

Explaining Differential Timing of Peaks of a Pathogen Versus a Faecal Indicator During Flood Events

McBride, G.B.¹ and M.N. Mittinty¹

¹ NIWA (National Institute of Water and Atmospheric Research), Hamilton, New Zealand

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EXTENDED ABSTRACT

During a flood event two separate entrainment phenomena commence. First, the rain water flowing overland towards the stream's banks entrains bacteria from faecal material deposited on the land during preceding dry weather. Second, the water in the streams has sufficient downstream velocity to entrain faecal material from the stream sediments and banks. However, recent sediment monitoring in a Waikato (New Zealand) stream draining intensive pastoral agriculture indicate that the important zoonotic pathogen *Campylobacter* may generally be absent from stream sediments, whereas an associated faecal indicator (*E. coli*) may be abundant. This observation provides the motivation for studying the differential timing of peaks of *Campylobacter* versus *E. coli*. Such timing behaviour has been observed during storm flood events, as shown in the following figure.

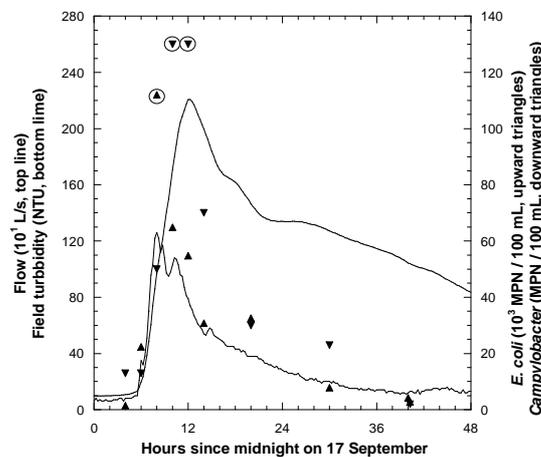


Figure 1. Concentrations of *E. coli* (Colilert[®]) and *Campylobacter* (MPN) measured on autosamples taken over a flood event in the Toenipi Stream, Waikato, New Zealand in September 2005, along with flow and turbidity. Peak microbial concentrations are annotated by ovals.

We seek to mimic this differential peak timing behaviour using a mathematical model based on kinematic wave theory. This has three main equations, for: (i) flow hydraulics, (ii) concentration of bacteria in the stream sediments, and (iii) concentration of bacteria in the stream water. These are solved using standard numerical techniques; analytical solutions have not been found (and may not exist). The solutions are for a standard test case reported in the literature, extended to include lateral inflow and entrainment. Results indicate that this relatively simple model can mimic the pattern found in the field, at least for the rising limb of the hydrograph. That is, the *E. coli* peak arrives before the flood peak, whereas the *Campylobacter* peak is coincident with, or follows after, that peak. The *E. coli* peak timing is consistent with the idea that these bacteria, being resident in the stream sediments, can be “mined” by the kinematic wave front which travels faster than the cross-section average water velocity. The *Campylobacter* peak timing is also consistent with kinematic wave theory when considering land runoff sources of the bacterium. It indicates that *Campylobacters* may enter streams through storm runoff, rather than via sediment entrainment, a result that could have important practical implications for the choice of effective Best Management Practices on farms.

However, it must be noted that the predicted concentrations after the arrival of the flood peak indicate that the model is probably not mimicking that region in a plausible manner. Further investigations of this kinematic wave approach appear to be called for, especially to examine at least five areas: (i) the influence of the ratio of duration of lateral inflow versus catchment time of concentration; (ii) time variation of lateral inflow concentration and flow; (iii) adoption of implicit difference equations (to reduce numerical dispersion in the results); (iv) using different entrainment assumptions; (v) examination of physical settings similar to those obtaining in streams monitored for both *E. coli* and *Campylobacter*. Such studies will be necessary to generalise, if possible, the results obtained herein.

