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Storm-induced *Escherichia coli* pulses in the Motueka River (2074 km^2) and the Sherry River (78.4 km^2) are modelled. The model focuses on the catchment outlets, representing key processes, including *E. coli* transfer to and from the river bed, with account taken of the hysteresis in, and non-linear, non-stationary, response of *E. coli* concentrations to river stormflows. The model fits the Motueka River observations well, but less well in the Sherry River. A greatly simplified description of headwater and riparian inputs is satisfactory at the larger catchment scale where near-field, in-channel processes dominate the response. Spatial heterogeneity in rainfall-run-off and faecal sources probably contribute to the poorer fit in the smaller catchment. Despite using a relatively small number of driving variables and parameters, the model has the potential to predict real-time *E. coli* input to Tasman Bay in river plumes causing shellfish and bathing beach contamination.

Keywords: integrated catchment management; Motueka River; water quality modelling; faecal contamination; mechanistic model; supply limited; storm-event; dynamic response; conceptual diagram

Introduction

Diffuse pollution from land mobilises three main categories of water pollutant: fine sediment that reduces water clarity and causes sedimentation issues, nutrients (primarily nitrogen and phosphorus) that promote nuisance algae and aquatic plant growths, and faecal microbes that are a risk to human health from contact with contaminated water or consumption of contaminated shellfish (Kay et al. 2006). Furthermore, mining and urban land uses may cause diffuse pollution by metals and other toxic materials (e.g. Campbell et al. 2004). Considerable research effort, including modelling, has been applied to understanding and quantifying various diffuse pollutants, but faecal microbes are probably least well studied

and understood. This is despite the inference (e.g. Kay et al. 2007) that a greater overall stream length may be impacted by faecal microbial pollution than by any other pollutant category, including sediment and nutrients.

An important task early in the Motueka Integrated Catchment Management (ICM) programme was the characterisation of water quality over the catchment (Fenemor et al. 2011). Young et al. (2005) reported water quality for the Motueka system based on 13 monthly samplings (October 2000–October 2001) of 21 sites at mainly baseflow conditions, augmented by monthly monitoring data since January 1989 at two sites in the National Rivers Water Quality Network (NRWQN). This study showed that water quality of the Motueka

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system was mostly very good; however, the Sherry River, draining about 3.8% of the total catchment, emerged as a microbially polluted 'hot spot', with *E. coli* concentrations well in excess of guidelines for contact recreation. The faecal pollution in the Sherry River was attributed to intensive pastoral farming, and specifically to regular crossings through the river by dairy herds moving between pasture and milking shed. A study in 2001 of the most up-stream dairy crossing on the Sherry confirmed that direct contact of cows with water during crossings was significantly polluting the river (Davies-Colley et al. 2004). Since 2007, all four habitual crossings on the Sherry River have been eliminated by construction of bridges, and faecal pollution is now substantially reduced although the river still fails to meet contact recreational guidelines (Ballantine et al. 2011).

Although the water quality of the Motueka Catchment is excellent overall, excepting the Sherry and some other pastoral subcatchments (Young et al. 2005), the microbial quality can be poor during high flows. McKergow & Davies-Colley (2010) found that *E. coli* concentrations in the main-stem Motueka River during storm flows were an order of magnitude, or more, higher than at baseflow, and often exceeded contact recreation guidelines. This finding is broadly consistent with earlier reports (Kay & McDonald 1980; Jenkins et al. 1984) including from dairy land elsewhere in New Zealand (Davies-Colley et al. 2008). An 'obvious' ramification of these stormflow 'pulses' is that microbially contaminated plumes from the Motueka River represent a major hazard to bivalve shellfish and bathing beaches in Tasman Bay. Accordingly, there has been interest in measuring *E. coli* dynamics in the lower Motueka River and in the river plume in Tasman Bay (Cornelisen et al. 2011).

In this paper, the faecal indicator bacteria (*E. coli*) is simulated in the main stem of the Motueka River and its small tributary the Sherry River, using a model based on that of

Wilkinson (2001, 2008) that is broadly similar to that of Hipsey et al. (2008).

A mechanistic model is required to adequately reproduce observed time-series of *E. coli* storm response pulses, because the relationship between faecal indicator concentrations and flow are non-linear, non-stationary (i.e. they vary from event to event) and exhibit hysteresis (the relationship is different on the hydrograph rise and fall) to varying degrees. Hence, a simple statistical relationship cannot represent this complexity. Mechanistic modelling builds a mathematical structure that represents the dominant processes and mechanisms and can simulate the observed dynamic behaviour in a repeatable manner with a single parameter set. Statistical models do not have 'state' variables, and hence cannot track and retain a memory of the system condition, i.e. in this case they cannot follow the accumulation and remobilisation of faecal bacteria in the channel store or on the catchment. A mechanistic model can account for these processes and mechanisms in order to simulate the observed *E. coli* variations reliably over time (e.g. Wilkinson et al. 1995; Wilkinson 2001; Collins & Rutherford 2004).

It is well known that catchment faecal microbial dynamics are strongly influenced by mobilisation from land and channel stores during storm flows (e.g. McDonald et al. 1982; Hunter et al. 1992). Although differences in the storm-event transport behaviour of different microorganisms once exposed to environmental pressures have been highlighted (e.g. Jamieson et al. 2004; Stott et al. 2011), Hipsey et al. (2008) reaffirm that the general processes which influence the fate and distribution of most of these microbes are similar to that presented by Wilkinson (2001, 2008), and in the current study, with the exception that Hipsey et al. (2008), included a separate treatment of sediment-bound and free microorganism transfer to and from the channel store. Other modelling studies have focussed strongly on quantifying faecal delivery from upland pastures, detailing different sources, livestock behaviours and pathways to the

stream network (Collins & Rutherford 2004). In-stream processes, such as settlement and remobilisation of faecal bacteria are important in riverine fluvial microbial dynamics.

Wilkinson et al. (1995) presented a model that used a distributed channel store to simulate multiple successive faecal coliform peaks in response to an artificial stepped hydrograph event, but later a simpler formulation was found to reproduce the observed pulses adequately (Wilkinson 2001). This later re-evaluation identified the role of flow-wave propagation in determining the timing and magnitude of the entrained faecal coliform pulses relative to the average velocity of the moving water (Wilkinson 2001; Wilkinson et al. 2006). Small faecal pulses coincided with wave-front arrival, and the main peaks arrived later at the mean flow velocity. The flow-waves travelled approximately 1.5 times faster than the mean velocity of the water, and the magnitude of the main pulses was proportional to that of the flow increment in m^3/s (Wilkinson 2001). This differential transport and arrival has been observed and modelled for faecal indicators and zoonotic disease agents in New Zealand (McBride 2011) and is significant for the understanding of the fluvial dynamics of faecal contaminants. As stated by Hipsey et al (2008) a generic model architecture that can be applied in many circumstances and to different contaminant microorganisms is attractive and the model of Wilkinson (2001, 2008) as presented here offers such potential.

The modelling employed data from two separate water quality monitoring campaigns (at very different spatial scales). These included regular storm-flow event sampling with stage-triggered autosamplers, and (pseudo-random) monthly sampling. The goals of the modelling were to improve understanding of faecal pollution sources and dynamics in the Motueka system, and provide a basis for flow-on prediction of contaminated river plumes in Tasman Bay with consequent threats to shellfish and bathing beaches.

Methods

Site description and data

This study was based on monitoring conducted in the Motueka River catchment in the upper South Island, New Zealand (Fig. 1). The Motueka River drains a catchment of 2180 km^2 (2047 km^2 upstream of the Woodmans Bend monitoring station, closest to the sea) and flows in a northerly direction for 110 km from the headwaters to Tasman Bay. Mean annual rainfall ranges from <1000 mm/year on the eastern side of the catchment to 3500 mm/year on the western side (Basher 2003). Median discharge near the river mouth is about 47 m^3/s with a mean annual low flow of around 13 m^3/s. Land use is varied and includes native forest in the southern and western headwaters, plantation forest across much of the eastern and central part of the catchment and pastoral farming and horticulture along the valley floors (Fig. 1). The catchment is sparsely populated with a total population of around 12,000, including about 7000 in the town of Motueka near the river mouth (Basher 2003).

The Sherry River drains a small western subcatchment (79 km^2) of the Motueka River where mean annual rainfall is approximately 1300 mm/year (Fig. 1b). The name 'Sherry' refers to the orange colour of the river water reflecting the rather high coloured dissolved organic matter (CDOM; indexed by the absorption coefficient at 440 nm, which averages about 2.8/m—high even for inland waters; Kirk 1994). Median discharge for the lower reaches at the Blue Rock recorder site is about 1.1 m^3/s, whereas mean annual low flow is about 0.22 m^3/s. The upper reaches of the Sherry Catchment are dominated by plantation forest with some residual native beech, whereas pastoral farming (dairying and some sheep-beef farming) is the main land use in the lower valley. Water sampling in the lower Sherry River has demonstrated comparatively high faecal pollution (Davies-Colley et al. 2004; Young et al. 2005).

