Modelling bacterial water quality in streams draining pastoral land

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Abstract

A model has been developed to predict concentrations of the faecal bacteria indicator *E. coli* in streams draining grazed hill-country in New Zealand. The long-term aim of the modelling is to assess effects of land management upon faecal contamination and, in the short term, to provide a framework for field-based research. A daily record of grazing livestock is used to estimate *E. coli* inputs to a catchment, and transport of bacteria to the stream network is simulated within surface and subsurface flows. Deposition of *E. coli* directly to streams is incorporated where cattle have access to them, and areas of permanent saturation ('seepage zones') are also represented. Bacteria are routed down the stream network and in-stream processes of deposition and entrainment are simulated. Die-off, both on land and in water, is simulated as a function of temperature and solar radiation. The model broadly reproduces observed *E. coli* concentrations in a hill-country catchment grazed by sheep and beef cattle, although uncertainty exists with a number of the processes represented. The model is sensitive to the distance over which surface runoff delivers bacteria to a stream and the amount of excretion direct to streams and onto seepage zones. Scenario analysis suggests that riparian buffer strips may improve bacterial water quality both by eliminating livestock defaecation in and near streams, and by trapping of bacteria by the riparian vegetation.
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1. Introduction

In recent years, the contamination of New Zealand's freshwaters by a range of indicator and pathogenic microorganisms has been studied under the Freshwater Microbiological Research Programme [1]. The results from this and earlier studies have confirmed that microbial contamination of freshwaters is widespread in New Zealand, with concentrations of the faecal indicator *Escherichia coli* often exceeding 1000 per 100 mL and with *Campylobacter* spp. and other pathogens often present. Such findings, coupled with the high incidence of notified campylobacteriosis [2] and cryptos-

poridiosis [3] compared to other developed countries, has raised concerns over the public health risk from pathogens of faecal origin (including *Campylobacter*, *Cryptosporidium* oocysts, *Giardia* cysts, and Salmonellae) in New Zealand's freshwaters. This risk to public health has substantial implications for land management practices. Furthermore, faecal contamination also restricts the recreational use of freshwaters and shellfish aquaculture in estuaries receiving agricultural drainage, and increases water supply treatment costs.

The sources of faecal contamination of freshwaters are often diverse and can include point source discharges of wastewater from sewage treatment and animal processing plants, and contamination by wild and feral animals. There is, however, good evidence, both within New Zealand and elsewhere, to indicate that grazing livestock are an important, diffuse source of faecal

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contamination to freshwaters [4,5]. This contamination arises through the delivery of faecal material in overland [6], and subsurface [7] flows to a watercourse and, where livestock have access to a stream, direct deposition of faecal material [8]. Mitigation measures with respect to this diffuse source of faecal pollution encompass a number of livestock management options within riparian zones, including riparian buffer strips [9], hereafter termed 'riparian retirement', and the treatment of contaminated catchment drainage waters within ponds and wetlands. The quantitative understanding of contamination and transport processes and the impact of mitigation measures are, however, limited. To achieve, for example, an order of magnitude decrease in rural stream bacteria concentrations, it is not known if fencing livestock from just the stream channel will suffice, or whether riparian retirement of, for example, 10 m on both sides of a stream is necessary.

To aid assessment of the impact of land management strategies upon faecal contamination, a dynamic process-based model has been developed that predicts mean daily *E. coli* concentrations in streams draining pastoral land. Earlier process-based models have successfully reproduced in-stream bacterial dynamics but have either excluded catchment inputs or incorporated a simple lumped value [10,11]. This precludes or limits their use as a tool to explore the impact of catchment management strategies. An alternative approach [12] addressed the catchment source in a spatially explicit manner, but excluded in-stream processes, which restricted prediction of faecal contamination to annual loads. The model described here incorporates and links both catchment and in-stream bacterial processes.

The long-term objective of the modelling is to aid prediction of the impact of land management strategies on faecal contamination of rural streams. In this respect, the aim is not to derive accurate predictions of bacterial concentrations at high frequency, but rather to develop a tool with which to examine the relative impact of mitigation measures. Consequently, a model based upon a subdaily time-step would be too detailed, particularly given the current limited understanding of a number of bacterial processes and, in any case, would be unable to capture the timing of sporadic incursions of stock to streams and seepage zones. Nevertheless, bacterial dynamics and the efficiency of mitigation measures are known to be strongly influenced by rainfall events. The use of a daily time-step enables these dynamics to be captured with a far smaller loss of information than would occur with a model based upon a mean annual time-step. In the short term, the aim of the modelling is to highlight areas of uncertainty with respect to process understanding, thereby providing direction and focus for field-based research. The model is broadly applicable to steep grazed hill-country catchments and, whilst components of it may be transferable to other pastoral landscapes, application to flatter dairy catchments would require the incorporation of new processes; artificial subsurface drainage, networks of open surface drains, and management of dairy shed wastes including discharge to land and waste treatment ponds.

This paper describes the model and its application to a grazed hill-country catchment within the Whatawhata research station, near the city of Hamilton, North Island, New Zealand. The sensitivity of the model is assessed and the impact of one land management scenario (riparian retirement) is explored. The model structure builds on a preliminary development [13] by incorporating the excretion of *E. coli* direct to streams, representation of seepage zones supported by field studies, and improvements to the representation of both surface and subsurface supply of bacteria to the stream.

2. Model structure

The model (Fig. 1) is based on a mass balance formulation that conserves the mass of *E. coli*. The catchment component of the model quantifies the *E. coli* delivery to the stream network by direct deposition, in drainage from seepage zones, within surface runoff and
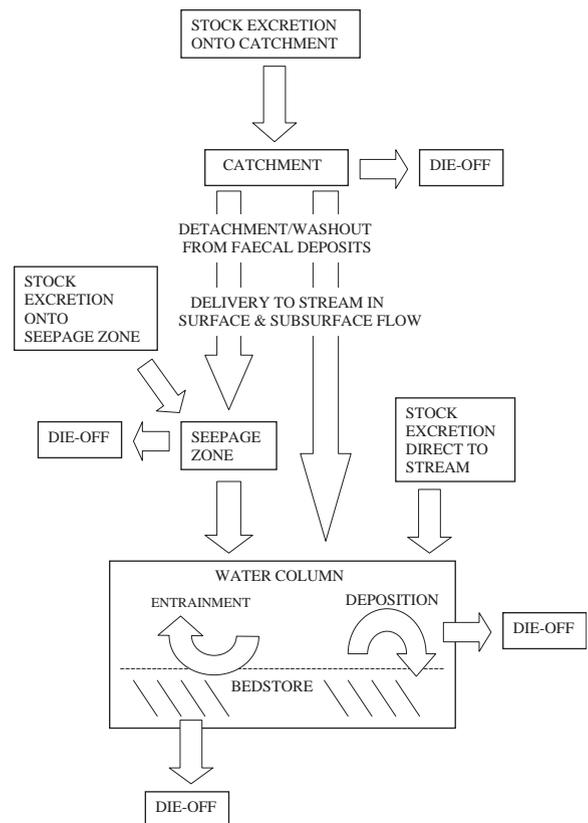

