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Fine sediment dynamics and hyporheic exchange

Distribution of clay-sized sediments in streambeds and influence of fine sediment clogging on hyporheic exchange

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Reference additions during the first revision

1) Alexandrov, Y., Laronne, J. B., & Reid, I. (2003) – This reference was added to indicate that high suspended sediment concentrations are observed in natural settings. (L 205)

2) Briggs, M. A., Lautz, L. K., & Hare, D. K. (2014) – This reference was added to indicate that modification in hyporheic flux and residence times could influence the biogeochemistry in streambeds. (L 438)

3) Briggs, M. A., Lautz, L. K., Hare, D. K., & González-Pinzón, R. (2013) – This reference was added to indicate that modification in residence times could influence the critical stream ecosystem services. (L 115-116)

4) Chen, X., Cardenas, M. B., & Chen, L. (2018) – This reference was added to highlight that the hyporheic exchange is sensitive to dune morphology. (L 193-194)

5) Coombs, J. S., & Melack, J. M. (2013) – This reference was added to indicate that high suspended sediment concentrations are observed in natural settings. (L 202)

6) Dallmann, J., Phillips, C., Teitelbaum, Y., Sund, N., Schumer, R., Arnon, S., & Packman, A. (2020) – This reference was added to indicate that only a few studies have investigated the clogging profiles in mobile streambeds. (L 461)

7) Datry, T., Lamouroux, N., Thivin, G., Descloux, S., & Baudoin, J. (2015) – This reference was added to indicate that streambeds are seldom homogenous and the size of sediments used in our study is commonly found in natural settings. (L 185-186)

8) Elliott, A. H., & Brooks, N. H. (1997a) – This reference was added to highlight that the experimental conditions in our experiments were similar to conditions maintained in previously published studies. (L 176)

9) Guo, J. (2015) – This reference was added to highlight that the sidewall friction could influence the hydraulics in the flumes. (L 177)

10) Hartwig, M., & Borchardt, D. (2015) – This reference was added to indicate that the fine sediment deposition could hamper the vertical hydrological connectivity in stream ecosystems. (L 100)

11) Herrero, A., & Berni, C. (2016) – This reference was added to support the fact that fine sediment accumulation has been investigated in topographically flat gravel beds. (L 144)

12) Khullar, N., Kothyari, U., & Raju, K. R. (2013) – This reference was added to indicate that previous studies have used sediments of similar sizes as used in our study. It also supports the experimental observation of variation in depositional profile with the change in suspended sediment concentration (L 187)

13) Malmon, D. V., Reneau, S. L., Katzman, D., Lavine, A., & Lyman, J. (2007) – This reference was added to indicate that high suspended sediment concentrations are observed in natural settings. (L 202)

14) Mol, J. H., & Ouboter, P. E. (2004) – This reference was added to provide evidence for the fact that the fine sediment input in streams has increased dramatically in recent decades due to human practices. (L 94-95)

15) Packman, A. I., Brooks, N. H., & Morgan, J. J. (2000b) – This reference was added to support our data analysis and indicate that equivalent penetration depth has been previously defined in the literature. (L 282)

16) Packman, A. I., Salehin, M., & Zaramella, M. (2004) – This reference was added to show that previous experiments have been conducted in flumes with a size similar to our flumes. It also shows that solute penetration depth could be limited in gravel beds due to higher bed roughness (L 170, 409)

17) Ren, J., & Packman, A. I. (2004) – This reference was added to highlight that the deposition of colloids in streambeds has implications for biogeochemical reactions in hyporheic zones. (L 442)

18) Ren, J., & Packman, A. I. (2004) – This reference was added to highlight that the deposition of colloids in streambeds has implications for biogeochemical reactions in hyporheic zones. (L 442)

19) Ren, J., & Packman, A. I. (2005) – This reference was added to highlight that the coupling between fine sediment dynamics and hyporheic flow has been largely studied in sandy streambeds. (L 147)

20) Ren, J., & Packman, A. I. (2007) – This reference was added to highlight that the coupling between fine sediment dynamics and hyporheic flow has been largely studied in sandy streambeds. (L 147)

21) Sadeghi, S. H., & Saeidi, P. (2010) – This reference was added to indicate that high suspended sediment concentrations are observed in natural settings. (L 204)

22) Shrivastava, S., Stewardson, M. J., & Arora, M. (2020) – This reference was added to support that deposition of fine sediments could alter the permeability and closely associated hydraulic conductivity. (L 427)

23) Soulsby, C., Youngson, A., Moir, H., & Malcolm, I. (2001) – This reference was added to indicate that clogging could modify the streambed permeability. (L 108)

24) Zhou, D., & Mendoza, C. (1993) – This reference was added to highlight that the roughness in gravel beds could limit the vertical solute transport. (L 409)

Abstract

In this work, the deposition of clay-sized fine particles (d_{50} = 0.006 mm) and its subsequent influence on the dune-induced hyporheic exchange are investigated. Fine sand (D_{50} = 0.28 mm), coarse sand (D_{50} = 1.7 mm), and gravel (D_{50} = 5.5 mm) grains were used to form homogenous model streambeds; one control - no clay input, and two treatments - increasing clay inputs for each grain type. The results indicate that the clogging profiles of clay-sized sediments may not be predicted accurately using the previously proposed metric based on the relative sizes of infiltrating and substrate sediments. Further, the depositional patterns vary with the initial concentration of clay particles in the surface water. The assessment of clogging profiles in coarse-grained model streambeds also reveals a preferential infiltration of the clay particles in the hyporheic downwelling regions. The results from the dye tracer test suggest that the accumulation of clay particles altered the exchange characteristics in the treatment flumes. For each grain size, the treatment flumes exhibit lower hyporheic flux and higher median residence times compared to their respective control flumes. The dye penetration depths were lower in treatment flumes with fine and coarse sand compared to their respective control flumes. Interestingly, higher penetration depths were observed in treatment flumes with gravel compared to their respective control flume potentially due to the generation of preferential flow paths in the partially clogged gravel beds. The clogging altered the hyporheic fluxes and residence times in the coarse-grained model beds to a greater degree in comparison to the fine sand beds. Overall, our findings indicate that the properties of both fine and substrate sediments influence the clogging patterns in streambeds, and the subsequent influence of fine sediment clogging on hyporheic exchange and associated processes may vary across stream ecosystems.

Keywords: clogging profile, fine sediment concentration, hyporheic zone, hyporheic flux, residence time distribution, depth of exchange, re-circulating flumes, sediment permeability

1 Introduction

The input of fine sediments to the streams has increased dramatically in recent decades, particularly due to human practices such as forestry, mining, and urban development (Mol & Ouboter, 2004; Owens, 2005; Wharton, Mohajeri, & Righetti, 2017). Excessive deposition of fine sediments on/into the streambeds has a detrimental influence on the overall physical, chemical and biological environment of the streambeds (Jones et al., 2012; Petts, Thoms, Brittan, & Atkin, 1989; Weigelhofer & Waringer, 2003). For instance, fine sediment accumulation could hamper hydrological connectivity across the sediment-water interface (SWI) in fluvial environments (Hartwig & Borchardt, 2015). This could limit the supply of oxygen and other nutrients for the biological community in the streambed (Tonina & Buffington, 2009). Fine sediment could also infiltrate up to a depth pertinent to macroinvertebrates migration (Vadher, Stubbington, & Wood, 2015) or fish spawning (Kemp, Sear, Collins, Naden, & Jones, 2011) and affect the activities of these organisms.

