Contribution of flow conditions and sand addition on hyporheic zone exchange in gravel beds

H. Marttila, S. Tammela, K.-R. Mustonen, P. Louhi, T. Muotka, H. Mykrä and B. Kløve

ABSTRACT

We conducted a series of tracer test experiments in 12 outdoor semi-natural flumes to assess the effects of variable flow conditions and sand addition on hyporheic zone conditions in gravel beds, mimicking conditions in headwater streams under sediment pressure. Two tracer methods were applied in each experiment: 2–5 tracer-pulse tests were conducted in all flumes and pulses were monitored at three distances downstream of the flume inlet (0 m, 5 m and 10 m, at bed surface), and in pipes installed into the gravel bed at 5 m and 10 m distances. The tracer breakthrough curves (total of 120 tracer injections) were then analysed with a one-dimensional solute transport model (OTIS) and compared with data from the gravel pipes in point-dilution pulse tests. Sand addition had a strong negative effect on horizontal fluxes (q_h), whereas the fraction of the median travel time due to transient storage (F_{200}) was determined more by flow conditions. These results suggest that even small additions of sand can modify the hyporheic zone exchange in gravel beds, thus making headwater streams with low sediment transport capacity particularly vulnerable to sediments transported into the stream from catchment land use activities.

Key words | flume, hydraulics, modelling, OTIS, sediment, transient storage

H. Marttila (corresponding author)
S. Tammela
B. Kløve
Water, Energy and Environmental Engineering Research Unit,
University of Oulu,
P.O. Box 3000, 90014 Oulu,
Finland
E-mail: *hannu.marttila@oulu.fi*

K.-R. Mustonen
T. Muotka
Department of Ecology and Genetics,
University of Oulu,
P.O. Box 3000, 90014 Oulu,
Finland

P. Louhi
Natural Resources Institute,
Paavo Havaksentie 3, 90570 Oulu,
Finland

T. Muotka
H. Mykrä
Finnish Environment Institute,
Freshwater Centre,
P.O. Box 413, 90014 Oulu,
Finland

INTRODUCTION

Extensive input of sediments into aquatic habitats is a growing global concern (Relyea *et al.* 2012). Land use practices such as agriculture, forestry and road construction increase the transport of fine sediments, and potentially the deposition of sediments onto the streambed (Owens & Walling 2002). Sediment transport is a natural process, but becomes harmful when exceeding the natural background level (Wagenhoff *et al.* 2011). The impacts of increased sediment flux on riverine biota are typically related to deposits rather than suspended material (Jones *et al.* 2012). In Finland, for example, peatland drainage has led to erosion and increased transport of fines, resulting in the filling of even entire channels of headwater streams (Marttila *et al.* 2012; Turunen *et al.* 2017).

Deposition, especially of fines, causes obstruction of gravel pore spaces and thus reduces hyporheic zone exchange (Zimmerman & Lapointe 2005). The hyporheic zone is a porous layer of the streambed affected by a small-scale exchange between the stream water and shallow groundwater (Harvey & Wagner 2000), and hyporheic zone exchange is a fundamental process for solute transport in streams. The interstitial pore spaces within the gravel bed not only provide a key habitat for many stream organisms but are also essential for stream biogeochemical processes (Triska *et al.* 1993). The hyporheic zone is defined as a subset of features termed 'transient storage zones' where water velocity is slower than in the advective flow of the main channel (Bencala & Walters 1983). Differentiation of the hyporheic zone from other surface stores in the field is challenging (Harvey & Wagner 2000; Runkel *et al.* 2003), and controlled conditions are therefore needed. Numerous

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studies have addressed transient zone processes at the channel scale (e.g. Choi *et al.* 2000; Wörman *et al.* 2002; Briggs *et al.* 2010), or studied the effect of fine sediment infiltration or solute transport into different streambed types (Einstein 1968; Packman *et al.* 1997; Packman & Brooks 2001). Typically, these studies have focused on the effects of bed forms or pressure distribution along the sediment–water interface on hyporheic exchange (Savant *et al.* 1987; Elliott & Brooks 1997).

