STORM FLUSHING OF FAECAL POLLUTION FROM LAND SOURCES

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Abstract

Faecal pollution is usually positively correlated with flow of rivers, and faecal bacteria (e.g., *E. coli*) concentrations are typically 2-3 orders of magnitude higher in storm-flows than baseflows. Consequently, storm-flows dominate pollution export and related impacts on downstream water uses, notably shellfish aquaculture. This paper reviews recent research that has elucidated mechanisms underlying the mobilisation of faecal pollution by storm-flows – which is usually assumed to reflect wash-in of faecal matter with overland flow. Storm-chasing studies show that faecal pollution typically peaks well *ahead* of hydrograph peaks. The timing reflects bacteria being entrained from sediments by accelerating currents rather than wash-in (which arrives later). Experimental work involving artificial floods (in absence of overland flow) and direct sampling of stream bed sediments has quantified these sediment stores of faecal microbes – which may be replenished by direct deposition by livestock into streams as well as storm-flow wash-in.

Introduction

Faecal pollution of waters, as indicated by faecal 'indicator' bacteria such as *E. coli*, represents a potential hazard to water supplies, water-contact recreation, and shellfish harvest (WHO, 2003). Sources of faecal contamination of waters include human wastes (sewage) and the faeces of wild animals, birds and domestic livestock (Ferguson et al., 2003; Smith and Perdek, 2004). Faecal contamination from non-human sources is often considered of lesser hazard to humans using waters than human sources, and this is certainly true for virus pathogens (Fong and Lipp, 2005) which are host-specific such that we can (usually) discount non-human sources. However, there are numerous so-called 'zoonotic' diseases of humans, including parasites such as *Cryptosporidium* as well as bacteria (e.g., *Campylobacter*) which are incubated by animals and can cause illness in humans, including by ingestion of contaminated water or shellfish (e.g., Graczyk et al., 2006). Microbial hazards in downstream waters including coastal waters, are typically high during and after stormflows (Chigbu et al., 2004; Fiandrino et al., 2003; Kelsey et al., 2004; Lipp et al., 2001) when faecal pollution is typically orders of magnitude higher than in baseflows (McDonald and Kay, 1981). The association of faecal pollution 'events' with stormflows is usually attributed to overland flow washing faecal matter from land sources into waters, but this is now recognised as an over-simplification .

This paper reviews recent studies that have elucidated pathways of faecal pollution to waters, and the processes of stormflow mobilisation of faecal microbial contaminants. Stream sediments are identified as the immediate source of stormflow faecal pollution peaks, rather than overland flow which, together with direct deposition of faeces by animals, serves mainly to recharge sediment stores.

Pathways of faecal microbes to waters

Faecal microbial sources include (leaks in) sewers conveying human wastes and storm drains conveying animal wastes and sewer overflows in urban areas; and septic systems, livestock and wild animals in rural areas (Smith and Perdek, 2004). Conceptually, faecal microbial pollution can reach surface water from these land-based sources by wash-in with overland flow or by travel through the soil profile to groundwater and thence seepage into surface waters. Undoubtedly both these processes occur, but the soil-groundwater route must be far less important than surface routes because of ‘filtration’ processes retaining microbes within soils and aquifers (Hunter et al., 1992). Furthermore, if groundwater flows were a dominant source of faecal microbes to surface waters we would expect concentrations in streams to be maximal at baseflow (when the groundwater contribution is proportionally high), rather than in stormflows as is typical. This leaves wash-in with overland flow as the likely dominant pathway by which faecal pollution moves from land sources to waters (Collins et al., 2007).

Overland flow in grazed pasture has been shown to have high concentrations of faecal indictor bacteria. For example, Collins et al (2005) conducted experiments with a large rainfall simulator, and showed that faecal pollution in overland flow on pasture hillslopes is a strong function of time since grazing livestock were present – presumably reflecting microbial dieoff in, and reduced mobility of, faecal deposits with increasing age.

Faecal pollution from wild animals and livestock can also reach waters directly when animals enter stream channels to drink or cross or to access riparian forage (Collins et al., 2007) or during deliberate herding across streams (Davies-Colley et al., 2004). This ‘direct deposition’ is particularly important with cattle and deer which, unlike sheep, are specifically attracted to water. Studies with dairy cattle showed that approximately 0.5% of their faeces are dropped directly into unfenced streams flowing through pasture (Collins et al., 2007). *E. coli* concentrations may increase in small streams downstream of dairy herds by up to 30-fold (author’s unpubl. data).

