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Sediment infiltration traps: their use to monitor salmonid spawning habitat in headwater tributaries of the Cascapédia River, Québec

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Abstract:

Sediment infiltration can clog salmon nests and reduce egg survival. As a countermeasure, environmental managers often deploy infiltration traps to monitor sediment infiltration. Traps provide a repeatable means of measuring infiltration and enable comparisons to be made between sites. Results from infiltration rates measured with traps have also been used to estimate infilling rates into salmon nests. Application of these data is questionable, as the composition of the bed and the amount of fine sediment within the bed is known to affect infiltration rates. Thus, infiltration rates measured with infiltration traps may differ from the infiltration rates occurring in redd and riffle gravels.

To examine how relationships between sediment infiltration rates varied between four watersheds, we continuously monitored suspended sediment transport, shear stress and infiltration rates at four sites over 5 months. We also compared infiltration rates measured with infiltration traps with changes in the hydraulic conductivity and subsurface grain size distribution of adjacent artificially constructed salmon nests and natural riffle gravels.

Among the four watersheds, clear differences in sediment infiltration rates were observed. The differences correlated with the subsurface silt content but no strong relationship existed between land-use or basin physiography/geology. Despite observing an average of 30 kg m^{-2} of sediment finer than 2 mm being deposited in the infiltration traps during the study, no change in redd or riffle substrate was observed. If the deposition rates measured with the traps reflect the processes in redds, enough sediment would have been deposited to inhibit egg emergence. However, no reduction in egg survival to the eyed stage was observed. In summary, our results show that infiltration traps with clean gravels can be used to detect intersite differences in sediment transport regimes. Extrapolations of sediment infiltration rates measured with such collectors to estimate infiltration rates in redds or riffles is, however, flawed. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS fine sediment; infiltration; salmon redds; spawning habitat; suspended sediment; infiltration traps; sediment deposition

INTRODUCTION

Environmental managers and scientists are frequently requested to monitor fine sediment (inorganic material generally finer than 2 mm) in gravel-bed streams, as fine sediment can be deposited in spawning gravels and inhibit the survival of incubating salmonid eggs (Chapman, 1988; Lisle, 1989; Havis *et al*., 1993). In order to monitor fine sediment infiltration, traps have frequently been used (e.g. Carling, 1984; Lachance and Dube 2004). Each study has tended to use a unique trap; but, in general, they all consist of a mesh container with a solid base filled with clean, finely graded gravels (e.g. Sear, 1993; Larkin *et al*., 1998; Walling *et al*., 2003; Lachance and Dube, 2004). Traps have been used as they provide a repeatable means of measuring the cumulative amount and nature of fine sediments infilling the bed. This enables easy comparisons between

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sites to be made, which can be used to evaluate the effects of land use on the supply of fine sediment (Davies and Nelson, 1993; Lachance and Dube, 2004).

Going beyond simple comparisons of the amount and type of sediment infilling traps, researchers have also attempted to assess the controls on fine sediment accumulation rates. Considerable attention has been given to suspended sediment and fine bedload transport processes as potential controls on infiltration (Meehan and Swanston, 1977; Carling, 1984; Carling and McCahon, 1987; Sear, 1993; Alonso *et al.*, 1996; Acornley and Sear, 1999). In order to evaluate these processes, sediment infiltration traps have frequently been used, and sediment infiltration rates have been empirically related to both suspended sediment and bedload transport intensity.

Other studies have shown that infiltration rates depend on the size of the sediment in transport compared with the size of the openings between the stones on the bed (Frostick *et al.*, 1984). This result has important implications for the study of sediment infiltration rates into salmon nests using infiltration traps. When using infiltration traps to measure sediment infiltration into salmon nests, the full grain size distribution found in salmon nests has not been reproduced. Thus, it remains unclear whether the sediment deposition rates measured with infiltration traps correspond to the rates that occur in actual salmon nests. Despite this uncertainty, recent research has extrapolated infiltration rates measured with traps to the infilling rates of salmon nests (Carling and McCahon, 1987; Sear, 1993; Acornley and Sear, 1999). In summary, there remains a need for clear guidelines describing how and when environmental managers and scientists should employ infiltration traps to study sediment infiltration in gravel-bed rivers.

The purpose of our research was twofold. First, we examined whether differences in the relationship between sediment infiltration rates in collectors and exposure to suspended sediment or shear stress could be detected between four neighbouring watersheds that have slightly contrasting bed sedimentologies and logging histories. Second, we compared infiltration rates measured with infiltration traps with changes observed in artificially constructed salmon nests and surrounding riffle gravels. We hypothesize that, although the results from infiltration traps can be used to compare streams and evaluate sediment deposition rates based on suspended sediment and shear stress measurements, the deposition rates measured may not be indicative of deposition rates into redd or riffle substrate.