Although the broad physical factors influencing hyporheic processes at the streambed interface have been extensively studied (see review by Cardenas 2015 and reference therein), the coupling and interactions between flow and additional sediment at the channel scale still remain little explored. At the sediment-scale, hyporheic processes are controlled by fine-scale granulometric features (size, shape, and composition of sediments) and interstitial flow patterns are a product of hydraulic gradient and stream bed porosity (see review by Boulton *et al.* 1998 and references therein). Also, depositional effects of fine sediment on gravel beds have been studied at the sediment scale (Schälchli 1992; Cui *et al.* 2008; Gibson *et al.* 2011), improving our understanding of the controlling factors in hyporheic zone exchange. Increased fine sediment fractions among the bed material can, for example, decrease the porosity and hydraulic conductivity of the streambed (Cui *et al.* 2008) by clogging the coarser bed material (Schälchli 1992). While the sediment-scale processes are rather well studied and mathematically modelled, more research is still needed to determine the extent of sediment-scale hyporheic processes to channel scale hyporheic exchange.

Using controlled experiment and replicates (totally 120 tracer injections) we examined the influences of different flow conditions and sediment depositions on hyporheic storage processes on gravel beds. We expect that flow strongly influences hyporheic storage responses, more strongly in low flow than in high flow, and deposited sediment interactions have different responses with flow conditions. To calculate the effect of flow and addition of fine sand on hyporheic zone conditions, we conducted a series of tracer experiments in flumes with different levels of flow and with or without added sediment. We used two parameters, the proportion of flow affecting the transient storage exchange (F_{200}) and horizontal average flux (q_h) inside the gravel bed, to test if we observed (i) decreasing F_{200} but increasing q_h values with higher flow rates, and (ii) reduced values for both parameters with added sediments.

METHODS

Experimental set-up

We conducted the experiment at Kainuu Fisheries Research Station, Paltamo, Finland, in autumn 2012, using 12 parallel 0.75 m wide and 12 m long artificial channels (hereafter flumes) supplied with water from a nearby lake. All flumes had a 30 cm thick gravel/cobble bed ($d_{50} = 23$ mm, porosity $= 0.40$) (Figure 1) and the amount of inflow was controlled individually for each flume. The gravel bed used represents the typical range of grain sizes for salmonid spawning beds (Louhi *et al.* 2008). Flume geometry was selected to mimic headwater streams suffering from sand siltation (Marttila *et al.* 2012; Turunen *et al.* 2017). For more information about the experimental set-up, see Mustonen *et al.* (2016).

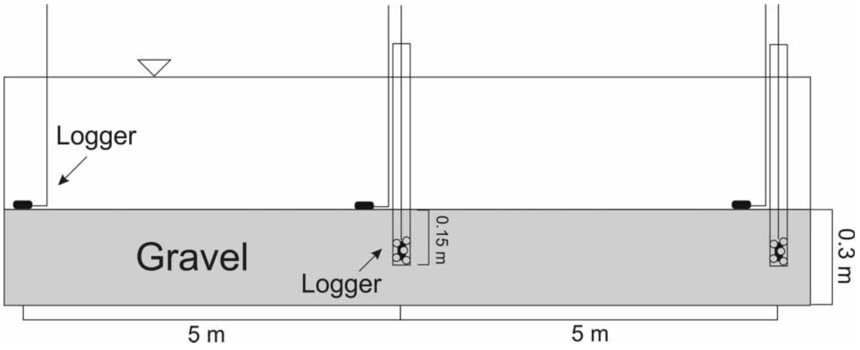

Figure 1 | Schematic representation of the experimental set-up in flumes for the tracer experiments. The total length of the flumes was 12 m.

