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Modeling the release of *Escherichia coli* from soil into overland flow under raindrop impact

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ABSTRACT

Pathogen transport through the environment is complicated, involving a variety of physical, chemical, and biological processes. This study considered the transfer of microorganisms from soil into overland flow under rain-splash conditions. Although microorganisms are colloidal particles, they are commonly quantified as colony-forming units (CFUs) per volume rather than as a mass or number of particles per volume, which poses a modeling challenge. However, for very small particles that essentially remain suspended after being ejected into ponded water and for which diffusion can be neglected, the Gao model, originally derived for solute transfer from soil, describes particle transfer into suspension and is identical to the Hairsine–Rose particle erosion model for this special application. Small-scale rainfall experiments were conducted in which an *Escherichia coli* (*E. coli*) suspension was mixed with a simple soil (9:1 sand-to-clay mass ratio). The model fit the experimental *E. coli* data. Although re-conceptualizing the Gao solute model as a particle suspension model was convenient for accommodating the unfortunate units of CFU ml^{-1}, the Hairsine–Rose model is insensitive to assumptions about *E. coli* per CFU as long as the assumed initial mass concentration of *E. coli* is very small compared to that of the soil particle classes. Although they undoubtedly actively interact with their environment, this study shows that transport of microorganisms from soil into overland storm flows can be reasonably modeled using the same principles that have been applied to small mineral particles in previous studies.

1. Introduction

One of the major themes in Dr. Sposito's work has been the role of colloids in the environment (e.g., Sposito 1983; Sposito and Schindler 1987; Sposito 1989; Heil and Sposito 1993a, 1993b, 1995; Sposito 1993; Chang and Sposito 1994; Chorover and Sposito 1995; Sposito and Malengreau 1998, among many more). Here we add to those pioneering studies by looking at the interactions between bio-colloids (bacteria) and raindrops to better understand the transport processes facilitating the exchange of colloids from soil and into overland flow.

The World Health Organization (WHO, 2011) considers water borne pathogens to be the most important water quality risk to address in the foreseeable future. Indeed, pathogens impair more kilometers of US rivers and streams than any other pollutant for US water bodies officially listed as impaired or failing to meet water quality standards for their designated uses (US EPA, 2010). Storm water is a primary transport pathway for many pathogens and increased concentrations are often correlated with large precipitation and snowmelt events (Falbo et al., 2013; Jamieson et al., 2003; Kistemann et al., 2002; Pettibone and Irvine, 1996; Simon and Makarewicz, 2009a; Simon and Makarewicz, 2009b; Traister and Anisfeld, 2006). An improved understanding of the transport mechanisms of microorganisms, like *Escherichia coli* (*E. coli*), will help in developing strategies for mitigating pathogen loads between the landscape and surface waters.

Previous studies of *E. coli* transport primarily focused on the attachment of *E. coli* to solid particles (Guber et al., 2005a; Guber et al., 2005b; Muirhead et al., 2006a; Muirhead et al., 2006b; Oliver et al., 2007), the transport of *E. coli* through soil columns (Smith et al., 1985; Barton and Ford, 1995; Barton and Ford, 1997; Schäfer et al., 1998; Powelson and Mills, 2001; Sherwood et al., 2003; Olson et al. 2005; Jiang et al., 2007; Truhlar et al. 2015), or the transport of *E.coli* in runoff over bare soil or through vegetated buffers (Muirhead et al., 2006a; Ferguson et al., 2007).

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Several studies used rainfall experiments to investigate rain-driven erosion of manure slurry amended soil or cowpats and the associated transfer of *E. coli* into runoff (Zyman and Sorber, 1988; Roodsari et al., 2005; Muirhead et al., 2005; 2006c; Ferguson et al., 2007; Kouznetsov et al., 2007). The experiments of Ferguson et al. (2007) included bare soil treatment, first as a control and then receiving *E. coli* enriched cowpats. Their objective was to determine how vegetation and microbe size influence microbial transport in runoff through statistical comparisons, i.e., the physical processes were inferred rather than explicitly explored.

We hypothesize that microorganism transfer between soil and overland flow during rainfall can be explained by the same underpinning processes that have been used to explain the transfer of other small particles (e.g., clay). We combine laboratory experiments and mechanistic models to test this hypothesis. This process has not been well described in previous research although it is important because it initiates nonpoint source pathogen pollution. We designed a simple experiment to investigate the rain-splash erosion of *E. coli* from soil into overland flow and applied two mechanistic models.