1. INTRODUCTION

New Zealand's reported rates of zoonoses are dominated by campylobacteriosis, a situation that has been worsening in recent years (Till & McBride 2004). This disease is caused by the pathogenic *Campylobacter* bacterium. Animals are its major "reservoir", and so identifying effective intervention strategies to minimise its transmission to humans requires consideration of its transport characteristics over land and in freshwater streams. However, management of faecal contamination of streams seldom relies on measurements of pathogens such as *Campylobacter*, using instead an "indicator bacterium" such as *E. coli*. These bacteria indicate both the general level of faecal contamination and also associated health risks to recreational water users. There are therefore good reasons why water quality managers should rely on such a faecal indicator bacterium. These include costs, and the lack of knowledge about which pathogen(s) should be assessed, given that some can be present when others are absent.

However, when investigating the behaviour of *Campylobacter* in the environment, care is needed to differentiate the deposition, survival and transport of *Campylobacter* versus *E. coli*. Experimental and field studies are indicating substantial differences between the behaviour of these two bacteria, in that: (i) *E. coli* are constantly shed by animals, whereas *Campylobacters* are shed only by infected animals, so that the depositional load is proportional to the bacterium's prevalence in local animal populations (Skelly & Weinstein 2003); (ii) laboratory and field studies show that the inactivation of *Campylobacter* under solar radiation is much faster than the equivalent rate for *E. coli* (Obiri-Danso *et al.* 2001, Sinton *et al.* 2007); (iii) field survival studies of bacterial dynamics within cowpats show that T_{90} values for *E. coli* are much larger than their values for *Campylobacter* (Sinton *et al.* submitted), and more recent studies for sheep pellets are demonstrating similar results (pers. comm., Dr L. Sinton, ESR, Christchurch, New Zealand); (iv) the peak concentration of *Campylobacter* in stream floods is roughly coincident with the flood peak, whereas the *E. coli* maximum occurs earlier, generally coincident with the turbidity peak (Donnison *et al.* 2006—see the example in Figure 1); (v) stream sediments can be replete with *E. coli* yet depauperate in *Campylobacter* (Snowsill 2007)—a result that had been anticipated by Donnison *et al.* (2006).

Item (v) has been used heuristically (pers. comm. Dr R. Davies-Colley, NIWA, New Zealand) to explain the differential timing of the flood

pollutographs for *E. coli* and *Campylobacter*, noted in item (iv). (Items (i)–(iii) will also have a bearing on this explanation, particularly to do with the relative magnitudes of the peaks.) This paper presents a simple conceptual model of these timing phenomena, and presents preliminary numerical solutions that may be used to investigate them—analytical solutions to these equations have proved elusive, and may not exist.

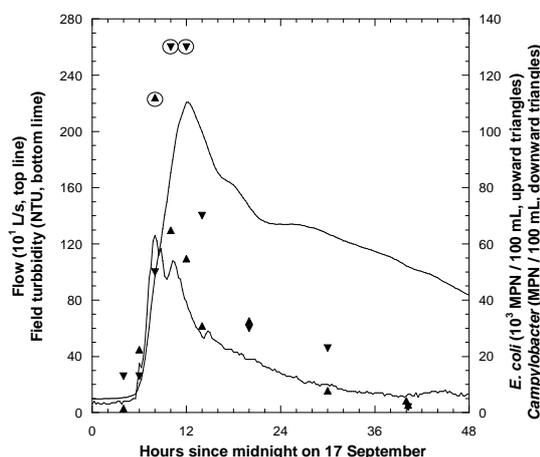


Figure 1. Concentrations of *E. coli* (Colilert®) and *Campylobacter* (MPN) measured on autosamples taken over a flood event in the Toenipi Stream, Waikato, New Zealand in September 2005, along with flow and turbidity. Peak microbial concentrations are annotated by ovals. (Source of data: Donnison *et al.* 2006, Lydiard & Davies-Colley 2006).

