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Riverbank Filtration: Comparison of Pilot Scale Transport with Theory

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Pilot-scale column experiments were conducted in this study using natural soil and river water from Ohio river to assess the removal of microbes of size ranging over 2 orders of magnitude, i.e., viruses (0.025−0.065 μm), bacteria (1−2 μm), and *Cryptosporidium parvum* oocysts (4−7 μm) under conditions representing normal operation and flood scour events. Among these different organisms, the bacterial indicators were transported over the longest distances and highest concentrations; whereas much greater retention was observed for smaller (i.e., viral indicators) and larger (i.e., *Cryptosporidium parvum* oocysts) microbes. These results are in qualitative agreement with colloid filtration theory (CFT) which predicts the least removal for micrometer size colloids, suggesting that the respective sizes of the organisms was a dominant control on their transport despite expected differences in their surface characteristics. Increased fluid velocity coupled with decreased ionic strength (representative of major flood events) decreased colloid retention, also in qualitative agreement with CFT. The retention of organisms occurred disproportionately near the source relative to the log-linear expectations of CFT, and this was true both in the presence and absence of a colmation zone, suggesting that microbial removal by the RBF system is not necessarily vulnerable to flood scour of the colmation zone.

Introduction

Riverbank filtration (RBF) is widely practiced as a first-step pretreatment of surface water during passage through riverbed material to a production well (*1, 2*). During passage, removal of biological (e.g., microbes) and abiotic (e.g., clays) colloids occurs via attachment to riverbed material (*1, 3*−*5*). As defined, RBF systems fall under the present Surface Water Treatment Rule (SWTR), which is based on the assumption that all sources of groundwater under the direct influence of surface water (GWUDI) are at risk of microbiological contamination. For regulatory purposes, a drinking-water well is classified as "under the influence of surface water" if a microscopic particulate analysis (MPA) shows the presence of algae, rotifers, *Giardia*, and other organisms commonly found in surface water (*6*). The MPA method (as currently defined) focuses primarily on larger particles, e.g., diatoms (4−140 μm), green algae (2−100 μm), and *Giardia* (8−18 μm).

The focus on larger particles by the MPA method runs counter to established theory regarding the removal of colloids during transport through porous media. Colloid filtration theory (CFT) provides quantitative prediction of removal as function of colloid and collector size, fluid velocity, and other system parameters (*7*−*11*). CFT yields the expectation that colloids in the 1−2 μm size range will be least retained in porous media; since these colloids undergo lesser diffusion relative to smaller colloids, and undergo lesser gravitational settling relative to larger colloids (Supporting Information, Figure S1). Many important pathogens are smaller in size than presently used MPA indicators, e.g., *Cryptosporidium parvum* oocysts (∼5 μm), bacteria (∼ 1 μm), and viruses (∼ 25 nm); therefore, GWUDI protocols, specifically the MPA method, may benefit by inclusion of indicators in the 1−2 μm size range.

A critical limitation of CFT is its inability to predict any colloid attachment when repulsion exists between colloid and collector surfaces (e.g., refs *12, 13)*. Unfortunately, repulsion is common under environmental conditions, emanating from adsorption of natural organic matter and other processes yielding electrosteric repulsion (*14*−*19*). Hence, the prediction by CFT that colloids in 1−2 μm size range undergo least removal may not apply in the environment; however, colloid removal was least for 1−2 μm size range in recent laboratory packed porous media column experiments where repulsion existed between the colloids and collectors (e.g., *13*).

The top 10 cm of the riverbed, referred to as the "colmation zone" (*20*), is thought to play a critical role in the elimination of contaminants and microorganisms due to its high microbial activity and relatively small grain size (*1, 21*). The vast majority of colloid removal occurs near the river, implicating the colmation zone as the dominant zone of colloid removal. The finer-grained porous media associated with the colmation zone are expected to yield greater removal (greater collector efficiencies or deposition rate coefficients) according to CFT (see Supporting Information, Figure S2). RBF practitioners express concern that removal of the colmation zone via flood scour may weaken the performance of RBF systems (*1*). However, the importance of the colmation zone (at least with respect to colloid removal) is called into question by the ubiquitously observed disproportionate retention of colloids near the source even in homogeneous porous media (*22*−*24*).

In addition to flood scour, important potential effects of storm events include decreased solution ionic strength (*1*) and increased fluid velocity. Under conditions where repulsion exists, the collector efficiency (or deposition rate coefficient) decreases with decreasing solution ionic strength for a given colloid and porous media (*25*−*27*). Increased fluid velocity promotes colloid transport, since the collector efficiency decreases with increasing fluid velocity according to CFT (e.g., refs *13, 28)* as shown in Supporting Information, Figure S3. Although in large river systems the solution ionic strength may change only mildly with changes in runoff,

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smaller river systems may undergo significant ionic strength changes in response to runoff events.