STUDY AREA

Study sites are in the upper reaches of the Cascapédia River watershed in the Gaspé Peninsula, Québec (Figure 1). The Cascapédia River is a north–south-flowing sixth-order river that drains into Chaleur Bay from the Chic-Choc Mountains of the Appalachian geological province. The river is more than 150 km long and supports a world-renowned Atlantic salmon sports fishery. In the study area, fine sediment loads are suspected to be a problem for salmonid reproduction due to intense forestry activities and the silt-rich nature of the local regolith. The regolith has developed on the Lac Branch Formation, consisting of extremely weathered and friable illmenite-rich Devonian mudstones.

Study sites consisted of riffles located on four headwater tributaries of the Cascapédia River, namely the Salmon Branch, Lac Branch, Brandy Brook and Berry Mountain Brook (see Table I). All sites are located on the Lac Branch Formation, within 10 km of each other and approximately 60 km from the river mouth. The bankfull width at the study sites ranged between 7 m (Brandy Brook) and 50 m (Salmon Branch). The riffles selected were considered suitable as Atlantic salmon spawning grounds, and some spawning activity occurred in 2001 and 2002 at the Lac Branch site.

A detailed investigation using bulk samples in conjunction with freeze cores (Zimmermann *et al.*, 2005) illustrated that the subsurface sediment (top 20 cm under the surface layer) in Brandy Brook was 1·5% silt. In comparison, Zimmermann *et al.* (2005) found that, at the other sites, between 0·7 and 1·2% of the subsurface sediment was silt (Table I). Based on bulk samples of more than 50 streams

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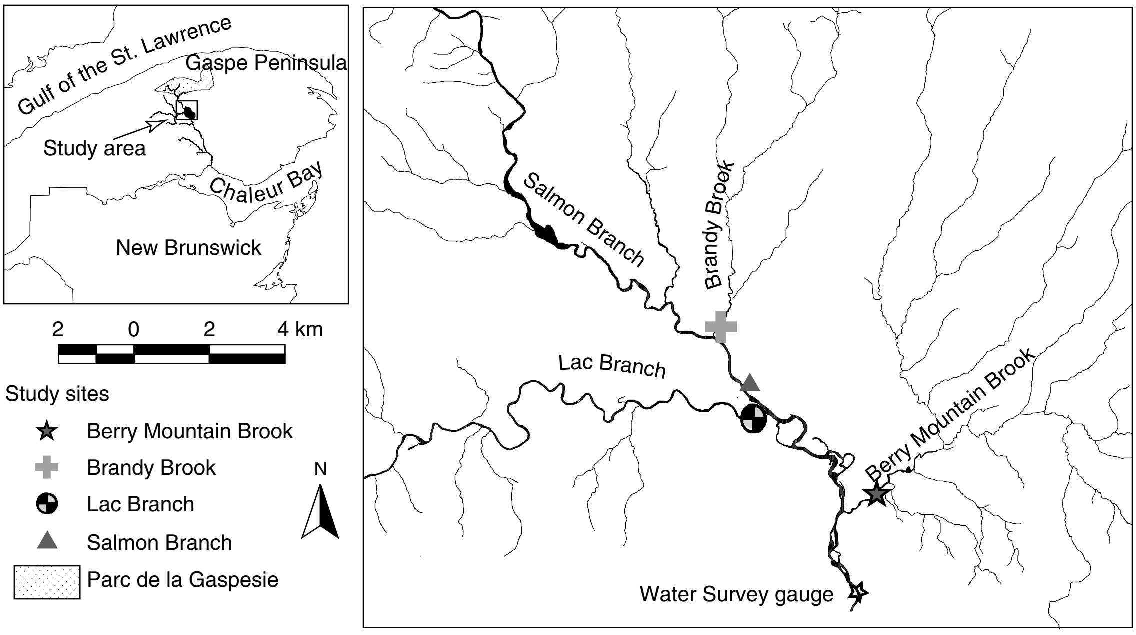

Figure 1. Location of study area and field sites

Table I. Description of study sites

	Brandy Brook	Berry Mountain Brook	Salmon Branch	Lac Branch
Basin area (km^2)	69	118	585	877
Stream order	3	5	5	6
Reach slope (1/1000)	7·7	5·5	3·0	1·7
Water surface slope across redds (%)[a]	7·0	10	7·0	5·3
D_{50} subsurface (mm)	26	30	28	26
Mean % <2 mm[b]	17	12	14	21
Mean % <64 μm[b]	1·5	0·69	0·87	1·2
Mean basin slope (°)[c]	12·6	10·0	11·3	8·0
Road density (km km^{-2})	1·77	1·56	1·23	2·09
Cut in preceding 3 years (%)	7·4	11·4	2·5	2·5
Cut in preceding 5 years (%)	9·2	13·4	6·2	18·2
Cut in preceding 10 years (%)	17·0	18·2	10·1	30·5
Geology				
Lake Branch Formation, Lower to Middle Devonian (%)	11·4	22·0	6·8	17·4
Battery Point Formation, Lower to Middle Devonian (%)		5·2		4·4
Cap Bon-ami Limestone/Grande Greve formations, Lower Devonian (%)	49·9	9·8	14·4	42·7
York Lake Formation, Lower Devonian (%)	38·7	62·9	23·5	24·8
Shickshock Group, Cambrian to Middle Ordovician (%)			42·0	5·2

[a] Average from measurements made during relatively high stage events.