Water quality and flow measurements
Motueka River

Water quality samples from the Motueka River were collected at Woodmans Bend (172.96° E, 41.13° S), 8 km upstream of the river mouth and above any tidal influence (Fig. 1b), as reported in McKergow & Davies-Colley (2010). Water levels are measured at Woodmans Bend
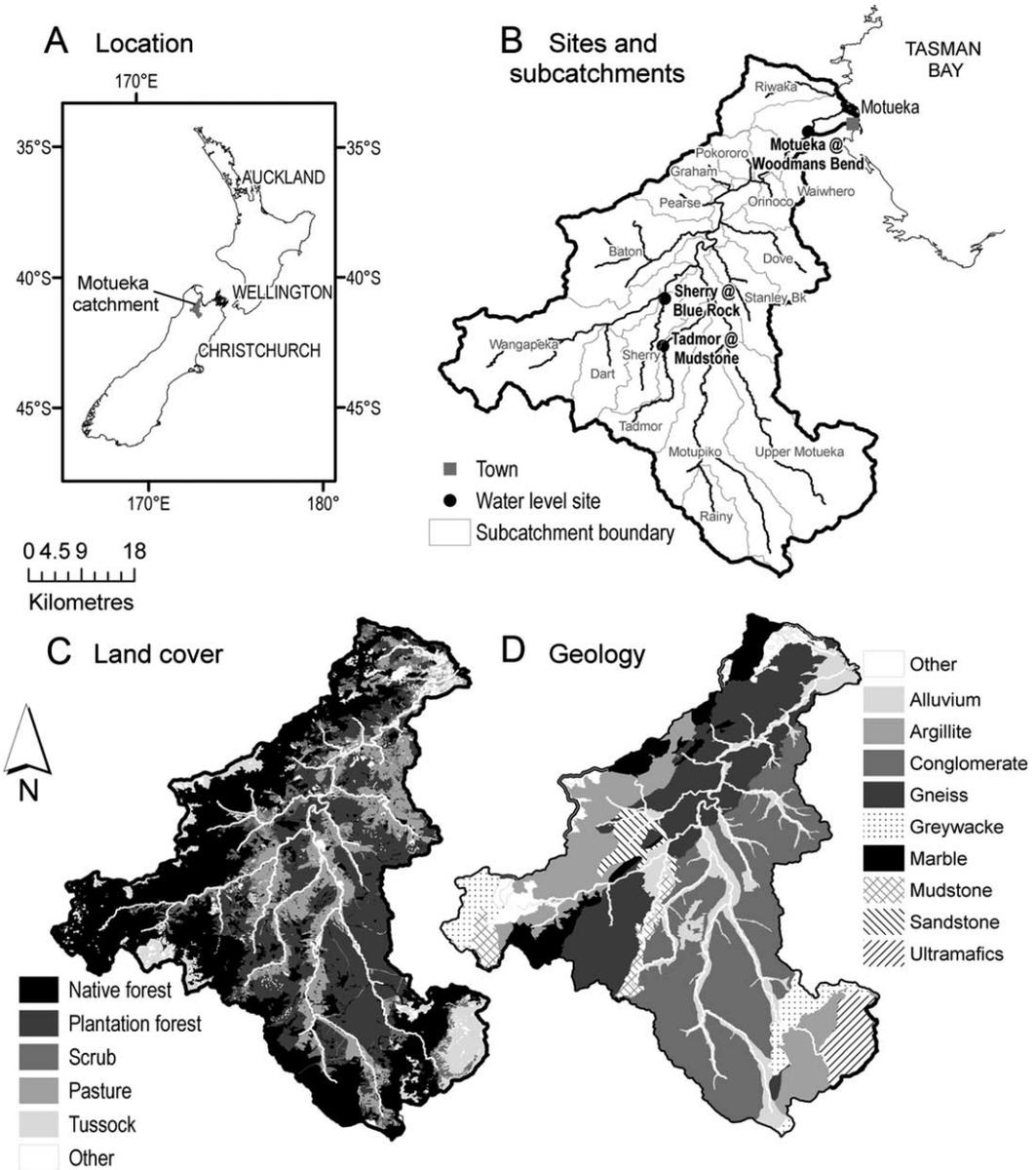

Figure 1 Map representation of **A,** the location; **B,** the river network and main sub-catchments with two major *Escherichia coli* sampling sites shown at the locations of hydrometric stations; **C,** land cover; and **D,** geology of the Motueka catchment.

every 15 min by a bubble gauge (Sutron Accu-bar; 0–15-m range) and converted to discharge via a stage-discharge rating. Field turbidity was measured every 15 min by an optical back-scatter sensor (Greenspan TS100; 0–2000 NTU) fitted with a pump jetting water across the lens to reduce biological fouling. The turbidity records were edited to remove short-term (usually single-value) spikes (e.g. because of items like leaves in the volume sensed by the backscatter detector) and drift related to bio-fouling. Monthly grab samples for *E. coli* were collected from May 2003 to October 2009. *Escherichia coli* were also measured on samples collected during storm events by an autosam-pler (ISCO 3700) over a 13-month period from June 2003. Sampling was activated when water levels exceeded a seasonally adjusted stage threshold and samples were collected on flow proportional time intervals ranging from 10 min to 22 h. Samples were retrieved usually within 24 h of collection and stored on ice during transport to the NIWA Hamilton water quality laboratory where they were analysed for *E. coli* and turbidity. *Escherichia coli* were enumerated mostly within 48 h of sample collection using the IDEXX Colilert Most Probable Number (MPN) method (method 9223B, APHA 2005), and results are expressed as culture forming units (cfu) per 100 ml.

Sherry River

Water quality samples were collected in the Sherry River at the Blue Rock flow gauging station (Fig. 1b), from November 2008 until October 2009. Up until 2008, no flow estimates were available for the Sherry. From 2008 onwards, flow was measured at Blue Rock using a pressure transducer (0–5 m range) and a Waterlog DAA H500XL data logger (DAA HX500 model). For 2003 and 2004, estimates of flow in the Sherry River were based-on a correlation with flow in the adjacent Tadmor catchment (Fig. 1b). A continuous field turbidity meter (Greenspan TS1200, 0–2000 NTU) was deployed at Blue Rock from October 2008

to October 2009, and data was logged every 15 min by the hydrometric logger. *Escherichia coli* was sampled at approximately monthly intervals from May 2003 to October 2009, mainly at low flow. In October 2008, a year-long storm event sampling campaign, similar to that at Woodmans Bend, commenced at Blue Rock. The autosampler was activated when stage exceeded 800 mm (*c.* 3800 l/s, 8.5 percen-tile flow) and samples were collected hourly until flows dropped below the trigger or until the sampler carousel was full with 24 samples. Monthly samples were stored on ice and transported by overnight courier to NIWA's water quality laboratory in Hamilton, whereas event samples were retrieved within 24 h and analysed by Cawthron Institute's water quality laboratory in Nelson. Monthly samples and a selection of storm water samples (3–8 samples per event; chosen to bracket the turbidograph) were analysed for *E. coli* and other variables including turbidity (Ballantine et al. 2011). *Escherichia coli* were enumerated as for Wood-mans Bend.

Autosampler quality assurance

Common concerns when using autosamplers for microbiological surveys are sample holding time (e.g. Pope et al. 2003; Stadler et al. 2008) and cross-contamination through carry-over from residues in the sampler pipework and mechanisms (e.g. Anderson & Rounds 2010; Solo-Gabriele et al. 2000). A holding time of 6 h is specified in investigations with a regulatory focus (e.g. Environment Agency 2000), for which samples should be held in the dark and chilled, to minimise deterioration from the 'as sampled' condition. For the current study, we had to relax these requirements to permit use of auto-samplers (without carousel chilling), which were triggered automatically by events. Pope et al. (2003) found that *E. coli* concentra-tions in samples held at less than 10°C were generally consistent with those measured within 8 h. Similarly, Stadler et al. (2008) reported only minor sample deterioration for holding

temperatures of around 5°C. So the main issue is the holding time within the instrument shack, *after* collection, but *before* auto-samples were retrieved and stored on ice. In the current study there would be negligible sample deterioration with extended holding times in autosampler carousels at winter (air) temperatures of around 6°C, but some deterioration could occur in summer with average air temperatures of around 16°C. Estimates of summer die-off, based-on a range of literature dark die-off parameters, θ and k_0 (Wilkinson 2008), suggest that *in the worst case* for fully 48 h holding before sample retrieval and chilling, up to 48% reduction in *E. coli* concentration might occur. Three summer events discussed below may have been subject to *E. coli* underestimation: 9 December 2008 and 12 February 2009 in the Sherry (Fig. 6 below), and 27 February 2004 at Woodmans Bend (Fig. 5 below), although there is no visual suggestion of low-bias vs model predictions.

The other concern with auto-samplers is carry-over of water from previous samples, especially with contrasting microbial contamination. Solo-Gabriele et al. (2000) found auto sampler carry-over of *E. coli* to be insignificant, and Stadler et al. (2008) demonstrated a close correlation with duplicate grab samples, with no evidence of bias from sample carry-over, so we consider this potential source of error can be discounted in our study.

Model description

Wilkinson et al. (1995) presented a model for the remobilisation of river channel store *E. coli* by artificially generated flood-pulses. This built on work by Kay et al. (1980) and Jenkins et al. (1984). The 1995 model was simplified and extended (Wilkinson 2001) to account for 'real-time' die-off (as a function of solar irradiance water temperature, turbidity and mean river depth), and diffuse inputs, and was successfully applied to 7 years of 4-weekly sampling data for a drinking water abstraction site on the Welsh River Dee in the UK (Wilkinson 2001).