E. coli (roughly a 1 µm diameter and 2 µm long rod - Neidhardt et al., 1990) is a colloidal particle, comparable in size to kaolinite clay particles (ranging from 0.1 µm to 2 µm - Mackinnon et al., 1993). However, it is difficult and expensive to quantify *E. coli* as either a number-of-cells or a mass-of-cells per volume of sample, in part due to possible or even likely aggregation. The simplest way to measure *E. coli* (and other bacteria) is to culture samples on agar plates and enumerate the concentration as colony-forming units (CFUs) per volume of sample. While this is a fairly standard and reasonably repeatable measurement technique, it is difficult to relate CFUs to bacteria numbers or masses. This is unfortunate, because the well-known Hairsine–Rose (1991) model is a good representation of small particle transfer from soil into overland runoff (e.g., Heilig et al., 2001; Gao et al., 2003; 2005), but it requires the initial mass ratios for all particle classes and, if we consider bacteria a particle class, this information is not known. Gao et al. (2004; 2005) adapted the Hairsine–Rose rain-impact concept to derive a solute transfer model. Because both models are predicated on the same fundamental principles, i.e., rain-impact ejects material from the soil surface into the overland flow and the depth of impact is discrete (described as either shield – e.g., Heilig et al. 2001 – or exchange layer – e.g., Gao et al. 2004), we suggest that they are identical when applied to colloidal transfer between soil and overland runoff.

2. Colloid suspension models

Bacteria are often classified as bio-colloids, which are somewhat different from the definition of particles used in erosion modeling, in part because they have near-neutral buoyancy and do not settle out of suspension very rapidly. However, they are obviously not solutes either. However, we think that with the appropriate caveats, the Hairsine–Rose erosion model and the Gao solute model are equivalent when subjected to the conditions required to model colloids, e.g., settling velocity and diffusion are negligible (See Tables 1 and 2 for all variables and parameters). Here we describe the two models as adapted to colloids (assuming constant ponding depth and rain rate), and then show that they are identical for our application.

2.1. Hairsine–Rose model

Following Hairsine and Rose (1991), soil can be characterized by equivalent mass-particle classes. Including bacteria as a mass-particle class introduces an almost certain unknown, so we propose normalizing all classes to the bacteria (*E. coli*) class, $i=1$. For the sake of this derivation and, indeed, our experimental design as described later, let us arbitrarily assume n mass-classes of clay and fn mass-classes of sand (other particle classes could be included, but we will assume a simple, *E. coli*-clay-sand soil here). So the total particle mass-classes, $I=1+(1+f)n$. We use a coefficient, M_{cfu}, to convert CFUs to mass of *E. coli*; this also establishes how many classes of clay and sand there will be.

The Heilig et al. (2001) version of Hairsine–Rose model adopts the assumption that once ejected by the raindrops, particles with low settling velocity,e.g., *E. coli* and clay, do not settle out of the ponded water (overland flow). Particles with high settling velocities, like sand, settle out of the overland flow quickly and deposit on the soil surface to form a shield layer which protects the soil underneath it from further erosion.

With the above assumptions, for the *E. coli* and clay classes (settling velocities ≈ 0), the suspension concentrations in overland flow are non-zero:

$$d_w\frac{dc_i(t)}{dt}=\frac{ap}{I}(1-H(t))-pc_i(t) \tag{1}$$

where $c_i(t)$ (g/ml) is the concentration of *E. coli* or of each class of clay in the suspension at time t, d_w (cm) is ponding water depth, a (g/ml) is the soil detachability, p (cm/min) is rainfall intensity, I is the total number of equal-mass particle classes, and $H(t)$ is the fraction of soil protected by shield layer at time t, with no erosion when $H=1$. The first term in the square brackets represents the rate at which i-class particles are ejected from the soil and the second term represents the rate at which they wash away in the overland flow. Because the rainfall-runoff is at steady state, the runoff rate is equal to the rainfall intensity, p.

The mass of the deposited sediment is the sum of the deposited mass of all the sand classes,

$$M_d=\sum_{i=n+2}^{(1+f)n+1}M_{di} \tag{2}$$

Following Hairsine and Rose (1991), the rate of accumulation of the deposited sediment, $\frac{dM_d(t)}{dt}$, is proportional to the rate at which clay and *E. coli* are ejected from the soil (Eq. 1). Therefore, it can be expressed as:

$$\frac{dM_d(t)}{dt}=\frac{fn}{I}ap[1-H(t)] \tag{3}$$

The $H(t)$ term in Eqs. 1 and 3 is given by Sander et al. (1996) as:

$$H(t)=\frac{M_d(t)}{M_d^*} \tag{4}$$

where $M_d{}^*$ (g/cm^2) is the mass of shield layer (sand) per unit area at complete shielding, i.e., when raindrop impact is prevented by the shield layer from ejecting underlying particles, i.e., $H=1$.

We define $N_e{}^*$ (g/cm^2) and $M_c{}^*$ (g/cm^2) to be the total ejected CFUs of *E. coli* and mass of clay per unit area, respectively, when $H=1$:

$$N_e^*=\int_0^T pc_{ecfu}(t)dt \tag{5}$$

$$M_c^*=\int_0^T pc_c(t)dt \tag{6}$$

where $c_{ecfu}(t)$ and $c_c(t)$ are the concentration of *E. coli* CFUs and concentration of clay at time t in the ponded water, respectively, and T is the time at which all the erodible clay has washed out of the experiment.

From the nonselective detachment, we obtain the following ratios:

$$N_e^*(t)M_{cfu}:M_c^*:M_d^*=1:n:fn \tag{7}$$

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