Fig. 1. The model framework.

in shallow groundwater (percolation). The model is spatially distributed and simulations are conducted on a cell-by-cell basis across a catchment. Catchment yields are linked to an in-stream component that routes bacteria down the stream network using predictions of flow and simulated processes of entrainment, deposition and die-off. Parameter values are given in Table 1, and are described below. Predicted *E. coli* concentrations have units of *E. coli* per 100 mL, whilst observed concentrations are in units of 'most probable number' MPN per 100 mL.

2.1. Hydrology

Predictions of daily surface runoff, percolation, and stream flow required by the *E. coli* model were derived from an application of Watershed Assessment Model (WAM, [14]). WAM uses a rasterized representation of a catchment whereby uniform grid cells (of a user-defined size) are assigned the dominant land use, slope angle and soil type at that location in the catchment. WAM incorporates GLEAMS [15], an agricultural model that provides predictions of surface runoff and percolation for each cell throughout a catchment. The other components of WAM input the water yield from each cell directly to the nearest stream reach (that is, there is no cell to cell transport) and route water down the stream network. The bacteria model, which is applied at the same cell size as WAM/GLEAMS, uses a series of equations to simulate the transport of *E. coli* from each cell to the nearest stream reach, and down the stream network. These equations incorporate the WAM/ GLEAMS hydrological predictions. For both WAM and the bacteria model, the catchment is divided into subcatchments each with an associated stream reach.

2.2. Seepage zones

Areas of permanent soil saturation or 'seepage zones' are found extensively throughout hill-country catchments in New Zealand. Commonly, they are located above, and drain directly into, headwater streams, forming where surface and subsurface flows converge.

Elsewhere, they develop above an impervious soil layer, often in riparian areas, where they drain directly to the stream network. Since seepage zones have been shown to provide an important source of faecal contamination [16], they are incorporated within the model.

Seepage zones vary in size, but are typically a few metres wide and no greater than 25 m in length, and their precise location is difficult to predict in the absence of fine-scale topographical and soils maps. Consequently, they are represented as a point source of faecal contamination, supplied with *E. coli* from surface and subsurface flows, and subject to direct deposition by grazing cattle. One seepage zone point source per subcatchment is simulated, and is assumed to drain directly to the stream reach associated with that subcatchment. Conceptually, each modelled seepage zone represents tens of small seepage zones found throughout that subcatchment. Since WAM does not explicitly model the movement of water down a hillslope, it is not possible to directly simulate the hydrology of seepage zones. Instead, the loss of *E. coli* from them is modelled as a function of the number of *E. coli* in the seepage store, and the magnitude of flow at the catchment outlet, Eq. (1). This formulation was based on preliminary field studies of seepage areas accessed by cattle [16]. These showed that the drainage of *E. coli* per day from a single seepage zone ranged between 10^4 and 10^8 MPN during low flow, with a yield of 10^7 MPN during a short intense rainfall event when concentrations peaked at 6×10^4 MPN per 100 mL. Die-off within seepage zones is assumed to follow the same rate as that elsewhere in the catchment.

$$S = S_{\mathrm{p}}(A\, e^{K_{\mathrm{seep}}Q}), \tag{1}$$

where S is the number of *E. coli* draining from a seepage zone per day (*E. coli* d^{-1}) and therefore direct to a reach, S_{p} is the number of *E. coli* within that seepage zone, Q is the mean daily flow at the catchment outlet ($\mathrm{m}^3\,\mathrm{s}^{-1}$), A (dimensionless) is the fraction of bacteria draining out at minimum flow, and K_{seep} is the drainage rate (*E. coli* m^{-3}), chosen to ensure that drainage of *E. coli* from seepage zones is $\leqslant 100\%$ during the largest flow event.

Table 1
Parameter values used to calibrate the *E. coli* model

Parameter	Value	Units	Description
Seepage zone; A, K_{seep}	0.1, 1.8	Dimensionless, *E. coli* m^{-3}	Determine how the rate of drainage of bacteria from seepage zones varies with flow
Radiation rate; K_{R}	100	MJ $\mathrm{m}^{-2}\,\mathrm{d}^{-1}$	Determines bacteria die-off due to sunlight
Temperature rate; K_{T}	100	°C	Determines bacteria die-off due to temperature
Surface runoff; K	25	mm d^{-1}	Determines delivery of bacteria in surface runoff
Stream proximity; K_{d}	0.025	m^{-1}	Determines distance over which bacteria are transported to the stream by surface runoff

2.3. The source and distribution of E. coli inputs

A detailed history of livestock grazing was used to quantify *E. coli* input to each field, delineated by fencing, on a daily basis (Eqs. (2)–(4)). The assumed *E. coli* excretion rate from cattle was 1.3×10^9 *E. coli* per animal per day [4], a figure in agreement with the authors' unpublished data. The excretion rate for sheep (*E. coli* per animal per day) was assumed to be one-sixth of that for cattle, reflecting their relative stock units [17].

$$\alpha = 1.3 \times 10^9, \tag{2}$$

$$\beta = \frac{1.3 \times 10^9}{6}, \tag{3}$$

where α is the *E. coli* excretion rate (*E. coli* d^{-1}) per cow and β is the *E. coli* excretion rate (*E. coli* d^{-1}) per sheep.

$$\varepsilon = \alpha n_{\mathrm{cows}} + \beta n_{\mathrm{sheep}}, \tag{4}$$

where ε is the total *E. coli* excreted (*E. coli* d^{-1}) by livestock within a given field, n_{cows} and n_{sheep} are the numbers of cows and sheep, respectively, within the field.

Studies of cattle behaviour indicate that time is spent in, or adjacent to streams, when cattle seek out water and high-quality riparian forage. For example, between 7% and 11% of defaecations were deposited directly into streams on a Colorado range stream [8]. In New Zealand hill-country pasture, the stream banks are often steep, limiting cattle access, and we expect that direct deposition may be at the lower end of the range observed in Colorado. The assumed rate of direct deposition to the stream is 8% of *E. coli* excreted from those cattle grazing in fields through which a stream flows (Eq. (5)). This figure is, however, unvalidated.

$$\phi = 0.08\alpha n_{\mathrm{cows}}, \tag{5}$$

where ϕ is the number of *E. coli* excreted by cattle, within a given field, direct to a stream reach (*E. coli* d^{-1}).