2. SIMPLE CONCEPTUAL MODEL

Consider a stream segment downstream of a dam outlet at the end of which a monitoring station is located. During a prolonged dry period, animals have been defaecating onto the riparian land and stream banks, and also directly into the stream, so filling up the land and sediment "stores" of faecal microbes (Muirhead *et al.* 2004). At time zero, rain begins to fall at a steady rate for a defined period. During this time the land runoff along the stream length is constant; after that time it ceases completely. The baseflow (from the dam) does not change during this event.

As the rain begins to fall, two separate entrainment phenomena commence. First, the water flowing overland toward the stream's banks entrains bacteria from soil and from faecal deposits on the land. Second, once this water enters the stream and combines with the baseflow from the dam, it has sufficient downstream velocity to entrain faecal material from the stream sediments and banks. Both these processes are flow-dependent.

Generally, one could expect that both processes would occur during a storm event. However, as noted item (v) above, there are indications that *Campylobacter* may generally be absent from stream sediments. This observation provides the motivation to consider two separate cases. First, where all *Campylobacter* in the stream water have been entrained from the land surface; and second, where all *E. coli* in the water have been entrained from the sediments only. The latter case is taken as an extreme example to exemplify the difference between the origin and transport of these two microbes. It is extreme because *E. coli* are also entrained from the land surface during flood events (Collins *et al.* 2007); nevertheless considerable elevations in stream concentrations of *E. coli* do occur during artificial flood events during which no land runoff occurs (Nagels *et al.* 2002, Muirhead *et al.* 2004).

To give quantitative effect to this simple model, we use the kinematic wave model in the form presented by Chapra (1997), extended to include both lateral inflow and sediment entrainment.

2.1. Assumptions about lateral inflow

We note that the first runoff flush can be expected to result from higher bacteria entrainment rates than later in the storm. However, the lateral land distance over which the former entrainment has occurred will be smaller than that occurring later in the storm when the entrainment rate *at a point* is lower, but the distance over which entrainment occurs is longer—compensating for the higher point-wise entrainment rate. Accordingly, during the constant overland flow period the delivery of bacteria to the stream could possibly be taken as zero-order (constant) during the runoff period; that is,

$$M_l = qC_l \quad (1)$$

where M_l [# T⁻¹ L⁻¹] is the land-derived bacteria delivery rate per unit channel length (“#” denotes numbers of bacteria), q [L² T⁻¹] is the overland flow rate per unit channel length, and C_l [# L⁻³] is the concentration of microbes in the lateral inflow. Both q and C_l are taken as constants.

2.2. Assumptions about entrainment

For in-stream processes, we assume that the finiteness of the sediment microbial store demands that the bacterial entrainment rate is first-order and proportional to the remaining store after entrainment has commenced. Also, following Valentine & Wood (1979) (see also Rutherford

1994), that rate is taken to be proportional to the floodflow velocity excess, that is,

$$M_s = e_s \left(\frac{U - U_b}{U_b} \right) S \quad (2)$$

where M_s [# T⁻¹ L⁻¹] is the delivery rate of entrained bacteria per unit channel length, e_s [T⁻¹] is the stream entrainment coefficient, U [L T⁻¹] is the cross-section average flow velocity (with value U_b at baseflow from the dam outlet), and S [# L⁻¹] is the store of bacteria in the stream sediments and banks per unit channel length. Entrainment occurs when $U > U_b$ but there is deposition when $U < U_b$.

3. TRANSPORT EQUATIONS

Three main equations are needed, for: (i) flow hydraulics (the “continuity equation”), (ii) concentration of bacteria in the stream sediments, and (iii) concentration of bacteria in the stream water. The continuity equation is derived using kinematic wave theory, for two reasons. First, the resulting equation is simpler than alternatives based on full consideration of momentum conservation. Second, recent results do show the importance of kinematic flood waves even in small streams, in that “there is a lag in the arrival of the flood water behind the rise in stage” (Krein & De Sutter 2001). Furthermore, Wilkinson *et al.* (2006) have postulated that the timing of peak faecal coliform bacteria concentrations during floods may be related to the passage of kinematic waves.

