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Hydrograph-based approach to modeling bacterial fate and transport in rivers

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ABSTRACT

A new approach, called hydrograph-based approach, is proposed for predicting bacterial concentrations in rivers. The new approach is relatively simple and efficient in terms of data requirements. It uses widely available hydrographs as the main input data for estimating flow and sediment transport parameters responsible for bacterial transport under varying flow conditions. The major component of the hydrograph-based approach is a new model, called VARTBacT model which is an extension of the Variable Residence Time (VART) model by including effects of unsteady flow, sediment transport, and bacterial decay/growth processes on bacterial transport and fate in rivers. The applicability of the new hydrograph-based approach is demonstrated through three case studies, each with distinct sediment and flow conditions: (1) steady low flow without sediment transport, (2) flood events with significant sediment transport due to watershed inputs, and (3) sediment resuspension from the streambed. While the sediment resuspension from streambed may be an important process for bacterial transport during high flows, results from this study indicate that the most important mechanism responsible for bacterial transport in streams is watershed loading during flood events and hyporheic exchange during low flow periods.

1. Introduction

Bacterial concentrations in rivers have been observed to be often much higher during storm events than during low flows. In fact, storm events export major part of the annual load of *Escherichia coli* (*E. coli*, fecal indicator bacteria) reaching as high as 98% (Chu et al., 2011; McKergow and Davies-Colley, 2010) in some rivers. Wilkinson et al. (1995) observed an increase in fecal coliform concentrations by 25 times during an artificial flood. Peak concentrations of bacteria have been found to occur usually during rising limb of a storm hydrograph (Davies-Colley et al., 1994; Jamieson et al., 2005b) well ahead of the discharge peak and close to the line of maximum flow acceleration (McKergow and Davies-Colley, 2010; Nagels et al., 2002). Artificial flood experiments without any watershed input of bacterial loads also showed a significant increase in *E. coli* levels during rising hydrographs (Muirhead et al., 2004). The bacterial concentration was often increased after the bed stress reached a certain critical value (Jamieson et al., 2005b) suggesting a close relationship between entrainment of riverbed sediment and bacterial concentration in the water column. As fecal coliforms are often concentrated near the sediment–water interface (SWI) and are mostly associated with fine particulates of low settling velocity (Wilkinson et al., 1995), accurate assessment of the entrainment of fine sediment from the channel bed is important to modeling bacterial transport, especially during high flow events.

Various numerical models have been developed to simulate bacterial transport and fate in rivers by considering the sediment and water column interaction. Jamieson et al. (2005a) studied controlling processes for fate and transport of enteric bacteria in alluvial streams by combining field

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experiments and mathematical modeling. A strain of *E. coli* was mixed with stream water and bed sediment, and loaded in streams to monitor the transport of sediment and *E. coli* at downstream locations. As the experiment was carried out during low and steady flow, no entrainment was included in their model. Bai and Lung (2005) added fecal bacteria transport component to the Environmental Fluid Dynamics Code model to study the impact of sediment transport process on fecal transport in rivers. The flux of fecal bacteria was linked with sediment dynamics across SWI. Hipsey et al. (2006) developed a model within an aquatic ecology model Computational Aquatic Ecosystem Dynamics Model (CAEDYM) to include sedimentation and resuspension processes in addition to other processes such as growth, mortality and predation. Although more generic, this model is more suitable for simulating microbial pollution in slowly flowing water bodies such as reservoirs and estuaries than for rivers during short storm events. Firstly, it has a relatively high input requirement. Secondly, the storm events in the rivers are often so short that some of the processes associated with the microbial fate are not important for overall simulation results. Moreover, the model ignores the dispersion process, which is one of the important processes affecting the pollutant transport in rivers. Rehmann and Soupir (2009) quantified the effect of interaction between sediment and water column for microbial concentration using one dimensional steady state model of transport in a river. Transport equations were derived for depth averaged microbial concentrations in the water column and sediment separately, and solved. The longitudinal dispersion process was ignored in their model. Cho et al. (2010a,b) followed the approach by Steets and Holden (2003) for bacterial transport by incorporating the resuspension and sedimentation terms into a net resuspension term in their models. Both used a simple formula for bed shear stress calculated based on flow velocity using a constant friction coefficient. Unlike the other two, Cho et al. (2010b) did not use sediment storage model but determined the bacterial concentration in bed sediment from model calibration. Recently, Gao et al. (2011) developed a numerical model based on DIVAST (Depth Integrated Velocities and Solute Transport Model) with a focus on predicting the effect of sediment fluxes on fecal bacteria levels in water column. The model was applied to several idealized case studies and also to an artificial flood study. Finally, Wilkinson et al. (2011) modeled *E. coli* pulses in Motueka River, New Zealand, using records of *E. coli* concentration during several storm events in 2003–2004. Their model domain consists of main river reach and subcatchments with three layers: riparian land, river reach water column and river reach channel storage. The model includes sediment resuspension and deposition processes along with a bacterial die-off term but does not use advection–dispersion equation and is very much site specific.