The model at the sub-catchment scale has three layers (Figs. 2 and 3):

(1) riparian pasture faecal inputs to the river network;
(2) river reach flowing water 'mass balance', and;
(3) river reach channel store mass balance.

Each of 19 sub-catchments are connected to the Motueka River main stem, which is split into five connecting river reaches, this 'semi-distributed' approach was chosen in order to examine the likely impact of the Sherry River on the overall *E. coli* concentrations near the outlet of the Motueka River.

The structure of the system can be presented in a 'conceptual diagram' (Fig. 2), representing the general system, including terms from the model Equations (4) and (5) (below). A more mathematical 'systems' type diagram may also be useful (Fig. 3). These are just two approaches that can be used to show the arrangement, connection and fluxes into, out of and storage within different compartments of the system. Pictorial diagrams with an overview narrative are becoming increasingly recognised as a valuable tool for the collection and visualisation of information about complex environmental systems, especially for the rapid communication of ideas to varied audiences (e.g. Dennison et al. 2007).

Faecal indicator dynamics in rivers are determined by two contrasting sets of processes associated with dry vs wet weather respectively (Fig. 4). During dry weather, transport of faecal matter is minimal; water tends to be shallow, is minimally light-attenuating and water travel velocities are slow, such that die-off dominates the time-variation in faecal indicator numbers. Following rainfall, river flows are elevated and the water is both deep and highly light-attenuating, there is usually cloud cover and travel times are short, and hence die-off related to sunlight is virtually switched off. Consequently, transport
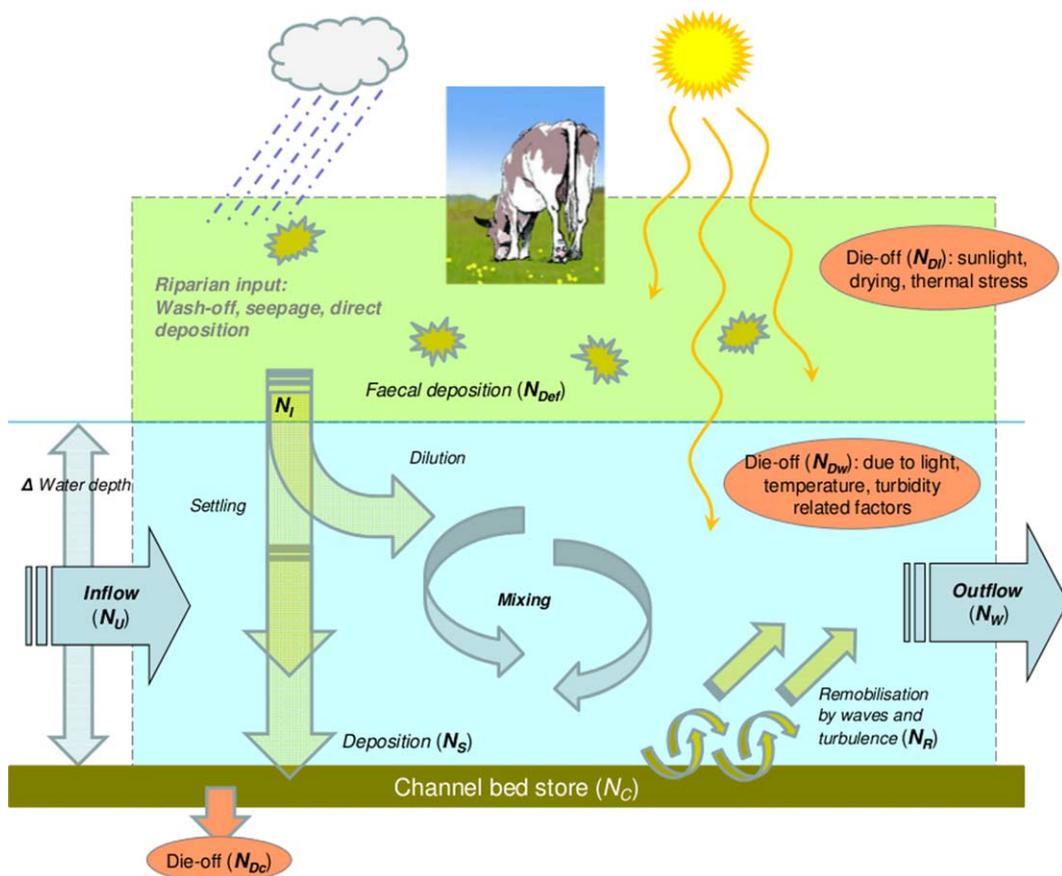
Figure 2 Conceptual diagram representing the key *Escherichia coli* model processes in a river reach with adjacent riparian pasture.

mechanisms dominate the dynamic variations in faecal indicators during stormflows.

As a narrative description of the role of the three layers in the model, the riparian faecal input layer produces a time-series of input *E. coli* numbers that varies according to the rate of die-off. It is greater in winter than in summer, and for each sub-catchment, the rate of input is scaled by the area of riparian pasture and the run-off yield, such that wetter sub-catchments deliver more faecal contamination than dryer ones. The riparian input is delivered directly to the river reach, without catchment storage, and then a proportion remains in suspension, whereas the remainder settles and is deposited in the channel store (according to

the flow state—during dry-weather flow, the majority of riparian input *E. coli* settle, whereas during storm flow the majority remain in suspension). This approach for catchment delivery is greatly simplified, and is justified in detail in the discussion. Each river reach has two layers: the flowing water and the channel store. The flowing water provides the mixing and transport environment for *E. coli* entering from upstream, from riparian input, transfer to and from channel-storage, and loss related to die-off. The dominant dynamic behaviour determining the modelled *E. coli* concentrations is the remobilisation of *E. coli* accumulated in the channel store. This is driven by the change in river discharge (flow). The channel store of
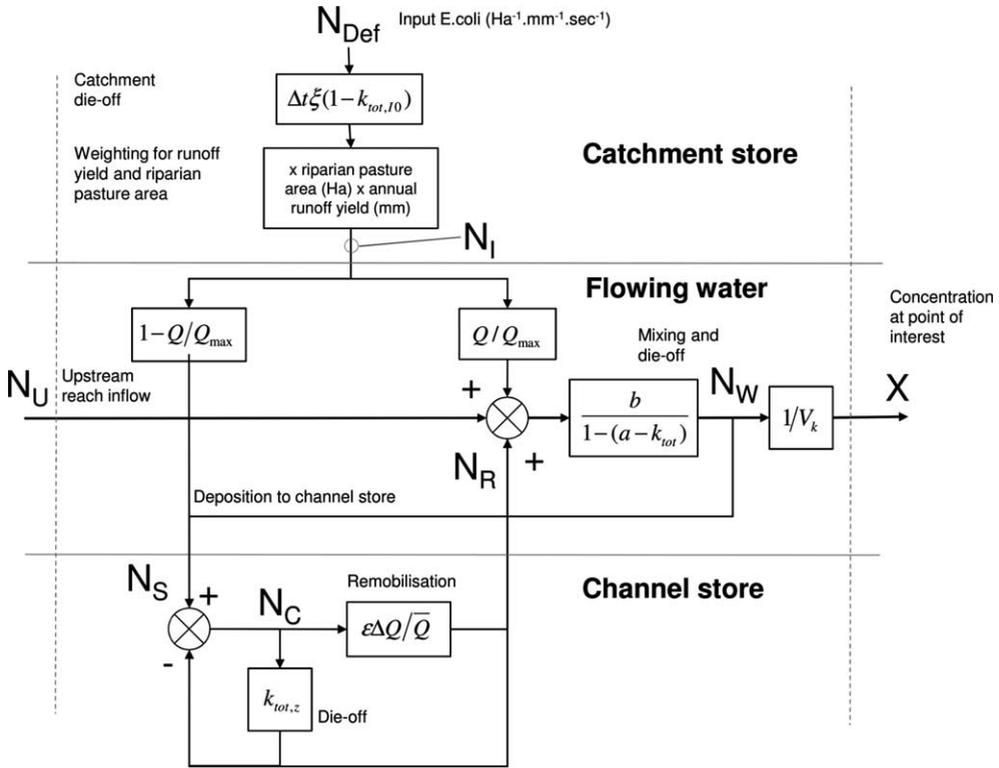
Fig. 3 Model arrangement for catchment input of *Escherichia coli* to the river network.

each river reach provides the 'reservoir' of *E. coli* that accumulates during dry weather and is remobilised by each storm-flow event resulting in the observed peaks of concentration. The model equations are as follows.