Deposition of fine sediments on/into the streambeds could modify the streambed permeability (Packman & MacKay, 2003; Soulsby, Youngson, Moir, & Malcolm, 2001), which in turn, is one of the important controls on the exchange of water/solutes across the SWI (Salehin, Packman, & Paradis, 2004; Sawyer & Cardenas, 2009). This exchange, generally described as hyporheic exchange, underpins several critical stream ecosystem services such as cycling of nutrients (Triska, Duff, & Avanzino, 1993), processing of organic matter (Pusch, 1996), and regulating temperature regime in surface and interstitial waters (Arrigoni et al., 2008). These functions are dominantly influenced by the hyporheic flow characteristics such as the hyporheic flux, residence times, and depth of exchange of solutes (Briggs, Lautz, Hare, & González-Pinzón, 2013; Harvey, Böhlke, Voytek, Scott, & Tobias, 2013; Marzadri, Tonina, Bellin, & Valli, 2016). Thus, any modification to these characteristics due to fine sediment accumulation in streambeds will have a direct influence on the overall stream ecosystem functioning.

The process of deposition of fine particles in pore spaces of the streambed is known as physical clogging (Brunke, 1999). The clogging profiles have been broadly divided into two types - a) internal and b) external (Blaschke, Steiner, Schmalfuss, Gutknecht, & Sengschmitt, 2003; Brunke, 1999). A streambed is referred to as internally clogged if fine sediments infiltrate the bed armor layer and deposit within the substrate material. When an additional fine sediment layer deposits on top of the bed, the streambed is referred to as externally clogged. The depositional patterns of fine sediments in coarser beds has been demonstrated to be influenced by variables such as the relative size of bed sediments and fine sediments (Gibson, Abraham, Heath, & Schoellhamer, 2009a, 2009b; Wooster et al., 2008), flow velocity (Cunningham, Anderson, & Bouwer, 1987), and bed shear stress (Parker, 1990; Schälchli, 1992; Wilcock et al., 1996). For instance, based on the relative size of the bed and infiltrating material, two kinds of infiltration mechanisms have generally been discussed in literature - a) unimpeded static percolation, and b) bridging (Gibson et al., 2009a, 2009b; Wharton et al., 2017). The unimpeded static percolation occurs when fine sediments fill up the voids in bed from the bottom upwards. When the size of infiltrating grains is larger relative to pore size, their penetration is restricted to shallow depths impeding subsequent infiltration leading to the formation of a fine sediment seal known as bridge layer (Gibson et al., 2009a). Some studies have also demonstrated the transport of fine sediments driven by hyporheic flow and their retention in hyporheic interstices (Packman, Brooks, & Morgan, 2000a; Rehg, Packman, & Ren, 2005).

Most of the previous laboratory investigations have studied the accumulation profile of fines in the gravelly substrate with flat topography (Beschta & Jackson, 1979; Gibson et al., 2009a; Herrero, Berni, & Camenen, 2015; Kuhnle, Wren, Langendoen, & Rigby, 2012; Wooster et al., 2008), whereas, the coupling between fine sediment dynamics and hyporheic flow has been largely studied in sandy substrates (Fox, Packman, Boano, Phillips, & Arnon, 2018; Packman et al., 2000a; Rehg et al., 2005; Ren & Packman, 2005, 2007). Further, the metric based on the relative size of fine and substrate sediments which is conventionally used to predict clogging profiles has been developed for fine sand (fine particles) and gravel (substrate) sediment system (Huston & Fox, 2015). The threshold ratios developed for this sediment system may not be applicable for other types of sediment systems as evidenced by a recent study (Fetzer, Holzner, Plötze, & Furrer, 2017). Moreover, studies focusing on the distribution of fine sediments within the topographical bed features (e.g. dunes) and its influence on the hyporheic exchange have gained momentum only recently (Fox et al., 2018; Jin, Chen, et al., 2019; Jin, Zhang, et al., 2019).

In this work, we investigate the deposition of clay-sized fine particles on/into the streambeds of different physical characteristics. Three types of substrate materials – fine sand (D_{50} = 0.28 mm), coarse sand (D_{50} = 1.7 mm), and gravel (D_{50} = 5.5 mm) were used to form homogenous model streambeds with dune-shaped morphology. These model streambeds are subjected to different initial concentrations of clay particles (d_{50} = 0.006 mm) and the subsequent clogging profiles are assessed. Fine sediment clogging in these model streambeds is expected to alter the hyporheic flow regime, and therefore, the hyporheic flux, residence times, and penetration depths of solute are evaluated by performing dye tracer tests in the experimental flumes.

2 Experimental methods

2.1 Experimental flumes and sediments

The experiments were conducted in Perspex built 3 m (L) x 0.2 m (W) x 0.4 m (D) re-circulating flumes in the Sexton Ecohydraulics laboratory at The University of Melbourne (Figure 1). Although the re-circulating flumes were small in size, the results of solute exchange

166 across the SWI obtained in similar-sized flumes are in good agreement with experimental
167 results from much larger flumes (Packman, Salehin, & Zaramella, 2004; Salehin et al., 2004).
168 The experiments were conducted with tap water (pH = 6.7, temperature range = 18-19.5 °C,
169 salinity = 220 µS cm^{-1}) and the flow rate (~1.6 l/s) in flumes was measured by GPI-TM series
170 flow meters. The slope (1:300, V:H) was adjusted using scissor jacks attached at the upstream
171 section of the flumes. Both flow rates and slopes were fine-tuned to attain uniform flow in the
172 flumes with an average flow depth of 9 cm. The friction from the smooth sidewalls could
173 potentially influence the flow characteristics (Guo, 2015), however, the boundary resistance
174 due to flume walls has been ignored in this work. The flow velocity (~8.8 cm/s) was measured
175 by dividing the discharge by cross-sectional area and was such that no erosion of bed grains
176 was observed. The Reynolds number in the experimental flumes was of the order of 10^4. These
177 hydraulic variables were similar across all the flumes.

178 The flumes were filled with fine sand (indexed as FS, D_{50} = 0.28 mm, porosity = 0.45), coarse
179 sand (indexed as CS, D_{50} = 1.7 mm, porosity = 0.37) and gravel (indexed as G, D_{50} = 5.5 mm,
180 porosity = 0.38) to form homogenous beds. These sediment sizes are readily observed in natural
181 settings, but the beds are generally heterogeneous (Datry, Lamouroux, Thivin, Descloux, &
182 Baudoin, 2015). Sediments with similar physical properties have been also used in several
183 previous laboratory investigations (Fetzer et al., 2017; Khullar, Kothyari, & Raju, 2013). The
184 experiments followed a control and treatment design with one control flume (C, no clay input)
185 and two treatment flumes (T1- low clay input and T2- high clay input) for each sediment type;
186 for instance, the control and treatment flumes with fine sand are referred to as FS-C, FS-T1,
187 and FS-T2 respectively (see Table 1 for details). The flumes were filled with pre-washed
188 sediments and were washed again in the flumes to get rid of any foreign material (e.g. dirt)
189 before forming dunes of the desired configuration (Figure 1). As the hyporheic exchange is
190 sensitive to bed morphology (Elliott & Brooks, 1997a, 1997b), the dunes were shaped by hand

to ensure that the dune height (3 cm) and the distance between two consecutive dunes' troughs or crests (24 cm) are uniform across all the experimental flumes.

Ball clay (d_{50} provided by the supplier = 0.006 mm) was used as fine sediment to clog the model streambeds. The mass of clay added into the treatment flumes was varied to obtain the required initial concentration of fine sediments (C_0^{fs}, g/l) in the water column (Table 1). The suspended sediment concentrations used in our study represent the scenarios when the streams are subject to high fine sediment input, for instance, from a burned land after a brief thunderstorm (Coombs & Melack, 2013; Malmon, Reneau, Katzman, Lavine, & Lyman, 2007). High suspended sediment concentrations have been also observed in previous field investigations studying suspended sediment regime in forested (Sadeghi & Saeidi, 2010) and ephemeral catchments (Alexandrov, Laronne, & Reid, 2003). For fine sand and coarse sand, the C_0^{fs} in their respective treatment flumes were 1.6 g/l and 3.2 g/l, while the C_0^{fs} values in treatment flumes with gravel were 3.2 g/l and 6.4 g/l. The choice of higher concentration in gravel beds relative to beds with other two grain types was based on preliminary experiments that indicated the former exhibits internal clogging i.e., suspended particles largely infiltrate into the gravel bed at all C_0^{fs} below 3.2 g/l. Doubling the initial concentration of clay particles in the water column enabled us to study the alteration in the depositional pattern of clay at increased fine sediment input.