The goal of this paper is to explore the influence of (1) organism size; (2) presence versus absence of riverbed material; and (3) decreased solution ionic strength coupled with increased solution velocity on the transport and retention of a suite of indicator organisms ranging in size from viruses (10s of nm) to protozoa (10s of μm), in a simulated field environment, in order to examine whether the observed trends are consistent with expectations from CFT. Consistency with the expectations of CFT would indicate that the processes operating in CFT (interception, diffusion, and sedimentation) are relevant under environmental conditions, yielding the expectation that models built on these processes can eventually be developed to provide quantitative estimates of colloid removal under conditions where repulsion exists.

Materials and Methods

Organisms and Cell Culture. The microbes used in this study included *C. parvum* oocysts (4−7 μm), bacterial indicators *Escherichia coli* (1 μm), DA001 (0.85 μm), OY107 (0.69 μm), and viral indicators PRD1 (65 nm) and MS2 (25 nm). Bacterial indicators used in this study are rod-shaped, whereas all other indicator organisms are spherical or rounded. Bacteria DA001 and OY107 were provided by University of Utah (UofU). All other microorganisms were provided by Arizona State University (ASU) at Tempe, AZ. The details of cell culture preparation of *C. parvum* oocysts, bacteria (DA001, OY107, and *E. coli*) and viruses (MS2 and PRD1) are provided in the Supporting Information.

Column Operating Conditions. A total of seven pilot-scale column experiments (Supporting Information, Table S1) were conducted of which six experiments were conducted at 3 m transport distances and one was conducted at a 9 m transport distance. All columns were 0.1 m in diameter. Ohio River sand with a uniformity coefficient of 2.35 was used for column packing. The columns were acclimated for a minimum of four months with Ohio River water at 1.2 m/day (normal operation of RBF). The details of column experiment setup, sediment packing and size classification, and acclimation time-periods are provided in the Supporting Information. During acclimation, dissolved oxygen (DO), total suspended solids (TSS), and UV-absorbance (254 nm) were monitored in the influent and effluent, the details of which are also provided in the Supporting Information. Column experiment pairs (explained below) were conducted every 2−3 weeks during the period from July to October (2007), during which time the river water temperature fluctuated from 27−30 °C. River water conductivity ranged from 473 μS in July to 537 μS in October. Total dissolved solids (TDS) in the influent fluctuated between 344 and 426 mg/L during this time period. The column porosities (ranging from 0.30 to 0.35) were estimated based on the volume of water required to saturate the media, and based on breakthrough time for fluorescein tracer and microbes in a 3 m packed column. The latter was estimated by dividing this breakthrough time by the porous media volume and volumetric flow rate.

Experimental Conditions. Columns were paired to reflect two conditions during the experiments: (1) normal or baseline operation of RBF system, i.e., low flow (1.24 m/day), high TDS (400 mg/mL) (higher ionic strength), and low TSS (2 NTU), with acclimation times of 112, 126, and 160 days, respectively; and (2) storm or challenge conditions, i.e., high flow (12.4 m/day) low TDS (200 mg/L) (lower ionic strength), and high TSS (20 NTU). The flow rates under baseline (1.24 m/day) and challenge conditions (12.4 m/day) were based on field data, the details of which are provided in the Supporting Information. For these two conditions, columns were also run under a scour condition, where the colmation zone of the riverbed (top 10 cm) was removed. Three pore volumes (8500 mL per pore volume) of microbial solution were injected, followed by three pore volumes of the same solution without microbes. Microbe injection concentrations are provided in the Supporting Information Table S1. All columns were operated in downflow mode.

Sample Collection and Analysis. The aqueous effluent and intermediate-port samples were collected at time-intervals to capture breakthrough and elution. During the course of a given experiment, the injection concentration was relatively constant shown by the standard deviations of three samples collected at 3, 8, and 14 h following initiation of injection (baseline conditions), and 0.3, 2, and 4 h following initiation of injection for challenge conditions (Supporting Information, Figure S9). A total of 22 sediment samples were collected from each 3 m column (32 sediments samples were collected from 9 m column) after completion of the column experiments. Cell recovery from the sediment is described in the Supporting Information. Bacteria DA001 and OY107 were analyzed using Bio-Ferrography (a modified immunomagnetic separation technique), *E. coli* were enumerated by membrane filtration, bacteriophages MS2 and PRD1 were enumerated via plaque assay, and *C. parvum* oocysts were quantified using an immunomagnetic separation technique. Details of these analyses are provided in the Supporting Information. In the breakthrough elution curves, samples which showed nondetect (complete removal of organism up gradient of the sampling port) were plotted as one-half of the method reporting limit. The number of microbes that exited each column was determined by integrating the area under the effluent breakthrough-elution curve, and the number microbes retained in each column was determined by summing the microbes recovered from each segment. Further details of sample collection and analysis are provided in the Supporting Information.