Faecal bacterial dynamics during stormflows

Faecal pollution at baseflows in rivers and streams is usually rather modest as measured by concentrations of indicators like *E. coli*. However, in stormflows indicator bacteria concentrations are typically 2-3 orders of magnitude higher (Hunter et al., 1992). For example, Donnison et al. (2006) reported *E. coli* concentrations of 100,000 cfu/100 mL during a large storm in two small streams in pastoral catchments which had median baseflow concentrations of order 100 cfu/mL.

The dynamics of faecal microbial pollution over storm hydrographs provides insight into processes (Wilkinson et al., 2006). A ‘first flush’ pattern, with faecal pollution arriving on the rising limb and well ahead of the flow peak, seems typical of storm events in both small streams and large rivers, and streams draining both rural and urban land. By way of example, Figure 1A shows *E. coli* concentrations compared with the storm hydrograph in a small stream draining intensive dairy-farming land. In this stream *E. coli* usually correlated moderately well with turbidity on storm events (Figure 1B), and the continuous *E. coli* curve (Figure 1A) was synthesised from the continuous record of turbidity obtained by an *in situ* nephelometer locally calibrated to *E. coli* using samples taken by auto-sampler (Davies-Colley et al., 2007). The *E. coli* peaks about the time when flows increase most rapidly on the rising limb (Figure 1A).

The association of faecal pollution with storms has often been taken, uncritically, as evidence of ‘wash-in’ of faecal matter in overland flow, and, as we saw in the previous section, wash-in does indeed occur. However, the timing of the faecal pollution compared to the flow peak is problematic for reasons as recently analysed by Wilkinson et al. (2006). The hydrograph travels as a wave down the channel at a speed appreciably faster than the average sectional velocity of the water (about 50% faster), whereas the faecal bacteria, once they are entrained in water, can only travel at the water velocity (Wilkinson et al., 2006). Therefore bacteria that are washed in by overland flow should arrive *after* the flow peak. Clearly therefore overland flow is not the cause of the peak faecal contamination occurring ahead of the flow peak (e.g. Figure 1A). A more proximal source must be invoked, and the stream sediments very close to the stream monitoring site are the most likely candidate (Wilkinson et al., 2006). Wash-in with overland flow merely recharges sediment stores.

Stream Sediment stores

Nagels et al. (2002) compared the dynamics of faecal bacteria in *artificial* floods to that in natural floods on the (pastoral) Topehahehae Stream, and demonstrated very similar behaviour in the absence of any rainfall and wash-in by overland flow during the artificial events. They interpreted sediment release as responsible for most of the faecal pollution mobilised on natural floods. Muirhead et al. (2004) reported an experiment on the same stream in which a series of three artificial flood events, created on each of three successive days, each flushed approximately 60% less than the preceding event. The three measured flood yields were regarded as the first three terms of an infinite series (which would be expected to flush every last bacterium from the stream reach), and summing this series permitted the sediment store to be quantified: 10^8 cfu/m^2 of streambed.

Attempts have been made to directly sample faecal bacteria in stream sediment. Muirhead (2001) used a simple corer to isolate a known area of sediment, and stirred the overlying water (simulating flood disturbance) to mobilise faecal bacteria from the sediment. Sandy areas of the Topehaehae Stream had concentrations ~10^8 cfu/m^2. Sampling of rocky reaches proved to be more difficult. Muirhead et al (2004) used water-blasting to disturb a rocky area of the Topehaehae Stream, and sub-sampling of the resulting muddy plume demonstrated similar sediment areal concentrations. These authors also measured *E. coli* in scrubbings of biofilms on (randomly sampled) surface rocks in this stream, and measured concentrations far too low (by 3 decades) to account for release in artificial floods. Surface rock concentrations actually *increased* after events (Muirhead et al., 2004), which was attributed to *E. coli* disturbed by the floods being taken up by the surface rock biofilms. The low initial concentrations of *E. coli* on surface rocks was attributed to inactivation by sunlight exposure (a well-known bacteriocide –

e.g., Sinton et al., 2002). In one experiment a hydraulic excavator was used to break through the armour layer of surface rocks and disturb the underlying sediment (hyporheic zone), mobilising its content of faecal bacteria. At twelve points sampled by excavator along a rocky reach of the Topehaehae Stream the areal concentration averaged 1.4 X 10^8 cfu/m^2 (CV = 67%) (author's unpublished data), in fair agreement with the three-day artificial flood experiment conducted on the same stream reach (Muirhead et al., 2004).