Despite efforts to include all processes in bacterial transport modeling, the transient storage effect was mostly ignored. It is well observed that natural streams possess permeable banks and bed sediment which create transient storage zones and thereby generate significant mass exchange between surface and subsurface waters due to the hyporheic exchange (Deng and Jung, 2009). Grant et al. (2011) measured the flux of fecal bacteria across the SWI in a small effluent stream with a turbulent flow and found that the hyporheic exchange controls the transport of bacteria across the SWI in turbulent streams. By combining dual tracer test results and the transient storage model (Runkel, 1998), Shen et al. (2008) showed that a bacteriophage P22 can be successfully used as a tracer in complex surface water environments. When the concentration of free *E. coli* is high in the water column during low flows, the mass exchange between storage zones and the main channel is substantial. Thereby, the transient storage is an important mechanism controlling bacterial transport and should be included in models for description of bacterial transport and fate in rivers.

The primary objective of this study is to present a simple yet effective approach to modeling bacterial fate and transport in natural streams. The new modeling approach should be applicable to both low flow and high flow (especially flood flow) conditions. To that end, the Variable Residence Time based (VART) model (Deng and Jung, 2009) is extended in this study to simulate bacterial fate and transport by taking into account: i) unsteady flow using a hydrograph-based approach, ii) effect of sediment transport on bacterial concentrations, and iii) bacterial decay/growth processes in addition to advection, dispersion, and hyporheic exchange processes included in the original VART model. The extended VART model is applied to simulate bacterial transport in natural streams under different sediment and flow conditions, ranging from steady low flow without sediment transport to flood events with significant sediment transport due to watershed inputs and sediment resuspension from streambed.

2. Model development

2.1. Conceptual model

Major processes controlling the fate and transport of bacteria in streams include advection, dispersion, transient storage (including hyporheic exchange), decay/growth, and resuspension/settling of attached fraction. While the advection and dispersion processes are generally included in mass transport models, other processes are selectively included. Two contrasting flow conditions controlling bacterial fate and transport are often encountered in natural streams: 1) low flow – when a stream has low flow discharge, shallow depth, clearer water, higher residence time, and clear weather with sunshine, and 2) high flow – when a stream has high flow discharge, deep and turbid water, lower residence time and generally cloudy weather with less sunshine. Accordingly, during the low flow there is a likelihood of higher inactivation rates due to longer residence time, clearer water and more sunlight. The exchange due to transient storage may also play an important role during low flow as the flow in the main channel is relatively small and slow. On the other hand, resuspension of sediment associated bacteria from the streambed, particularly during rising flows, and subsequent deposition during receding flows may play a dominant role during storm events (Wilkinson et al., 2011). Due to shorter residence time and favorable environment for survival of bacteria in water column, the solar inactivation plays less