Riparian Pasture Input

The faecal loading for each sub-catchment or reach,

$$N_I = \Delta t \; \xi \; (1 - k_{\text{tot,I0}}) \; N_{Def} \; A_{RP} \; q_s \qquad (1)$$

where N_I is the input from the catchment (including direct faecal deposition from animal access and crossings) to the river reach per time-step, ξ is an optional dimensionless random number with average of 1 and varying between 0 and 2, $k_{\text{tot,I}}$ is the time varying overall land surface die-off rate (h^{-1}), N_{Def} is

the number of *E. coli* defecated per ha per mm run-off yield per unit time, A_{RP} is the reach or sub-catchment (20 m wide) riparian pasture area (ha), and q_s is the estimated annual sub-catchment run-off yield (mm) (Basher 2003). During dry weather, the majority of non-point source faecal bacteria entering a river have been found to be deposited into the channel store (e.g. Biskie et al. 1988). The proportion of N_I delivered into the flowing water at each time interval is:

$$N_I(Q/Q_{\max}) \qquad (2)$$

and into channel storage:

$$N_I(1 - Q/Q_{\max}) \qquad (3)$$

where Q is the discharge at time t, and $Q_{\max}$ is the peak discharge for the entire period being

Dry weather state

Land surface:
• Defecation and net accumulation
• Die-off due to sunlight and drying

Water column:
• Loss by deposition to (and accumulation in) channel store
• Die-off maximum due to light penetration and slow flow velocity (long residence times)

Cloud, Rainfall, Increasing flow, Remobilisation

Wet weather state

Land surface:
• Remobilisation of faecal matter
• Preferential pathway runoff
• Die-off minimal

Water column:
• Remobilisation from channel store
• Input from catchment
• Die-off minimal (elevated turbidity, short residence time)
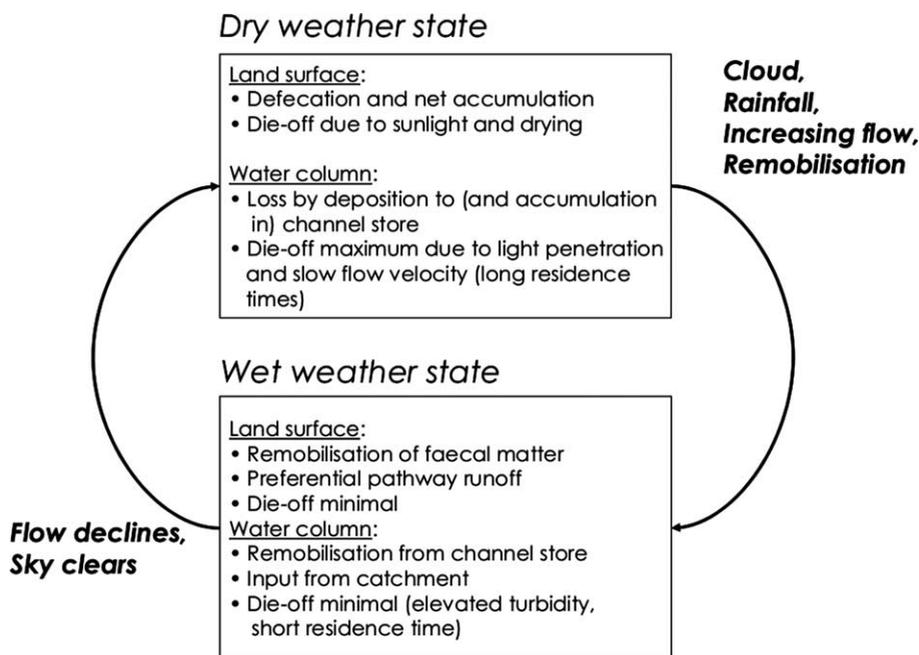
Flow declines, Sky clears

Figure 4 Schematic representing the transition from wet to dry weather processes associated with faecal indicator dynamics in river catchments.

modelled. The riparian pasture areas were derived from GIS land cover data (LCBD2).

River reach 'mass-balance'

The river reach layers, the flowing water, and the channel store are linked (Figs. 2 and 3), and their dominant activity is mainly flow dependent as indicated in Fig. 4. The basic mass-balance equation for the flowing river water is:

$$N_W = (N_U + N_I + N_R) - (N_S + N_{Dw}) \quad (4)$$

where N_W is the number of E. coli in the water column, N_U is the upstream inflow, N_R is the number of E. coli remobilised from the channel store, N_S is the number lost by deposition into the channel store, N_{Dw} is the loss because of die-off in the water column. The channel store mass-balance is:

$$N_C = N_S - (N_R + N_{Dc}) \quad (5)$$

where N_{Dc} is the loss related to die-off in the channel store and the other terms are as

previously defined. Table 1 summarises the model variables and parameters and their units.

The detail of the river reach model components is rather more complicated. The flowing-water layer is based upon a river dispersion (mixing) model (e.g. Wallis et al. 1989; Price et al. 2000). For a simple one-dimensional model such as that presented here, an important simplifying assumption is that the water is completely mixed across the channel cross-section (Henderson-Sellers et al. 1988). In its simplest version (quasi-steady-flow for a conservative solute), this mixing model is formulated as follows:

$$\frac{dX_t}{dt} = \frac{Q_t}{Ve_t} U_{t-\tau} - \frac{Q_t}{Ve_t} X_t \quad (6)$$

where X_t is the concentration (mass or number per unit time) at the reach outlet at time t, U_t is the upstream inflow concentration, τ is the advective time-delay (time units), Q_t is river discharge (m³/s), and V_e is the effective mixing volume (m³) and V_e/V is the proportion of

Table 1 Summary of model variables and parameters and their units.

Variable or parameter	Description	Units
Key driving variables		
Q	Stream discharge	m³/s
I	Solar irradiance	W/m²
T	Water temperature	°C
$CDOM$	Coloured dissolved organic matter (indicated by absorption coefficient at 440 nm)	m⁻¹
$Turb$	Nephelometric turbidity	NTU
Model internal and state variables		
X_t	Model output *E. coli* concentration	cfu/100 ml
N_W	Number of *E. coli* in the river reach	cfu
N_U	Upstream input of *E. coli* numbers	cfu
N_C	*E. coli* in channel store	cfu
N_R	Number of *E. coli* remobilised from the channel store	cfu
N_I	Lateral input of *E. coli* to river reach	cfu
N_S	Number of *E. coli* deposited in channel store	cfu
$N_{Dl}, N_{Dw,} N_{Dc}$	Number of *E. coli* died-off from, land, water and channel compartments	cfu
V, V_e	Reach volume and effective mixing volume	m³
z_t	Average water depth	m
$k_{tot,l/w/c}$	Overall die-off rate (on land, water or channel store)	h⁻¹
k_s	Deposition rate	h⁻¹
Adjusted 'model fit' parameters		
N_{Def}	Number of *E. coli* defecated into the catchment store	cfu/ha/mm/s
ε	(Channel store) remobilisation coefficient	h⁻¹
v_s	Average settling velocity	m/day
Df	Dispersion adjuster, to increase/decrease mixing	dimensionless
a_w, a_l, a_c	Die-off adjustment factors; water, land, channel store	dimensionless
t	Time (*note that coded temporal discretisation intervals (Δt) are 1 hour for the Motueka@Woodmans Bend, and 15 minutes for the Sherry@Blue Rock*)	seconds
τ	Reach travel time	h
Fixed literature parameters		
θ	Slope of darkness die-off response to water temperature	dimensionless
α	Slope of the irradiance and die-off equation	dimensionless
β	Exponent of the irradiance and die-off equation	dimensionless
K_d	Light (irradiance) attenuation coefficient with depth	m⁻¹
Computed system characteristics		
T_m	Mixing volume residence time	h

'dead zone' in the reach, expressed in the literature as the 'dispersive fraction' (Wallis et al. 1989). The amount of dispersion can also be characterised by 'mixing residence time' ($T_m = V_e/Q$). A channel with a longer T_m disperses more than one with a shorter T_m, and hence produces a less sharp peak with a longer duration. V_e as a proportion of the total river volume (V) has been found to decrease slightly with increasing flow (e.g. Wallis et al. 1989; Reynolds et al. 1991). In bed-rock channels, the decrease in V_e relative to V has been found to be greater (Richardson & Carling 2006).

The full mass-balance equation for the number of *E. coli* in the flowing water in each river reach (i.e. not including the channel store) is:

Change in water numbers = upstream input − (dispersion + settlement + die-off) × number in reach + number remobilised from channel store + riparian pasture input.

which is given by:

$$\frac{dN_W}{dt} = \frac{Q}{Df \cdot V_s} N_{U(t-\tau)}$$
$$- \left\{ \frac{Q}{Df \cdot V_s} + \frac{v_s}{z} + k_{tot,W} \right\} N_W + N_R$$
$$+ N_I^{Q_t}/Q_{Max}$$

$$(7)$$

where terms are as previously defined (note that suffix (t) for variables has been left off, refer to Table 1), and:

$$N_R = \varepsilon(\Delta Q/Q_{ave})N_C \qquad (8)$$

where ε is the channel remobilisation coefficient (dimensionless), ΔQ is the flow increment, and Q_{ave} is the average discharge for the entire period being modelled. Remobilisation is constrained to occur only on rising flows. Settlement to channel-storage is given by

$$v_s/z, \text{ and } N_S = (v_s/z)N_W \qquad (9)$$

and v_s is the settling velocity (m/day) and z is the average water depth (m),

$$N_{Dw} = N_W \, k_{tot,w} \qquad (10)$$

where $k_{tot,w}$ is the time-variable water-column die-off rate (h^{-1}).

Deposition is used here to refer to the accumulation of microorganisms into the channel store, deposition is only said to have occurred when a particle reaches the river bed and actually stops moving (Graham et al. 1990). Deposition is a function of water depth, and the greater the water depth, the lower the probability of a particle being deposited. As Jenkins (1984) demonstrated, remobilisation and deposition are related to bed-substrate factors and by inference to channel habitat patchiness. The hyporheic zone is a key part of the channel store in cobble bed rivers (e.g. Muirhead et al. 2004), where microorganisms will be deposited from the water as it is exchanged through the channel substrate. Muirhead et al. (2004) demonstrated that the disturbance of river channel cobbles and gravel by artificial floods resulted in similar remobilisation of faecal indicator microorganisms into the water column compared with natural flood events.

