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Influence of Vertical Fluxes on the Clogging of Riverbed by Fine Sediment

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Abstract

Many species living in the hyporheic zone of rivers, such as fishes and benthos, are sensitive to the excessive presence of fine sediment. These particles tend to reduce the connectivity between the hyporheic zone and the surface flow by filling the pore and clogging the riverbed. The construction of dams, the regulation of the flow and straightening of rivers have increased the degree of clogging of many rivers in the past decades by changing the regime of floods and sediment transport. To propose solutions and improve the quality of river ecosystems, the knowledge on the process of clogging still needs to be improved. This study focuses on the influence of the exchanges between the groundwater and the surface flow on the clogging of the riverbed. This parameter, despite its importance, has been very little studied. In this research, the gradient of pressure between the surface flow and the groundwater has been systematically varied to observe its influence on permeability and the depth of clogging. Experiment were carried out in a flume and showed a much faster process of clogging for high gradient of infiltration. Fine sediment deposited in the substrate in all experiment including in the presence of upwelling. As fine sediment accumulate in the substrate, the filter resistance increase faster and does not present a linear increase as supposed in previous research.

Keywords: *Fine sediment ; Clogging ; Hyporheic layer ; Permeability ; Spawning fish*

1. INTRODUCTION

The connectivity between the hyporheic zone and the surface flow is essential for the development of benthos and the reproductive success of spawning fish. The infiltration of fine sediment leads to the clogging of riverbeds, reducing porosity and water exchanges between surface water, the hyporheic zone and groundwater. The alteration of streambed habitat for fish and benthos through clogging is well recognized (Pulg et al. 2013).

During the two last centuries, the natural flow regimes of rivers and streams all around the world have been heavily altered by anthropogenic activities. River morphology was modified for flood protection, by dam construction and agricultural land reclamation for agriculture and settlement. Moreover, many rivers are exposed to increased inputs of fine sediments, giving rise to high degrees of clogging in terms of intensity as well as spatial expansion. The knowledge on the parameters influencing the clogging of riverbeds and their effects are important to improve the response to altered stream environments and develop adapted solutions in function of the local conditions.

Various mechanisms influence the clogging of riverbed by fine sediment. The main parameters involved in the process are the surface flow conditions, the characteristics of the riverbed substrate, the concentration of fine sediment and the hyporheic flow (Wooster et al. 2008). When bedload transport is low, fine particles deposit in the pores of the hyporheic layer, creating a clogged layer, until the substrate is mobilized by the flow and release fine particles back into the river (declogging). In the clogging process, hyporheic flows play a crucial role by conveying particles below the armour layer. Hyporheic flows depend on the size of the pores in the substrate and surface flow turbulence (Fries et al. 2010), but also on vertical exchanges driven by the riverbed morphology or connection with the groundwater.

Exchanges between groundwater and surface flow have a large impact on the process of clogging (Wharton et al. 2017). In the presence of groundwater infiltration (downwelling), the substrate acts as a filter that blocks suspended particles and creates a clogged layer. In the case of exfiltration (upwelling), clogging is impeded. Despite its relevance for the depth and density of the clogged layer, so far, little attention has been payed to the effect of infiltration and exfiltration on the degree of clogging.

The goal of this research is to analyze the influence of the infiltration gradient on the clogging of a defined substrate in a laboratory flume. The evolution of the clogging process is analyzed in terms of permeability, and the final degree of clogging is also analyzed through the sampling of the substrate. It includes an experiment with upwelling conditions. The comparison of the results with the existing literature can lead to the improvement of the models currently used to estimate clogging in the riverbed substrate.

2. THEORETICAL BACKGROUND

The deposition of fine sediment and the formation of a clogged layer in the hyporheic zone can take place in absence of downwelling, as shown by different studies. In that case, the effect of the surface flow and grain-size distribution of the substrate plays an important role in the mechanism called advective pumping. Fries et al. (2010) link the deposition rate with the permeability Reynold number, $R_K = \sqrt{K}u_*/\nu$, with K the permeability, u_* the shear velocity and ν the kinematic viscosity of water. It follows that a bigger grain-size distribution increases the deposition of suspended particles (Mooneyham and Strom 2018).