Field observations at Whatawhata, [16] showed that cattle are attracted to seepage zones for grazing. Observations of the distribution of faecal material showed that the number of pats deposited on or adjacent to a seepage zone typically ranged between 20% and 40% of the total within that field, and, on one occasion, reached in excess of 75%. We assumed, but this remains unvalidated, that cattle attraction to seepage zones varies seasonally: their attractiveness being greater in summer as the pasture elsewhere dries out. The excretion of *E. coli* to seepage zones, and the assumed seasonality in this process, is represented within the model by a sinusoidal relationship whereby $\pm 10\%$ is superimposed on an average rate of 30% (Eq. (6)).

$$\zeta = \frac{30 + 10 \sin\left(\dfrac{2\pi}{365} d_{\mathrm{num}}\right)}{100} (\alpha n_{\mathrm{cows}} - \phi), \tag{6}$$

where ζ is the number of *E. coli* excreted onto a seepage zone (*E. coli* d^{-1}) and d_{num} is the day number of the simulation (where the simulation encompassed from 1 November 2000 to 31 October 2001).

Observations by the authors suggest that most fields (60–70%) have a seepage zone within them, the exceptions generally being those located upon or near ridge tops. This pattern was represented within the model. Simulated additions of *E. coli* to seepage zones are summed to enable one zone per subcatchment to be modelled.

Once *E. coli* deposited directly to streams and onto seepage zones was quantified, the remaining bacteria, including all those excreted by sheep, were assumed to be spread uniformly throughout a field. That is, sheep are assumed to have no attraction to riparian zones or seepages zones. No account was made of *E. coli* excretion by wild animals, nor of the possible growth of *E. coli* once excreted [18].

The modelled excretion rate of *E. coli* to each catchment cell, lying within a given field, is described by

$$\omega = \varepsilon - \phi - \zeta \frac{\text{area of cell}}{\text{area of field}}, \tag{7}$$

where ω is the *E. coli* excreted (*E. coli* d^{-1}) to a catchment cell.

2.4. Catchment die-off

E. coli survival is strongly influenced by sunlight and temperature [19], so available radiation and temperature data were combined using the simple formulation of the preliminary model [13] to determine rates of catchment *E. coli* die-off (Eq. (8)).

$$C_{\mathrm{d}} = \left(\frac{R}{K_{\mathrm{R}}} + \frac{T}{K_{\mathrm{T}}}\right) C_{\mathrm{p}}, \tag{8}$$

where C_{d} is the number of *E. coli* to die each day (*E. coli* d^{-1}) from the catchment pool, C_{p} is the number of *E. coli* in the catchment pool, R is the mean daily radiation (MJ $\mathrm{m}^{-2}\,\mathrm{d}^{-1}$), T is the mean daily temperature (°C), K_{R} is a radiation rate coefficient (MJ $\mathrm{m}^{-2}\,\mathrm{d}^{-1}$), K_{T} is a temperature rate coefficient (°C). Values for K_{R} and K_{T} were chosen to ensure die-off rates lay within a plausible range.

2.5. Surface transport of E. coli to the stream network

Transport within surface runoff is a mechanism by which *E. coli* are known to reach surface waters [20], and this is represented in the model by a two-stage process.

2.5.1. Stage 1

Firstly, detachment or washout of *E. coli* from faecal deposits is simulated using a relationship with the

amount of predicted surface runoff (Eqs. (9) and (10)).

$$Z = C_p \frac{O}{K}, \quad O < K, \tag{9}$$

$$Z = C_p, \quad O \geqslant K, \tag{10}$$

where Z is the *E. coli* detachment or washout rate (*E. coli* d^{-1}), O is the (WAM-predicted) surface runoff (mm d^{-1}), and K (mm d^{-1}) is a runoff coefficient such that should O be greater than K, then the whole pool (in that cell) is assumed to be washed out.

2.5.2. Stage 2

In the second stage, transport to the stream network of a proportion of the bacteria washed from deposits, is simulated. This amount is determined by the combination of a delivery index and the amount of surface runoff generated within a storm event. The delivery index has three components: proximity to stream, slope and flow accumulation.

The potential for re-deposition of transported *E. coli* increases with distance flowed over the catchment surface. Consequently, the delivery index incorporates a stream proximity factor (Eq. (11)) that describes a negative exponential relationship with distance. This approach has been adopted previously [12] and broadly reflects studies [21,22] that have shown that grazing near a channel increases stream bacterial levels, whilst grazing some distance from a channel has little impact.

$$P = 0.5 \, e^{-K_d \, d}, \tag{11}$$

where P is the stream proximity index which ranges between 0 and 0.5, d is the distance from a given cell to the nearest stream reach (m), and K_d (m^{-1}) is the stream proximity coefficient.

Slope angle is incorporated within the delivery index (Eq. (12)) due to its influence upon the momentum of overland flow. The mean slope angle between a cell and the nearest stream reach is used in an approach similar to that elsewhere [12].

$$Y = Y_k \bar{Y}, \tag{12}$$

where Y is the slope index, $\bar{Y}$ is the mean slope angle of the land surface between a cell and its nearest stream reach. Y_k is a coefficient to ensure that S lies between 0 and 0.25.

Flow accumulation (Eq. (13)) was derived from a digital terrain model within a GIS and quantifies the number of upslope cells that could potentially contribute surface flow to a given cell. This analysis identifies the dominant flowpaths within a catchment and enables those cells along such a pathway to be given a stronger weighting factor with respect to bacterial delivery. This approach attempts to account for the influence of topography upon hydrological pathways.

$$F = F_k \lambda, \tag{13}$$

where F is the flow accumulation index, λ is the GIS-derived flow accumulation, scaled (for computational ease) to range between 0 and 10, and F_k is a coefficient to ensure F lies between 0 and 0.25.

Since values within the stream proximity index are weighted to range between 0 and 0.5, whilst those of the slope and flow accumulation indices ranged between 0 and 0.25, summation of these factors resulted in a delivery index ranging between 0 and 1 (Eq. (14)).

$$I = P + Y + F, \tag{14}$$

where I is the surface delivery index.

The adoption of a delivery index avoided the complexity associated with simulation of cell to cell transport of water and bacteria. Considerable uncertainty is associated with it, however, and relatively arbitrary decisions have been made, for example the choice of weighting factors, with respect to its formulation. No distinction is made of the mechanism of transport within the model although it is likely that in reality, bacteria are transported attached to sediment and clumps of faecal material, as well as dispersed coliform-forming units suspended in overland flow.