Faecal pollution budget

On both the natural and artificial flood studies reviewed in the previous two sections (Muirhead et al., 2004; Nagels et al., 2002), turbidity was found to be moderately to strongly correlated to *E. coli* over hydrographs (e.g., Figure 1B). There is no 'universal' correlation of these variables of course, and even at the one stream site the overall correlation can be rather weak because of different sediment /bacteria mobilisation on different events. However on any one event the correlation is typically close enough to be useful for experimental purposes, such as estimating quantities of *E. coli* released.

A study on the Toenepi Stream, in an adjoining catchment to the Topehaehae where the artificial flood and sediment studies were done, used the correlation of *E. coli* and turbidity to estimate export of *E. coli* on individual storm events and compile an annual budget (Davies-Colley et al., 2007). Thirty separate storm events were analysed over a 12-month period, and on 25 of these events auto-samples were analysed for *E. coli* in order to 'calibrate' turbidity measured continuously by field nephelometer (e.g., Figure 1).

Stormflows accounted for 95% of the total annual *E. coli* export from the Toenepi Catchment (Davies-Colley et al., 2007). The total annual export of faecal pollution (1.6 X 10^{14} cfu/yr) is about 6% of the expected total production by the dairy cows and other livestock in the catchment (cfu/yr), assuming each cow produces 1.3 X 10^9 cfu/day (Wilcock et al., 1999). This seems a high percentage export and presents a challenge to the dairy industry to reduce its load of faecal pollution on downstream users such as the shellfish industry.

Conclusions

Recent research, reviewed in this paper, has shown that direct deposition by livestock is an important pathway of microbial pollution in pastoral agricultural streams, augmenting wash-in by overland flow during stormflows. Stormflows of faecal pollution are the main hazard in waters downstream, including shellfish harvesting. However, the peaks of faecal contamination associated with stormflows come not from wash-in (which would arrive appreciably later), but from mobilisation of faecal stores in the stream sediment. These sediment stores have been quantified using artificial floods (in absence of rain causing wash-in) to flush out faecal microbes, and various direct sediment-sampling approaches. Faecal pollution export from an intensively dairy-farmed catchment over a year was dominated by floods which accounted for 95% of total export (and amounted to about 6% of expected production by the livestock). The experimental work that has been reviewed here has prompted new experimental studies and underpins current modelling efforts including prediction of shellfish contamination.

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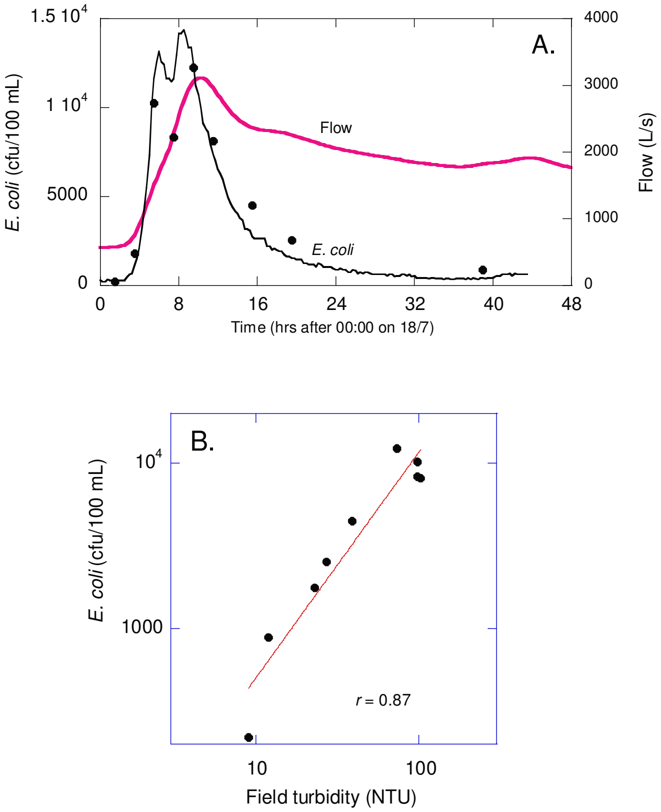

Figure 1. Typical faecal pollution dynamics during stormflow as illustrated by data for the Toenepi Stream, Waikato Region NZ. A. Time series for *E. coli* as measured (solid points) and simulated from the turbidity correlation (continuous line - calculated from the relationship in Panel B) are shown in relation to the flow hydrograph. B. *E. coli* versus turbidity as measured *in situ* by a continuously recording nephelometer.