The channel store is essential to the functioning of the model and represents the aggregate of processes associated with the accumulation of bacteria deposited from the water column and later remobilised by storm flow (Wilkinson et al. 2006). Jamieson et al. (2004) showed that critical shear stress for entrainment of cohesive sediments and associated faecal bacteria is directly proportional to flow, but their study did not assess channels of coarser bed material where hyporheic exchange is an important mechanism. Wilkinson (2001) experimented with the use of discharge, flow velocity, water depth and wetted perimeter as analogues for channel remobilisation forcings, but found that discharge produced the best model simulations. Wilkinson (2001) also had additional entrainment terms to account for steep-fronted waves associated with reservoir

releases, as well as, for turbulent burst-sweep action, which may maintain erosion at elevated but slowly varying flows (Garcia et al. 1996). In the current study with natural gradually varying rainfall-run-off generated flow waves, the model could be simplified to the 'wave-front disturbance', $\Delta Q/Q_{ave}$, term only. This was adequate to simulate the remobilisation of faecal bacteria successfully from the channel store. In the formulation applied here, the model effectively lumps together the channel and catchment stores of faecal bacteria. The assumption being that the two stores are supply limited systems (e.g. VanSickle & Beschta 1983; Jeje et al. 1991; Hunter et al. 1992; Wilkinson et al. 1995) and act in a similar manner. Both accumulate faecal bacteria during dry weather and these are flushed during storm-events resulting in high concentration pulses. At the larger catchment scale, the integrating effect of the catchment is assumed to be sufficient that localised variations in input are not noticed at the outlet of the system. This may be a function of the size of the defecating units themselves, i.e. the cattle and sheep, relative to the catchment. At larger scales, the movement of the animals from different grazing lands only results in localised effects, such that in a small catchment the movement of stock is more likely to have a direct influence on the adjacent river length.

The mass-balance for the river-reach channel store is:

Change in channel store numbers = riparian input + deposition from water column − (remobilisation + die-off) × channel store number,

$$\frac{dN_C}{dt} = N_I(1 - \frac{Q}{Q_{Max}}) + \frac{v_s}{z}N_W$$
$$- (\varepsilon\frac{\Delta Q}{Q_{ave}} + k_{tot,c})N_C \qquad (11)$$

where all terms are as previously defined (Table 1).

Die-off in the model is driven by sunlight and water temperature and influenced by light attenuation through the full depth of the water column. Gameson & Gould (1975) reported that the effect of sunlight on coliform die-off was additive such that the total die-off can be expressed: $k_{tot} = f(Temperature) + f(Sunlight)$.

The equations relating *E. coli* die-off to sunlight intensity (irradiance) and light attenuation are taken from the literature (e.g. Pommepuy et al. 1992; Auer & Niehaus 1993). The equation for temperature is derived from common observations in the literature (as reviewed by Wilkinson 2001 and Hipsey et al. 2008).

Die-off is related to the 'strength' of sunlight (solar irradiance, denoted by I, units: W/m^2) by a power law

$$k_i = \alpha I^\beta \qquad (12)$$

where β is dimensionless. For sunlight penetration into the water column, depth-averaged irradiance is given by the Morowitz (1950) equation (e.g. Sarikaya et al. 1987; Qin et al. 1991; Auer & Niehaus 1993):

$$I_{z,avg} = \frac{I_{0,avg}}{K_d z}\{1 - e^{-K_d z}\} \qquad (13)$$

where I_0 is the irradiance at the water surface and K_d is the irradiance attenuation coefficient. K_d was estimated from measurements of optical variables (visual clarity, turbidity and CDOM) as part of water quality survey at both Woodmans Bend and Blue Rock (November 2007 to October 2009), using the algorithm of Davies-Colley & Nagels (2008).

Die-off related to temperature alone is effectively the darkness die-off (in the absence of sunlight) and is much slower than in sunlight. Die-off in natural waters increases exponentially with temperature according to the equation

$$k_{T2} = k_{T1} \times 10^{\theta\Delta T} \qquad (14)$$

where ΔT is the change in temperature (°C), k_{T1} and k_{T2}, are the previous and current die-off

rate (h^{-1}), respectively, and θ is the slope of $log_{10} k_T$ plotted vs temperature:

$$\theta = \frac{log_{10} k_{T2} - log_{10} k_{T1}}{\Delta T}$$

An alternative formulation for k_T is

$$k_T = 10^{K_0 + \theta T} \qquad (15)$$

This gives the die-off for any temperature, relative to the reference die-off at $T = 0°C$, k_0 and $K_0 = log_{10} k_0$.

The mean values of θ and k_0 from various studies as summarised by Wilkinson (2001) are 0.0285 and 0.1067, respectively, and have been used in the study presented here (see also the summary of parameter values in Hipsey et al. 2008). The two die-off components are combined to give a value of overall die-off per day for average light intensity in the water column,

$$k_{tot,w} = a_w \left(10^{K_0 + \theta T} + \alpha I_{z(avg)}^{\beta} \right) \qquad (16)$$

on the land surface ($z = 0$),

$$k_{tot,l} = a_l \left(10^{K_0 + \theta T} + \alpha I_{z(0)}^{\beta} \right) \qquad (17)$$

and in the channel-store (for irradiance at the average water depth)

$$k_{tot,c} = a_c \left(10^{K_0 + \theta T} + \alpha I_z^{\beta} \right) \qquad (18)$$

where a_w, a_l, a_c are adjustment coefficients for model fitting (Table 1).

Model application and calibration

The first model of the Motueka River storm-event pulses (in Wilkinson 2008), a single at-a-point model, could reproduce the observed *E. coli* pulses but the river mixing parameter values were implausible. Hence a semi-distributed approach with linking river reaches and appropriate travel-time delays was applied to simulate the degree of dispersion needed (Wilkinson 2008). This approach was further refined by dividing the Motueka River catchment into 19 sub-catchments. These are the

basic calculation unit (boxes) for the model. One river reach is defined for each sub-catchment and there are an additional five linking river reaches along the main channel of the Motueka River (Fig. 1b). The linking reaches were defined based on digitised stream lengths. The model was applied at two scales; the whole Motueka River and the Sherry sub-catchment. For the Motueka River application, a 1-h model time step was used. This worked well with the observed *E. coli* data and seemed appropriate to the size of this river at Woodmans Bend. In the Sherry River sub-catchment, a 15-min time step was used (the smallest sampling data interval for hydrometric monitoring) because the catchment is smaller and more flashy in its response. A backwards difference approximation scheme is used in application of the model, and all parameters and variables are adjusted from time units of days or hours or seconds, as required, to work in units of the time-step.

The *E. coli* model was calibrated using measured bacteria concentrations (McKergow & Davies-Colley 2010; Ballantine et al. 2011). The influence of the Sherry on the main Motueka River was then investigated by running the Sherry model with driving variables for 2003–4, with Sherry flow (prior to installation of the Blue Rock hydrometric station) estimated from the neighbouring Tadmor River at Mudstone. The Sherry model output was then input to the Motueka model. The assumption implicit here, was that the faecal storm-event response of the Sherry River had not changed significantly between 2003–4 and 2008–9, which seems reasonable. The 15-min Sherry *E. coli* simulations were summed to hourly values prior to being input to the Motueka model. The model fit was achieved by manually adjusting the parameters and was assessed using a variety of means: (1) the visual fit of discrete observed vs 15- or 60-min modelled values; (2) the correspondence of the upper and lower percentiles and median concentrations; and (3) the value of the Nash–Sutcliffe efficiency measure 'E' (Nash &

Sutcliffe 1970); E varies between $-\infty$ and 1 (perfect fit). Model *E. coli* values are expressed in cfu (culture forming units).

Results

Model parameters: Motueka and Sherry Rivers

The Sherry River required a greater rate of *E. coli* input (adjusted by N_{def}, Table 2) than the main Motueka River model, and a greater remobilisation rate. The other model fit parameters were the same.

Motueka River time-series

Variations in *E. coli* concentration follow a log-normal distribution and $\log_{10}$ transformation of the data makes visual comparison of the time-series easier (Fig. 5), and the central tendency is best described by the median or geometric mean.

The model appeared to fit both the 'shape' and magnitude of observed *E. coli* concentrations at Woodmans Bend over most events quite well (Fig. 5c), including accounting for complex (non-linear, hysteretic, and otherwise varying) dependence on flow in a way that statistical models cannot. Simulated channel store *E. coli* numbers show, as expected, a 'saw tooth' pattern with an opposite trend from the water concentrations of *E. coli*, because the bacteria are transferred between channel store and water column, depending on flow conditions (Fig. 3). The channel store builds up gradually between hydrograph events then drops abruptly as the channel store is flushed. The channel store tends to be lower during wet weather when clusters of floods flush *E. coli* out of storage.

Only 14 dry weather flow *E. coli* samples were available for the modelled period for the Motueka River at Woodmans Bend. Around half of these values lie below the model line, and the other half are above or close to the line. The observed value from August 2003 is very low (Fig. 5b), and inconsistent with the other low values that occur within a few weeks of a storm-event. It is possible that this particular value may be biased low. The catchment input layer does tend to constrain the range of possible dry-weather flow values and it would be possible to have a greater time variability in N_i by increasing the die-off seasonality, and or introducing a seasonality to N_{Def} or reformulating the catchment input layer to incorporate a more realistic treatment of the catchment store. The dry weather samples demonstrate that the *E. coli* concentrations are low in the Motueka River at Woodmans Bend between storm events; however, further work would be required to identify the inter-storm and diurnal *E. coli* dynamics in detail.