For clay addition, suspension of a known mass of clay was formed in tap water (2 l) and stirred for approximately 3 hours. Due to the background salinity of tap water, the clay particles flocculate and the d_{50} rises to 0.022 mm as measured by the particle size analyzer (Mastersizer 3000). The suspensions of clay were injected into the water column of treatment flumes over one recirculation cycle (~90 s). The settlement/infiltration of fines was photographed from flume walls at regular intervals to observe the clogging profiles. The average depth of the clogging layer ($\overline{D}$, m) formed due to the deposition of clay particles on top of the bed and the average infiltration depth of clay particles into the bed ($\hat{D}$, m) were measured manually through the flume walls (20 measurements were made between consecutive crests and troughs). The time taken for clay particles to deposit on/into the model streambeds varied across the treatment flumes (FS-T1- 3 days and FS-T2- 5 days, CS-T1- 2 days and CS-T2- 3 days, G-T1- 1 day and G-T2- 2 days). No re-suspension of clay particles was observed throughout the experiments as seen through the flume walls.

Huston and Fox (2015) proposed a metric, $\frac{D_{50}}{d_{50}\sigma_{ss}}$, ($D_x$ and d_y denote the diameters than which x% and y% of particles in the substrate sediments and fine sediments respectively are finer. σ_{ss} is the geometric standard deviation of substrate sediments calculated as the square root of the ratio of D_{85} to D_{15}) to predict the clogging profiles. Based on their work, the unimpeded static percolation would occur if this ratio is >27 and bridging would be observed otherwise. The ratio, $\frac{D_{50}}{d_{50}\sigma_{ss}}$, was calculated for the three sediment systems (Table 2) and the predicted clogging profiles were compared with the observed depositional patterns of clay particles.

2.2 Tracer test to measure hyporheic exchange characteristics

After complete deposition of clay particles, tracer-grade rhodamine WT (fluorescent dye tracer) was added slowly into the water column over one re-circulation cycle to ensure rapid and homogenous dye mixing. The dye concentration in surface water ($C(t)$, ppb) decreased due to mixing with pore water and this decline was monitored using Turner Designs Cyclops 7 sensors. The experiments were ceased when an equilibrium dye concentration (C_{eq}, ppb) is attained (rate of change of dye concentration in the surface water is close to 0) leading to uniform dye concentration in the water column and hyporheic zone. It took ~10 days for fine sand, ~6 days for coarse sand, and ~15 hrs for gravel beds after the dye injection to reach the equilibrium stage. Tap water was manually added into the flumes during the experimental runs to compensate for evaporative water loss and to ensure that the experiments were conducted with a constant water volume. The rhodamine WT tracer was used at a small concentration ensuring conservative behavior and the experiments were performed in a closed room to prevent the photochemical decay of the dye.

2.3 Data analysis

The time series (temperature-corrected) of normalized dye concentration ($C^*(t)$), calculated as the ratio of $C(t)$ to initial dye concentration after homogenous mixing (C_0, ppb), was fitted to an exponential equation using the principles of least square method to obtain the mathematical functions for the observed dye concentrations. Each of these functions fits their respective observed data closely as indicated by the estimated root mean square errors (< 0.005). The curves for these mathematical functions are presented as the breakthrough curves in this work. The hyporheic flux (*q,* m/min) was estimated from the initial gradient of the breakthrough curve and it represents the volumetric flow rate averaged over the bed surface area (A, m^2).

The average residence time function ($\overline{R}(\tau)$), denoting the fraction of dye particles that entered the bed at time t close to 0 and remain in bed at a time t = τ, was calculated based on the approach presented in Elliott and Brooks (1997b). The slope of $\overline{R}(\tau)$ is indicative of the return flux of dye particles from the bed to the water column. In their approach, a set of coupled equation needs to be solved;

$$m(t) = \overline{q} \int_{\tau=0}^{t} C^*(t-\tau)\overline{R}(\tau)d\tau \ldots\ldots\ldots\ldots\ldots \textit{(Equation 1)}$$

$$C^*(t) = 1 - \frac{m(t)}{d'} \ldots\ldots\ldots\ldots\ldots\ldots \textit{(Equation 2)}$$

where,

261 m (m) is related to the depth of penetration of solutes into the bed and it represents the accumulated mass per unit plan area of bed (A, m^2) divided by C_0, and d' (m) is the ratio of the total volume of water in the flume system (excluding the pore water) (V_{sw}, m^3) to A.

264 On substituting m(t) from Equation 2 in Equation 1 we get,

265 $d'(1 - C^*(t)) = q\,[\bar{R} * C^*]$………….……*(Equation 3)*

266 We apply Laplace transform to Equation 3 and rearrange it to get,

267 $\mathcal{L}\{[\bar{R} * C^*]\} = \frac{d'}{q}\,\mathcal{L}\{1 - C^*(t)\}$………….……*(Equation 4)*

268 $\mathcal{L}\{\bar{R}\}.\mathcal{L}\{C^*(t)\} = \frac{d'}{q}\,\mathcal{L}\{1 - C^*(t)\}$………………*(Equation 5)*

269 Further rearranging and taking inverse Laplace transform such that,

270 $\bar{R}(\tau) = \mathcal{L}^{-1}\frac{\frac{d'}{q}\mathcal{L}\{1 - C^*(t)\}}{\mathcal{L}\{C^*(t)\}}$………………*(Equation 6)*

271 The mathematical function for the observed dye concentration is input into Equation 6 to arrive at the $\bar{R}(\tau)$. The median (RT_{med}) and mean (RT_{mean}) residence times were subsequently calculated from the obtained residence time distribution.

274 The normalized equilibrium dye concentration was used to establish the mass balance of dye at the beginning and the end of experiments to estimate the volume of water in the hyporheic zone (V_p, m^3) which mixes with the surface water. In general, the mixing between surface and pore water due to the exchange across SWI results in non-uniform dye concentration in the bed (Elliott & Brooks, 1997b). As a measure of dye exchange with the bed, we determine the 'equivalent penetration depth' ($\bar{d}$, m) as proposed in previous laboratory investigations on hyporheic exchange (Elliott & Brooks, 1997b; Packman, Brooks, & Morgan, 2000b). It is defined such that if the dye were to homogenously mix and produce uniform dye concentration in the bed up to this depth (and unmixed below), the net dye exchanged across the SWI equals

the actual exchange occurring due to non-homogenous dye mixing. Mathematically, it can be expressed as the ratio of V_p to A. As the average hyporheic flux is related to the depth of exchange (volume of water exchanged) and mean residence times, another estimate of average hyporheic flux (q') was calculated as the ratio of $\overline{d}$ to RT_{mean}.