We conducted two different experiments. In the first set (1) we used three different flow levels with no added sediment. The applied flow levels were: (i) low ($2.6\ \mathrm{L\,s^{-1}}$, mean depth: 0.04 m and mean current velocity: $0.1\ \mathrm{m\,s^{-1}}$); (ii) intermediate ($18.2\ \mathrm{L\,s^{-1}}$, 0.08 m and $0.3\ \mathrm{m\,s^{-1}}$); and (iii) high ($67.4\ \mathrm{L\,s^{-1}}$, 0.15 m and $0.5\ \mathrm{m\,s^{-1}}$). In the second set of experiments (2), the flow levels were as in experiment 1 (i)–(iii), but fine sediment ($22\ \mathrm{L\,m^{-2}}$) was distributed evenly across six randomly selected flumes. Grain size for fine sediment ($d_{10} = 0.4$, $d_{50} = 1.1$ and $d_{90} = 3$ mm) was selected to represent the typical grain size observed in siltated small streams (Marttila *et al.* 2012). Sand addition generated approximately 80% sediment cover (sediment thickness was 1–2 cm), corresponding to the amount of sediment observed in streams that drain severely impacted catchments in NE Finland (Marttila *et al.* 2012; Turunen *et al.* 2017). No additional transport of suspended sediment in the flumes was observed during the experiment. During both experiments, current velocity (at 0.6 × depth, Mini-Water®20, Schiltkecht, Switzerland) and water depth (cm) were measured at 21 points along regular transects in each flume. The discharge was measured from weirs located at the end of each flume.

Hydraulic parameters and hyporheic storage within the gravel bed of each flume were measured by injecting a conservative tracer (NaCl, 5% concentration) into the flumes. A 10-min injection pulse was added to the upper end of the flume. The change in electrical conductivity (EC) was measured at 2 s intervals at 0 m, 5 m and 10 m downstream (logger installed in bed surface) and inside the gravel at 5 m and 10 m downstream using automatic EC dataloggers (Campbell Scientific CR10X). The sensors in the gravel bed were installed at 15 cm depth within pipes with boreholes at the lower 5 cm. To minimise random testing errors, all tracer tests were repeated two to five times as individual tracer pulses and hydraulic parameters were calculated for each test using one-dimensional solute transport model (OTIS) and horizontal average flux (for details, see section 'Analyses of tracer-pulse data'). Each sensor was calibrated with flume water and EC values were transformed to NaCl concentrations. After the flume pulse experiment, another tracer pulse (NaCl) was injected in every borehole and the exponential decrease in concentration was logged (see Käser *et al.* (2012) for assumptions of the method).

Analyses of tracer-pulse data

Injection pulse experiments

Parameters from transient storage in the flumes were obtained by nonlinear regression using the OTIS-P (hereafter OTIS) (Runkel 1998). OTIS uses a finite-difference model to solve paired partial differential equations describing solute transport in channels (for more details, see https://water.usgs.gov/software/OTIS/). OTIS is widely used and has sufficient flexibility to estimate transition and hyporheic zone changes in various riverine environments (Runkel 1998). Although the model only accounts for a single-storage zone, and thus cannot separate surface transient storage and hyporheic transient storage exchange, it still offers a flexible tool to estimate total transient storage change. For OTIS modelling we used measured data from measurement locations at 0 m, 5 m and 10 m, where 0 m represented the upstream boundary conditions while data from 5 m and 10 m locations were used for OTIS modelling.

We used OTIS to produce estimates of cross-sectional area (A, $\mathrm{m^2}$), storage zone cross-sectional area (A_s, $\mathrm{m^2}$), dispersion coefficient (D, $\mathrm{m\ s^{-2}}$) and storage zone exchange coefficient (α) simultaneously using nonlinear regression. When performing nonlinear regression, the model run was checked to achieve weighted residual sum of squares (RSS) and/or parameter convergence, which guarantees parameters unique in the modelling (https://water.usgs.gov/software/OTIS/). These estimates were used to determine the fraction of the median travel time due to transient storage F_{200} (Equation (14) of Runkel 2002). The F_{200} parameter reflects the interaction between advective velocity and transient storage. For the purposes of comparing values of F_{200} from different flumes and experiments, we used reach length of $L = 200$ m to standardise the values (Runkel 2002); thus, all values reported are for F_{200}.