Sherry River time-series

Escherichia coli in the Sherry River was not as easily modelled as in the main Motueka River (compare Figs. 5 and 6). In general, the Sherry *E. coli* concentrations are characterised by fewer observations than in the Motueka at Woodmans Bend (96 as opposed to 252), and there are few observations immediately prior to the events, and there were fewer inter-storm samples (seven as opposed to 14 at Woodmans Bend). Simulations for the steeper hydrograph events tend to fit the observations reasonably well. Peaks driven by broader topped hydrograph events were less well simulated, with the

Table 2 Model calibration parameters.

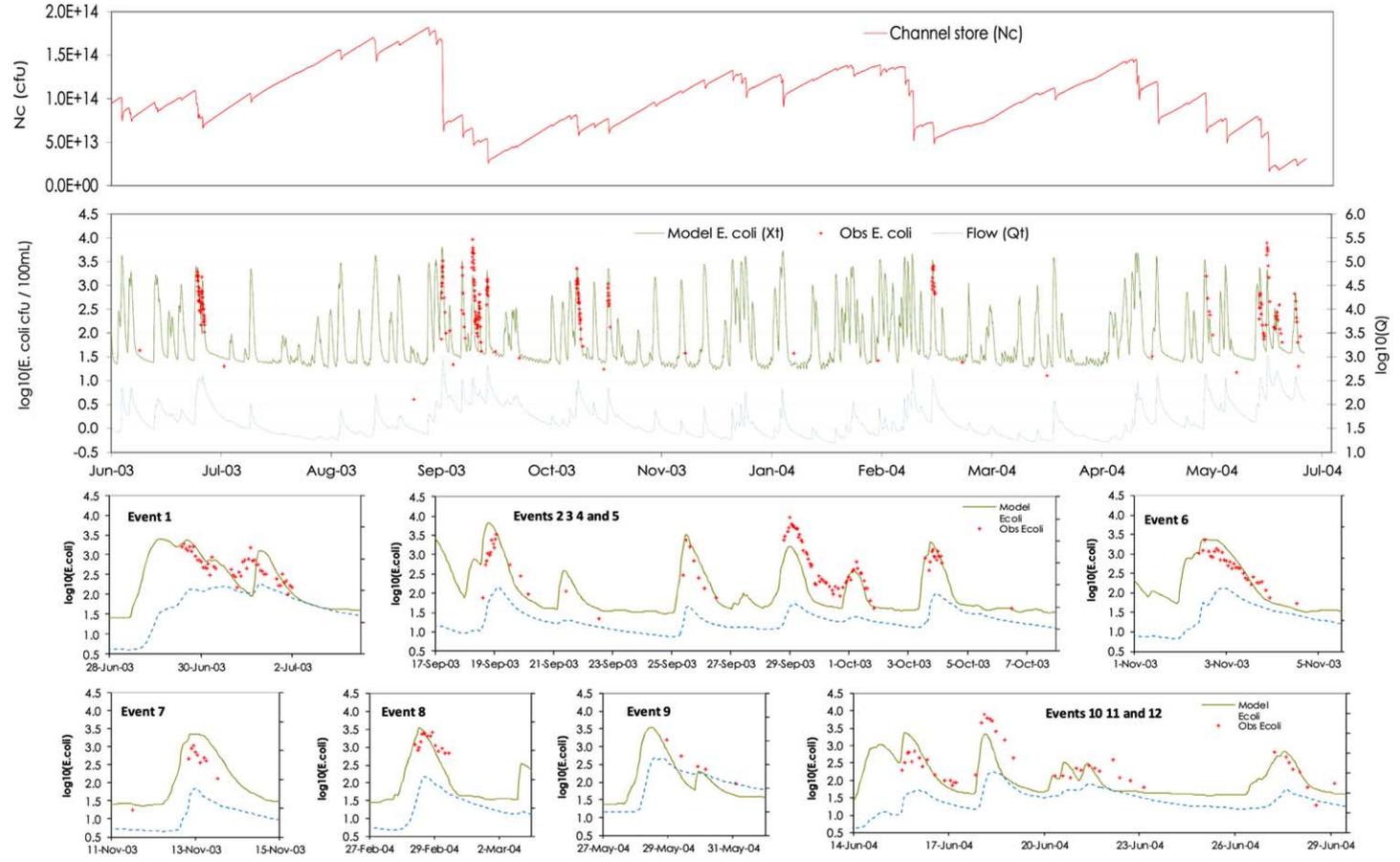| Location	N_{Def} (cfu/ha/mm/s)	v_s, settling velocity (m/day)	Df, dispersion adjuster	E, remobilisation (h^{-1})
Motueka@Woodmans Bend	850	2.0	1.20	0.20
Sherry@Blue Rock	1500	2.0	1.20	0.35

Figure 5 Modelled time-series and observed *Escherichia coli* concentrations in the Motueka River at Woodmans Bend from May 2003 to December 2004; channel store numbers in the most downstream river reach (top); water concentrations and discharge for events numbered sequentially; and excerpts showing detail of individually numbered events (bottom).
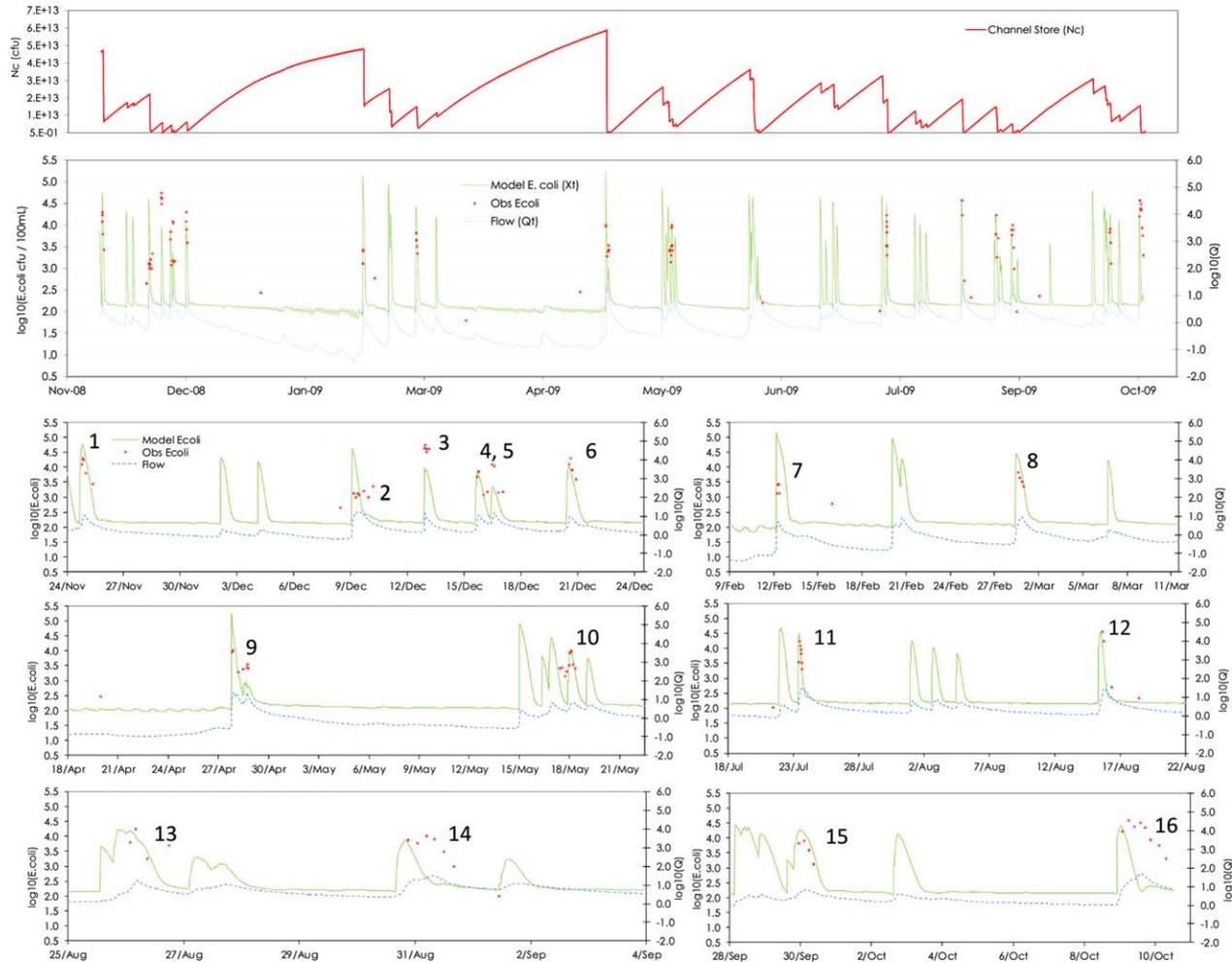
Figure 6 Modelled time-series and observed *Escherichia coli* concentrations in the Sherry River from November 2008 to October 2009; channel store numbers in the downstream most river reach (top); water concentrations and discharge (middle); and excerpts (below) showing detail of individually numbered events.

observed peaks generated by broad hydrograph events tending to remain high for longer than those simulated. The cause of this is not clear. Possibly catchment stores persist and 'feed' these events; suggesting that at the smaller catchment scale a more detailed description of the catchment store and delivery system is needed. From a closer examination of the flow events, it is apparent that the hydrographs are often composed of more than one peak or rise, which suggests the arrival of water from different parts of the catchment at different times, or even the arrival of groundwater. An investigation of the rainfall time-series might help to clarify this by examining the structure of the triggering rainfall events, but this has not yet been undertaken.