3 Results

3.1 Observation of clogging

The model streambeds exhibited both internal and external clogging as observed from the flume walls (Table 1). Whilst the clay particles deposited on top of the beds in FS-T1, FS-T2, and CS-T2, infiltration of fines was observed in CS-T1, G-T1, and G-T2 (Figures 2-4). The $\overline{D}$ was higher in FS-T2 than FS-T1 (Table 1). In CS-T1, the deposition of fine sediments into the bed was observed all along the flume. The infiltration of clay particles was limited to the top 3 cm of the bed and it occurred largely at the stoss side of the dunes. The infiltration of fines at the lee side of the dune was very shallow (< 1 cm). A similar infiltration pattern was observed in G-T1, but the clay particles infiltrated to deeper bed regions (at both stoss and lee side of the dunes) compared to CS-T1 (Table 1). In G-T2, slightly deeper ingression of clay particles was observed compared to G-T1. Besides, a patchy deposition of clay particles on top of the bed was observed in the former. The ratio, $\frac{D_{50}}{d_{50}\sigma_{ss}}$, in coarse sand and gravel beds was greater than the threshold value (> 27) predicted for the occurrence of unimpeded static percolation (Table 2). This ratio was less than 27 for the fine sand-clay sediment system.

3.2 Hyporheic exchange characteristics

For all three sediment types, treatment flumes exhibited lower q (estimated from breakthrough curves presented in Figure 5) than their respective control flumes (Table 1). The q in both FS-T1 and FS-T2 were lower by <10% than FS-C. The q in CS-T1 and CS-T2 were lower than CS-C by ~24% and 69% respectively. The q in G-T1 and G-T2 were lower than G-C by ~43%

and ~93% respectively. The calculated *q'* was consistently lower than *q* (within 70% of the *q*). The trend of modification in *q'* across all the flumes was similar to *q*.

For fine and coarse sand, the $\overline{d}$ in the treatment flumes were lower compared to their respective control flumes (Table 1). The treatment flumes subjected to highest C_0^{fs} for both the sediment types (i.e., FS-T2 and CS-T2) exhibited lowest $\overline{d}$. Contrastingly, G-T1 and G-T2 exhibited greater $\overline{d}$ than the G-C (greatest in G-T2).

The flumes with gravel beds exhibited lower RT_{med} and RT_{mean} than flumes with fine and coarse sand (Table 1). For each sediment type, the RT_{med} and RT_{mean} were longest in treatment flumes subjected to highest C_0^{fs} (FS-T2, CS-T2, G-T2). The RT_{mean} were longer in CS-T1 and G-T1 but shorter in FS-T1 than their respective control flumes. The return flux of dye from the model streambeds is proportional to the slope of $\overline{R}(\tau)$ (Figure 6). A consistent trend noted for each sediment type was that the slope of $\overline{R}(\tau)$ initially increases less rapidly in the treatment flumes compared to their respective control flumes i.e., the dye particles initially exited the bed slowly in the former. For each sediment type, the initial dye transport was slowest through the hyporheic zones of model streambeds subjected to highest C_0^{fs}.

4 Discussion

4.1 Fine sediment infiltration profiles

The infiltration patterns in treatment flumes could be largely attributed to the transport of clay particles due to advective pumping and gravitational settling mechanisms. For all the treatment flumes, a preferential deposition of clay particles at the stoss-side of the dunes indicates transport of fines along the downward advective hyporheic flow paths as also demonstrated in some previous investigations (Chen, Packman, Zhang, & Gaillard, 2010; Jin, Chen, et al., 2019). The fine sediment infiltration at the lee-side of the dunes occurred potentially due to the settling of particles. This argument is supported by results from a recent study (Jin, Chen, et al., 2019) which demonstrated that fine particles do not accumulate at the lee side of the dunes in the absence of settling phenomenon. The lee side of the dunes corresponds to the upwelling zones and the deposition of clay particles in these areas indicates that settling velocities of the particles dominated the upwelling hyporheic flow. The size of pores between the gravel grains is expected to be larger than pores in the other two sediment types. Consequently, the clay particles could get transported readily into the gravelly substratum via the mechanisms of advective pumping and gravitational settling. Besides, turbulent pulses could generate at the SWI in gravel beds as observed in previous investigations (Carling, 1984; Roche et al., 2018). We speculate that this turbulence could have further assisted the transport of fine sediments into the gravel beds.

Huston and Fox (2015) proposed that unimpeded static percolation would occur in sediment beds if the value of the ratio, $\frac{D_{50}}{d_{50\sigma ss}}$, is greater than 27. Comparatively, the value of this ratio in our study was ~twice in coarse sand-clay sediment system and ~seven times greater in gravel-clay sediment system. However, the infiltration of clay particles occurred only to a limited depth, and bridging was observed in the coarse-grained model streambeds. This signifies that the threshold ratio for the occurrence of unimpeded static percolation in beds subject to clay-sized infiltrating particles could be significantly higher than the previously proposed threshold. Our finding is consistent with results from Fetzer et al. (2017), in which silt-sized particles formed a bridging layer in the substrate sediments (comprising of sand) even when the value of $\frac{D_{50}}{d_{50\sigma ss}}$ was ~37.

The trapping of infiltrating particles within the pore matrix would have occurred by the mechanism of filtration via physicochemical interaction with bed sediments and physical straining (Bradford, Yates, Bettahar, & Simunek, 2002; Karwan & Saiers, 2009). Upon settling within the pores, the clay particles got attached to the surface of bed grains due to attractive

355 forces between the sediments. It can be anticipated that the retention of clay particles due to
356 straining would occur when the pore size was narrower than the size of the infiltrating particles.
357 Although the pore size distribution was not assessed in this work, the pore size between bed
358 sediments could be estimated using the Heron's formula as presented in previous studies
359 (Herrero & Berni, 2016; Huston & Fox, 2015). This involved simplifying the bed geometry
360 and assuming spherical bed particles with the diameter as D_{50}. The pore sizes for fine sand,
361 coarse sand, and gravel grains were estimated to be ~0.04 mm, ~0.26 mm, and ~0.85 mm
362 respectively. At this point, it is important to consider the effect of the surface properties of
363 cohesive clay particles. In our work, the clay particles flocculated in the water column due to
364 the background salinity of the tap water which subsequently influenced the settling and
365 depositional characteristics of these particles in the model streambeds. The difference between
366 the estimated pore size in fine sand and the size of flocculated clay particles was not large, and
367 therefore, the clay particles were trapped at the surface layer and no infiltration was observed.
368 Amongst the coarser grains, the clay particles were more susceptible to trapping in coarse sand
369 compared to gravel due to the smaller size of pores in the former. Consequently, vertical
370 transport of clay particles occurred only up to shallow depths in the coarse sand bed compared
371 to the gravel beds.

372 Given that the hydraulic variables and the physical properties of bed in treatment flumes of a
373 particular grain type were similar, the observation of different clogging profiles amongst them
374 (Table 1) could be attributed to different initial concentrations of clay particles in the water
375 column as also observed previously (Khullar et al., 2013). We anticipate that at high fine
376 sediment concentration, a large proportion of fine sediments tend to infiltrate the pores
377 resulting in clogging of voids at a faster rate and eventually forming a bridging layer which
378 impedes further infiltration of fine sediments into the bed. In coarse sand, the pores were small,
379 thus, bridging by clay sediments occurred close to the interface and impeded subsequent clay

infiltration leading to the formation of a clogging layer at the surface. For gravelly substrate, large surface voids allowed the infiltration of a greater amount of clay particles before the formation of a bridging layer. As a consequence, both fine sediment infiltration and formation of a spatially patchy and thin bridging layer at the bed surface was observed in G-T2.

4.2 Influence of clogging on hyporheic exchange

The alteration of hyporheic flow characteristics in treatment flumes could be attributed to the deposition of fine sediments on/into the model streambeds. As also shown in previous investigations (Packman & MacKay, 2003; Rehg et al., 2005), fine sediment clogging reduced the bed permeability at the SWI via - a) formation of a seal of fine sediment layer on the top, and/or b) infiltration of fine sediments into the pore spaces. In both cases, the exchange across SWI is obstructed and consequently, the treatment flumes for each sediment type exhibited lower q and longer RT_{med} compared to their respective control flumes. The impedance of exchange across the SWI is also confirmed by the slow initial transport of dye particles in the model streambeds as evaluated from the slope of average residence time function (Figure 6) which could be attributed to the deposition of clay particles on/into the bed.