The surface delivery index is used in conjunction with the volume of surface runoff generated (and the runoff coefficient) to determine the proportion of *E. coli* washed out from faecal deposits that reaches a stream or seepage zone during an event (Eqs. (15) and (16)). Of this proportion, 50% is assumed to be transported directly to the nearest modelled reach and the remaining 50% is added to the point source seepage zone associated with that subcatchment. This proportioning of surface runoff between stream reach and seepage zone is based on field observations that suggest that a substantial proportion of surface runoff and percolation converges within a seepage zone. The 50-50 split is, however, unvalidated.

$$L = \left(I \frac{O}{K} \right) Z \quad O < K \tag{15}$$

$$L = I \, Z \quad O \geqslant K \tag{16}$$

where L is the number of *E. coli* delivered in surface runoff to the nearest reach or seepage zone (*E. coli* d^{-1}).

2.6. Subsurface transport of E. coli to the stream network

Sampling of soil water under grazed paddocks at Whatawhata [16] found *E. coli* down to a depth of 80 cm. Following cattle access to a field, soil water *E. coli* concentrations were elevated within seepage areas, sometimes to $> 5 \times 10^3$ MPN per 100 mL. Generally, however, concentrations were an order of magnitude lower than this, and typically fell to $< 10^2$ MPN per 100 mL a few days after cattle removal. These results indicate that subsurface flows are a source of faecal

contamination to streams. In order to simulate this process, a subsurface source of *E. coli* was incorporated into the model. This was achieved through a percolation index, ranging between 0 and 0.1, which is derived through a linear relationship with the amount of percolate for a given cell and day of simulation. The amount of *E. coli* delivered to the stream in percolation is a product of the *E. coli* pool on the soil surface and the percolation index (Eq. (17)), and cannot exceed 10% of the available pool on a given day (typically, however, percolation provides <1% of the available pool). In addition, it is assumed that only percolation generated within 50 m of a stream is capable of delivering *E. coli* to that stream; at distances beyond this, it is assumed that all bacteria will have been filtered out or will have died off prior to reaching the channel.

WAM predicts percolation only as soil water that drains from the base of the lowest modelled soil horizon (90–110 cm deep). In reality, however, considerable lateral subsurface flow may occur, particularly in the near surface layers where *E. coli* concentrations and flow rates are likely to be relatively high. Conceptually therefore, the model prediction of percolating *E. coli* is envisaged to include both lateral and vertical subsurface contributions. *E. coli* supply to the stream in percolation is predicted once die-off and deposits direct to seepage areas and the stream network have been quantified. Fifty percent of the percolation loss in a single event is then released to the nearest reach over that and the following 29 d in a declining exponential relationship with time (Eq. (18)). The remaining 50% is transported to the nearest seepage zone.

$$U = C_p H, \tag{17}$$

$$G = 0.16\,e^{-0.15J}\,U, \tag{18}$$

where U is the *E. coli* within percolating water (*E. coli* d^{-1}), H is a percolation index ranging between 0 and 0.1, J is the number of days after a percolation event occurs and ranges between 0 (the day that percolation occurs) and 29. G is the *E. coli* delivered by percolation to the nearest reach or seepage zone each day (*E. coli* d^{-1}).

2.7. In-stream bacterial dynamics

2.7.1. Entrainment and deposition

The dynamic transfer of bacteria to and from the streambed can result in marked changes in stream bacteria concentrations with time [11]. Both deposition and entrainment within the model are dependent upon flow. Because of the association of bacteria with bed-sediments, the proportion that is entrained within a reach is assumed to follow a power law function as is commonly used for suspended sediment function (Eq. (19)), similar to an earlier model [10]. Values of a

and b were chosen such that the amount of bacteria entrained approached 100% of that available in the bed store during the largest flow event observed over the period of simulation. Deposition was modelled using a similar, but inverse relationship with flow (Eq. (20)). A threshold value of flow was used, above which no deposition occurs. Since flow was only validated at the catchment outlet, the proportion of entrained or deposited bacteria derived for the outlet each day, was assumed to be applicable to all reaches in the stream network.

$$E = B(aQ^b), \tag{19}$$

where E is the *E. coli* entrainment rate (*E. coli* d^{-1}) in a given reach, B is the number of *E. coli* in the bed store of that reach, Q is the mean daily flow at the outlet (m^3 s^{-1}), and a and b are coefficients.

$$D = W(uQ^{-v}), \tag{20}$$

where D is the *E. coli* deposition rate (*E. coli* d^{-1}) in a given reach, W is the number of *E. coli* suspended in the water column of that reach, and u and v are coefficients.

2.7.2. Die-off

Numerous studies have identified those factors that determine bacterial die-off in the water-column [23,24] and, as with die-off on the catchment, temperature and light are of primary importance. These two factors determine simulated water-column die-off, Eq. (21), as for the preliminary model [13], and values for K_R and K_T are the same as those used to model catchment die-off (Eq. (8)). Following a rise of flow above base level, water column die-off is set to zero. This is because predicted flow velocities in the application described indicate that the time of travel from a headwater reach to the catchment outlet is only a few hours during a storm event, limiting the time available for die-off. In addition, suspended sediment concentrations increase with increasing flow so reducing the penetration of sunlight through the water column.

$$W_d = \left(\frac{R}{K_R} + \frac{T}{K_T}\right) W, \tag{21}$$

where W_d is the die off rate of suspended bacteria (*E. coli* d^{-1}).

Bacterial die-off within sediment bed stores remains poorly understood although the association of bacteria with sediment is thought to extend survival due to screening from sunlight, and protection from larger protozoa. Nutrient supply and the hostile behaviour of natural biota [25] appear to be the primary controls upon bed store die-off. These complex processes are not represented within the model, however, and *E. coli* die-off within the bed occurs at a constant rate.

2.8. Mass balance

Since the *E. coli* 'mass' is conserved within the model, the rate of change of *E. coli* within a catchment cell (*E. coli* d^{-1}) is described by

$$\frac{dC_p}{dt} = \omega - L - U - C_d, \tag{22}$$

whilst the rate of change of *E. coli* within a seepage zone (*E. coli* d^{-1}) is

$$\frac{dS_p}{dt} = \zeta - S - C_d, \tag{23}$$

and the rate of change of *E. coli* suspended within a given reach (*E. coli* d^{-1}) can be expressed as

$$\frac{dW}{dt} = \nabla + L + G + E - D - W_d - \Omega, \tag{24}$$

where ∇ is the input of *E. coli* from upstream (*E. coli* d^{-1}), Ω is the outflow of bacteria from the reach (*E. coli* d^{-1}) and L and G represent the delivery of *E. coli* (*E. coli* d^{-1}) from the subcatchment associated with the reach.