The simulated dry weather flow *E. coli* concentrations show a lack of variation in concentration over time-scales of days and weeks, but with a noticeable diurnal fluctuation driven by daytime sunlight inactivation (Fig. 6). There were few observations against which to fit the dry weather response, but it might be expected that inter-storm concentrations would exhibit a greater variation because of riparian and direct faecal inputs. In the model, the lack of variation is a consequence of the riparian input layer. Similarly, the diurnal variation would only be observed if the night-time riparian input exceeded the slower darkness rate of die-off, and is an artefact of the simplistic treatment of catchment inputs.

The simulations of the channel store in the Sherry River display a marked 'saw tooth' pattern with large variations. The bed store builds up in an exponential pattern between events then is abruptly flushed to low levels by storm wave fronts. The Sherry bed store pattern (Fig. 6a) contrasts with that of the main-stem Motueka (Fig. 5a) in displaying more abrupt drops related to storm events.

Comparison of model fit

The paired observed and modelled values can be compared directly in *x–y* plots (Fig. 7)—

which show good agreement overall for the Motueka River at Woodmans Bend (Nash-Sutcliffe E = 0.54), but more scatter overall in the Sherry at Blue Rock (E = 0.092). The model upper concentration for the Motueka River was around 4500 *E. coli*/100 ml but several observations exceeded that. The Motueka model generally had symmetric scatter either side of the 1:1 line (Fig. 7a). Modelled concentrations for Events 4 and 11 are underestimated (see also Fig. 5). The low model
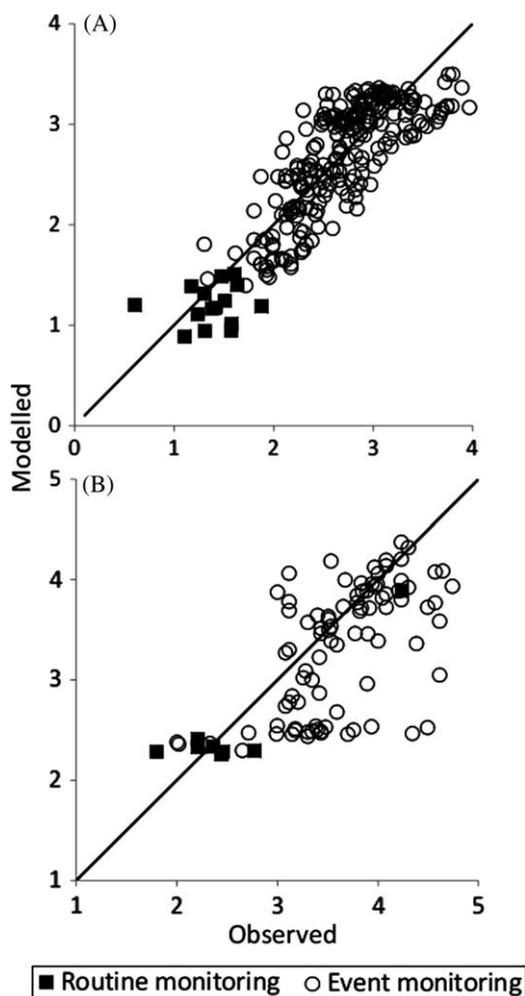

Figure 7 Event by event *x–y* plots of modelled and observed $\log_{10}$ *Escherichia coli* concentrations in the Motueka (**A**) and Sherry (**B**) rivers.

values for the Sherry give the impression of bias; however, examination of the time-series plot (Fig. 6) shows that this 'bias' is generally related to events where the model peaks and drops rapidly, but the observed event pulses remain elevated for longer. This issue is discussed below in the context of broad-topped hydrographs and the treatment of catchment inputs in the model.

Escherichia coli *storm dynamics and dispersion characteristics*

Several measures were calculated to characterise, and for comparison of, certain aspects of the *E. coli* event responses in the Motueka and Sherry Rivers (Table 3, see also Figs. 5 and 6). The mixing and dispersion characteristics for a 10-km reach are represented by the mixing time constant T_m. The peak duration measures the length of time (h) that the *E. coli* concentration is elevated above 'background' conditions for each pulse. *Escherichia coli* peak sharpness was calculated as the log of the ratio of peak to baseline concentration divided by peak duration (expressed in days) for each event.

There were distinct differences between the *E. coli* storm pulse characteristics in the Sherry and the Motueka Rivers. Modelled dispersion in the Sherry River remains relatively constant

and less than in the Motueka River (at Woodmans Bend) over a wide range of flow conditions. Longer mixing time constants apply at low flow and shorter time constants apply at high flow. At Woodmans Bend, the mixing characteristics vary more with flow and time constants are more than twice those in the Sherry at low flow. At high flow the mixing time constant drops (from 2.5) to 1.5 h.

The storm-event pulses in the Sherry were shorter in duration, had higher peaks and were between two and five times sharper than at Woodmans Bend in the Motueka River. The Motueka *E. coli* peaks were longer than those in the Sherry by a factor of 1.46 (compare Figs. 5 and 6; Table 3) and varied between 5.0 and 39 h, whereas the shorter Sherry River pulses had durations of between around 3 and 26 h. The median peak sharpness for the Sherry model pulses in 2008/9 was 6.5 (Table 3). The sharpest peak had a sharpness of around 50. The peak sharpness values at Woodmans Bend were generally about half those in the Sherry River, indicating peaks of longer duration with sharpness values varying from 2 to around 10. The observed *E. coli* pulse data for both rivers show that less steep or rounded hydrographs, resulting from extended rainfall events (in contrast to sudden intense downpours), tended to result in longer duration *E. coli* peaks (e.g. 9

Table 3 Summary statistics for model characteristics for the Motueka (M) and Sherry Rivers (S), S/M and M/S show the ratios of the characteristics for each river.

		10th percentile	Median	95th percentile	Comments
Mixing time constant T_m (h)	S	1.09	1.07	1.04	Greater dispersion in the Motueka River, maximum at low flow
	M	2.56	1.78	1.53	
	M/S	*2.36*	*1.66*	*1.47*	
Pulse duration (h)	S	3.3	13.8	25.7	Longer duration *E. coli* pulses in the Motueka River
	M	5.0	17.0	39.0	
	M/S	*1.50*	*1.23*	*1.52*	
Peak sharpness (ratio)	S	4.3	6.5	51.9	*E. coli* peaks in Sherry River sharper than in the Motueka River
	M	2.0	3.3	9.4	
	S/M	*2.17*	*2.00*	*5.50*	

December 2008, 31 August 2009 and 9–10 October 2009).

Discussion

This paper has presented simulations of faecal indicator bacteria (*E. coli*) concentrations in the Motueka River and its much smaller tributary the Sherry River. The results provide a number of general observations about faecal pollution dynamics in river systems and provide some insight into the differences between the dynamics in catchments of very different scales. Consequently, much of the discussion below approaches different aspects of scale related issues relevant to temporal dynamics and the spatial aspects of faecal source areas.

Scale temporal dynamics in response

Differences in the temporal dynamic nature of the *E. coli* response at Woodmans Bend and Blue Rock were observed, as measured by peak sharpness and dispersion. These differences are in part a function of scale, but may also relate to the degree of contamination. In terms of scale, in larger catchments issues of timing of arrivals from sub-catchments, the spatial distribution of rainfall, in-stream mixing and the dissipation (attenuation) of flood waves will increase the tendency for responses to be spread-out over time (e.g. Beven 1987). Conversely, in smaller catchments, a closer coincidence of pollutant delivery from different parts of the catchment is expected. In the Sherry the relatively small catchment scale and rapid response to hydrological events results in sharp *E. coli* peaks. The main stem of the Motueka River is much cleaner than the Sherry River, since in the southern and western Motueka River sub-catchments, there are relatively microbially pure waters including drainage from large areas of native forest, plantation forest and scrub-land (Fig. 1c), as well as karst-fed streams that drain areas extending into the Kahurangi National Park

(Young et al. 2005). In contrast, the Sherry has a high proportion of pastureland with high livestock numbers (about three cows per hectare on dairy farms in the Sherry Valley) causing elevated faecal microbial pollution.

Peaks from local and distant sources

Faecal indicator bacteria such as *E. coli* tend to accumulate in the channel store with distance downstream, and as a generalisation, channel disturbance becomes more significant, as a source for recontamination of the overlying water, with distance downstream (Hunter et al. 1992; Nagels et al. 2002; Collins & Rutherford 2004; Muirhead et al. 2004). Remobilisation of channel stores tends to concentrate bacteria on the hydrograph rise (Wilkinson 2008). This is also a consequence of the increasing bed-store with distance downstream. The dispersive mechanism spreads and attenuates peaks. The dispersion and remobilisation mechanisms counteract each other, since remobilisation tends to increase peak sharpness, whereas dispersion (mixing processes) acts to attenuate and spread the remobilised faecal bacteria in the wake of (behind) the flood wave. Observations suggest that bacteria in event pulses are derived from local sources in the river network (McKergow & Davies-Colley 2010). Bacteria derived from distant upstream locations have been mixed, and diluted into the tail of the hydrograph, and a proportion settle back into the channel store before reaching the point of interest. The bacteria in the hydrograph rising limb must be locally derived from (channel stores in) the immediate river reaches upstream. The emergence of the use of microbial tracers (e.g. Wyer et al. 2009; Cornelisen et al. 2011) presents a promising approach for devising experiments to elaborate on the source composition of bacteria in flood-pulses and hence better understand in-stream transport mechanisms.