The clogging in treatment flumes with fine and coarse sand resulted in a smaller depth of hyporheic exchange ($\overline{d}$) in comparison to their respective control flumes. However, $\overline{d}$ in treatment flumes with gravel beds were greater than G-C which could be potentially attributed to preferential flow through clogged gravel beds. The spatially patchy deposition of clay particles in highly porous gravel grains could have generated preferential flow paths through which the dye was transported into deeper regions (Chen et al., 2010). Oppositely, continuous heterogeneity observed in dune-shaped streambeds has been reported to compress the hyporheic zone (Tonina, de Barros, Marzadri, & Bellin, 2016). Note that the $\overline{d}$ values in the experimental flumes suggest that the pore water was not completely mixed with the water column. Amongst the three sediment types, the $\overline{d}$ was greatest in control flume with coarse

405 sand (CS-C). However, one would expect mixing up to a greater depth in G-C given that the permeability of gravel would be higher than that of coarse sand. The lower mixing depths in the gravel beds compared to the coarse sand beds could be attributed to higher roughness in the former due to larger grain size. It has been well established in several previous investigations that larger pore size in gravelly substrate causes a non-zero velocity at the bed surface and results in exponentially decreasing flow with the depth (Packman et al., 2004; Zhou & Mendoza, 1993).

412 The degree to which hyporheic exchange characteristics were modified due to clogging by clay-sized sediments differed between fine- and coarse-bedded model streambeds. For instance, both FS-T2 and CS-T2 exhibited external clogging with similar depths of the clogging layer at the top. While the q in the former was only marginally lower compared to FS-C, a reduction of ~70% in q was observed in the latter compared to CS-C. Similarly, RT_{med} and RT_{mean} in treatment flumes with coarse grains were affected to a greater degree than fine sand compared to their respective control flumes. The difference in the extent to which fine sediment clogging influences the hyporheic fluxes or residence times in model streambeds could be attributed to the difference in intrinsic permeability of the parent bed material. The dune-induced advective pumping of water/solutes is expected to be more dominant in coarse grains due to their higher permeability compared to fine sand. Consequently, the hindrance to the rate of dye transfer across the SWI was proportionally larger in the former after deposition of the low permeability clogging layer. The treatment flumes with fine and coarse sand were subject to similar clay concentrations, and the comparison of exchange characteristics between them suggests that the clogging by clay-sized particles could potentially have a greater impact on the hyporheic flow regime in coarse-bedded streams.

428 *4.3 Implications of the research*

Fine sediments are ubiquitous in the stream environment and their accumulation in the streambed could potentially alter the permeability or closely related hydraulic conductivity of the bed sediments (Shrivastava, Stewardson, & Arora, 2020). Our work highlights that the deposition of fine sediments on/into the streambeds could be spatially patchy and may also exhibit temporal variability with changes in fine sediment concentration in the surface water. Thus, the hydraulic conductivity of streambeds is expected to exhibit spatio-temporal variability due to clogging. This holds implications for the modeling frameworks that aim to predict exchange across the SWI but assume streambeds as homogenous media with constant hydraulic properties in space and time. The experimental results also call for developing a more holistic metric for predicting the transport and deposition regime of cohesive sediments (e.g. silt and clay) taking into account their electro-chemical properties in addition to the relative size difference between the substrate and suspended particles.

The alteration in hyporheic flux and residence times due to clogging could potentially influence the biogeochemical cycling of nutrients and contaminants (Briggs, Lautz, & Hare, 2014; Harvey et al., 2013). Further, colloidal particles have been demonstrated to interact with reactive solutes (e.g. metals such as zinc and copper), therefore, the deposition of colloids on the streambed or within the hyporheic zone has implications for fate and transport of associated solutes (Ren & Packman, 2004a, 2004b). The modification in the biochemical transformation of solutes in the hyporheic zones would directly influence the overall quality of surface and sub-surface waters in stream ecosystems.

4.4 Limitations and future work

The results from our laboratory investigation provide useful insights into fine sediment dynamics in streams, however, the re-circulating flumes are yet a simplistic representation of fluvial environments. The model streambeds were homogenous and the clay particles used as fine sediments had a specific grain size distribution and chemical properties. In natural settings, streambeds are heterogeneous and are exposed to fine material of a wide range of size and chemical composition that may potentially interact with the bed differently. Further, all the experiments were conducted at a constant and low discharge, thus, do not mimic the wide range of flow conditions in streams that may potentially result in different clogging patterns at a given fine sediment concentration.

Future research could be directed to study the depositional profiles of fine materials exhibiting a range of different physico-chemical characteristics on/into streambeds of heterogeneous sedimentary, topographical, and hydraulic properties. More experimentation under diverse conditions would assist in developing a more comprehensive approach to predict the clogging profiles of cohesive fine sediments. Further, mobile streambeds are observed in several natural settings but only a few studies have investigated the deposition profiles of fine sediments in non-stationary beds (Dallmann et al., 2020; Dudill, Frey, & Church, 2017). We suggest that imminent studies should also explore the accumulation profile of fine sediments in a mobile bed framework. Moreover, field evidence of the fine sediment distribution and its influence on hyporheic exchange must also be gathered.

5 Conclusions

The experimental observations from a series of laboratory experiments reveal that the interplay of clay-sized suspended sediments with the bed material is complex. When the sizes of infiltrating clay particles and pores within the bed are similar, the former accumulate at the bed surface leading to the formation of a clogging layer as observed in the model streambeds comprising of fine sand. The infiltration of clay particles was observed in model streambeds composed of coarse sand and gravel grains with a greater average penetration depth in the latter. The results reveal that the threshold ratio based on the relative size of infiltrating and substrate material used to predict the clogging profiles may not apply to clay-sized sediments as the depositional pattern of such cohesive particles is also influenced by the electro-chemical forces between the fines. The results also indicate that depositional patterns were influenced by the concentration of clay particles in the water column. When subject to lower suspended sediment concentration (1.6 g/l in coarse sand and 3.2 g/l in gravel beds), the clay particles infiltrated into the bed with no accumulation at the bed surface. At higher concentrations (3.2 g/l in coarse sand and 6.4 g/l in gravel beds), the clay particles tend to deposit at the bed surface potentially due to enhanced cohesive interactions between them leading to aggregation of clay particles in the water column. The visual observations also provide evidence of the preferential deposition of fine sediments along the hyporheic flow paths.

For each sediment type, the deposition of clay-particles on/into the model streambeds altered the hyporheic flow regime with greater influence in treatment flumes subjected to the highest fine sediment input. As a result of clogging, lower hyporheic flux and longer median residence times were observed in the treatment flumes of each sediment type compared to their respective control flumes (no clogging). The penetration depths of solute were smaller in treatment flumes with fine and coarse sand compared to their respective control flumes. For gravelly substrate, the penetration depth was larger for treatment flumes compared to the control flume potentially due to the generation of preferential flow paths in the partially clogged porous gravel beds. Finally, the experimental results highlight that clogging by clay-sized particles has a greater influence on the hyporheic flow regime in coarse-grained beds than in beds comprising of fine grains.

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682 *Data Availability Statement:* The data that support the findings of this study are available from the corresponding author upon reasonable request.

Figure Captions

Figure 1: Schematic representation of the re-circulating flume used for conducting the experiments. The flume consisted of baffles at both upstream and downstream sections. The test section was 2.4 m long where the sediments were filled, and the bed was manually shaped to obtain regular dunes (height: 3 cm and wavelength: 24 cm) at the bed surface. The valves and pump attached to the flume set-up are represented by 'V' and 'P' in black circles respectively. The flow rate in the flume was controlled by the pump controller (not shown) attached at the downstream end of the flume. The drain pipe was attached at the downstream end to empty the flume water.