Results and Discussion

Retention as a Function of Indicator Organism Size. The sample collection frequency differed between different experiments, preventing the averaging of curves. The reproducibility of the experiments is demonstrated by columns 1, 3, and 5 (Figure 1 and Supporting Information,Table S1), which represent baseline operation. The breakthrough-elution curves and profiles of retained microorganisms show that very similar results were obtained in these columns, with viruses showing greater retention than bacteria in all cases. Column 5 included all indicator organisms examined in the study and is used henceforth for comparison to challenge conditions.

The microorganisms in the size range >2 μm (i.e., *C. parvum oocysts*) underwent complete removal (greater than 3 orders of magnitude removal) over a 3 m transport distance (Figures 2A and 3B). None of these microorganisms were detected at a transport distance of 0.05 m from column inlet (data not presented). In contrast, the microorganisms in the size range <2 μm (i.e., bacteriophages PRD1 and MS2, and bacteria *E. coli* DA001 and OY107) were transported at significant concentrations over a 3 m transport distance. Among the <2 μm microorganisms, the viral indicators were more strongly attenuated (had much lower relative breakthrough concentrations) than the bacterial indicators (Figures 2A, 2B, 3A and 3B). The above observations are in qualitative agreement with CFT which predicts a minimum deposition rate (lowest retention) for colloids in the intermediate size range around 1−2 μm (e.g., bacteria), since these colloids undergo lesser sedimentation and lesser diffusion than larger (e.g., protists) and smaller (e.g., bacteriophage) organisms, respectively, as discussed in the Introduction (and Supporting Information, Figure S1). Deposition rate coefficients from eqs 3 and 4 in Supporting Information, Table S2) reflect the