[b] Based on composite samples constructed by combining freeze core and bulk sample grain size distributions, see Zimmermann *et al.* (2005). Means based on $n = 3$ for Brandy Brook, $n = 2$ for Berry Mountain Brook and $n = 1$ for Salmon and Lac branches.

[c] Calculated based on the slope value for each pixel from a digital elevation model of the watersheds. Geology from Carbonneau (1959).

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in the Cascapédia watershed, Wilson (2002) also found that lower Brandy Brook had more silt within the subsurface layer than any other stream in the watershed. Within the regional context, based on comparable bulk sample data, the tributaries of the Cascapédia River tend to have an order of magnitude more silt ($<0\cdot065$ mm) and very fine sand ($0\cdot125$–$0\cdot064$ mm) than other salmon rivers located in eastern Québec (Petite Cascapédia, Bonaventure, St Marguerite and Nouvelle rivers; sources Honeywill *et al.* (1995), Payne (1995), Society Cascapédia Inc. (unpublished data on bulk samples of substrate along the Cascapédia River, 2000), Tanguay (2000), Coulombe-Pontbriand (2001) and Wilson (2002)).

METHODS

Measuring suspended sediment concentrations

An optical backscatter sensor (OBS) was used at each of the study sites to monitor turbidity over a 5 month period, during which eight or nine runoff events occurred at each site. The turbidity of the stream was sampled at 1 Hz, and averaged over 1 min every 3 min. A single turbidity–suspended sediment concentration relationship (Figure 2) was developed based on numerous 2 L water samples. Water sampling was done 15 cm above the bed adjacent to the turbidity sensor during a range of flow conditions at all four sites. Initially, individual power relationships were developed for each stream; however, our analysis indicated that there was no significant difference between the best-fit lines for three of the streams. The best-fit line from Lac Branch was significantly different; however, no suspended sediment samples at relatively high concentrations were collected at this site.

A suspended sediment event was defined as a storm runoff period lasting longer than 30 min with a suspended sediment concentration greater than 3 mg L^{-1}. For each storm, the length of the suspension event, the peak and mean suspended sediment concentrations and the total dose of the suspension event (in mg L^{-1} day^{-1}) were calculated as illustrated in Figure 3. All suspended sediment events were considered capable of transporting bedload material as well, and the peak shear stress during the suspended sediment event was determined.

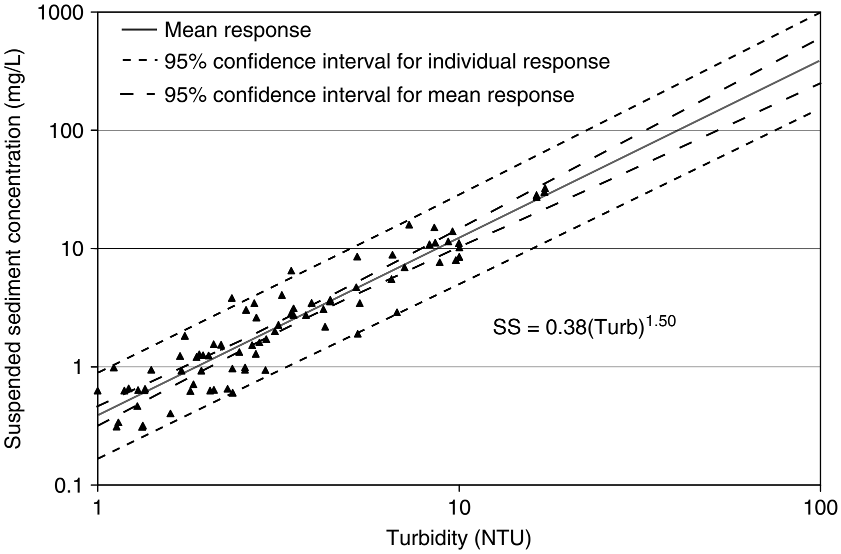

Figure 2. Turbidity versus suspended sediment concentration relationship. The 95% confidence interval gives the range expected for individual and median measures of suspended sediment concentration based on a mean value of turbidity (Montgomery and Peck, 1992)

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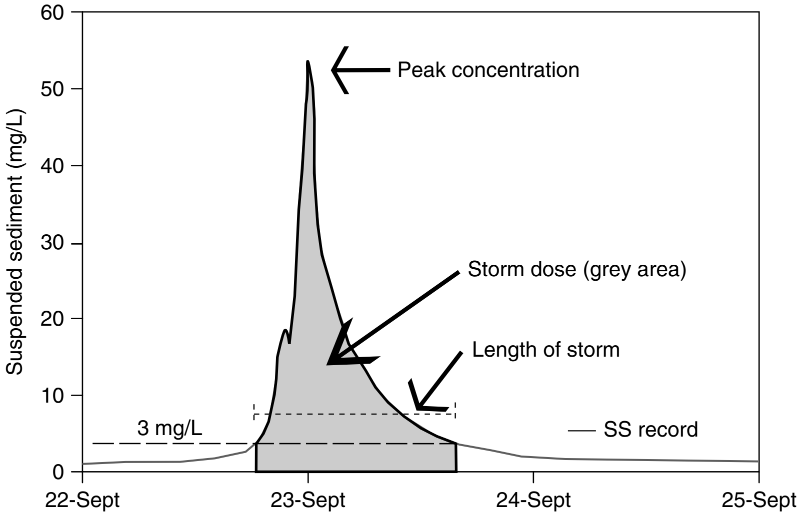

Figure 3. Definition diagram: characterization of a suspended sediment event and of suspended sediment dose-exposure

Estimating peak shear stresses during storms

Water level stage gauges were installed just upstream and just downstream of the redds at each of the four sites in order to measure water surface slopes and infer bed shear stresses across the redds (Figure 4). Water level and depth were then measured manually and recorded during a range of flows. Concurrently, the Water Survey of Canada gauge (#01BG005), located just downstream from the study sites (see Figure 1), recorded discharge hourly, and a pressure transducer at the Brandy Brook site recorded water levels every 20 min. Flow depths at storm peaks were determined based on empirical rating relationships linking water depths measured at each of the manual stage gauges to stage measurements at one of the two instrumented gauges. For Brandy and Berry Mountain brooks, the manual water depth measurements were regressed against the continuous record of water stage from Brandy Brook. For the Salmon and Lac Branch sites, water depth measurements were regressed against the discharge record from the Water Survey of Canada gauge. For each site the regressions yielded significant ($p < 0{\cdot}01$) linear relationships, with R^2 values of 0·84 or larger, based on 23 or more manual measurements of water depths.

To estimate the peak shear stress during an event, Duboy's formula ($\tau_o = \rho g h S$) was used. Herein, ρg is the specific weight of water, h is the water depth and S is the water surface slope measured during relatively high flow events over streamwise distances ranging between 4·5 and 12·5 m.

Measuring sediment infiltration in artificial redds

To monitor the amount of fine sediment deposition in redds, sediment collectors were installed just downstream of the pit within artificial redds. Each site had six redds and six collectors (see Figure 4). The redds were excavated using a gasoline-powered water pump to wash sediment downstream in an attempt to mimic an Atlantic salmon cutting its redd (see Zimmermann and Lapointe, 2005). On average, fresh artificial redds contained 41% less sediment finer than 2 mm than ambient riffle substrate, approximately mimicking natural redds (Kondolf *et al.*, 1993). The sediment collectors (see Lachance and Dube (2004)) were filled with 16–32 mm sediment. They are constructed from two cylindrical buckets (1 L volume) set inside of each other and have a large tray attached to the bottom. The buckets, 13·5 cm height, have multiple matching 1·3 cm diameter holes that enable water and sediment to pass through them from the sides and from the top, ensuring that the collectors capture sediment efficiently (Carling, 1984). The collectors were buried in the gravel such that the open top, 12 cm in diameter, was flush with the bed. Before removal, the outer bucket

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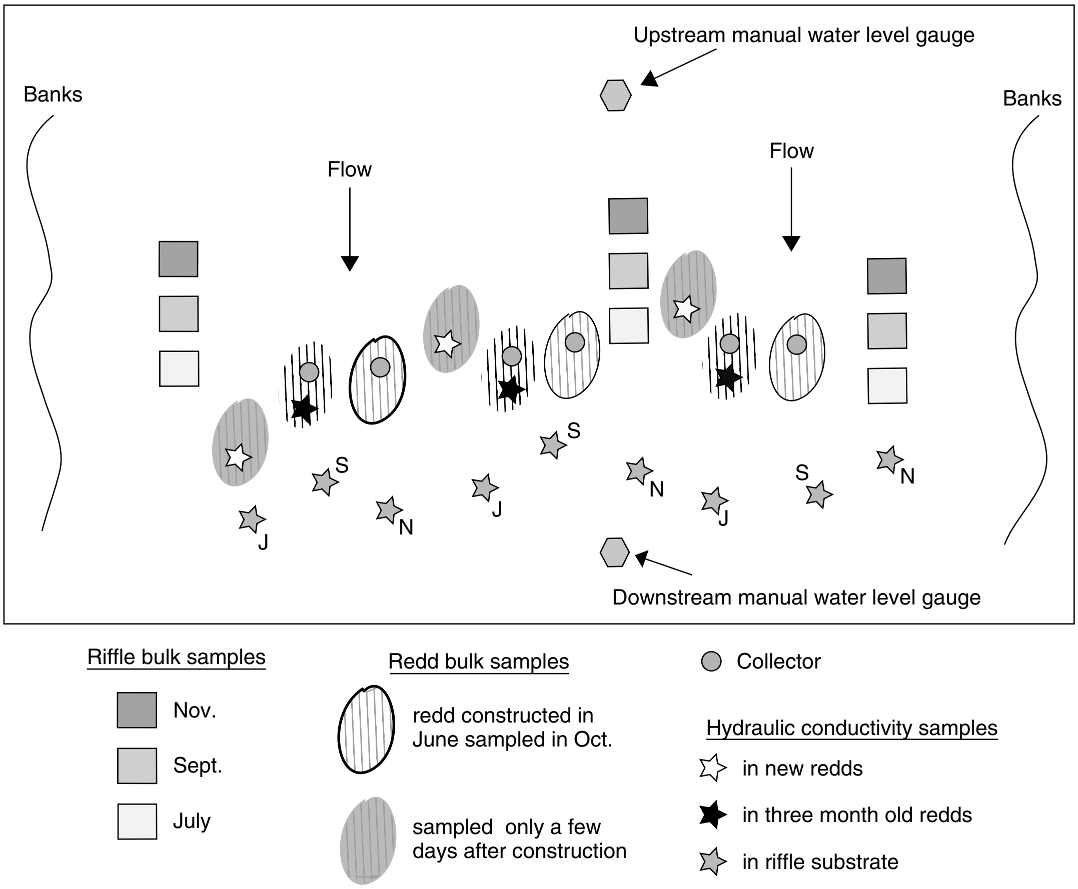

Figure 4. Schematic illustrating gravel sampling programme for any of the four sites. The hydraulic conductivity and grain size distribution of redds were only sampled at the sites on the Lac and Salmon branches. The 'J', 'S' and 'N' associated with the riffle samples of hydraulic conductivity represent the sampling completed in July, September and November respectively

is rotated so the holes are sealed; finally, a third outer container is lowered underwater and sealed on to the large tray attached to the base of the smaller buckets. This ensured that the infiltrated silt and sand remained in the collectors when they were extracted from the water. Sediment from collectors was dried and sieved at ϕ intervals. Large gravel particles were at times caught on the lower tray of the collectors during extraction and inadvertently became part of the sample. To avoid this source of bias, only infiltrated sediment finer than 2 mm, the fraction considered to be fine sediment herein, was considered in further analysis.

Monitoring seasonal evolution of riffle and redd substrate

To monitor whether sediment was deposited in redds or riffles during the summer and fall a series of substrate bulk samples were used, as no accepted field technique can precisely monitor through time the fine sediment content of a given, fixed substrate volume. Existing sampling techniques unacceptably disturb substrate structural characteristics. At each study site, three sets of riffle substrate samples (in June, September and November) were thus extracted (Figure 4). Each of these sets consisted of three bulk samples, spread across the crest of the riffle. In total, 36 bulk samples were taken (4 sites × 3 seasons × 3 samples). New bulk samples were extracted sequentially just upstream of previous bulk sample locations, rather than adjacent to them, since natural grain size variability is greater across the stream channel than along the stream channel (Adams and Beschta, 1980).

Bulk samples were taken within a flow isolation cell, in 30 to 70 cm deep water. The cell design allows water to flow slowly through the cell and into a fine (77 µm) mesh bag downstream in order to limit the amount of fine sediment washed away while sampling (Payne and Lapointe, 1997). The cell had 3 cm of soft foam along its base in order to reduce the size of gaps between the bed and the base of the cell. On average, subsurface samples contained 140 kg of sediment. The largest stone in the samples was generally between 128 and 256 mm in diameter, allowing the percentage fine sediment to be assessed properly without undue bias due to truncation of coarser bed fractions. Sub-samples (5 kg) of the sediment finer than 16 mm ensured 0·1% accuracy was attained for the <16 mm fraction, based on Church *et al.* (1987).

To assess whether fine sediment was deposited in artificial redds during the July–October period, in October, at the Lac and Salmon sites, we measured the subsurface grain size distribution of three redds that had been constructed in early July and had been subjected to 3 months of suspension events. For comparison, at the same time we bulk sampled three redds that had just been created (see Figure 4).

Measuring hydraulic conductivity

A Mark VI standpipe was used in order to estimate the *in situ* hydraulic conductivity of the gravel within redds and riffles. The majority of the sample sets consisted of three or four good-quality hydraulic conductivity measurements per site, per visit. To assess the variability of the technique better, between 7 and 22 replicate *in situ* tests of hydraulic conductivity were conducted on the same day at least once at each stream. The core tube used in this study was identical to that of Barnard and McBain (1994), apart from the addition of a foam and rubber skirting that sits at the bed surface (Terhune, 1958). The operator stood on the skirting during sampling to reduce water flow down the outside of the tube. The rate of water extraction necessary to maintain a 2·5 cm head difference was related to hydraulic conductivity and corrected to 10 °C using the calibration relationships presented in Barnard and McBain (1994). Barnard and McBain (1994), Pollard (1955) and Terhune (1958) and the literature on salmonids (e.g. Peterson, 1978; Chapman, 1988) use the term permeability to describe the results from the Mark VI standpipe. This is an old and now incorrect use of the term permeability, as the pumping tests have the units of a velocity and depend on the temperature and viscosity of the water, in addition to the permeability of the substrate. The term hydraulic conductivity is used throughout this paper to conform with contemporary groundwater nomenclature.

RESULTS

Summer and fall suspended sediment events

Figure 5 illustrates the discharge record from the Cascapédia River gauge from April to December 2001. During the 5 months of continuous suspended sediment monitoring, between 6 and 10 rain-based suspension events (*sensu* Figure 3) occurred at each of the four sites. In general, suspended sediment events lasted about 1 day and occurred on all four streams simultaneously. Based on the Water Survey of Canada's 34 years of record, the largest events reached approximately 50% of the mean annual flood (recurrence interval equal to 2·33 years), whereas the smaller freshets were 10% of the mean annual flood. The smallest events monitored occur 3·5 times per year on average, and the largest events occur 1·4 times per year. Multiple painted rocks installed across the riffles, of slightly smaller calibre than the D_{50} of the surface substrate, were not moved during these events, indicating that the bar surface remained stable. We monitored sediment infiltration in relatively low-magnitude events, as larger events would be associated with bed material scour, which would confound our measurements of deposition (see Larkin *et al.* (1998) as an example of such problems).

Background suspended sediment concentrations ranged between 0·3 and 1 mg L^{-1}. During suspension events the average suspended sediment concentration (total dose/length of event) varied between 2 and 10 mg L^{-1}, and the median peak concentration of the suspension events varied between 10 and 30 mg L^{-1} (Table II). For the four streams, the highest concentrations inferred from the turbidity record during the field

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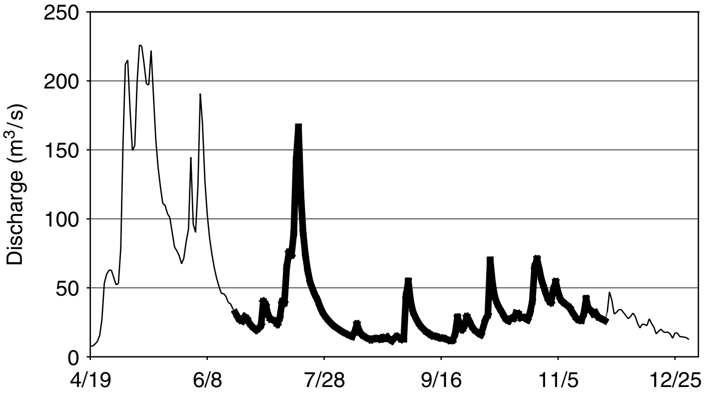

Figure 5. Discharge record from the Water Survey of Canada gauge for 2001. The dark black line illustrates the study period

Table II. Suspended sediment (SS) event characteristics from summer and fall of 2001[a]

	Brandy Brook	Berry Mountain Brook	Salmon Branch	Lac Branch
Number of events	8	9	6	6
Probable number of events not recorded[b]	0	0	2	2
Mean peak concentration (mg L^{-1})	15	40	26	76
Median peak concentration (mg L^{-1})	11	9·8	15	30
Maximum concentration (mg L^{-1})	43	170	99	380
Mean total dose (mg L^{-1} day)	2·7	8·4	7·1	27
Median total dose (mg L^{-1} day)	2·4	5·8	4·7	5·9
Mean length of SS event (day)	0·93	1·0	1·1	1·5
Median length of SS event (day)	0·64	0·73	1·1	0·65
Mean average concentration of suspension event (mg L^{-1})	2·9	7·4	5·1	10
Median average concentration of suspension event (mg L^{-1})	1·7	4·5	4·0	7·4

[a] For definition of suspension events and dose measure used see Figure 3.

[b] During some events there was no record of suspended sediment as the OBS sensor was not working.

season varied between 43 and 380 mg L^{-1}. Based on eight, 20 L water samples taken during suspension events at the various sites, suspended sediment had a median size of coarse silt; only a small portion (18%) of the suspended sediment was coarser than 0·25 mm (medium sand), and most of this appeared to be needle and leaf fragments. On all but Brandy Brook, the highest concentrations recorded occurred in the middle of July during a low-pressure system that lasted 6 days (Figure 5). This weather system was composed of a few large, intense convective rainstorms that triggered landslides in at least two of the watersheds.

Fine sediment infiltration during study events

At each of the four sites, six collectors containing clean 16–32 mm gravel were deployed throughout the summer and fall (a total of 24 active collectors at any time). Half of the collectors at each site were removed and replaced with clean collectors after each suspended sediment event. The other half (three collectors at each of the four sites) were only removed at the end of the field season.

The majority (up to 90%) of the sediment deposited in the collectors during the summer and fall was inorganic in origin; infill ranged in size from silt to pea gravels and appeared to fill the collectors from the bottom up. As mentioned earlier, the bed surface remained stable during the floods. The material in the

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collectors included both phase-one bedload (granules) and suspended load (silt). Jackson and Beschta (1982) defined phase-one transport as the transport of bedload overtop of a stable riffle substrate and it generally consists of fine gravel and medium to coarse sand originating from pools or channel margins. In contrast, phase-two bedload transport occurs when the entire bed surface is mobilized.

Over the 5 months of summer and fall deployments, 8·4 kg m^{-2}, 8·1 kg m^{-2}, 4·5 kg m^{-2} and 0·58 kg m^{-2} of sediment finer than 2 mm was deposited, on average, in the collectors at the Berry Mountain, Brandy, Lac and Salmon sites respectively. At each site, sediment deposition varied considerably between deployments, depending on event magnitude. Very little sediment was deposited in the collectors in the absence of suspension events. Collectors deployed during a 2 week period in August, a month without suspension events, had averages of 0·25 kg m^{-2} and 0·083 kg m^{-2} of sediment finer than 2 mm and finer than 0·25 mm deposited in them respectively. This yields average infiltration rates of only 0·017 kg m^{-2} day^{-1} and 0·0059 kg m^{-2} day^{-1} respectively. In contrast, during suspension events, the average infiltration rate (material finer than 2 mm) based on event duration was 2·6 kg m^{-2} day^{-1} (range: 6·8 to 0·11 kg m^{-2} day^{-1}). Thus, infiltration rates during storms were between one and three orders of magnitude larger than the background rate observed when there were no suspension events.

Figure 6 shows the average grain size distribution of the sediment finer than 2 mm that infiltrated in collectors during the summer and fall. The D_{50} is 620 μm, and most of the sediment deposited was medium and coarse sand. Overall, 80% of the sediment deposited in the collectors had diameters larger than 0·25 mm; based on the observed calibre of storm suspended load (above), this fraction would have primarily travelled as bedload during the flood. On average, only 4% of the deposited sediment was silt grade, the median size of suspended fractions.

Across all sites and events, the infiltrated D_{50} was not significantly related ($p > 0{\cdot}05$) to the total amount of sediment deposited in collectors or to the total suspended sediment dose of suspension events. In contrast, Sear (1993) illustrated that the infiltrated D_{50} can change with time, in some systems, depending on the magnitudes of the flow and the sediment supply.

From early November to mid April a second set of collectors, six per site, were deployed while the rivers were covered in ice to monitor infiltration during the winter months while eggs were in the gravel. On average, 9·9 kg m^{-2} of sediment finer than 2 mm was deposited in these collectors (deposition varied from 1·4 to 25 kg m^{-2}). Within these collectors, on average, 9% of the sediment finer than 2 mm was silt sized. The data from the collectors left in throughout the winter are excluded in the remaining portion of the paper, except for a short discussion of over-winter egg survival, as it was not possible to collect data on suspended sediment or shear stress during the ice-covered winter season.

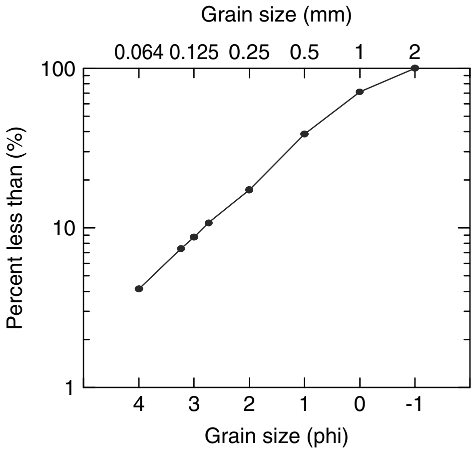

Figure 6. Average grain size distribution for sediment finer than 2 mm deposited in the collectors during the summer and fall of 2001

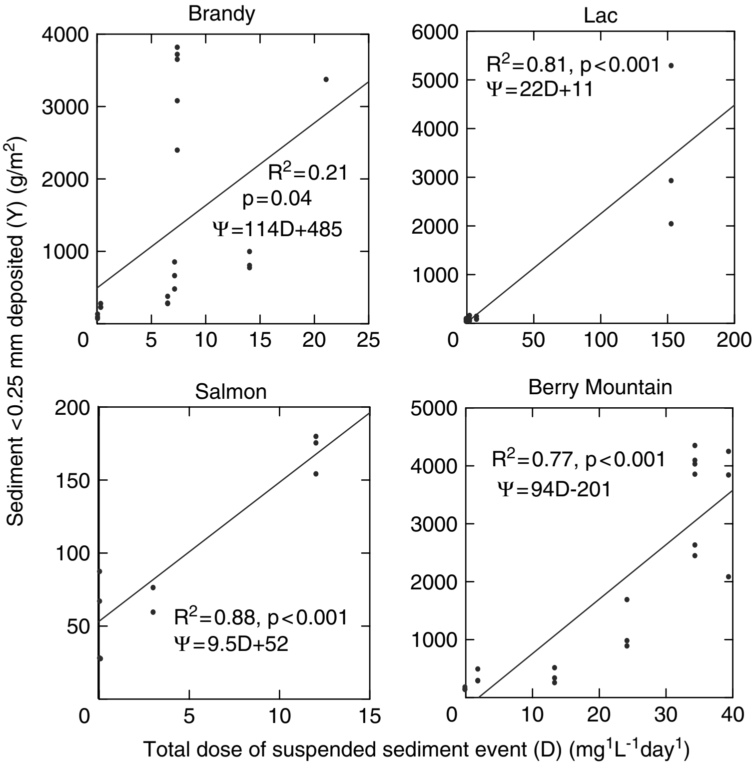

Figure 7. The relationship between the amount of suspended sediment (<0·25 mm) deposited ψ and the total suspended sediment dose during suspension events D (defined in Figure 3 as area under the curve) at the four study sites

Sediment infiltration rates as a function of suspended sediment dose

Carling (1984) has previously related the infiltration rate of finer than 2 mm sediment to average suspended sediment concentration in a flume. In a similar manner, we examined the relation between fine sediment infiltration and suspended sediment dose. However, unlike Carling (1984) we only consider infiltrated fractions finer than 0·25 mm, since this is the sediment likely to be travelling in suspension (see ‘Summer and fall suspended sediment events’ section). Time-integrated suspension dose D during events (see shaded area under the curve, Figure 4) was tested as a potential predictor of total sediment infiltration finer than 0·25 mm (ψ), as D reflects both average concentration and event duration. Figure 7 shows the best-fit relationships for the four streams, with considerable scatter. The data from collectors deployed during August (when there were no events) are plotted in Figure 7 on the abscissa at a nominal 0·1 mg L^{-1} day^{-1}, which is slightly less than the smallest event observed (0·3 mg L^{-1} day^{-1}). The slope estimates of the regressions were significantly different (standard errors of the estimates do not overlap) between all the streams except Brandy and Berry Mountain Brook. Brandy Brook had the most sediment deposited per unit dose of suspended sediment (114 g m^{-2} day^{-1} mg^{-1} L). Slightly less sediment was deposited at Berry Mountain Brook (94 g m^{-2} day^{-1} mg^{-1} L), and nearly an order of magnitude less sediment was deposited per unit dose of suspended sediment at the Lac and Salmon Branch sites (22 g m^{-2} day^{-1} mg^{-1} L and 9·5 g m^{-2} day^{-1} mg^{-1} L respectively). In Figure 7 the data from Berry Mountain Brook display a curved-linear response, and the data from the Lac Branch site is clearly unevenly distributed. For these reasons the linear model used here may not be the most appropriate model; however, it is utilized here as it is the simplest model that fits all four streams. There are insufficient data to define the form of the relationship between dose and deposition unambiguously.

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Shear stress and sediment deposition

At each site, water depths and water surface slopes across redds were measured 20–30 times during the field season. Water surface slopes did not vary with stage over the observed ranges in stage, and average water surface slopes are given in Table I. Measurement errors associated with water depths were estimated to be 5 cm, and water depths varied between 26 and 48 cm. Based on the error associated with the estimates of water depths (~15%) and water surface slopes across redds (35%), the shear stress estimates have a root-mean-square uncertainty of approximately 38%. The error in energy slope due to non-uniform flow (i.e. convective accelerations over the riffles) was found be insignificant compared with the errors associated with the depth and water surface slope estimates. Additional errors associated with horizontal convergence of flow were ignored, as the flow was horizontally uniform and the redds were located near the centre of the channel. Figure 8 illustrates the relationship between shear stress and the amount of sediment between 0·25 and 2 mm (fine bedload) deposited at the four sites. At Brandy Brook, significantly more fine bedload was deposited (analysis of covariance (ANCOVA), $p < 0{\cdot}001$) per unit shear stress than at the other sites.

Seasonal changes in redd and ambient riffle hydraulic conductivity and fine sediment content

Figures 9 and 10 respectively summarize the hydraulic conductivity and the sand content data from replicate ambient riffle substrate (outside of redds) samples at each site in late July, mid September and early November. Whereas the median sand content increases at Berry and Brandy and the conductivity decreases at Lac, