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Retention and remobilization dynamics of fine particles and microorganisms in pastoral streams

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ABSTRACT

Both microbial metabolism and pathogen retention and remobilization are dependent on downstream transport of fine particles, which migrate in a series of deposition and resuspension events. All fine particles, including clay minerals, particulate organic carbon, nutrients and microbes, are often considered to be transported similarly in the environment because of a lack of specific observations comparing their relative transport. We conducted a tracer injection study to compare the transport and retention of the fecal indicator bacterium *Escherichia coli*, synthetic inert fluorescent fine particles, and a dissolved conservative tracer. We found that the fluorescent fine particles and bacteria were transported similarly, with both having greater retention than the solute tracer. We used a stochastic model to evaluate in-stream retention and migration of the solute, fluorescent particles, and *E. coli*. The best-fit model parameters indicate that different stream reaches had varied retention characteristics, but always showed greater retention of fluorescent particles and *E. coli* compared to the solute tracer. Direct measurements within known retention areas after the injection showed that the majority of the fluorescent particles and *E. coli* were retained near the sediment–water interface in macrophyte stands or filtered within the top 3 cm of the streambed sediment. Both the tracer particles and *E. coli* were retained within these regions for multiple months following the injection experiment. The stochastic model properly captured the wide range of storage timescales and processes we observed in the stream. Our results demonstrate the importance of the streambed sediment and in-stream macrophytes as short- and long-term reservoirs for fine organic particles and microbes in streams.

1. Introduction

Fine particles drive critical geomorphological, biogeochemical, and ecological processes in streams and rivers, including contaminant transport, carbon dynamics, and nutrient cycling (Battin et al., 2008; Bradford et al., 2013; Hope et al., 1994; Rabalais et al., 2002). We define fine particles broadly as particles having sizes <10 μm (colloids) or larger particles with sizes 10–100 μm and low specific gravity, where Stokes

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settling velocity is low and deposition due to gravitational settling is negligible. Fine particles of biogeochemical interest include particulate organic carbon, sediment-bound phosphorus, and particulate forms of nitrogen (Cushing et al., 1993; Hope et al., 1994, Rabalais et al., 2002). Microorganisms, including pathogens, also meet this definition of fine particles (Bradford et al., 2013; Pachepsky and Shelton, 2011). Based on the small size, similar slightly negative surface charge, and low Stokes settling velocity, the transport mechanisms of many fine particles are expected to be broadly similar. An obvious difference, however, is that microbes are inactivated under environmental stressors such as solar UV radiation and protozoan ingestion, but some microbes, such as bacteria, can also potentially grow within streams (Battin et al., 2008; Chekabab et al., 2013; Leclerc, 2003; Litton et al., 2010). Less understood microbial properties can potentially impact their environmental transmission, including surface properties, extracellular structures, and their potential ability to respond to environmental conditions (e.g. metabolism and motility) (Bradford et al., 2013; Chekabab et al., 2013; Ishii and Sadowsky, 2008; Jamieson et al., 2004).

Fine particles are known to episodically deposit and resuspend during downstream transport (Newbold et al., 2005; Packman et al., 2000a,b; Drummond et al., 2014). Microorganisms also migrate downstream through a series of deposition and resuspension events resulting in a wide range of microbial residence times in the streambed. For example, the favored freshwater fecal indicator bacteria *Escherichia coli* has been shown to survive in streambeds for up to six weeks (Jamieson et al., 2004) and other microbes, notably cysts of protozoan parasites like *Cryptosporidium*, are much more persistent (Eisenberg et al., 2005). Deposition of microorganisms and fine organic particles mainly occurs through advective delivery into the subsurface sediments or in-stream structures, such as macrophytes or woody debris (Packman et al., 2000a, b; Ren and Packman 2002; Fries and Trowbridge 2003; Searcy et al., 2006; Grant et al., 2011; Karwan and Saiers 2012, Drummond et al., 2014). Microorganisms and other fine particles can then be trapped within storage areas by filtration within subsurface sediments, attachment to in-stream debris and macrophytes, or entrapment within biofilms at the sediment–water interface (Battin et al., 2003; Arnon et al., 2010; Drummond et al., 2014).

Several studies have reported that stormflows greatly elevate concentrations of fine particles, including microbes. Stormflow fluxes of indicator bacteria may be 5 orders of magnitude higher than at baseflow (e.g. McKergow and Davies-Colley, 2010). The usual assumption is that these organisms are introduced by land runoff, but the extremely rapid increases in *E. coli* concentrations at the start of hydrographs during high flow events indicates they must be resuspended mainly from in-channel stores (e.g Muirhead et al., 2004; Stott et al., 2011). Although there have been numerous laboratory studies of microbial transport, very few have been conducted at the field scale. Tracer injection studies can be used to obtain direct estimates of advection, dispersion, retention, and release within streams (Fischer et al., 1979; Stream Solute Workshop, 1990; Harvey and Wagner, 2000). The recommended practice for these experiments is to combine in-stream measurements of the added constituents with direct measurements within potential areas of deposition, such as streambed sediments, to provide independent information on retention and release processes (Harvey and Wagner, 2000; Boano et al., 2014).

The goal of this study was to improve understanding of the transport of solutes, fine organic particles, and bacteria in streams, focusing particularly on the exchange between water and in-channel storage reservoirs that control capture and retention. We injected multiple tracers into a pastoral stream, observed their downstream transport and retention in streambed sediments and stands of submerged macrophytes, and simulated their behavior using a stochastic transport model. We specifically compared the transport, deposition, and resuspension of tracer particles and *E. coli* in order to differentiate the processes that control the behavior of bacteria relative to other fine particles having comparable physical and chemical characteristics.

2. Methods

2.1. Approach

We injected conservative, particulate, and bacterial tracers into a small pastoral stream and observed their in-stream transport at three downstream sites for times much longer than the mean water travel time through the study reach. A conservative solute, rhodamine WT, was used to characterize in-stream transport and exchange with underlying and surrounding sediments (hyporheic and riparian areas). Fluorescent fine particles and the fecal bacterium *E. coli* were co-injected with the conservative tracer. Measurements of fluorescent fine particles and *E. coli* in sediment cores and submerged macrophytes complemented the in-stream observations. Within the experiment we consider short-term as the timeframe of the injection experiment and long-term as the months following the experiment.

2.2. Site description

The Toenepi stream is located close to the city of Hamilton, Waikato, New Zealand. This stream was chosen for study because it is subjected to considerable inputs of fecal bacteria from dairy cattle, and it has been well-studied previously (Wilcock et al., 1999, 2007; Davies-Colley et al., 2008; Stott et al., 2011). The study site used for the experiments reported here incorporates a 208 m reach located 1.8 km upstream of the hydrometric site studied previously by Stott et al., (2011). The streambed is composed of both clay/silt and fine/medium sand intermixed with seasonal emergent vegetation. The stream can become weed-choked during summer low flow; however the first third of the experimental reach generally has low vegetation biomass due to shading from overhanging trees.

Four sampling sites were located along the experimental reach. A map of the injection experiment is shown in the Supporting Information (SI). Site 1 was located ~9 m upstream from the injection site to determine background concentrations of tracers and *E. coli* in the stream. Site 2 was located ~63 m downstream of the injection site (immediately downstream of the Morrinsville Road - State Highway 23 crossing