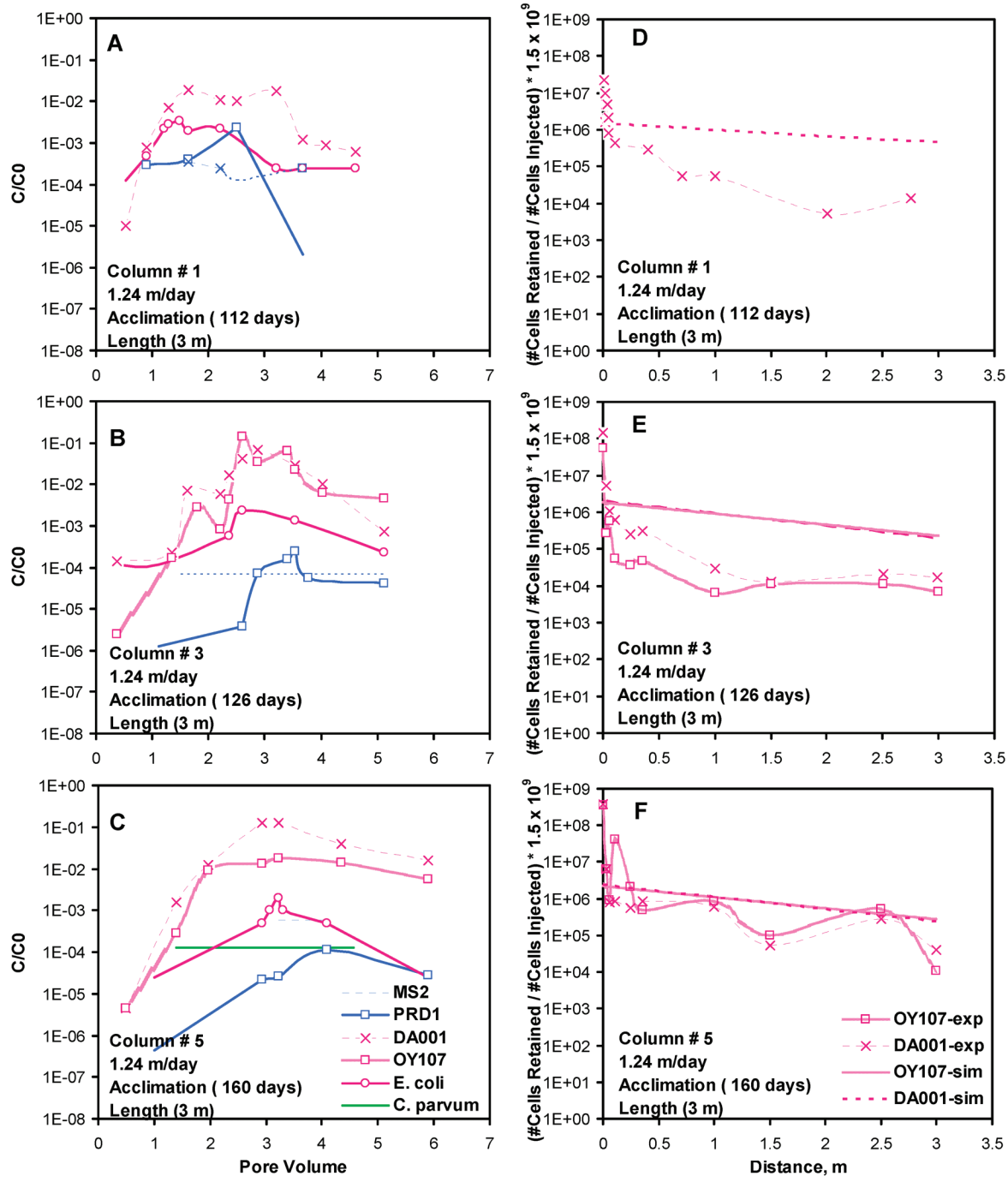

FIGURE 1. Breakthrough-elution curves (A, B, and C) and retained profiles (D, E and F) of microbes at low flow (1.24 m/day)-high ionic strength (400 mg/L)-low turbidity (2 NTU) and high flow (12.4 m/day)-low ionic strength (200 mg/L)-high turbidity (20 NTU) under nonscour condition. Flat straight lines of MS2 in (B) and (C) and *C. parvum* oocysts in (C) represent their complete removal (data below detection limit).

opposite trends observed in the breakthrough concentrations, as expected, where viruses and oocysts show higher deposition rate coefficients relative to bacteria. The apparent deposition rate coefficients for MS2 and PRD1 (3.5 day^{-1} and 3.3 day^{-1}, respectively) may potentially be influenced by inactivation. However, these rate coefficients are similar to those reported by Schijven et al. (*29*) who showed that inactivation rates for MS2 (0.03 day^{-1}) and PRD1 (0.12 day^{-1}) were relatively low in agreement with other studies that they cited, leading to their conclusion that attachment was the major removal process in their system. Although the temperature used in Schijven et al. (*29*) and their cited studies was relatively low (4−7 °C), additional studies (*30, 31*) showed that inactivation was still relatively low (0.18−0.32 day^{-1} and 0.05−0.12 day^{-1} for MS2 and PRD1, respectively) even at room temperature.

Bacteriophage PRD1 (65 nm) showed greater breakthrough concentrations (less removal) relative to MS2 (25 nm), possibly due to their dissimilar sizes (in accordance with CFT). However, the factor of 2−3 difference in size is likely insufficient to overrule other influences on their retention (e.g., surface chemistries of the microbe and the media). For example, despite similar experimental fluid velocities to this study (~1.5 m/day), Kinoshita et al. (*32*) reported greater removal of PRD1 relative to MS2 in column experiments using Cape Cod soil, and Schijven et al. (*2, 29*) reported similar removal of MS2 and PRD1 in field scale