In the presence of infiltration or exfiltration, due for instance to exchanges with groundwater, the deposition through advective pumping is modified, with an average flow through the substrate helping or respectively limiting the intrusion of fine sediment. The effect of infiltration on clogging has been mostly studied in the case of groundwater refilling or industrial filtering setups, but very few studies explores the influence of infiltration on the clogging of riverbed. (Cunningham et al. 1987) studied the effect of fine sediment size and surface flow velocity on the infiltration flow, but did not analyze different gradients. (Schälchli 1993) investigated the influence of the gradient of infiltration on a big set of different substrates and conditions, by measuring the evolution of the hydraulic conductivity. The model he developed is detailed in the next section. (Fetzer et al. 2017) also carried out experiment measuring the hydraulic conductivity, with experiments using different infiltration discharges, but without analyzing in detail the influence of the initial flow rate.

2.1 Cake filtration analogy

The cake filtration theory expresses the reduction in time of the permeability of a medium composed of a filter layer on top of which fine particles accumulate and create a layer with very low permeability, due to the small size of pores. As the thickness of the layer increases, permeability k decreases, and the filter resistance $\gamma = h_s/k$, with h_s the depth of the filter medium, increases linearly with the mass of accumulated fine sediment (Figure 1). That theory is used by Schälchli (1993) to model the clogging process, where the substrate acts as a filter and particles form a clogged layer inside the pores. The linear relation was confirmed based on most of the experiment carried out for that study, which considered medium fine sediment concentration (ranging from 25 to 1200 mg/L, typically around 200 mg/L). The maximum amount of fine sediment infiltrated at the end of an experiment was measured around 1.5 kg/m^2. However, a non-negligible number of experiments did not show a linear relation. Schälchli (1993) also noted that some experiments reached a maximum filter resistance, meaning that equilibrium was reached between particle deposition and erosion.

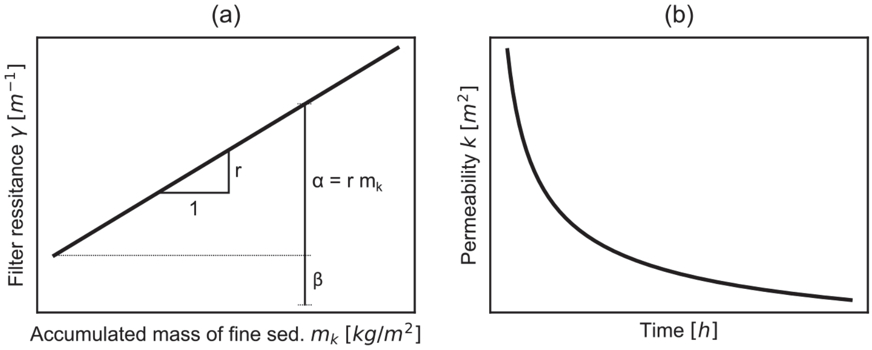

Figure 1. Cake filter model according to Schälchli (1995, 1993). (a) linear relation between accumulated mass of fine sediment and filter resistance, with β the initial filter resistance; (b) resulting evolution of permeability with time with constant parameters of surface flow, gradient and concentration.

2.2 Depth of clogging

The depth of clogging has been studied using mainly sand, transported essentially as bedload on gravels (Cui et al. 2008; Gibson et al. 2009; Huston Davis L. and Fox James F. 2015; Wooster et al. 2008). The fine sediment fraction, relative to the maximum amount that can fit in the pores, follows an exponentially decreasing pattern when fine sediment is unable to be transported across the substrate layer. None of those experiments show the influence of the gradient of infiltration, since no suspended sediment is used. Based on his experiments, Schälchli (1993) concludes that infiltration increases the depth at which fine sediment can be transported in the substrate. Therefore, the amount of fine sediment required to reach a given permeability is increased.