3. Model application

The model was applied to the Upper Mangaotama, a 259 hectare, headwater catchment located within the Whatawhata research station ($175°15'$E; $37°47'$S), North Island, New Zealand (Fig. 2). Elevation ranges between 95 and 340 m, and the catchment is characterized by steep slopes, up to $53°$. Mean annual rainfall and mean daily air temperature are 1600 mm and $13.7°$C, respectively. The land was cleared of native forest about 75 years ago and revegetated with clover and pasture grasses, although occasional remnant native trees are still present. Current land use is sheep and beef grazing (2.3:1 ratio as stock units) with an average of 12 stock units per hectare. The catchment is dominated by yellow-brown earth soils that, in places, incorporate or are overlain by, volcanic ash.

WAM and the bacteria model were both applied at a 10×10 m cell size, and 37 subcatchments, each with an associated stream reach, were simulated. Daily rainfall and mean monthly radiation, temperature, and wind data are required as input to WAM and were derived from data recorded at the Whatawhata meteorological station.

Model simulations were conducted for the period from 1 November 2000 to 31 October 2001. Observed streamwater *E. coli* concentrations from the catchment outlet (site A, Fig. 2) and an upper reach (site B, Fig. 2) were available over this period. These were obtained from a fortnightly sampling programme and were used to validate the model predictions. The model was
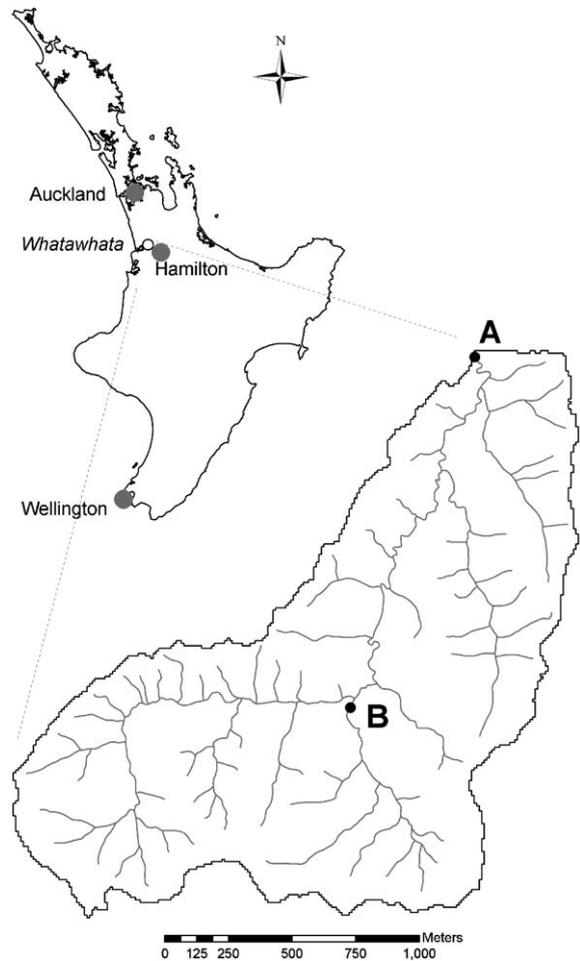

Fig. 2. The location of the Whatawhata research station on the North Island, New Zealand, and the stream network and sampling sites, A (flow and *E. coli*) and B (*E. coli* only) within the Upper Managaotama catchment, Whatawhata.

calibrated to the observed data at the catchment outlet (site A) and verified using the observed time-series from site B. Stock data describing the number and location of sheep and cattle, were available for the period of model simulation. Stock access to the steep headwaters of the catchment ceased in July 2001 on retirement of this area into pine. Cattle were generally, but not exclusively, kept out of fields that enabled access to a stream (B. Carlson—AgResearch, New Zealand, personal communication), but field observations suggested that they generally still had access to seepage zones. Such stock exclusion is the exception in New Zealand hill-country in which livestock usually have unrestricted access to streams.

4. Calibration and results

4.1. Catchment

WAM predicted catchment percolation and surface runoff were 730 and 323 mm, respectively, over the 12-month period of simulation, in response to 1545 mm of rainfall. The number of *E. coli* estimated to reach the stream network varied markedly within and between events due to the variability in rainfall, weather, and stock number and location. Values for K_R and K_T were chosen so that simulated catchment die-off rates (C_d, d^{-1}) ranged between 0.37 and 0.5 in summer and between 0.15 and 0.25 in winter. These are comparable to the range of die-off rates (0.3–0.67 in summer, and 0.22–0.23 in winter) reported for *E. coli* in soil [26].

K was set to 25 mm d^{-1} so that in typical runoff events the model simulated washout (the loss immediately from a deposit) of approximately 5–25% of the available bacterial store. During very large events (occurring perhaps 5 times a year), washout approached 100% of the available store.

Predicted *E. coli* concentrations in surface runoff typically ranged between 10^2 and 10^6 *E. coli* per 100 mL encompassing those observed (10^4–10^6 MPN per 100 mL) on a hillside at Whatawhata during heavy rainfall (authors' unpublished data).

The simulated daily loss of *E. coli* from seepage zones typically ranged between 10^5 and 10^8 *E. coli* d^{-1} and broadly reflected results from field monitoring of seepage areas accessed by cattle [16].

