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Geomorphic controls on fine sediment reinfiltration into salmonid spawning gravels and the implications for spawning habitat rehabilitation

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ABSTRACT

Anthropogenic activities often increase the flux of fine sediment to fluvial environments. In gravel-bed streams the extent to which augmented fines loading causes the degradation of vital interstitial habitats is determined by factors controlling fines infiltration into channel substratum. Previous research suggests that substrate pore constriction size, intensity of upwelling interstitial flow, and the quantity of fines transported across the bed surface (i.e., exposure dose) are three important factors controlling substrate fines content. Few field studies have investigated the interactive effects of these physical factors. We constructed 17 experimental redds in brook trout spawning microhabitats in a boreal forest stream in Quebec, Canada, to investigate the role of pore constriction size, hyporheic flow, and exposure dose on substrate fines content. To simulate the effect of spawning in coarsening the substrates, redds were partially cleaned of coarse sand and of all fine sediment (<0.5 mm). Results show that coarse sands and fine gravel (0.5–4 mm; filter class) acted as a filter of percolating fine sediment (<0.5 mm). We found that this filtering effect (i.e., lower fines density at egg pocket depth) occurred at sites where the proportion of the filter class in the substratum above egg pocket depth exceeded a threshold value of 18%, as indicated by a statistically significant step-function response between fines gradient with depth and the filter class content in the uppermost layers of the bed. Results also indicated that fines content at depth was unrelated to fines exposure. Estimated upward seepage rates were well below the threshold velocity that would inhibit the percolation of medium-grained sand (i.e., 0.5 mm) into the bed. These results suggest that within these gravel-bed spawning substrates the abundance of filter classes was the primary determinant of fines content at depth. This study highlights the importance of considering filter class content in the implementation of spawning habitat rehabilitation schemes and when assessing the susceptibility of incubation microhabitats to augmented fine sediment loading to streams.

1. Introduction

In a gravel streambed, the interstitial spaces between the sediment particles provide important habitats for a wide variety of streambed dwelling macroinvertebrates (Williams and Hynes, 1974; Olsen and Townsend, 2003) and are critical for the early life stage survival of streambed spawning fishes (e.g., salmonids; Bjornn and Reiser, 1991). The availability of these vital interstitial spaces is negatively related to the proportion of very fine sediments (i.e., silt and sand) within the gravel framework (*sensu* Carling and Reader, 1982). It is now well established that in gravel-bed substratum salmonid egg-to-emergence survival is also negatively related to substrate fines content (Chapman, 1988; Jensen et al., 2009). The deleterious effect of excess fine sediment on streambed dwelling organisms in conjunction with the tendency of many human activities in watersheds (e.g., forestry, agriculture, road construction) to increase the flux of fine sediment into fluvial systems has spurred research into the processes modulating the infiltration of fine fractions into gravel-bed substrates (Einstein, 1968; Beschta and Jackson, 1979; Lisle, 1989; Cui et al., 2008). While numerous laboratory investigations have contributed to an improved understanding of the dynamics of the infiltration process, comparatively little research has been undertaken to investigate fines infiltration into actual gravel-bed spawning substrates, where channel morphology and substrate structure will be more varied and flow conditions and sediment transport patterns are likely to differ significantly from those created in laboratory flumes.

'Filtering fractions' present in the in situ gravel framework are known to impede fines infiltration (Lisle, 1989; Meyer et al., 2005). Previous laboratory work (summarized in Gibson et al., 2009) on this filter effect has shown that the process of fine sediment (i.e., sand and silt) infiltration into beds of static gravel is particularly sensitive to the size ratio between infiltrating particles and the framework particles. In a bed of uniform spheres, the size of the pore constrictions through which fines can percolate: (i) scale as 0.15–0.40 times the diameters of the framework particles; and

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(ii) is influenced by how tightly these framework particles are packed together (Frings et al., 2008). However, gravel-bed substrates commonly consist of a wide range of particle sizes complicating such simple geometric scale laws uncovered in the laboratory using uniform or bimodal framework mixtures. Laboratory work investigating sand infiltration into complex frameworks composed of a wider range of gravel sizes suggests that the size of the pore constrictions (*Dc*) modulating the infiltration process scale with the relatively finer framework fractions. This relationship has been expressed as $Dc = 0.20 \cdot D_{15}$ where D_{15} is the maximum diameter of the smallest 15% of the particles in a granular mixture (Kenney et al., 1985).

However, spawning bed grain size composition is not static. During redd excavation and embryo burial, fluvial spawners (e.g., salmon and trout) reduce the proportion of fine sediment within gravel-bed substratums (Kondolf, 2000). The reaccumulation of fine sediments within the redd framework during the period of embryo incubation is a key factor influencing embryo survival. Increased embryo mortality occurs where fines accumulations around egg pockets reach densities that reduce oxygen flux to embryo membranes, or where fines clog the interstitial spaces required for the successful emergence of hatched embryos (Greig et al., 2005; Franssen et al., 2012). The reaccumulation of fines within gravel beds is determined by the processes controlling (i) sediment delivery to the surface of the redd; (ii) subsurface infiltration of fines; and (iii) the remobilization of the bed by threshold flow events (Sear et al., 2008b).