3. METHOD AND EXPERIMENTAL SETUP

3.3 Experimental setup

Experiments were carried out in a 6.2 m-long, 15 cm wide recirculating flume equipped to reproduce the clogging process under different gradients of infiltration and exfiltration (Figure 2). To provide exchanges between the groundwater and the surface flow, the bottom of the flume was connected to an adjustable weir outside the flume to set a chosen gradient of seepage. The water discharge of surface flow and infiltration flow was measured using electromagnetic flowmeters. The flow level along the flume was measured using ultrasound probes. The pressure inside the substrate layer was measured using piezometers in 2 sections, at different levels including near the bottom of the substrate. The concentration of fine sediment was measured using 2 calibrated turbidimeters placed at both ends of the flume.

The substrate was composed of a unimodal mix of rounded sand and gravel ranging from 0.1 to 8 mm, forming a 31 cm-high layer. Fine sediment consisted in white quartz flour ranging between 0 and 63 µm. It was kept in suspension in the water tank and other parts of the system using air bubbles.

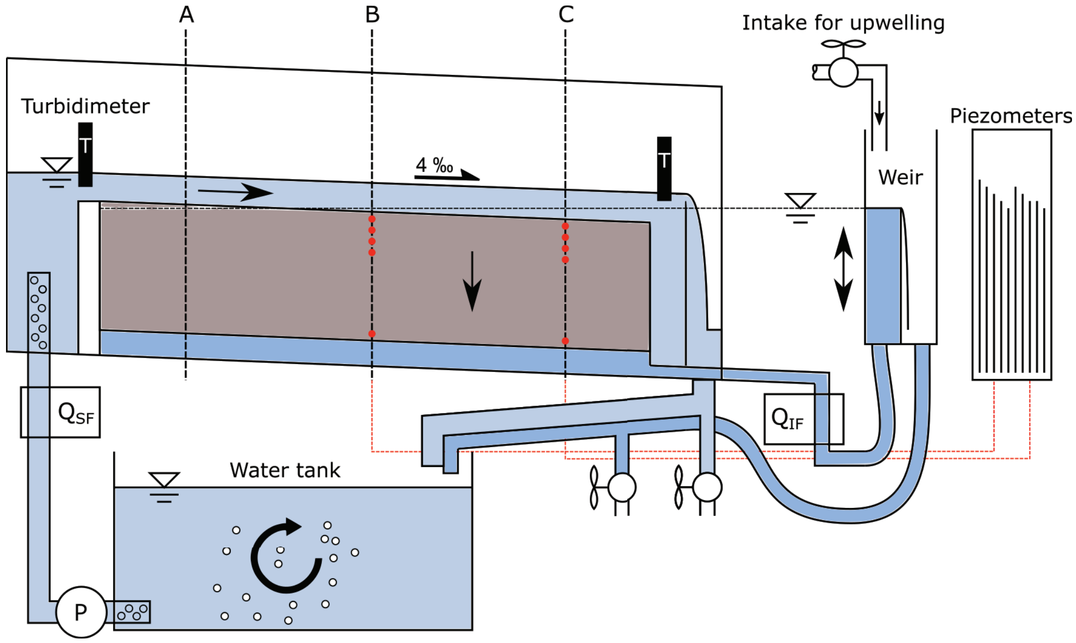

Figure 2. Experimental setup used to analyze the influence of the gradient on clogging. The three sections A, B and C correspond to the location of sampling. Q_{SF} and Q_{IF} are respectively the surface and infiltration discharge flowmeters.

3.4 Method

Experiments aimed at observing the effect of different gradient between the surface flow and the bottom of the substrate layer, on the permeability and distribution of fine sediment in the substrate. All other parameters were set constant, such as the discharge, the slope and the grain-size of substrate and fine sediment. The substrate was cleaned of the fine sediment below 100 µm. The surface layer was composed of the upper part of the substrate grain-size distribution (4-8 mm).

Fine sediment was added in the main tank with a target concentration of 1 g/L. It was added at variable time steps depending on the rate of deposition. Usually, fine sediment was added when the concentration dropped around 0.8 g/L. Since the experimental setup could not be stopped and restarted, experiment ran overnight without new addition of fine sediment, allowing the observation of deposition rate over long period.

