of faecal pollution may be compared with the total (expected) production of bacteria by livestock in the Toenepi Catchment. Cattle deposition of *E. coli* seems to vary appreciably, but an average of 1.3×10^9 cfu/cow/day may be appropriate for grass-fed dairy cattle (e.g. Wilcock 2006). On that basis the 5,000 cattle (mostly dairy) in the Toenepi Catchment would be expected to have produced about 2.4×10^{15} cfu/year. The total export in Table 1 (1.6×10^{14} cfu/y) corresponds to roughly 6% of this (expected) *E. coli* production. This proportional export seems quite high considering the many opportunities for dieoff due to environmental exposure of microbes in faeces and in water, and represents a challenge to the dairy industry to reduce its impact on the environment by widespread adoption of BMPs (Collins *et al.* 2007).

Collins *et al.* (2007) reported that about 0.5% of dairy cow faeces are deposited into streams to which cows have unrestricted access. In the Toenepi Catchment, about 46% of stream length is fenced (Wilcock *et al.* 2006), so we may assume about $(1 - 0.46) \times 0.5\%$ of dairy faeces go into the stream and open drain network of the Toenepi Catchment (neglecting *E. coli* loss by dieoff). So direct deposition accounts for only about 0.23% of the production (not including dieoff), compared to about 6% measured stream export. Therefore the majority of the export can be attributed to overland flow and subsurface drainflow (of faecal pollution flushed through soil horizons) during storms.

CONCLUSIONS

Faecal pollution dynamics and loads of stormflows were studied in the intensively dairy-farmed Toenepi Catchment.

E. coli peaks well ahead of flow on the rising limb of storm flow hydrographs, which complicates calculation of fluxes and loads. However, stormflow *E. coli* concentration correlates with turbidity in this stream, so we used a continuously-recording turbidimeter to simulate 'continuous' *E. coli* concentrations from which *E. coli* fluxes (cfu/s) and loads (cfu) were calculated. An automatic sampler was used to collect samples every 2 hrs over stormflow hydrographs for microbial analysis (within 48 hr) to 'calibrate' field turbidity in a 12-month period of 'storm-chasing'. *E. coli* (cfu) yield on 30 individual events increased more rapidly than event size owing to a trend to increasing event mean concentration with increasing event size. The sum of export in the storm events amounted to 95% of the total annual *E. coli* export from the Toenepi Catchment. The stream exported about 6% of the (expected) total *E. coli* production in cattle faeces within the catchment.

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