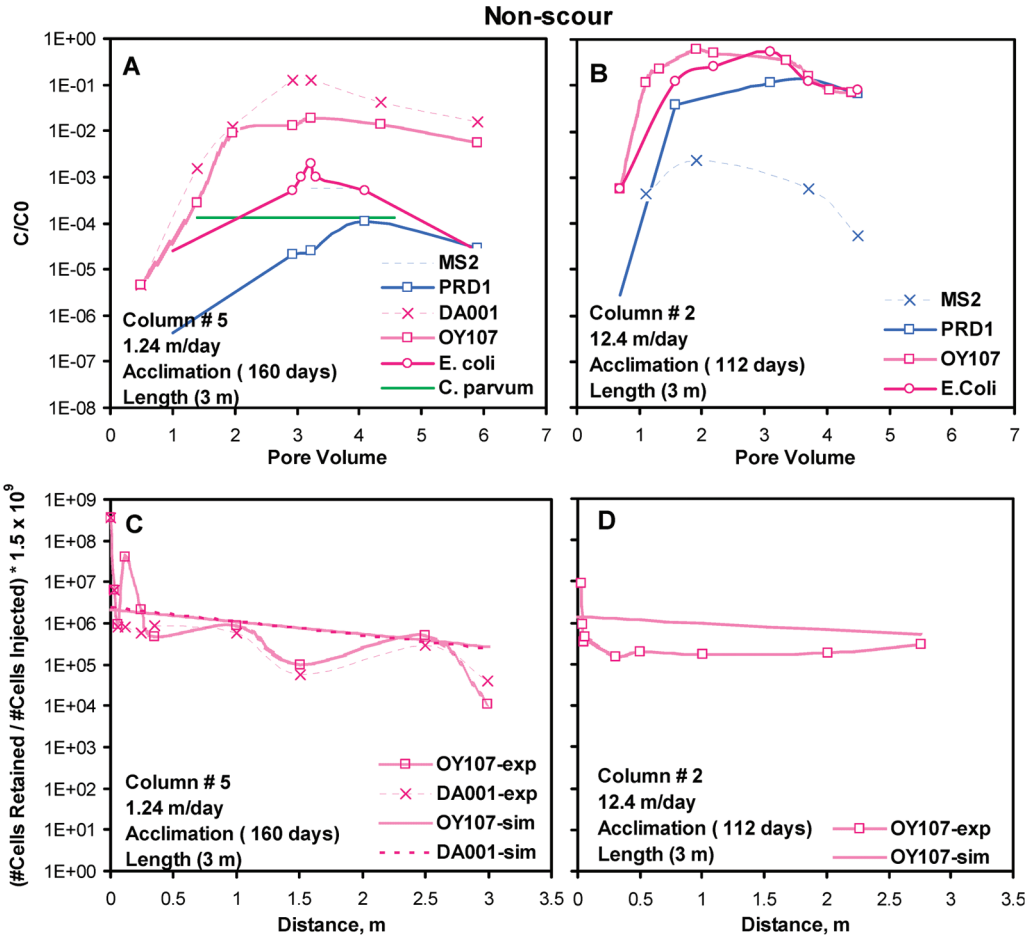

FIGURE 2. Breakthrough-elution curves (A and B) and retained profiles (C and D) of microbes at low flow (1.24 m/day)-high ionic strength (400 mg/L)-low turbidity (2 NTU) and high flow (12.4 m/day)-low ionic strength (200 mg/L)-high turbidity (20 NTU) under nonscour condition. Flat straight lines of MS2 and *C. parvum* oocysts in (A) represent their complete removal (data below detection limit).

studies conducted at Castricum, Netherlands. Notably the solution pH was similar in the above studies and this study (5.5−6.5).

In contrast to our finding,, which is that removal as a function of size is broadly consistent with theory, Hijnen et al. (*34*) asserted that greater removal was observed of *E. coli* (~1 μm) than *C. parvum* oocysts (5 μm) and bacteriophage MS2 (25 nm) in their experiments. However, their observation was based on breakthrough curves that were less-than-optimally defined (large scatter in the breakthrough concentrations). Notably, the authors concluded that straining occurred for bacteria and oocysts, and that the greater retention of bacteria represents "variability of straining". This reflects the peculiar evolution of the definition of straining over the past decade. Straining as traditionally defined is entrapment in pore throat too small to pass (*35, 36*), and given this definition, straining should of course increase with organism size. Other recently identified mechanisms of retention such as wedging in grain-to-grain contacts and retention in zones of low fluid drag via association with secondary energy minima (e.g., refs *37*−*40*) are not necessarily proportional to colloid size since they are also influenced by fluid velocity and solution chemistry (*39, 40*). The recent tendency to attribute multiple forms of attachment to straining confuses the issue, since the term straining cannot simultaneously represent both entrapment in pore throats too small to pass and these other mechanisms of retention.

Recently, Wielen et al. (*41*) stated that bacteria were removed at higher rates than viruses during transport through saturated media on the basis of other studies (*42, 43*). However, neither of these references (*42, 43*) performed transport studies, whereas ref *43* cited other studies that indicated that viruses were transported between 1000 and 1600 m in channeled limestone (*44, 45*), and bacteria were transported to 600 m in glacial out-wash sand (*46*). Clearly, comparison of virus versus bacterial transport between these two different contexts is not warranted.

In partial agreement with our results, Schijven et al. (*33*) reported 6-log removal of bacteriophages MS2 and PRD1, which was greater than that for larger *Clostridium* spores (5-log removal), at 8 m transport distance for deep well injection into a sandy aquifer. However, *E. coli* showed greater removal than the viruses and spores (7.5-log removal) in contrast to their own observed trend between viruses and spores, as well as our observed trend with microorganism size.