The measurement of the piezometer and surface flow levels, as well as the infiltration discharge allows the calculation of the global hydraulic conductivity and permeability of the flume (Equation 1). Since the gradient varies slightly along the flume, the calculation considers a spatially averaged gradient.

$$k = \frac{K\nu}{g} \text{ with } K = \frac{Q_{IF}}{iA} \qquad [1]$$

With k the permeability, K the hydraulic conductivity, ν the kinematic viscosity, Q_{IF} the infiltration discharge, i the gradient and A the surface of infiltration.

Experiments were stopped when the evolution of infiltration discharge and piezometers were reaching a plateau. After each experiment, samples of the substrate were collected to analyze the vertical distribution fine sediment content in the substrate. Samples were collected in 3 locations (Figure 2). At each section, the substrate was removed by layer ranging between 1 and 12 cm, with thinner layers close to the top of the substrate, where most of the fine sediment deposits.

Each sample was then analyzed by separating the fine sediment from the substrate using a sieve and water. The weight of fine sediment and substrate were measured separately as well as an estimation of the porosity of the substrate. The quantity of fine sediment relative to the total mass of fine sediment that can fit into the pores of the substrate (saturation) is then calculated to analyze the results.

In total, 5 different gradients were analyzed and are presented in Table 1.

Table 1. Table of experiments with some important characteristics.

Experiment	GRADIENT	SURFACE DISCHARGE	$K_{INIITAL}$	C_{MEAN}
	[%]	[L/s]	[$\cdot 10^{-11}$ m^2]	[g/L]
1	3.6	2.3	8.3	0.82
2	6.6	2.2	8.9	0.72
3	19.6	2.3	8.7	0.73
4	39.6	2.3	8.1	0.68
5	-5.4	2.3	13.0	0.75

4. RESULTS

The permeability decreases faster relative to time for high gradient, as shown in Figure 3. It appears also that permeability decreases faster when concentration is high. The result for exfiltration shows a decrease of the permeability with time. However, the quantity of fine sediment deposited in the substrate cannot be estimated from the product of exfiltration by the concentration. The experiment has shown some difficulties to keep a regular infiltration flow during the whole duration of the experiment, which explains some discontinuities.

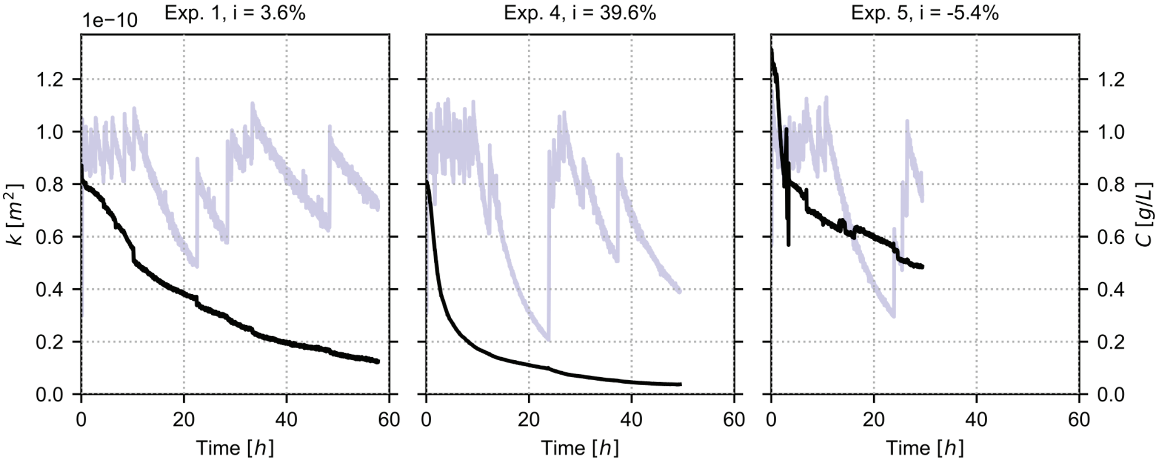

Figure 3. Evolution of permeability in function of the time for a selection of 3 tested gradients of infiltration and exfiltration. The concentration in the surface flow is also plotted. All experiments start from approximately the same permeability except experience 5.