Figure 2: Fine sediment deposition profile in treatment flumes with fine sand (FS) subject to initial concentrations of clay particles in the water column as - a) 1.6 g/l (FS-T1) and b) 3.2 g/l (FS-T2). For both the flumes, clay particles accumulated at the bed surface and no infiltration was observed. The thickness of the clogging layer at the bed surface was higher in FS-T2 in comparison to FS-T1.

Figure 3: Fine sediment deposition profile in treatment flumes with coarse sand (CS) subject to initial concentrations of clay particles in the water column as - a) 1.6 g/l (CS-T1) and b) 3.2 g/l (CS-T2). Infiltration of clay particles was observed in CS-T1 up to a limited depth, while only a thick clogging layer was observed at the bed surface in CS-T2.

Figure 4: Fine sediment deposition profile in treatment flumes with gravel (G) subject to initial concentrations of clay particles in the water column as - a) 3.2 g/l (G-T1) and b) 6.4 g/l (G-T2). Almost all the suspended clay particles infiltrated into G-T1 up to a limited depth. In G-T2, both infiltration of clay particles and the formation of a spatially patchy and thin layer of clay deposits at the bed surface was observed.

Figure 5: The observed (markers) and fitted (lines) normalized dye concentration profiles in the water column of the control and treatment flumes with - a) fine sand b) coarse sand, and c) gravel beds. The observed concentration was fitted by using the principles of least square method. The observed and fitted data points match closely as the root mean square error (RMSE) values for all the fits are less than 0.005.

Figure 6: Flux-weighted cumulative residence time distribution for the dye tracer in control and treatment flumes with - a) fine sand b) coarse sand, and c) gravel beds. The slope of the average residence time function is indicative of the return flux from the bed. For each grain type, the slope of the residence time function in the treatment flumes initially increases less rapidly compared to their respective control flumes indicating that the clogging in the former hindered the dye transport through the hyporheic zone.

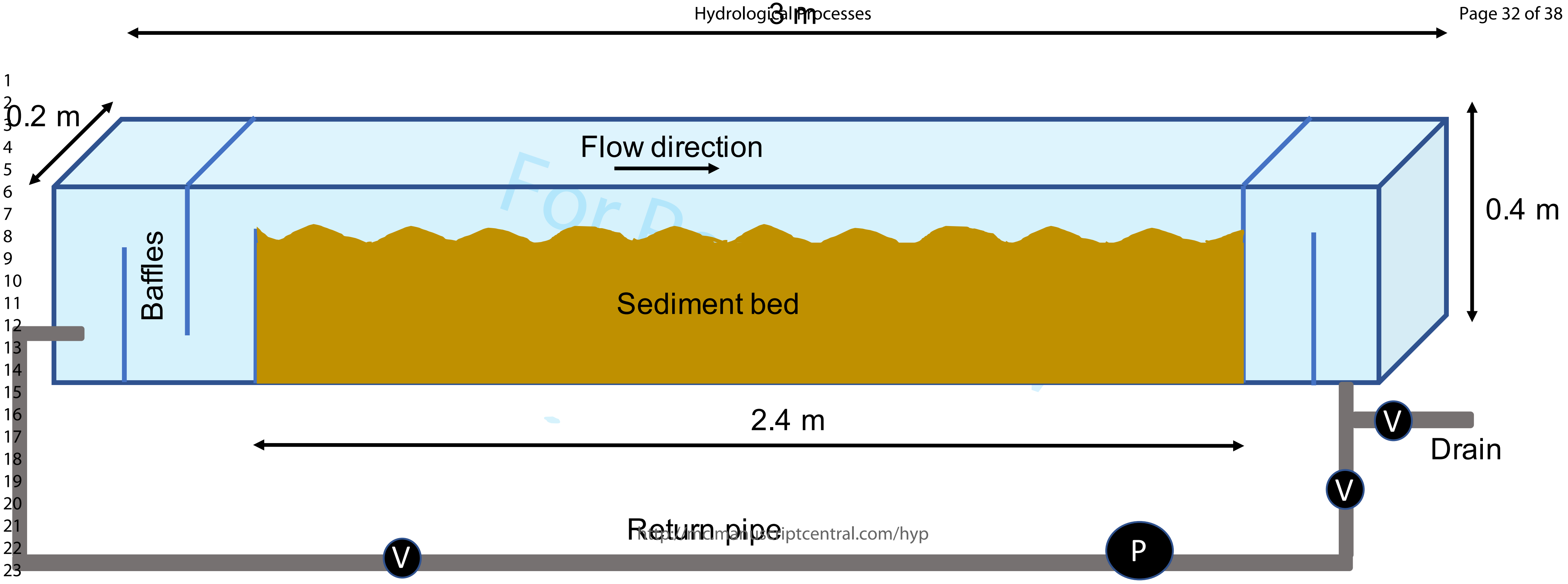
Table 1: Details of clogging and characteristics of hyporheic exchange in control (C) and treatment (T) flumes comprising of fine sand (FS), coarse sand (CS) and gravel (G) grains. C_0^{fs} represents the initial concentration of clay particles in the surface water, $\overline{D}$ represents the average depth of clogging layer at the bed surface, $\hat{D}$ represents the average infiltration depths of clay particles in the bed, and q and q' represent the average hyporheic fluxes estimated from the initial gradient of the breakthrough curves and as the ratio of $\overline{d}$ to RT_{mean} respectively.

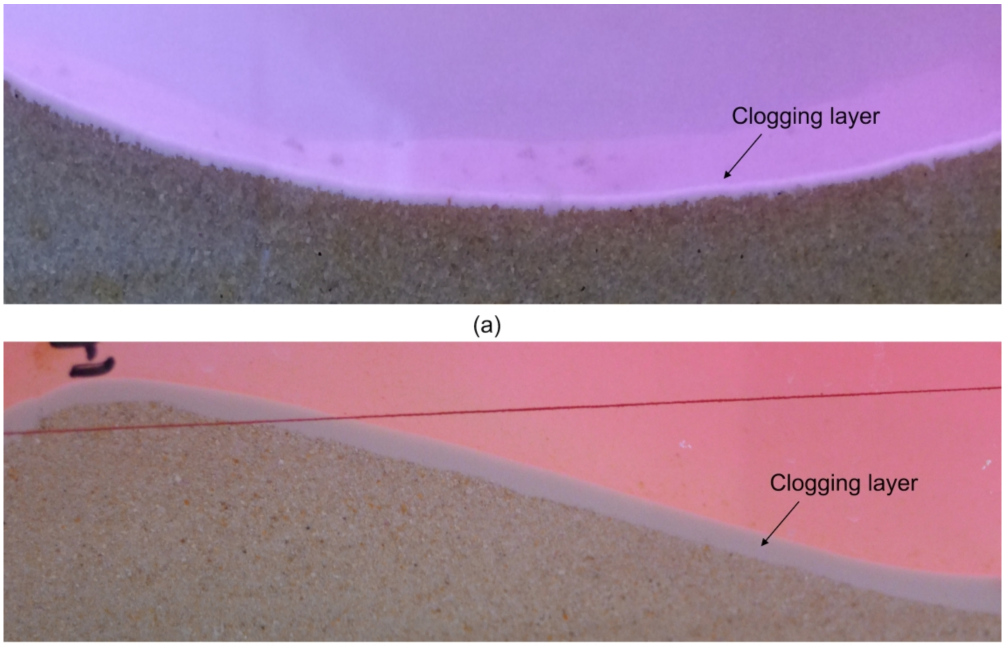
Flume index	C_0^{fs} (g/l)	Clogging type	$\overline{D}$ x 10^{-3} (m)	$\hat{D}$ x 10^{-3} (m)	Median residence time (h)	Mean residence time (h)	Equivalent penetration depth (m)	q/q' x10^{-7} (m/h)
FS-C	0	-	-	-	19	63	0.044	2.2/1.9
FS-T1	1.6	External	2 ± 0.3	0	31	53	0.035	2.1/1.8
FS-T2	3.2	External	4 ± 0.4	0	40	64	0.034	2/1.5
CS-C	0	-	-	-	3	9	0.267	92/83
CS-T1	1.6	Internal	0	14 ± 9	4	13	0.221	53/48
CS-T2	3.2	External	3 ± 0.2	0	13	30	0.219	28/20
G-C	0	-	-	-	0.4	1.4	0.132	296/255
G-T1	3.2	Internal	0	44 ± 12	1.3	2.7	0.145	170/148
G-T2	6.4	Internal and External	2.5 ± 0.3	47 ± 13	1.8	3.7	0.165	153/123