Analysis of gravel pipe tracer data

We used the horizontal average flux method developed by Hazell (1998) (see Käser *et al.* (2012) and adapted by Käser *et al.* (2012)) to evaluate hyporheic zone conditions, with tracer curve data (point-dilution) from loggers within the gravel bed. This method provides an estimate of the horizontal average flux (q_h) in the hyporheic zone:

$$q_h = -\frac{\pi r}{2t\alpha}\ln\left(\frac{C_t}{C_0}\right) \tag{1}$$

where t is the time, C_0 is the peak tracer concentration after the injection minus the background concentration, C_t is the tracer concentration at time t minus the background concentration, r is the radius of the piezometer and α is an adjustment factor (set to 2 here). The slope $\ln(C_t/C_0)/t$ in Equation (1) was calculated by simple linear regression. q_h was calculated for both measurement tubes, but we did not observe any statistically significant differences between the upper and lower points. Thus we used average values from both locations from individual tracer inputs. We used two-way Anova (fitted with R function aov) to test whether sand addition, flow conditions or their interactions had an effect on F_{200} and q_h values.

RESULTS AND DISCUSSION

To study whether addition of fine-graded sediment and varying flow conditions change hydrodynamic transient storage and infiltration to the streambed interface, we evaluated these effects using two independent measurements and calculations. F_{200} describes how a large proportion of flow is affecting the transient storage exchange and it has been recommended for tracer-pulse transient storage studies (Runkel 2002), whereas q_h measured directly from the gravel bed indicates horizontal average flux inside the gravel bed. Both methods, transient storage modelling with OTIS model and salt dilution test from gravel pipes, indicated that flow conditions and additional fine sediment in gravel beds caused significant changes to hyporheic zone conditions (Figure 2). The results supported our first hypothesis (Figure 3(a)) and flow conditions significantly affected the fraction of the median travel time due to transient storage (F_{200}) ($F = 9.470, p = 0.004$) and the horizontal average flux (q_h) ($F = 57.35$, $p = 0.000$). Especially F_{200} values at high-flow conditions were lower than at low and medium flows, indicating that during higher flows a smaller proportion of flow influenced transient storage exchange between flow and gravel bed (Figure 3(a)). Our results support the earlier findings of the inverse relationship between hyporheic residence and with flow rates (Saenger *et al.* 2005). In natural streams, high-flow conditions and high water velocity typically reduce the time for interaction between surface and storage waters and thus reduce the relative storage size, whereas the opposite occurs during low flow and low-velocity conditions (Harvey & Bencala 1993). Unlike F_{200}, the horizontal average flux (q_h) measured from gravel pipes increased notably with increasing flows (Figure 3(a)). Our results thus indicate that flow conditions affect streambed interface processes in gravel beds, which is in accordance with previous findings (Cardenas 2015).

Our working hypothesis was to find reduced transient storage values with added sediments. Results with q_h supported our hypothesis and the addition of sand-sized sediment to gravel beds caused a significant reduction of q_h (Figure 2(b), $F = 17.25$, $p = 0.0000$), being two to four times smaller than without added sediment (Table 1, Figure 3(b)). Only a small increase with the increasing flow was observed (Figure 2(b)). This result confirms that even minor additions of sand-sized particles can affect the hyporheic exchange in gravel bed and thus agrees with findings by Packman *et al.* (1997) and Packman & Brooks (2001) from other streambed types. Fine particles infiltrate through porous bed material and form a clogging layer that impairs interstitial flow patterns (Schälchli 1992; Cui *et al.* 2008; Gibson *et al.* 2011). The clogging process is influenced by size, shape, and concentration of the suspended load, and size and shape of the bed material. While particles such as coarse sand travelling near the bed or as bed load can cause rapid clogging of gravel surface, the finer suspended particles can travel deeper into the gravel and cause a larger decrease in bed sediment permeability (Fetzer *et al.* 2017). Contrary to our hypothesis, the effect of sand addition on F_{200} values was smaller (Figure 3(b)) and flumes with and without sediment did not show significant differences ($F = 1.456$, $p = 0.236$); median tended to be lower in treatments with sediments in all flow levels (Figure 2(a)). This indicates that added sediment had only a minor effect on the proportion of flow (F_{200}) influencing the transient storage exchange between flow and gravel bed. Sand addition and flow had a significant interaction ($F = 13.93$, $p = 0.0001$) on q_h, showing a stronger effect of sand with increasing flow velocity (Figure 2(b)). The stronger effect of additional fine sediment than increased flow on hyporheic exchange agrees with previous findings