It is interesting to express the increase of the filter resistance γ in function of the accumulated mass of fine sediment in the substrate, in a similar way as Schälchli (1993). The mass of fine sediment deposited in the substrate can be first estimated from the product of the concentration and the infiltration flow. Since deposition also occurs without infiltration gradient, an additional quantity should be added to the infiltrated quantity calculated in the first estimation. This quantity is discussed in next chapter. Figure 4 shows the results of the filter resistance in function of the accumulated mass of fine sediment. Similar curve shapes can be observed, with the filter resistance increasing faster than the mass of fine sediment. All curves follow the same slope in the beginning, before diverging into what appears like different asymptotes.

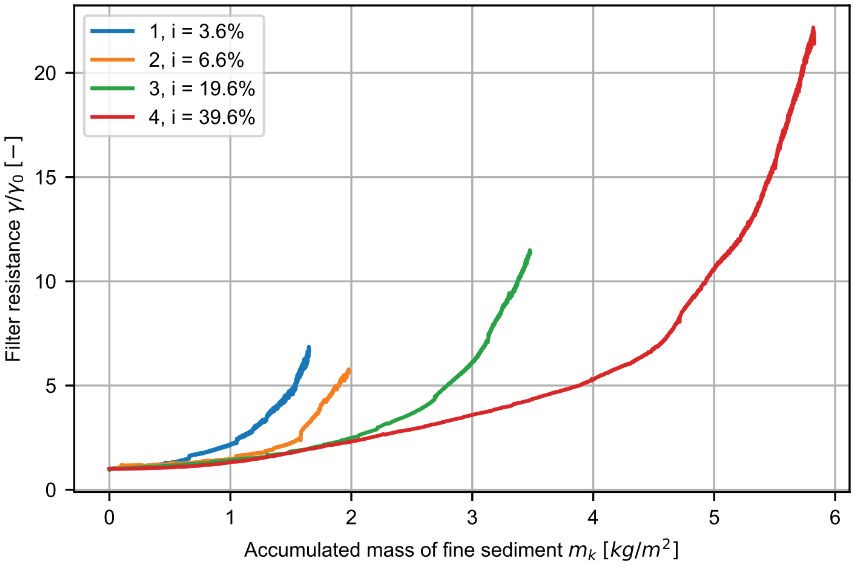

Figure 4. Evolution of filter resistance ($\gamma = h_S/k$) in function of the accumulated mass of fine sediment in the substrate. A sharper increase is observed at some point for each curve. High gradients need a more important quantity of fine sediment before the filter resistance increases faster.

Vertical concentration profiles of fine sediment in the substrate, presented on Figure 5, show similar patterns for all different gradient. According to the existing literature, the curves fit well the shapes observed in most cases of riverbed clogging. The concentration decreases rapidly after a few centimeters, expressed here as relative depth with respect to mean substrate diameter D$_m$. The use of a large grain-size distribution leads to the presence of a wide range of local permeability and pore space, resulting in a wider range of concentrations.