Table 2: Calculations to obtain the metric, $\frac{D_{50}}{d_{50}\sigma_{ss}}$, proposed in the literature (Huston & Fox, 2015) to predict the clogging profiles. The D_x and d_y denote the diameters than which x% and y% of particles in the substrate sediments (fine sand, coarse sand and gravel) and fine sediments (clay) respectively are finer. Note that the flocculated diameter has been used for the clay particles to perform these calculations.

Sediment system	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)	d_{50} (mm)	σ_{ss}†	$\frac{D_{50}}{d_{50}\sigma_{ss}}$
Fine sand-clay	0.17	0.28	0.41	0.022	1.55	8.2
Coarse sand-clay	1.2	1.7	2.2	0.022	1.35	57.1
Gravel-clay	3.9	5.5	6.4	0.022	1.28	195.2

† geometric standard deviation of substrate sediments calculated as $\sqrt{\frac{D_{85}}{D_{15}}}$


3 m
0.2 m
Flow direction
0.4 m
Baffles
Sediment bed
2.4 m
V
Drain
V
Return pipe
V
P

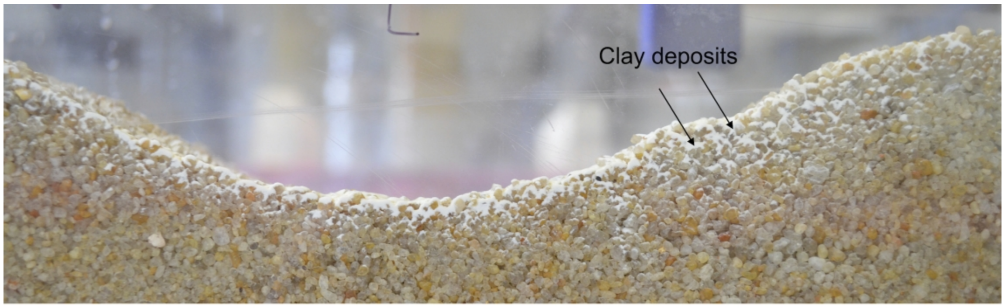


(a)

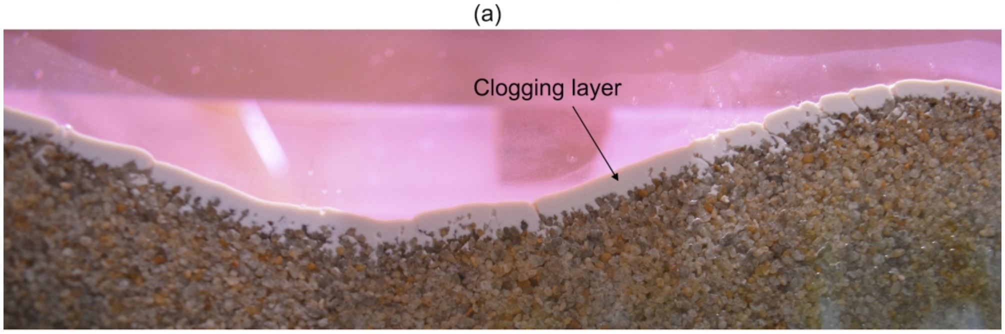
(b)

Figure 2: Fine sediment deposition profile in treatment flumes with fine sand (FS) subject to initial concentrations of clay particles in the water column as - a) 1.6 g/l (FS-T1) and b) 3.2 g/l (FS-T2). For both the flumes, clay particles accumulated at the bed surface and no infiltration was observed. The thickness of the clogging layer at the bed surface was higher in FS-T2 in comparison to FS-T1.

70x48mm (900 x 900 DPI)



(a)



(b)

Figure 3: Fine sediment deposition profile in treatment flumes with coarse sand (CS) subject to initial concentrations of clay particles in the water column as - a) 1.6 g/l (CS-T1) and b) 3.2 g/l (CS-T2). Infiltration of clay particles was observed in CS-T1 up to a limited depth, while only a thick clogging layer was observed at the bed surface in CS-T2.

70x48mm (900 x 900 DPI)