Analytical solutions to the *differential* equations we derive have not been found, and may not exist. Accordingly we approximate them by explicit *difference* equations for which solutions are obtained by standard numerical methods. Explicit (cf. implicit) methods have been chosen to simplify the computations, which were performed using Microsoft VisualBasic.

3.1. Continuity equation

Application of mass conservation principles leads to the well-known equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (3)$$

where A [L²] is the stream cross-section area, Q [L³ T⁻¹] is the stream discharge (with baseflow value Q_b , at the dam), x [L] is distance along the channel, and t [T] is time since flood commencement— q has been defined above. Each term in (3) has units [L² T⁻¹].

Following Chapra (1997), we adopt the key assumption of kinematic wave theory—that the discharge is a function of depth alone—and use the metric units form of the Manning equation

$$Q = \frac{1}{n} \frac{A^{5/3}}{P^{2/3}} \sqrt{\theta} \quad (4)$$

where θ [dimensionless] is the channel slope, P [L] is the wetted perimeter, and n [dimensionless] is the Manning roughness coefficient. This equation can be solved for

$$A = \alpha Q^\beta \quad (5)$$

where

$$\beta = \frac{3}{5} \text{ and } \alpha = \left(\frac{n P^{2/3}}{\sqrt{\theta}} \right)^{3/5} \quad (6)$$

The value of α becomes nearly constant for a rectangular channel much wider than it is deep—because we then have $P \approx B$, where B [L] is the channel width. The value of α is then

$$\alpha \approx \left(\frac{n B^{2/3}}{\sqrt{\theta}} \right)^{3/5} \quad (7)$$

Differentiating (5) with respect to time and substituting the result into (3) we have the kinematic wave equation (Chapra 1997) augmented by lateral inflow

$$\frac{\partial Q}{\partial x} + \alpha \beta Q^{\beta-1} \frac{\partial Q}{\partial t} = q \quad (8)$$

By substituting forward-time/backward-space differences, (8) can be represented by the approximate difference equation

$$\frac{Q_i^n - Q_{i-1}^n}{\Delta x} + \alpha \beta (Q_i^n)^{\beta-1} \left(\frac{Q_i^{n+1} - Q_i^n}{\Delta t} \right) \approx q \quad (9)$$

where, for example, $Q_i^n = Q(i\Delta x, n\Delta t)$, etc., such that $i = 1, 2, \dots, i_{\max}$ and $n = 0, 1, 2, \dots, n_{\max}$ (i counts downstream distance steps; n counts time steps). This can be solved explicitly for the unknown stream discharge

$$Q_i^{n+1} \approx Q_i^n + (U_c)_i^n \left(\frac{Q_{i-1}^n - Q_i^n}{\Delta x} + q \right) \Delta t \quad (10)$$

in which

$$U_c = \frac{Q^{1-\beta}}{\alpha \beta} \quad (11)$$

is the celerity of the kinematic wave [L T⁻¹]. This is always greater than the cross-section average velocity of the stream water (Chapra 1997, pp. 255–256), defined by $U = Q/A$.

3.2. Sediment bacteria equation

We assume that the bacteria (and sediment) in the stream bed do not move downstream whilst in the bed, but can be entrained into the water column and so be convected downstream in the water (so there is no $\partial/\partial x$ term). In that case we simply have

$$\frac{\partial S}{\partial t} = -e_s \mu S : \mu = \frac{U - U_b}{U_b} \quad (12)$$

where all variables are as defined earlier (Section 2.2). Each term in (12) has units [# L⁻¹ T⁻¹]. Using backward-time differencing for the temporal derivative, the approximating difference equation is

$$S_i^{n+1} \approx (1 - e_s \mu_i^n \Delta t) S_i^n \quad (13)$$

The initial density of bacteria in the bed, S_0 [# L⁻¹], is taken to be constant down the channel.