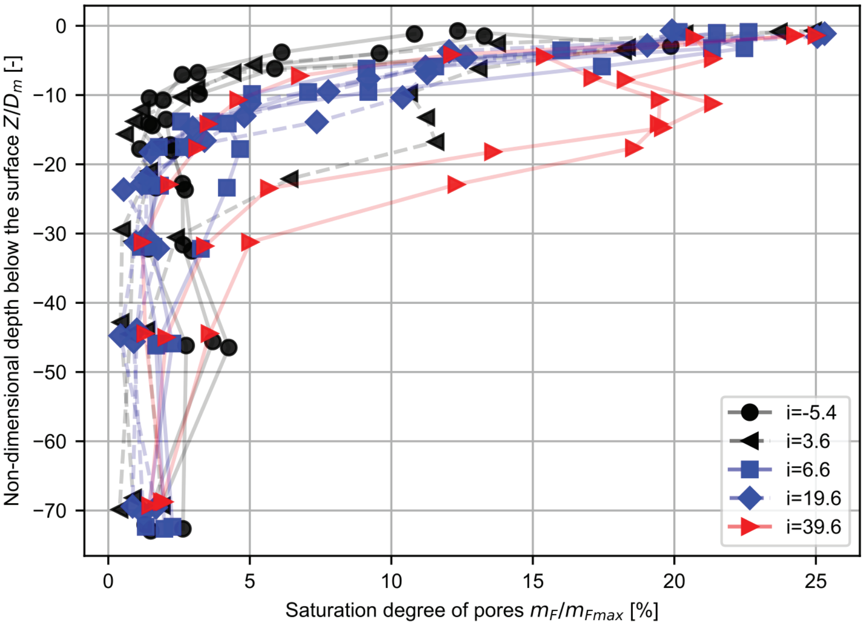

Figure 5. Filling of pores by fine sediment for all tested gradients of infiltration and exfiltration at the three sampling locations. The different curves have been grouped by class of gradients. Black curves correspond to gradients around 0, blue curves to medium gradients and the red curves to the highest gradient tested.

The filling of pores next to the surface reaches similar levels for all the different gradients of infiltration. The experiment with exfiltration shows however a much smaller fraction. Apart from the top layer, higher gradients show higher degrees of saturation. The highest degree of saturation is reached for the experiment with the highest gradient (39.6%). One location of the experiment 1 (i = 3.6 %) shows a high quantity of fine sediment up to a depth of 25 D_m. It was observed that an important amount of fine material was present in some areas of that sample, corresponding to gravel “nests”, where fine sediment could easily percolate.

Fine sediment fraction reaches a residual value deeper in the substrate for high gradient. In the case of exfiltration, this level is already reached after less than 10 D_m, whereas the same level is only reached at around 50 D_m for i = 39.6%. Even though the measurement error on the weight ratio of fine sediment over gravel for each sample stays around 0.3 %, the collection of the samples in the flume and the measurement of porosity may introduce some sources of error.

5. DISCUSSION

5.1 Evolution of permeability

In opposition to most of the results of Schälchli (1993), no maximum filter resistance was observed in all experiments. Instead, the filter resistance seems to point to the complete sealing of the substrate. The increasing slope of the curve of filter resistance in function of accumulated mass of fine sediment in the substrate may be explained by the gradual filling of pores. According to the cake filtration theory, the accumulation of fine particles produces a homogenous layer of fine particles with its corresponding filter resistance, or permeability. Such a layer is not building up in the substrate of a riverbed. Fine particles, dragged by interstitial flow, settle at different depths through various mechanisms including bridging of the pores, deposition by gravity and cohesion forces with the substrate. The pore volume is reduced as more particles deposit, and the available space for the seepage flow is reduced. As presented in the model developed by (Cui et al. 2008), a uniform capture coefficient of the substrate implies that particles are distributed with decreasing quantity with depth. It is suggested that this coefficient of capture is in reality increasing with the filling of the pores, resulting in most of the particles deposited near the bed surface as observed in the vertical concentration profiles. Permeability is closely related to porosity and the size of pores, with a non-linear relation. Therefore, it is highly reduced near the surface and increase with depth.

The asymptote that each curve in Figure 4 tends to follow can be explained by the fact that as the filling of pores grows, only the finest fraction of suspended sediment deposit in the substrate. A maximum filter resistance would be reached if that hypothesis does not apply to the fine sediment (i.e. uniform grain-size distribution) and the top of the clogged layer is eroded at the same time as particles are deposited.

The use of the product of the concentration by the infiltration discharge to estimate the mass accumulated in the substrate leads to an underestimation of this quantity. It has a more important influence on low gradient results, since advective pumping can be responsible for a proportionally more important share of the deposition process. In the case of exfiltration, this process is the only one responsible for the accumulation of fine sediment. An estimation of the amount of fine sediment deposited by advective pumping must take into account the total quantity added to the system, and the deposition in dead zones of the experimental setup. Rough estimations situate the mass of sediment deposited through that process to account for about 60% of the calculated mass on Figure 4 for the lowest gradient of infiltration (3.6%). A more precise quantification will be treated in a future publication.

The variation observed between the different gradients on Figure 4 may be explained by the force exerted by the gradient on particles, which is able to transport them in deeper layer of the substrate for high gradients. By distributing particles in a bigger volume, the pores take longer to be filled with fine sediment, explaining the higher mass of fine sediment needed to reach the same level of permeability. For low gradients, particles accumulate in the top layers, resulting in a faster increase of the filter resistance.

The drop of permeability in the beginning of the experiment with exfiltration may be due to some rearrangement of the substrate following the change of flow direction and some maintenance work in the flume. After that first drop, it reaches a value comparable to the other initial permeability. Some internal clogging process might also have affected the permeability, as is suggested by the higher fine sediment fraction at around 45 D_m on Figure 5.

5.2 Clogging depth

The results of experiment 5, with a gradient of exfiltration, agrees with the measurement of Schälchli (1995) where no deposition of fine sediment was observed below i = -15%. The deposition of fine sediment still take place, but a clear reduction of the quantity is observed.

The more important depth of clogging and degree of saturation observed as gradient increase follows a clear tendency. However, the distinction between the 5 different gradients analyzed is not obvious, despite large differences in accumulated mass of fine sediment m_k. The deposition process is stochastic and depends widely on the distribution of the different grain-size in the riverbed. Also, the sampling process, despite all the care given to the collection of precise layers, introduces some sources of errors. Gravel nests can affect a lot the final result as shown on one of the profiles for i = 3.6% on Figure 4. Some boundary effects also take place on the side of the flume, where the pore space is affected by the wall and lower velocity are observed. Comparisons between the visual appreciation of the clogging depth on the transparent wall of the flume and the concentration profiles shows that clogging cannot be estimated by pictures from the side of the flume.

The degree of filling of the pores next to the surface stays below 25%. This observation suggests that there is potentially a physical limitation to reach 100%. During the collection of the samples, fine sediment always seemed to fill all the pores available near the surface of the substrate. More research is needed to understand if measurements fail to evaluate correctly the degree of saturation or if a non-negligible amount and size of pores are unachievable to fill. It is also interesting to note that the degree of consolidation, evaluated empirically during the collection of samples, was much higher in the experiment with i = 39.6%. It suggests that the porosity of fine sediment was smaller, due to the infilling of very small particles inside the fine sediment medium.

5.3 Significance on rivers

It appears clearly that in the case of high gradient of infiltration, an important mass of fine sediment can accumulate in the substrate in a very short time. For instance, the permeability is divided by 4 after about 9 hours with a gradient of some 40%, whereas it would take more than twice the time to reach the same level with a low gradient of about 4%, given a constant concentration of suspended sediment. In a river, it means that the flushing of reservoir, for example, would have more detrimental effect on the clogging of the riverbed if that river contributes significantly to the recharge of the groundwater.

6. CONCLUSIONS

The clogging of riverbed substrate under different gradients of infiltration and exfiltration showed that this parameter has an important influence on the process. For a same concentration of suspended fine sediment, the reduction in time of the permeability is much faster. The evolution of the filter resistance with the accumulated mass of fine sediment is not linear. Despite following a similar growth in the beginning, the filter resistance starts to increase sharply after reaching a certain amount of fine sediment that depends on the gradient of infiltration. No maximum filter resistance was reached. The vertical concentration profiles of fine sediment in the substrate were in agreement with other researches. The influence of the gradient lies in a deeper penetration of fine sediment for high gradient, with a higher degree of saturation of the pores. Deposition of fine sediment was also observed under a low gradient of exfiltration. More research is needed to include the deposition of fine sediment by advective pumping, especially for low gradients, and find a relation to quantify better the influence of the gradient between surface flow and the groundwater.

7. ACKNOWLEDGEMENTS

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