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Removal efficiencies and attachment coefficients for *Cryptosporidium* in sandy alluvial riverbank sediment

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ABSTRACT

Riverbank filtration has been shown to be effective for removing viable *Cryptosporidium parvum* oocysts. Drinking water systems that employ riverbank filtration may receive additional treatment credits beyond that which they can obtain using traditional engineering approaches. In order to develop guidance for removal effectiveness, screening level predictive modeling by colloid filtration theory combined with advection and dispersion modeling is potentially useful. Currently, only few studies have measured basic effective colloid filtration parameters for *Cryptosporidium* oocysts with naturally occurring riverbank sediments. In the focus of this study we conducted flow column experiments in triplicate and measured effective attachment rate coefficients for sandy river sediments of the Southern Great Plains which are low in organic matter. We found that for sediment sampled from these high-energy rivers there was no apparent dependency of *C. parvum* removal with carbon content, bacterial colony forming units, or with gross texture properties of the sands. The differences in particle size distribution for the sediments suggested that straining did not play a role in removal efficiency. First-order colloid attachment rate coefficients followed lognormal distribution functions. The coefficients also appeared to be unrelated to the differences in particle size distributions of the sediments, bacterial counts, or levels of total carbon or total organic carbon. Using Monte Carlo analyses, the lowest observed 5th percentile was 8.0×10^{-6} min^{-1} and the highest observed 95th percentile was 1.6×10^{-3}. Total log_{10} removals ranged from 23 to 200 m^{-1}. These results have application for screening level colloid filtration modeling of riverbank filtration in these systems.

1. Introduction

It is well known that *Cryptosporidium parvum* is a protozoan parasite that causes gastrointestinal illness and is transmitted by ingestion of oocysts excreted by humans or animals. The largest outbreak associated with contaminated public water in the United States was due to *C. parvum*. In 1993, approximately 403,000 people in Milwaukee, Wisconsin became ill

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when an ineffective filtration process led to the inadequate removal of *C. parvum* oocysts in one of two municipal water treatment plants (Mac Kenzie et al., 1994). From 1984 to 2002, at least ten cryptosporidiosis outbreaks associated with contaminated drinking water were reported in the United States, and some of these were thought to have been associated with inadequate groundwater filtration from surface water sources (U.S. Environmental Protection Agency, 2005).

The Long Term 2 Enhanced Surface Water Treatment Rule (LT2) was finalized and published in the *Federal Register* on January 5, 2006 (71 FR 654). This rule establishes bank filtration as a pre-treatment credit option available under certain conditions to public water systems using raw water with high levels of *Cryptosporidium*. Riverbank filtration is accomplished by installing wells adjacent to rivers, streams, or reservoirs, to draw water from these relatively abundant sources through their natural surrounding sediments. This process exploits the filtering, adsorptive, and reactive capabilities of alluvial sediments. It may reduce levels of organic matter, pathogenic microorganisms (bacteria, viruses and protozoa), prior to traditional engineered treatment (Berger, 2002). LT2 allows the establishment of treatment removal credits for *C. parvum* and *Giardia* according to criteria specified in the rule. Sites which have alluvial or glacially-derived aquifer materials comprising the bank filtration medium may be eligible if in a sediment sample core at least 90 percent of the length the grains are less than 1.0 mm diameter.

A recent study by Weiss et al. (2005) used monitoring at three LT2-eligible facilities for a variety of microbial contaminants and found that riverbank filtration was effective at removing *C. parvum*, but called for more studies that can identify mechanisms of removal. Gupta et al. (2009) observed complete removal of *C. parvum* oocysts in sandy riverbank sediments of the Ohio River within a distance of 5 cm. Gollnitz et al. (2005) and Gollnitz et al. (2004) also provided strong evidence that riverbank filtration is very effective in removal of *Cryptosporidium* at riverbank filtration sites in Ohio and Wyoming, in sandy riverbank sediments. Although the removal effectiveness of riverbank filtration systems is known to be good and *C. parvum* outbreaks are rare, there is a need to measure commonly used parameters that can be applied in predicting riverbank filtration effectiveness through modeling. These include attachment rate coefficients associated with sediment particle size properties.

There have been only a few papers describing methods for detecting *C. parvum* oocysts in natural sediment. These have included the work of Mawdsley et al. (1996a) who employed a complex series of washing and centrifuging steps, staining and epifluorescence microscopy. Walker et al. (1998) used both a PCR method and an immunofluorescence method. Kuczynska and Shelton (1999) used an immunofluorescence method. Walker and Redelman (2004) used fluorescent microscopy and flow cytometry. Molloy et al. (2006) used an immunomagnetic separation method. All of these methods have been ad hoc and subject to differing detection limits and recovery. There remains a need to develop standard protocols for detecting viable *C. parvum* oocysts in soils and sediment in order to facilitate increased use of studies that are more focused on transport. Because of the limitations on enumerating oocysts from natural sediments, the specific mechanisms which have been identified for ideal colloids and ideal porous media may be difficult to discern in natural systems.

From a modeling perspective, limitations and strengths of various modeling approaches have been recently described in a concise review by Tufenkji (2007). Most of the limitations arise due to non-classical effects that have been observed in experiments under ideal conditions. The complexity of interacting colloid transport mechanisms in porous media flow suggest that fully stochastic modeling approaches may be of value (Bradford and Toride, 2007). Using highly controlled experiments with ideal colloids and/or porous media, recent studies have shown that microbial transport is likely to be governed by physical processes which are not always in complete concordance with classical colloid filtration theory. Descriptions of the complications in the mechanisms of transport are numerous and have been the subject of many recent experimental and modeling studies. Despite these many limitations, screening level models which use classic colloid filtration theory will likely continue to be utilized, at present, in applied predictive modeling efforts. In some cases these models may be parameterized using probabilistic or statistical interpretations from effective parameters, which have rarely been reported for natural riverbank sediments with viable *C. parvum* oocysts. We use the phrase "effective parameters" to emphasize that although the parameters of colloid filtration theory have arisen from purely physical reasoning, in practice they still have meaning in modeling field scale studies, yet may be non-ideal compared to their original intended meaning. Monte Carlo methods are often used in this modeling approach (e.g., Faulkner et al., 2003). Determination of the parameters and their distributions for mechanistic models requires primarily laboratory studies for which greater control of degrees of freedom can be achieved. In all cases where modeling is used and applied at the field scale, good knowledge of the conceivable range of parameter variation and propagation through the model is needed. In some cases, the spatial and temporal scales being considered may affect the results, and the representative elementary volume for the field scale as compared to those of laboratory scales may be important. Results from laboratory scale experiments may help determine these spatial scaling effects in model applications.

In cases where macropore flow is important in the transport of *Cryptosporidium* (e.g., Mawdsley et al., 1996b) the evaluation of the risk of contamination by *Cryptosporidium* should not be based on classical porous media transport phenomena (Harter et al., 2008). In this work we do not consider the effects of macropore flow although they may be an overriding factor under field conditions. We did not see evidence of macropore flow in the current study.

In this paper we conducted flow column studies to measure log removal and effective first-order attachment rate coefficients for natural sediments from riverbank aquifers common in the Southern Great Plains. We employed a method described herein with column flow studies to observe the associated retention of oocysts in the sediment. The approach of observing the profile of retained organisms rather than flow column effluent breakthrough is thought to yield more accurate information on colloid transport parameters than does