The mass recovery of cells that exited the column (Supporting Information Table S3) was determined from integration of breakthrough-elution curves. These recoveries demonstrate the greater retention of the viral relative to the bacterial indicators; however, the mass recovery was incomplete in several experiments, indicating that recovery of retained bacteria from the sediment was incomplete. The poor mass-recovery from the sediment may also reflect the influence of acclimation; whereby the production of Biofilm materials may inhibit the recovery of injected cells (e.g., ref *47*). As well, predation may have reduced the bacterial population following injection (e.g., *48*), and this effect would presumably have been greater on the sediment (longer residence time) than the mobile aqueous phase. Recovery

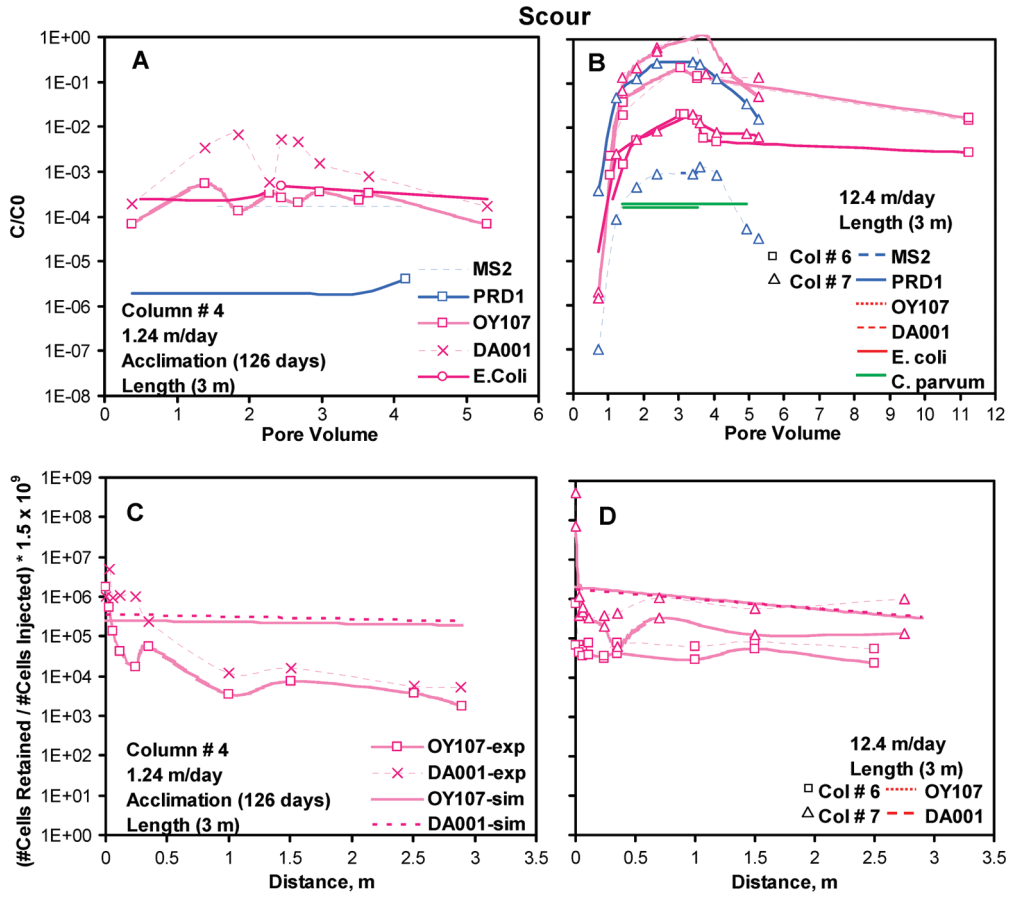

FIGURE 3. Breakthrough-elution curves (A and B) and retained profiles (C and D) of microbes at low flow (1.24 m/day)-high ionic strength (400 mg/L)-low turbidity (2 NTU) and high flow (12.4 m/day)-low ionic strength (200 mg/L)-high turbidity (20 NTU) under scour condition. Columns 6 and 7 in (C) and (D) were conducted at an acclimation time of 160 and 206 days, respectively. Flat straight lines of MS2 in (A) and *C. parvum* oocysts in (B) represent their complete removal (data below detection limit).