4.2. In-stream

Simulated mean daily flow provided an acceptable reproduction of the observed values, although some discrepancies are apparent at both high and low flow (Fig. 3). Observed flow peaked sharply (>800 L s^{-1}) during two storm events, but otherwise rose no greater than 500 L s^{-1} in response to rainfall. Flow fell to a minimum, <20 L s^{-1}, during early February 2001.
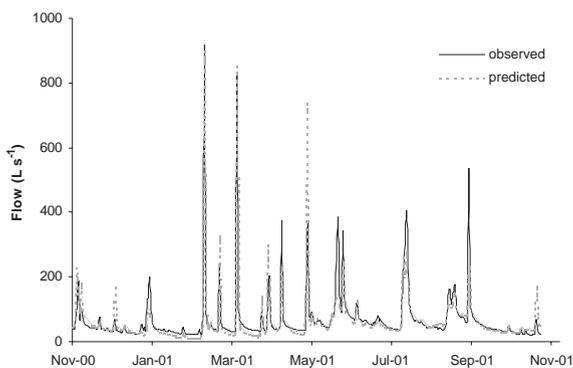
The model broadly reproduced the observed pattern of *E. coli* concentrations in the outflow reach (Fig. 4). Both predicted and observed concentrations typically vary between 5×10^1 and 10^3 *E. coli* per 100 mL during periods of low flow, whilst, during storm events, predicted concentrations vary between 10^3 and 10^4 *E. coli* per 100 mL. The simulated storm period response is only partially validated, however, since the observed concentrations are primarily limited to periods of low to moderate flow. A broad correlation between flow and concentration is apparent, although the number of stock, their location, and antecedent flows all influence this relationship. During the three largest flood events, the magnitude of flow appears to limit the predicted *E. coli* concentration. In reality, these events probably entrained a near channel pool of *E. coli* by overbank flow, a process not captured by the model. The scatter plot (Fig. 5) illustrates correlation between observed and predicted values (Pearson's correlation coefficient = 0.71; Spearman's rank correlation coefficient = 0.48), with considerable scatter apparent. The mean daily time-step of the model contributes to discrepancies between observed and predicted values. For example, the presence of cattle within a stream leads to the deposition of faecal material direct to the water column and a disturbance of the bed causing bacteria to be entrained. Sampling during or immediately following such cattle activity is likely to result in elevated bacterial concentrations that the model, using a daily time step, is unable to reproduce. In-stream cattle activity is the likely cause of the maximum observed concentration of 6×10^4 MPN per 100 mL recorded during low flow in December 2000 (Fig. 4). Additionally, *E. coli* concentrations have been observed to rapidly vary 2–3 orders of magnitude in response to changes in flow [11], behaviour that is not captured by the model.

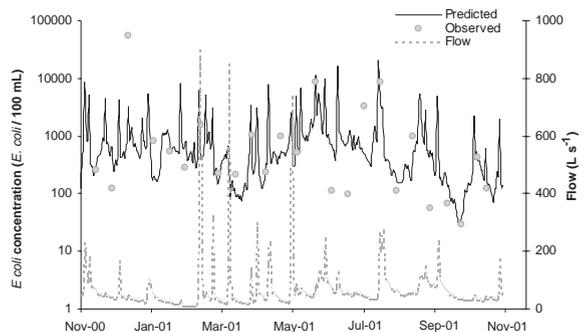Fig. 3. Observed and predicted mean daily flow (L s^{-1}) at the catchment outlet (Site A).

Fig. 4. Predicted mean daily *E. coli* concentrations (*E. coli* per 100 mL), instantaneous observed *E. coli* concentrations (MPN per 100 mL), and predicted mean daily flow (L s^{-1}) at the catchment outlet (Site A).

The total daily *E. coli* flux in the outflow over the course of the simulation varies markedly, between 9×10^8 and 2×10^{12} *E. coli* d^{-1}. Simulated water column die-off rates (at baseflow) are the same as catchment die-off rates, and are encompassed by the wide range of values found in the literature [24,27].

Simulated numbers of *E. coli* in the outflow reach bed store (Fig. 6) ranged between 10^7 and 10^{11} *E. coli*, reflecting reworking of the store through entrainment and deposition. These values represent an approximate concentration range of up to 10^9 *E. coli* per m^2 of stream bed, and are broadly comparable to those entrained by artificial floods (10^3–10^9 MPN m^{-2}) in a nearby, but more lowland stream [28]. During moderate storm events, the model simulates entrainment of bacteria within, and therefore loss from, the outflow reach. This loss is replenished, however, by bacteria entrained and transported from upstream and the net result is generally no significant change in the outlet bed store of bacteria. During large events, entrainment is greater and little or no deposition occurs, causing marked depletion of the outflow bed store as with the series of large floods from early February to late May 2001 (Fig. 6). During dry periods, assuming flow is low enough to promote deposition, *E. coli* from seepage zones, percolation and direct deposition, gradually replenish the bed store.

The model broadly reproduces observed concentrations in the upper reaches of the catchment (Fig. 7). Marked discrepancies are apparent, however, particularly during June 2001 when overprediction of up to an order of magnitude occurs.

5. Sensitivity analysis

Considerable uncertainty exists about many of the processes represented and coefficients used within the model. Simulations were undertaken to assess the model sensitivity to particular parameters. These focused upon the relative contribution of overland flow, excretion directly to streams, and onto seepage areas. Whilst it is recognized that uncertainty with other processes may also influence the model predictions, die-off rates broadly reflect those in the literature, and subsurface delivery of bacteria is thought not to be marked due to filtration by the soil matrix.

The model's sensitivity to the delivery of bacteria by surface runoff was explored by varying the stream proximity coefficient (K_d, Eq. (11)). In the baseline simulation, the stream proximity coefficient (K_d) was set to 0.025 so that at a distance of 50 m the proportion of bacteria (within a cell) that can potentially be delivered to the nearest stream network falls to c. 15%. In the sensitivity analysis, K_d was set, in turn, to
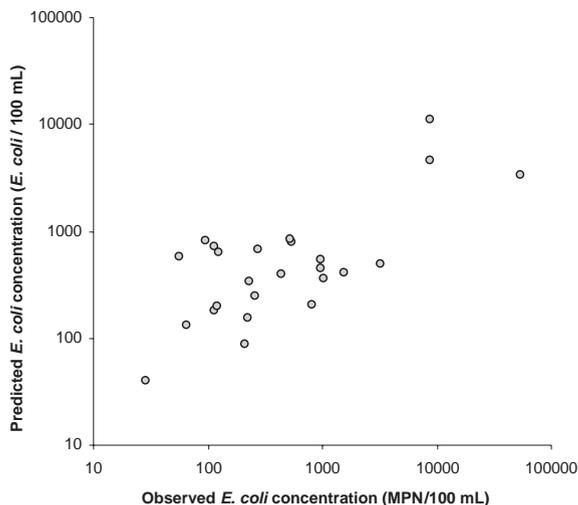

Fig. 5. Scatter plot illustrating the relationship between predicted mean daily (*E. coli* per 100 mL) and instantaneous observed *E. coli* concentrations (MPN per 100 mL) in the catchment outlet (Site A).
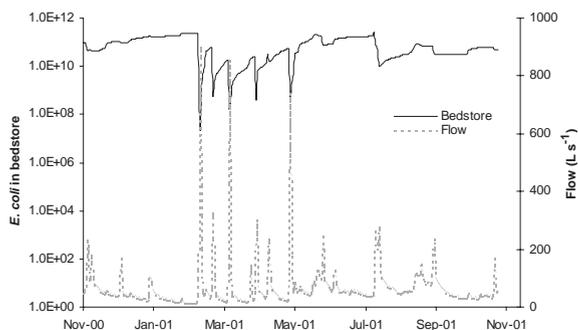