3.3. Aquatic bacteria equation

From mass conservation principles we obtain

$$\frac{\partial AC}{\partial t} + \frac{\partial QC}{\partial x} = q C_i + e_s \mu S : \mu = \frac{U - U_b}{U_b} \quad (14)$$

where $C(x, t)$ [# L³] is the concentration of bacteria in the stream water—all other variables have been defined. Each term in (14) has units [# L⁻¹ T⁻¹]. Using backward-time differencing for the temporal derivative and defining a segment volume as $V = A\Delta x$, the approximating difference equation is

$$\frac{(VC)_i^{n+1} - (VC)_i^n}{\Delta t} \approx \quad (15)$$

$$(QC)_{i-1}^n - (QC)_i^n + (q C_i + e_s \mu_i^n S_i^n) \Delta x$$

Now, noting that the lateral inflow adds a volume of $q\Delta x\Delta t$ to each segment during each time step, we can write the term $(VC)_i^{n+1}$ as

$$(VC)_i^{n+1} = [V_i^n + (Q_{i-1}^n - Q_i^n + q\Delta x)\Delta t] C_i^{n+1} \quad (16)$$

Substitution into (15) gives

$$C_i^{n+1} \approx \frac{V_i^n C_i^n + [Q_{i-1}^n C_{i-1}^n - Q_i^n C_i^n + (qC_l + e_s \mu_i^n S_i^n) \Delta x] \Delta t}{V_i^n + (Q_{i-1}^n - Q_i^n + q \Delta x) \Delta t} \quad (17)$$

The numerator represents the mass in the segment i at the previous time step, while the denominator represents its volume.

3.4. Difference equations to be solved

The main difference equations are (10), (13) and (17). In solving them we make use of ancillary equations [(5) and (11)] along with appropriate initial conditions and boundary conditions.

4. RESULTS

Before applying the model to a problem with lateral inflow and sediment entrainment, we first checked its performance against a test case reported by Chapra (1997). This concerns an 80 km rectangular channel with a sinusoidally varying boundary condition (at the dam) for discharge (Q) containing a constant bacteria concentration (C). The parameters and inputs are listed on Table 1.

Table 1. Chapra test case inputs.

Variable	Value	Units
Baseflow, Q_b	2.5	$\text{m}^3 \text{s}^{-1}$
Channel slope, θ	0.004	–
Bottom width, B	15	m
Manning's coefficient, n	0.07	–
Distance step, Δx	1000	m
Time step, Δt	600	s

Our results exactly matched those reported by Chapra (1997). We then applied the model to the same channel, but now with constant upstream flow boundary condition ($Q_b = 2.5 \text{ m}^3 \text{ s}^{-1}$, $C_b = 0$), with entrainment and lateral inflow variables given in Tables 2 and 3.

Table 2. Inputs for *E. coli* case.

Variable	Value	Units
Initial bed density, $s_0 (= S_0/B)^a$	10^8	$\# \text{ m}^{-2}$
Entrainment coefficient, e_s ,	40	per day
Lateral inflow, q	0.5	$\text{L s}^{-1} \text{ m}^{-1}$
Concentration in the lateral inflow, C_l	0	per 100 mL
Inflow duration	0–6	h

^a pers. comm. Dr R. Davies-Colley, NIWA, New Zealand

Table 3. Inputs for *Campylobacter* case.

Variable	Value	Units
Initial bed density, $s_0 (= S_0/B)$	0	$\# \text{ m}^{-2}$
Entrainment coefficient, e_s ,	0	per day
Lateral inflow, q	0.5	$\text{L s}^{-1} \text{ m}^{-1}$
Concentration in the lateral inflow, C_l	100	per 100 mL
Inflow duration	0–6	h

Results from these simulations are displayed on Figures 2 and 3.