exceeded 200% in two cases (bacteria DA001 and OY107 in column nos. 5 and 7), suggesting that some bacterial growth occurred (e.g., a doubling of the bacterial population) during residence on the sediment or in solution. The negligible background concentrations of DA001 and OY107 prior to breakthrough (Figures 1 and 3) indicate that any potential background concentrations did not contribute significantly to the mass balance. Given the nonoptimal recoveries of cells, the deposition rate coefficients (i.e., the magnitude of retention) were determined from the breakthrough-elution curves using eqs 3 and 4 (see filtration model in the Supporting Information) to match the magnitude of the steady-state breakthrough plateaus. The retained profiles were used to examine the distribution of retained cells as a function of distance from the source. The factor of 2 influence of bacterial growth/recovery is far below the order-of-magnitude differences observed between the different indicators, as well as the differences in retained concentrations with transport distance. Hence, we believe that our observations stand despite the nonoptimal recoveries in some cases. It should be noted that in most studies recovery is not even attempted (particularly at this spatial scale); hence, the nonoptimal recoveries obtained here do not lower the quality of this study relative to others.

Influence of Presence Vs Absence of Colmation Zone (Top 10 cm of Riverbed). DA001 and OY107 were disproportionately retained near the source (nonlog-linear distribution from source) both under scour (removal of colmation zone) and nonscour conditions (compare Figure 2C and D and Figure 3C and D) and for both the low flow condition (compare Figures 2C and 3C) and high flow condition (compare Figures 2D and 3D). The simulations using filtration model (see Supporting Information) in Figures 2C and D and 3C and D represent a fit to the observed retained mass using a spatially constant deposition rate coefficient. The measured concentration of retained cells decreased more rapidly than the simulated concentrations as a function of transport distance, thereby indicating that the deposition rate coefficient effectively decreased with increasing transport distance, a so-called "hyper-exponential" deviation from existing CFT. Similar hyper-exponential shapes for the retained profiles are shown for bacteria DA001 and OY107 in replicate columns under baseline operation of RBF (Figure 1D–F).

The equivalent hyper-exponential shape of the retained profiles under nonscour and scour conditions confirms that the preferential retention of cells near the source is not dominantly controlled by the colmation zone of the river bed. Therefore, scour of the colmation zone during flood may not significantly reduce colloid removal as is typically assumed by RBF practitioners. Any observed association of flood conditions with reduced RBF performance may instead be linked to saturation of previously unsaturated sediment, which mobilizes colloids via entrainment of fluid menisci and associated microbes into the mobile water (*49*−*52*), and which may create "shortcut" flow pathways from the surface to the RBF well (*53, 54*). However, this particular issue is site specific, and lies beyond the scope of this paper.

The hyper-exponential decrease in concentration of retained cells is also supported by the deposition rate coefficients obtained from breakthrough concentrations at different port locations (Supporting Information, Figure S10). Under all experimental conditions, deposition rate coefficient (and deposition efficiency) varied over orders of magnitude

with transport distance, in agreement with the shapes of the profiles of retained cells.

In terms of mass retained, the removal of the colmation zone of riverbed material (scour) impacted the retention of microbes, but there was no consistent effect observed, since the retention sometimes increased and was sometimes unchanged in response to scour. Surprisingly, a significant increase in retention in response to scour was observed for lower flow condition (Figures 2A and 3A), whereas under the higher flow condition (Figures 2B and 3B), no significant effect of scour was observed for all microbes except *E. coli*, which showed nearly a factor of 10 increase in retention. The unexpected effect of scour (higher retention of microbes) during normal operation (lower flow condition) did not result from increased aqueous volume above the sediment in response to scour, since this volume (810 mL) was negligible relative to one pore volume (~8500 mL), and since the measured influent concentrations were consistent throughout the injection (Supporting Information Figure S9). Furthermore, the scour columns showed lesser head loss (~15 cm) relative to nonscour columns (50−134 cm), as expected. The unexpected increased retention of microbes in the scour columns may reflect an influence of increased oxygen penetration during the scour (excavation) process, which may have produced metal oxyhydroxides (favorable attachment sites) in the sediment. This possibility is supported by measured reductions in oxygen concentrations with downgradient distance, and sensitivity of the depth of penetration to flow rate, as well as notable hydrogen sulfide odor in the effluent in the acclimated columns (data not presented).