Fig. 6. Predicted mean daily flow (L s^{-1}) and predicted total number of *E. coli* in the outlet bedstore (site A).
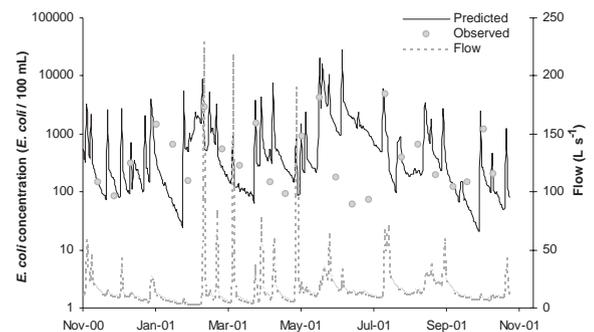

Fig. 7. Predicted mean daily *E. coli* concentrations (*E. coli* per 100 mL), instantaneous observed *E. coli* concentrations (MPN per 100 mL), and predicted mean daily flow (L s^{-1}) in an upper reach (Site B).

0.25 and 0.0025, and the potential delivery at 50 m was effectively zero, and 45% respectively. The impact upon *E. coli* concentrations at the catchment outlet is marked (Fig. 8), and the model is clearly sensitive to the distance over which bacteria are delivered to the stream network. The difficulty in quantifying delivery by surface runoff is likely to impart an uncertainty of about $\pm 10^3$ *E. coli* per 100 mL to the modelling predictions during average storm events. Fig. 8 also illustrates the influence of the number of stock, with the greatest delivery of bacteria by surface runoff not necessarily occurring during the largest events. The model is also sensitive to the proportion of bacteria that are excreted directly onto seepage zones (Fig. 9). Setting seepage zone excretion to zero across the catchment results in a clear decrease in simulated *E. coli* concentrations at the catchment outlet. The exclusion of cattle from seepage zones may therefore have benefits with respect to bacterial water quality.

Varying the percentage of *E. coli* excreted directly to streams, between 1% and 15%, showed no marked

impact (<200 *E. coli* per 100 mL) upon stream concentrations. This can be attributed to the policy of exclusion of cattle from streams over the period of simulation. To better assess the model sensitivity to direct deposition, the stock record for the catchment area above site B was modified: for most of the period of model application, between five and 25 cattle were simulated to be present in fields that allowed them access to streams. This was in addition to sheep grazing that remained unaltered from the genuine stock record. In contrast to predictions using the genuine stock record, the resulting simulations (Fig. 10) show a more marked sensitivity to varying direct deposition between 1% and 15%.

6. Scenario analysis

A key long-term objective of the model development is to improve assessment of the influence of land management practices upon faecal contamination. One such scenario has been explored: the impact of riparian retirement. Permanent fencing to exclude livestock from stream channels and a proportion of riparian land is recognized as, potentially, an effective measure to reduce faecal contamination by grazing cattle. Any such benefits would be achieved by preventing the deposition of faecal material direct to streams and near-channel contributing areas. Additionally, the dense vegetation associated with riparian buffer strips theoretically reduces the momentum of surface runoff, and traps faecal material within it. Two riparian retirement simulations were conducted. The first used the original grazing record (with limited stream access) and encompassed the whole of the catchment including headwater streams. The second used the modified grazing record and was run only for the catchment above site B.
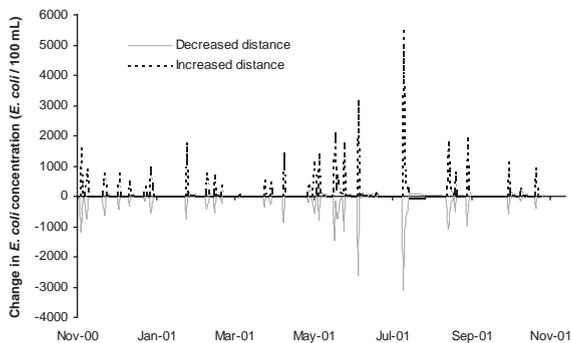

Fig. 8. Predicted change in *E. coli* concentration in the outlet (*E. coli* per 100 mL) in response to increasing ($K_d = 0.0025$) and decreasing ($K_d = 0.25$) the distance over which surface runoff can potentially deliver bacteria to the nearest stream reach, relative to the baseline simulation ($K_d = 0.025$).
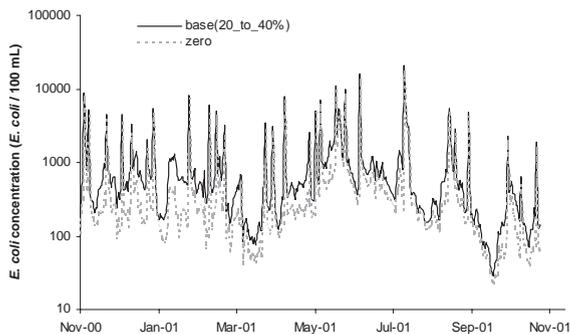

Fig. 9. The impact of varying the *E. coli* excretion rate (as a percentage of total *E. coli* excreted) to seepage areas upon concentrations (*E. coli* per 100 mL) in the catchment outlet (Site A).
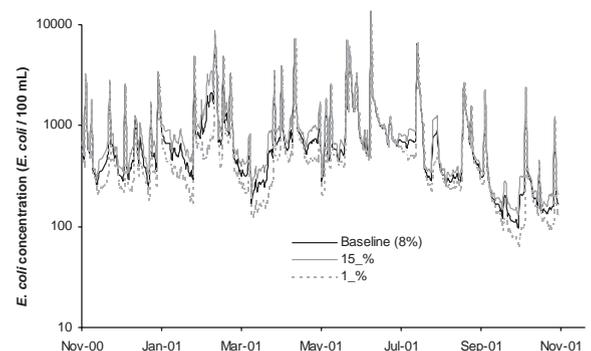

Fig. 10. The impact of varying the percentage of faecal material deposited directly to streams. Predictions of *E. coli* concentration (*E. coli* per 100 mL) are illustrated for site B, and incorporate a simulated stock record whereby cattle had access to streams.