Several field studies investigating the factors modulating fines accumulation in gravel beds report the formation of sand seals at the bed surface (Lisle, 1989; Meyer et al., 2005). Sand seal formation suggests that the uppermost layers of the stream bed have acted as a filter for fine sediment. Field observations indicate that the filter effect for particles smaller than 0.5 mm in diameter will be stronger where there is an increased proportion of coarse sand and fine gravel (i.e., 0.5–4 mm; filter fractions) in the upper layers of the gravel bed (Meyer et al., 2005). The variable presence of these filter fractions can modulate in a complex way the relation between fines reaccumulation at depth and the amount of fine sediment in transport over the bed over a period (hereafter termed exposure dose). For example, an increased probability of pore space bridging at higher fine sediment transport rates (Wooster et al., 2008) suggests that under some conditions fines accumulation rates at depth may be inversely related to exposure dose. Additionally, Schälchli (1992) suggested that upward seepage flux in the substrate may have a negative relationship with fines accumulation. These various relationships suggest that exposure dose is not necessarily the only (or primary) determinant of fine sediment accumulation within incubation microhabitats.

We do not know of any study in a natural river system that has simultaneously investigated the effects of variable substrate composition, interstitial seepage flux, and exposure dose on fines reaccumulation in gravel beds. To improve our understanding of the infiltration process, we constructed experimental redds at sites where brook trout were previously observed to have spawned. Brook trout are well known to position redds in association with vertical substrate flow patterns (Curry and Noakes, 1995; Guillemette et al., 2011; Franssen et al., 2013). Thus, brook trout is a good model species with which to investigate the role of upwelling flow in modulating fines reaccumulation into incubation microhabitats. Experimental redds were thoroughly cleansed of fine sediments (i.e., <0.5 mm diameter grains, see Methods section) to simulate the effect of spawning in winnowing away fines (Kondolf, 2000). Each redd was paired with a local sediment trap to measure the relative exposure of the redd to the fines in transport across the bed during the 9-week study period. At the end of the experiment, the substrate composition of each redd was determined using freeze-core sampling to preserve substrate fines content and substrate stratigraphy. Specifically, these installations were used to answer the following questions related to the reaccumulation of fine sediment within the experimental redds: (i) is a filtering effect of reinfiltrated fine sediments (i.e., reduction of <0.5 mm size class with depth) positively associated with a higher proportion of filter sized particles (i.e., 0.5 to 4 mm diameter grains based on geometric relations described in Frings et al., 2008) and negatively related to the estimated size of the framework pore constrictions (*Dc*; as defined in Kenney et al., 1985); (ii) are upward vertical seepage rates through the redds negatively related to the quantity of reinfiltrated fine sediment; (iii) is the amount of reinfiltrated fines positively related to horizontal seepage velocity through the redd; and (iv) is the amount of reinfiltrated fines positively related to the amount of fine sediment in transport across the redd (i.e., the 'exposure dose' as measured by local sediment traps)?

2. Study location

2.1. Geographic setting

The study sites (Fig. 1) are located in first- and second-order trout-bearing streams situated in the Réserve Faunique des Laurentides (RFL), a 7861 km^2 wildlife reserve situated north of Quebec City, Canada (47°35′ N., 71°13′ W.). The RFL is situated in a relatively high precipitation continental mountain climate (for southern Quebec), with a mean annual precipitation of ~1600 mm (Environment Canada, 2007). The flow regimes of these tributaries are characterized by high spring flows from snowmelt with peak flows typically occurring in mid-May. Flood flows of a similar (or greater) magnitude can occur between June and November but are of a much shorter duration. Stream channels are typically incised from 0.5 to 3 m below the boreal forest whose principal constituent tree species are black spruce (*Picea mariana*), white birch (*Betula papyrifera*), and balsam fir (*Abies balsamea*). Streams are nutrient poor with limited growth of periphyton. Brook trout is the dominant fish in the RFL, representing 98% of the 2002 sport fishing catches (Gouvernement du Quebec, 2003).

2.2. Geologic and geomorphic setting

Study sites are located on the Laurentian Plateau (Upland) a hilly peneplain geologically sited within the Grenville province of the Canadian Shield. Peaks extend to 100–200 m above the valley floors, which are situated at an elevation of c. 750 m above sea level. The region has undergone repeated glaciations the most recent of which ended c. 10,000 years ago (Occhietti et al., 2011). Bedrock consists of granitic and metamorphic rocks that are covered in most areas by a thin layer (i.e., several meters) of glacial and fluvioglacial deposits (Scott, 1976). In valley bottoms, the thickness of these deposits may exceed 10 m. Surficial deposits are derived from bedrock and are noncalcareous, coarse-grained (i.e., sand and gravel) with low silt and clay content. These deposits are the main aquifers supplying groundwater to streams. Soils in this area are predominantly ferro-humic podzols (Sanborn et al., 2011).

3. Methods

Between August 14 and 20, 2008, we constructed 17 experimental redds along three small streams designated by milepost distance from south to north along the principal highway through the RFL: KM104 (47°18′39″ N., 71°10′56″ W.), KM143 (47°38′13″ N., 71°14′22″ W.), and KM161 (47°47′18″ N., 71°13′24″ W.). To cover variations in stream size and sedimentology of known trout spawning streams, we installed five, ten, and two redds, respectively, along streams KM104, KM143, and KM161. Stream KM104 is a first-order stream with an average channel width of ~3 m. Its streambed is composed of sand and gravel with subsurface D_{50} and D_{84} at spawning sites in the range of 2 to 10 mm and 10 to 50 mm, respectively (Franssen, unpublished doctoral research). Study reaches containing several naturalized log–step features created by the partial burial of