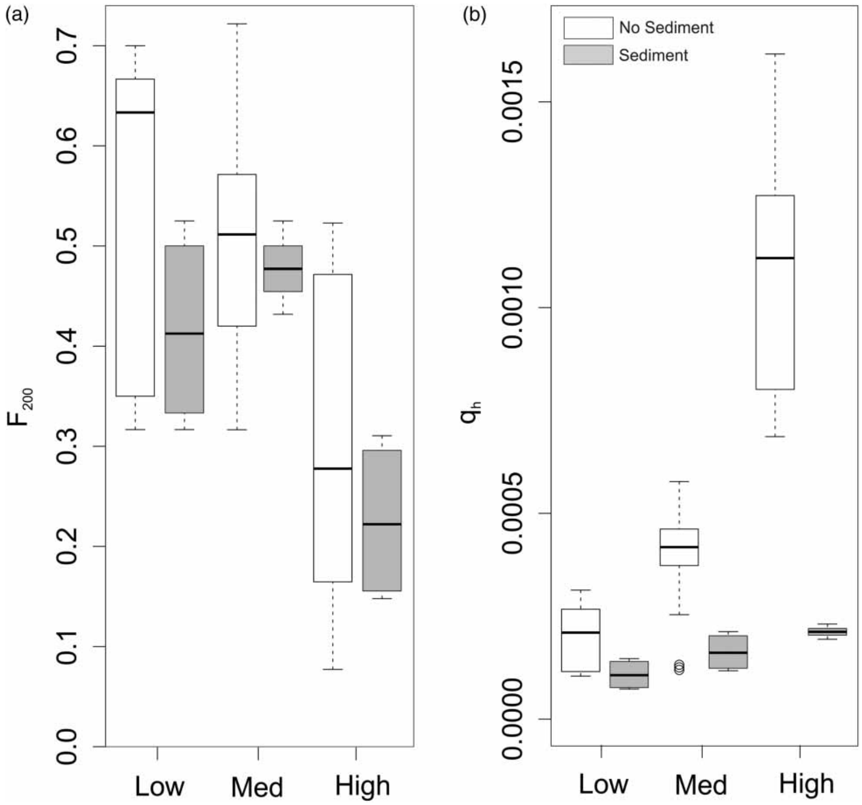

Figure 2 | (a) The fraction of the median travel time due to transient storage (F_{200}, from transient storage OTIS modelling) and (b) the horizontal average flux (q_h, gravel pipes) values for different flow levels (low, medium and high), and with or without sediments. Boxplots represent medium, IQR and quartiles within 1.5 IQR and includes results from all individual tracer experiments conducted.

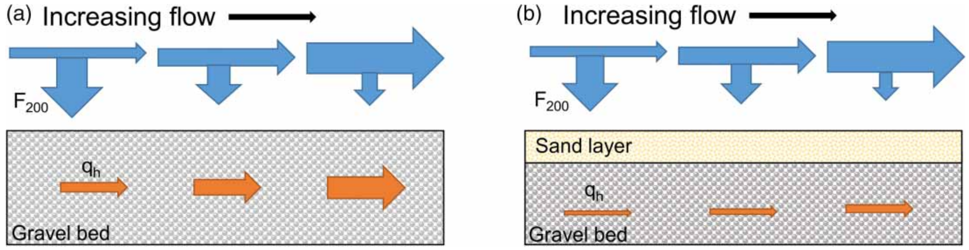

Figure 3 | Conceptual model of the effects of sedimentation and flow on the transient storage exchange. During higher flows without added sediment (a), a smaller proportion of flow influenced transient storage exchange (F_{200}) between the water column and the gravel bed, whereas the horizontal average flux (q_h) increased notably with increasing flows. Added sediment (b) had only a minor effect on the F_{200} values but caused a significant reduction of q_h.