River network as a contamination shunting system

Assuming that upstream catchment microbial inputs and remobilised bacteria tend to become mixed and spread into the hydrograph tail and settle back out of suspension, a proportion of the bacteria from distant sources will be shunted through the river network with successive storm-events. As die-off in the channel store seems to be slow (with most storage probably in the—comparatively dark—hyporheic zone), the microorganisms comprising a given storm-pulse may be of very mixed 'age' composition, some taking weeks to arrive from distant sources, whereas others are from more recent and local sources. The relative contribution of local channel accumulations, and more distant land- and channel-derived inputs, has been under consideration in studies by Muirhead et al. (2004), Nagels et al. (2002) and McBride (2011). For the smaller Sherry River catchment, wash-in may be expected to contribute a greater part of the observed peaks, and is probably more a consequence of the relatively small-scale channel store accumulations. In the Sherry catchment, the channel can only accumulate inputs from local sources, whereas in the larger Motueka catchment, the whole extended catchment area contributes to 'loading up' the channel stores, such that the contribution to storm peaks greatly outweighs the catchment wash-in.

Inter-storm microbial levels

During dry weather, the settlement of particle-associated *E. coli*, clear water, shallow depths, slower flushing and strong sunlight exposure, all combine to favour rapid die-off in the water column—by about a factor of 10 every day. In the Motueka River, dry weather *E. coli* concentrations are low (around 30 cfu/100 ml), whereas Sherry River values are around a factor of 10 higher. The higher Sherry values probably result from proximal contamination by livestock, particularly cattle, accessing the channel network.

Faecal export rate

In 2008, the export rate from the (mixed land use) Motueka was 6.6×10^8 cfu/km^2/h (Table 4, column iii) and from the Sherry, 2.0×10^9 cfu/km^2/h (Table 4, column ix). These export rates are consistent with those published by Kay et al. (2008), who reported values ranging between geometric means of 2.5×10^8 and 2.5×10^{10} cfu/km^2/h for rough grazing land during low vs high flow, and 8.3×10^8 and 1.2×10^{11} for improved pasture. Export rates from catchments that were predominantly woodland had geometric mean export rates between a factor of 10 and 100 less than the pasture catchments (Kay et al. 2008). The export rate for the Motueka catchment, which has areas ranging from intensive grazed pasture through to plantation and native forest (Basher 2003), is around 2.5 times the geometric mean dry-weather rate for rough grazing in the UK studies, from the Sherry the export rate is around 2.5 times the dry-weather geometric mean for improved pasture.

Influence of the Sherry at Woodmans Bend

In order to test the influence of the Sherry sub-catchment on *E. coli* levels in the Motueka at Woodmans Bend, the Sherry model was run for 2003/4 using driving data for that period and the calibration parameters for 2008. The output faecal time-series was substituted into the model for the Motueka at Woodmans Bend, which was re-run (Table 4, column iii and iv). The influence of the Sherry faecal output at Woodmans Bend in the absence of other inputs was tested by switching-off all other sub-catchment bacterial inputs (Table 4, column v). The Sherry catchment is more densely stocked with cattle and other livestock than the average of the Motueka catchment, and the export values in Table 4 suggest that roughly 8% ($5.3 \times 10^7 / 6.6 \times 10^8$) of the *E. coli* export at

Table 4 Summaries of observed and modelled *E. coli* concentrations in the Motueka@Woodmans Bend and Sherry@Blue Rock.

| | Motueka@Woodmans Bend | | | | | Sherry@Blue Rock | | | |
| | 2003/4 | | | | | 2008 | | 2003/4 | |
	i. Obs.	ii. Model paired values	iii. Model all values	iv. Model*	v. Model†	vi. Obs.	vii. Model paired values	viii. Model all values	ix. Model
n	253	253	10967	10967	10967	97	97	35216	43851
90th percentile	2375	2284	724	743	51	20777	20675	433	636
Median	456	399	35	35	2	3400	3805	142	147
5th percentile	37	39	20	19	0.5	201	140	102	112
Export rate, cfu/km²/h			6.6E + 08	6.6E + 08	5.3E + 07			4.0E + 09	2.0E + 09

*Model with 2003/4 Sherry model output used as input; †model with Sherry faecal input only (N_{Def}=0).

Woodmans Bend was derived from the Sherry, representing only 3.8% of catchment area. So despite the higher concentrations draining the Sherry, the die-off and settlement occurring during travel through the channel network to Woodmans Bend reduce the load by a factor of around 37.

Catchment faecal input

The riparian input layer of the model is a significant simplification of catchment faecal delivery processes and mechanisms (e.g. Collins & Rutherford 2004). Wilkinson (2001) used a constant catchment faecal input rate (adjusted only by die-off) and achieved a comparable model efficiency with a more detailed description of catchment input mechanisms.

The constant faecal input rate N_{Def} (cfu/ha/mm/s) is referred to as a defecation rate, but the multiplication by catchment run-off yield means that this name is misleading. The use of run-off yield as a further adjustment to sub-catchment inputs was intended to account for the large gradient in rainfall and hence run-off from south-west to north-east in the Motueka catchment (Basher 2003), based-on the assumption that areas with greater rainfall deliver more microorganisms to the river system. In the current formulation, this adjustment is simply a multiplication, which in some sub-catchments effectively increases the defecation rate. A more conceptually appealing approach (without changing the modelling results) might be to apply the yield adjustment as a 'faecal delivery efficiency' ranging from 0 to 1, and thus the term defecation rate for N_{def} would still be valid. The adjustment for flow yield takes no account of rainfall temporal variability, this being already accounted for by the river flow, which is the key driving variable. These simplifications of the approaches used by Wilkinson (2001) and Collins & Rutherford (2004) appear to be valid at the larger catchment scale (i.e. the Motueka River), but at smaller scales where river mixing and channel accumulation are less dominant relative to land-based dynamics (such

as might be expected in the Sherry River) a more detailed description of the variability with time of catchment inputs may be needed.

Final comment

Beven & Freer (2001) point out that in modelling complex environmental systems there are usually many model structures and sets of calibration parameters that produce acceptable result, and this is true of the work presented here. More than 17 model versions with different formulations were investigated in an attempt to improve some aspect of the model fit or the conceptual representation of the system. The results presented here present just one (the 'best' [compromise between model complexity and explanatory power] in our judgement) example. It would be possible to try out alternative structures undertaking many weeks of further work. The datasets used only characterise the end behaviour of two systems, and to make further progress in refining the models and our understanding of these systems, more surveys and data would be needed; notably measurement of channel stores and *E. coli* distributions, specific assessments of *E. coli* storm pulses for each major sub-catchment, longitudinal profiles within the Sherry, tracer tests to confirm the travel-times and mixing characteristics of key reaches across a range of typical discharge values. Having said this, to be able successfully to simulate the *E. coli* pulses passing Woodmans Bend in the Motueka River, with a small number of readily available driving variables, is a useful advance towards prediction of *E. coli* in coastal waters, and potentially provide warnings for bathers and to the shellfish industry of non-harvest periods.

Conclusions

Small catchments such as the Sherry Catchment tend to react rapidly to storm events, producing short duration ('sharp') *E. coli* peaks. Stormflow *E. coli* peaks are of longer duration in the much larger Motueka River. In smaller catchments, the degree of mixing and dispersion is lower, the channel store remobilisation rate is greater, and the contribution of land-based sources is likely to be greater (since the relative magnitude of the channel store is less).

Under stormflow conditions, the action of river mixing and dispersion means that event-derived microorganisms (either washed-in or remobilised from the channel store) from distant parts of the catchment contribute minimally to the *E. coli* peak observed at the catchment outlet. Steep *E. coli* peaks, arriving ahead of hydrograph peaks, at the Motueka outlet, reflect the resuspension of microorganisms from (nearby) channel stores (McKergow & Davies-Colley 2010).

A river system acts as a shunting mechanism for faecal indicator bacteria, which may be displaced by several successive storm-events before eventually reaching the catchment outlet (unless die-off has occurred).

The simplified treatment of catchment delivery processes, loads and the accumulation and flushing of land-based faecal reservoirs, used in this model is suitable for larger catchments, but at the smaller scale of the Sherry Catchment, a more conceptually complete treatment seems desirable. In addition, the specific spatial and temporal patterns of rainfall and erosion may need to be accounted for to characterise smaller catchments adequately where faecal source patchiness may have a greater influence on the observed in-stream dynamics.

Stormflow pulses of poor microbial quality in river plumes have major implications for downstream bathing and shellfish harvesting waters. Simulation of faecal contamination using models such as that presented here have a potentially valuable application to protection of bathing and bivalve shellfish raising waters that are episodically contaminated by plumes from even fairly 'clean' rivers such as the Motueka.

Acknowledgements

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