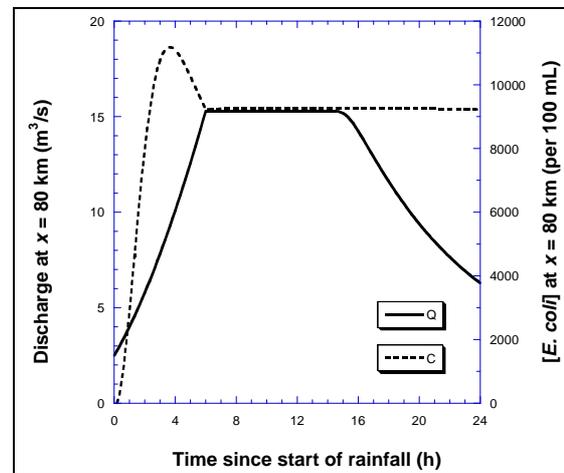


Figure 2. Results for the *E. coli* case. *E. coli* concentration is denoted by the dashed line.

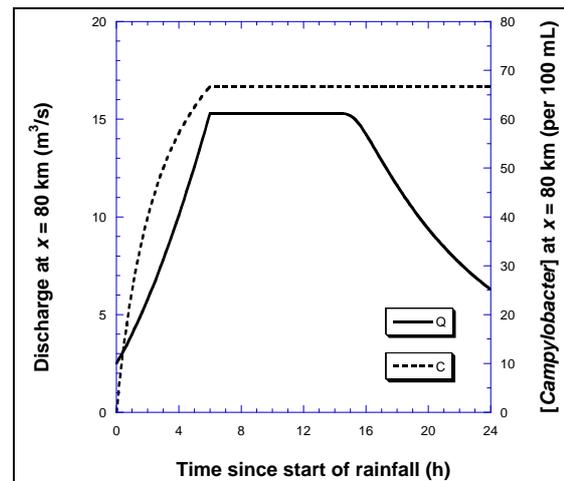


Figure 3. Results for the *Campylobacter* case. *Campylobacter* concentration is denoted by the dashed line.

5. DISCUSSION AND CONCLUSION

The results of this test case for the rising limb of the hydrograph on Figures 2 and 3 display some features of the pattern observed in field data shown on Figure 1. That is, the *E. coli* peak arrives before the flood peak (Figure 2), whereas the *Campylobacter* peak is coincident with the flood peak, as is also observed. That is, this relatively simple model can mimic the pattern found in the field for the rising limb of a flood hydrograph. In particular, the arrival of the *E. coli* peak ahead of the flood peak is consistent with the idea that *E. coli*, being resident in the stream sediments, can be “mined” by the kinematic wave front which travels faster than the cross-section average water velocity. In contrast, the *Campylobacter* peak coincides with, or even could follow after, the flood peak. This is consistent with the observation that kinematic wave theory can show that that “the pollutograph lags the hydrograph” (Chapra 1997), particularly in the absence of a lateral inflow and presence of bacteria in the water discharged from the dam. It indicates that *Campylobacters* may enter streams through storm runoff, rather than via sediment entrainment, and this could have important practical implications for the choice of effective Best Management Practices on farms, a topic of increasing interest in New Zealand—Lake *et al.* (2007), McBride & Chapra (in prep.).

However, it must be noted that the predicted concentrations after the arrival of the flood peak indicate that the model is probably not mimicking that region in a plausible manner (even though the plateau in the hydrograph is consistent with kinematic wave theory—Henderson 1966). This may reflect the inappropriateness of the assumption that the concentration and flow of the lateral inflow are constant.

Further investigations of this kinematic wave approach appear to be called for, especially noting the view stated by Singh (2002) that little work has been reported on kinematic microbial transport in surface water systems. In doing so, a number of considerations should arise:

- the influence of the ratio of duration of lateral inflow versus catchment time of concentration;
- time variation of lateral inflow concentration and flow
- adoption of implicit difference equations (to reduce numerical dispersion in the results);
- using different entrainment assumptions

- application of the model to physical settings similar to those obtaining in streams monitored for both *E. coli* and *Campylobacter*.

Such studies will be necessary to generalise, if possible, the results obtained herein.

6. ACKNOWLEDGEMENTS

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