(Saenger *et al.* 2005), highlighting the dominating role of siltated sediment on streambed processes.

Observed effects of deposition of additional sediment and flow conditions on hyporheic zone processes in the gravel-bed interface agree with the few existing studies (Carling 1984; Schälchli 1992; Gibson *et al.* 2011). These studies illustrate the general phenomenon that as infiltration into gravel becomes limited by the upper sediment layer, the responsiveness of hyporheic zone processes to flow conditions diminishes. Therefore, the development of the siltation layer on the gravel bed determines infiltration possibilities. Our results thus highlight that additional fine sediment is harmful in all conditions, not only during low flow periods in headwaters but also in larger rivers with higher stream velocity. In larger streams, gravel beds typically regenerate during flood conditions, but in smaller headwater

Table 1 | Mean values of different hydraulic parameters from the experiment: A = modelled cross-sectional area (m^2), A_s = reach-averaged storage zone cross-sectional area (m^2), α = hyporheic storage exchange rate (s^{-1}), F_{200} = the fraction of the median travel time due to transient storage (OTIS transient storage modelling), and q_h = average horizontal flux (m s^{-1}) (gravel pipe data)

Discharge level	Sediment treatment	A	A_s	α	F_{200}	q_h
Low	No	$9.33 \times 10^{-2} \pm 2.66 \times 10^{-2}$	$3.83 \times 10^{-2} \pm 1.60 \times 10^{-2}$	$5.00 \times 10^{-2} \pm 9.32 \times 10^{-2}$	$5.49 \times 10^{-1} \pm 1.68 \times 10^{-1}$	$2.02 \times 10^{-4} \pm 8.22 \times 10^{-5}$
Low	Yes	$6.00 \times 10^{-2} \pm 0.00$	$2.00 \times 10^{-2} \pm 0.01 \times 10^{-2}$	$6.00 \times 10^{-2} \pm 5.66 \times 10^{-2}$	$4.17 \times 10^{-1} \pm 1.18 \times 10^{-1}$	$1.10 \times 10^{-4} \pm 4.44 \times 10^{-5}$
Medium	No	$6.00 \times 10^{-2} \pm 3.01 \times 10^{-2}$	$6.44 \times 10^{-2} \pm 2.20 \times 10^{-2}$	$2.50 \times 10^{-2} \pm 1.50 \times 10^{-2}$	$4.77 \times 10^{-1} \pm 1.53 \times 10^{-1}$	$4.08 \times 10^{-4} \pm 9.79 \times 10^{-5}$
Medium	Yes	$6.50 \times 10^{-2} \pm 7.07 \times 10^{-3}$	$5.00 \times 10^{-2} \pm 0.01 \times 10^{-2}$	$6.00 \times 10^{-2} \pm 5.66 \times 10^{-2}$	$4.77 \times 10^{-1} \pm 3.21 \times 10^{-1}$	$1.65 \times 10^{-4} \pm 5.55 \times 10^{-5}$
High	No	$4.50 \times 10^{-2} \pm 1.22 \times 10^{-2}$	$5.17 \times 10^{-2} \pm 3.66 \times 10^{-2}$	$5.83 \times 10^{-2} \pm 3.31 \times 10^{-2}$	$2.98 \times 10^{-1} \pm 1.66 \times 10^{-1}$	$1.10 \times 10^{-3} \pm 3.04 \times 10^{-4}$
High	Yes	$6.00 \times 10^{-2} \pm 1.41 \times 10^{-2}$	$3.50 \times 10^{-2} \pm 2.12 \times 10^{-2}$	$5.50 \times 10^{-2} \pm 0.92 \times 10^{-2}$	$2.24 \times 10^{-1} \pm 9.92 \times 10^{-2}$	$2.12 \times 10^{-4} \pm 1.11 \times 10^{-5}$