Riparian retirement was incorporated within the model by excluding deposition directly to streams and to those grid cells adjacent to them, thereby simulating stock exclusion from within 10 m of a stream. GLEAMS was used to determine the relationship between the amount of surface runoff and sediment trapping efficiency for a 10 m wide grass buffer. The modelled buffer was represented by a greater hydraulic roughness than that of the grazed pasture upslope, this therefore simulated a greater flow resistance as surface runoff flowed into a buffer strip. Relationships were derived for the range of soil types, slope angles and slope curvatures within the Upper Mangaotama catchment, and were assumed to be applicable to bacteria. This assumption may have led to an over-estimate of the trapping efficiency of buffer strips with respect to *E. coli*; although many bacteria are likely to be transported attached to sediment, others may be entrained within surface runoff as dispersed coliform-forming units, and may be less readily trapped. One relationship was applied per subcatchment using the dominant soil type, and typical slope angle and curvature. Typically, these described a non-linear relationship whereby trapping efficiency reached >80% during small events, but fell to <10% during very large events. The rate of excretion of *E. coli* onto seepage zones, and the drainage of bacteria from them was assumed to be unaffected by the riparian planting. All bacteria trapped within a riparian strip were assumed to die, and could not therefore be washed out in subsequent events. Field studies [29] provide support for this assumption.

The impact of the first riparian simulation upon concentrations in the catchment outlet, relative to the baseline simulation, is illustrated in Fig. 11. Predicted percentage reductions in *E. coli* concentration range
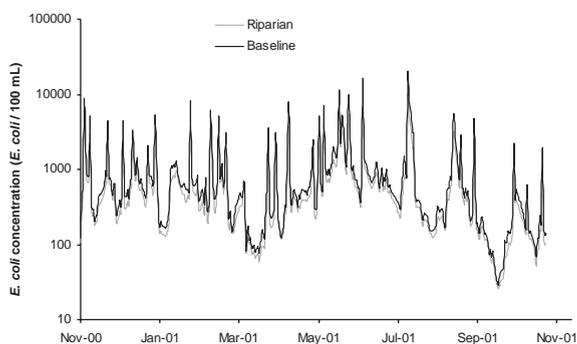

Fig. 11. The impact of riparian retirement, 10 m either side of all reaches, upon *E. coli* concentrations (*E. coli* per 100 mL) in the catchment outlet (site A). The baseline simulation used a grazing record whereby stock were mostly excluded from streams.
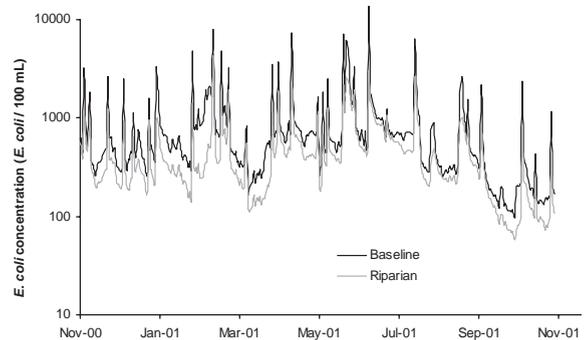

Fig. 12. The impact of riparian retirement upon *E. coli* concentrations (*E. coli* per 100 mL) at site B, both the baseline and riparian predictions incorporate a simulated stock record. Under the baseline simulation cattle had access to streams.

between 2% and 57% with a median decrease of 22%. It is important to note, however, that over the period of simulation an effort was made by farm managers to limit the accessibility of cattle to streams, and this was reflected in the record of stock location incorporated into the model. The predictions under this simulation may therefore under-represent the improvement expected from riparian retirement within hill-country catchments. The second riparian simulation illustrates a more marked decrease in concentrations at site B, using the constructed stock record (Fig. 12). The predicted decrease in *E. coli* concentration, relative to baseline, ranges between 3% and 82%, with a median of 35%.

7. Conclusions

A dynamic bacterial water quality model that couples catchment and in-stream processes has been developed for grazed hill-country catchments in New Zealand. The model builds on a preliminary development [13]. A daily record of grazing livestock enables estimation of the number of *E. coli* excreted onto a catchment. Transport of *E. coli* from the catchment to the stream network is simulated within surface and subsurface flows, and excretion of *E. coli* directly to streams is incorporated where cattle have access to them. Areas of permanent soil saturation or seepage zones are also represented within the model. These zones occur extensively throughout the hill-country and much of the drainage from a catchment flows through them. Field studies have shown that cattle are attracted to seepage zones for grazing, depositing considerable faecal material upon them, so excretion of *E. coli* onto seepage zones is represented within the model. The catchment loss of *E. coli* is linked to an in-stream component that routes

bacteria down the stream network. In-stream processes of entrainment, deposition and die-off are also simulated, and the model provides mean daily predictions of streamwater *E. coli* concentrations.

Despite the ability of the model to broadly reproduce observed *E. coli* concentrations in a rural stream, considerable uncertainty exists with respect to some of the processes represented. This limits confidence in the assessment of the impact of various management practices upon levels of faecal contamination. Understanding of the relationship between the delivery of bacteria within surface runoff and stream proximity is particularly limited. Field studies are desirable to quantify the variation of delivery with slope, soil, and distance to stream. Similarly, although the role of seepage zones as a source of faecal contamination has been identified, understanding of their behavior remains incomplete (for example, the moist shady conditions within seepage zones may aid microbial survival, relative to elsewhere upon the hillside), and model representation is currently based on a preliminary field study.

The model was shown to be sensitive to the delivery of bacteria by surface runoff, and the excretion rate of *E. coli* to seepage zones. Excluding cattle from seepage zones may therefore improve bacterial water quality. Using the observed record of stock history, little sensitivity was apparent with respect to the excretion rate of *E. coli* direct to the stream network. This is because the simulation encompassed a period during which farm managers attempted to minimize cattle access to streams. Greater sensitivity was apparent, however, through the use of a constructed stock record whereby cattle were simulated to graze in fields with unrestricted access to streams. Cattle behaviour studies are required to improve quantification of direct deposition.

An initial exploration of the impact of riparian retirement predicted an improvement in bacterial water quality with a reduction in both peak and baseflow *E. coli* concentrations. The predicted decreases ranged between 2% and 57% (with a median of 22%) using the observed stock record whereby, under recent changes in land management, stock were generally excluded from streams. Use of a simulated stock record that permitted stock access to streams typically predicted a greater decrease in *E. coli* concentration (3–82%, with a median of 35%) in response to riparian retirement. Whilst riparian retirement is predicted to lead to improved bacterial water quality, the steep topography of the catchment appears to limit the efficiency of riparian buffer strips in attenuating faecal microbes. The simulation of riparian entrapment here may represent a best-case scenario since all bacteria were assumed to enter a buffer strip attached to sediment. In reality, a number of bacteria may be transported as dispersed coliform-forming units, rendering them less susceptible to entrapment. However, little information has been published regarding bacterial attachment to sediment despite the likely importance of this process in determining microbial transport by surface runoff and entrapment within riparian vegetation. Consequently, uncertainty remains as to the efficiency of riparian buffer strips in attenuating faecal microbes.

Acknowledgements

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