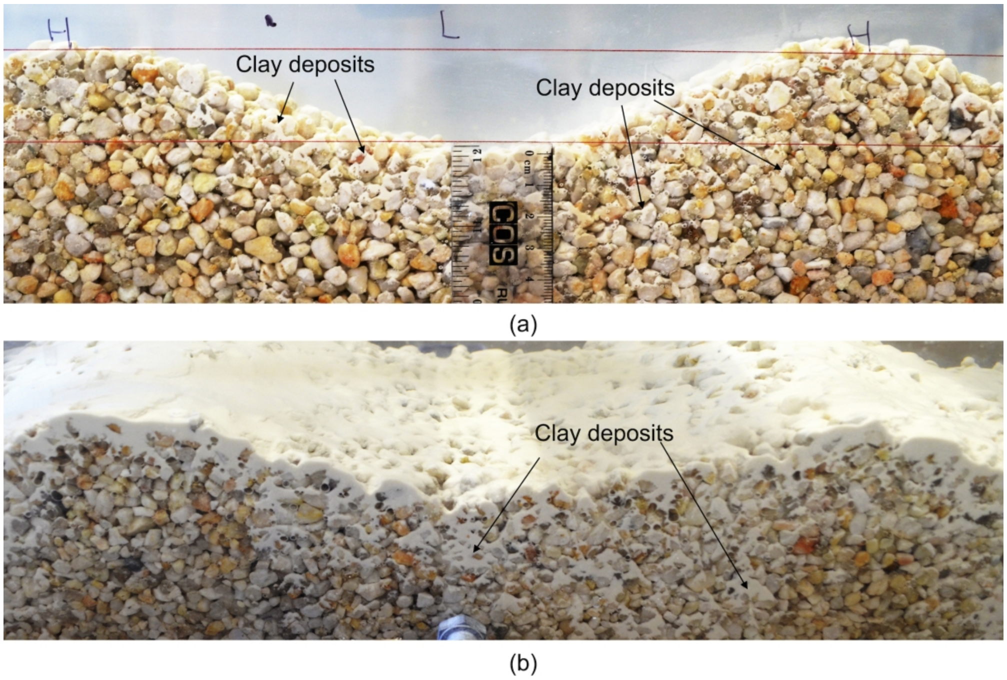
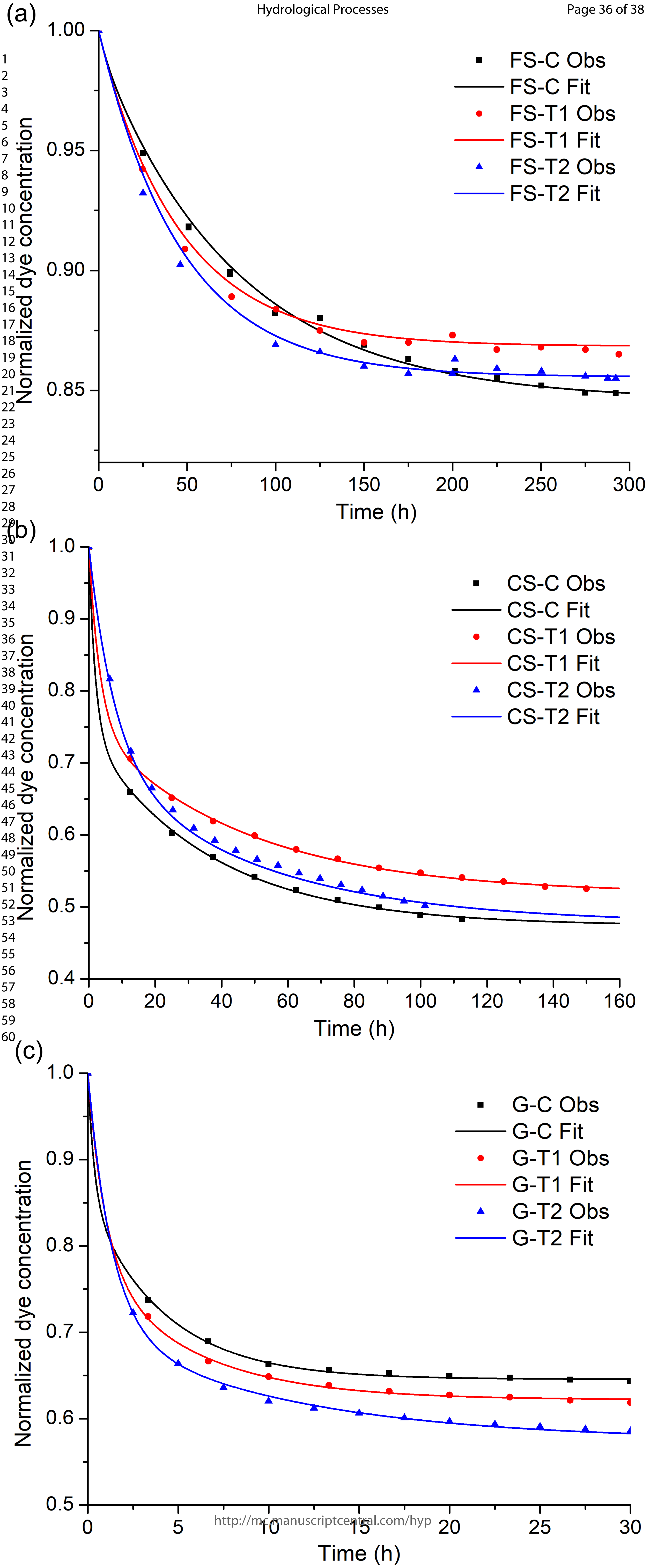
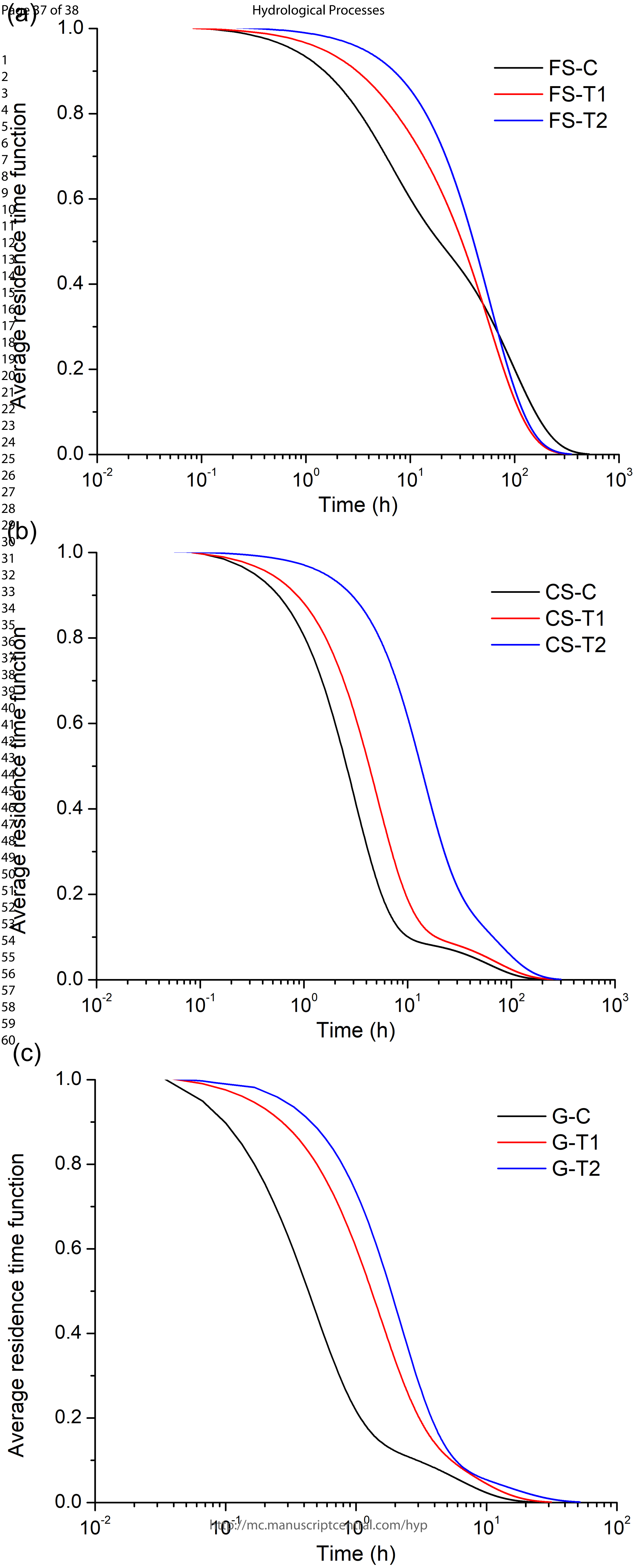


Figure 4: Fine sediment deposition profile in treatment flumes with gravel (G) subject to initial concentrations of clay particles in the water column as - a) 3.2 g/l (G-T1) and b) 6.4 g/l (G-T2). Almost all the suspended clay particles infiltrated into G-T1 up to a limited depth. In G-T2, both infiltration of clay particles and the formation of a spatially patchy and thin layer of clay deposits at the bed surface was observed.

70x48mm (900 x 900 DPI)


(a)
Normalized dye concentration
Time (h)
FS-C Obs
FS-C Fit
FS-T1 Obs
FS-T1 Fit
FS-T2 Obs
FS-T2 Fit
(b)
Normalized dye concentration
Time (h)
CS-C Obs
CS-C Fit
CS-T1 Obs
CS-T1 Fit
CS-T2 Obs
CS-T2 Fit
(c)
Normalized dye concentration
Time (h)
G-C Obs
G-C Fit
G-T1 Obs
G-T1 Fit
G-T2 Obs
G-T2 Fit


(a)
Average residence time function
1.0
0.8
0.6
0.4
0.2
0.0
FS-C
FS-T1
FS-T2
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Time (h)
(b)
Average residence time function
1.0
0.8
0.6
0.4
0.2
0.0
CS-C
CS-T1
CS-T2
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Time (h)
(c)
Average residence time function
1.0
0.8
0.6
0.4
0.2
0.0
G-C
G-T1
G-T2
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
Time (h)

Distribution of clay-sized sediments in streambeds and influence of fine sediment clogging on hyporheic exchange

Shivansh Shrivastava*, Michael J. Stewardson, Meenakshi Arora

Results from re-circulating flume experiments suggest that the clogging profiles for clay-sized sediments could not be predicted by using the conventional metric based on the relative size of bed and fine sediments. The distribution of clay particles was observed to be dependent on the initial concentration of clay particles in the surface water. Clogging due to the clay-sized particles was observed to modify hyporheic flow regime with a greater influence on the coarse-grained streambeds.