streams with flat topography even large floods may not have the required stream power to resort the bed (Gooderham *et al.* 2007). Thus in headwaters especially, additional sand can have long-term negative effects on hyporheic zone processes in gravel beds. Transport of sediments from catchment land uses to headwater streams often leads to extensive sedimentation, being often the main cause of the poor ecological condition in these streams (Turunen *et al.* 2017). Understanding the drivers affecting hyporheic zone processes is a key to successful management of streambeds affected by sediment deposition. For stream restoration, our results suggest that cleaning of gravel beds from additional sediments and preventing transport of new sediments is essential for restoring hyporheic processes. In headwaters, even small increases in erosion and deposition of sediments to stream channels (Owens & Walling 2002) can have a significant influence on hyporheic zone conditions.

Impaired hyporheic zone flux causes negative impacts on the amount of oxygen and biogeochemical conditions within the hyporheic zone. Infiltration of fine sediments into gravel beds reduces permeability and decreases interstitial flow velocity (Zimmerman & Lapointe 2005), as was also observed in our study. In our semi-natural flumes, sediment hyporheic storage was the only transient storage, allowing us to calculate the effect of sediment addition and different low levels on hyporheic zone processes in gravel-bed streams. Siltation and filling of the pore spaces within the bed sediment not only decreased hyporheic zone exchange but also affected horizontal fluxes. This indicates that sediment deposition does not only have local consequences on hyporheic exchange but can also diminish channel scale horizontal fluxes. Adequate hyporheic flow within the streambed is crucial for many stream organisms (Stanford & Ward 1988) as well as for stream metabolism (Grimm & Fisher 1984; Mulholland *et al.* 1997). Decreased flow infiltration or horizontal fluxes within the gravel bed decreases oxygen concentration, which is vital for good habitat conditions and within-substrate chemical processes. For example, the survival and development of fish eggs and embryos are dependent on dissolved oxygen levels in the hyporheic zone (Louhi *et al.* 2011). In natural channels, geomorphological variations greatly alter transient storage and hyporheic zone exchange (Orr *et al.* 2009), rendering estimation of the actual hyporheic zone processes within gravel beds extremely challenging. Thus, controlled experiments such as the present study also offer valuable information for stream restoration and management actions.

Even though our results show that flow conditions and added sediment affect transient storage conditions in the gravel bed, the experiment had few limiting elements. Our experiment contained only sand-sized sediment, which did not allow use to study the effect of particle size on hyporheic exchange in gravel beds. In natural systems transported sediments contain variable particle sizes and especially the finest particles may infiltrate to deeper layers within the gravel bed. Also, a naturally existing armour layer may diminish transient storage conditions in gravel beds. Future studies should explore the effects of variable particle sizes and volumes on channel scale transient storage conditions in controlled flow conditions and with sufficient replication. Furthermore, our experiment could only measure overall changes, and future studies should assess the spatial variation of transient storage conditions at variable flow conditions and different levels of sedimentation.

CONCLUSIONS

Our results highlight the significance of flow conditions and fine-graded sediments on hyporheic exchange in gravel beds. This study complements previous considerations of dynamics of infiltration processes in gravel beds and pinpoints the importance of controlling the transport of fine sediment fractions for the conservation practices and successful restoration. According to our results, however, the influence of sand addition on transient storage in gravel beds is not straightforward. The joint effect of sediment deposition and flow was stronger during high-flow conditions than low or medium flow conditions, indicating that sand reduces hyporheic exchange, especially during high-flow events. Our results thus highlight that even low sediment input rate can alter the hyporheic zone exchange in gravel beds also during high-flow conditions. Control of fine sediments is imperative especially at headwater streams where stream power is often insufficient to naturally clean the gravel beds.

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