Coupled Influence of Increased Flowrate and Decreased Ionic Strength. Under nonscour conditions, the microbes were consistently removed to a greater extent under lower flow-higher ionic strength (1.24 m/day, 400 mg/L TDS and 2 NTU TSS) relative to higher flow/lower ionic strength (12.4 m/day, 200 mg/L TDS and 20 NTU TSS) conditions, as shown by the magnitudes of the breakthrough plateaus, which are lower in Figure 2A relative to Figure 2B (see also Supporting Information Table S1). The order of magnitude increase in fluid velocity coupled to factor of 2 reduction in ionic strength resulted in greater than 3 orders-of-magnitude increase in the relative breakthrough concentrations of MS2 (Figure 2A and B), 3−4 order of magnitude for PRD1, and 1−2 orders of magnitude increase for the bacterial indicators (DA001, OY107, and *E. coli*). The influence of coupled decreased ionic strength and increased fluid velocity also held under the scour condition where the colmation zone of the riverbed material was removed (compare Figure 3A and B, Supporting Information Table S1).

These findings are consistent with CFT, where increased fluid velocity decreases the collector efficiency by reducing the ability of colloids to diffuse and settle across fluid streamlines in order to reach the grain surface, as discussed above (Supporting Information Figure S3). These findings are also qualitatively consistent with the expectation from DLVO theory (*55, 56*) that reduced ionic strength increases the distance over which electric double layer repulsion extends, increasing the energy barrier (caused by repulsive interaction between colloids and collectors) to deposition and yielding lesser retention of microbes.

Notably, the order of magnitude increase in fluid velocity coupled to decreased ionic strength had a much greater effect on the bacteriophage relative to the bacteria (Figures 2A, 3A, and 1A and C). Bacteriophage retention decreased an order of magnitude or more, whereas bacterial retention decreased only by a factor of about 3. The greater effect of fluid velocity on bacteriophage relative to bacterial breakthrough is not expected from CFT, since retention as a function of fluid velocity (according to CFT) yields parallel trends (Supporting Information Figure S3) for colloid sizes ranging from 10 nm to 1 μm, indicating an equivalent effect of fluid velocity for these different colloid sizes. The greater influence of fluid velocity on bacteriophage relative to bacteria in the experiments may potentially reflect differences in their mechanisms of retention in the presence of an energy barrier, e.g., wedging versus retention in zones of low fluid drag via association with secondary energy minima (*40*), the latter corresponding more strongly to smaller colloids and being more strongly affected by fluid velocity.

An important expectation from increased solution velocity, according to CFT, is to even out the distribution of retained concentrations as a function of transport distance (Supporting Information Figure S4). This expectation seems to be borne out in the data, where increased fluid velocity (coupled to reduced ionic strength) yielded a more even distribution of retained microbes down-gradient of the source (after the first few cm) (compare Figure 2C and D). The observation held for the scour condition (compare Figure 3C and D). The implication of the above observations is that microbes may be transported over long distances under high flow and low ionic strength conditions that may be associated with high runoff events including storms and snowmelt events.

Implications. The qualitative agreement of our results (trends with organism size and fluid velocity/ionic strength) to expectations from CFT indicates that the processes operating in CFT (interception, diffusion, and sedimentation) are relevant under environmental conditions (in the presence of energy barrier). These processes bring colloids close to the surface, but it is well-known that colloid attachment is prevented by typical energy barriers in mechanistic simulations supporting CFT, and that there is no mechanism in the mechanistic model constituting CFT to allow colloid attachment in the presence of energy barriers (*12, 57*). Recent studies demonstrated several mechanisms of colloid retention in the presence of energy barriers, including wedging in grain-to-grain contacts (*39, 40*), retention in zones of low fluid drag via association with secondary energy minima (*39, 40*), surface roughness (*58, 59*), and surface charge heterogeneity (*60−63*). Incorporating these mechanisms of colloid retention in the presence of an energy barrier into mechanistic models is expected to allow prediction of both the trends and the magnitude of colloid retention under environmental conditions.

Regardless of the impact of flood scour on the colmation zone we observe disproportionate removal of colloids near the source, suggesting that scour of the colmation zone may not reduce RBF system performance with respect to colloid removal. Our results unexpectedly showed greater removal of colloids under scour conditions, likely due to deeper oxygen transport and precipitation of attractive metal oxyhydroxides. However, to what extent this enhanced removal of colloid may occur under field conditions is not clear, and warrants further investigation.

Acknowledgments

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Supporting Information Available

Details regarding filtration model, cell culture preparation and analysis, pilot scale column experiment setup, column dissection, particle size distribution of sediment, DO content in effluent and influent, TSS (turbidity) in effluent and influent, fluorescein-tracer breakthrough at normal operation

of RBF, sample collection and analysis, experimental conditions, injection concentrations of individual microorganisms, deposition rate coefficient determination, and mass-balance are provided. This material is available free of charge via the Internet at http://pubs.acs.org.

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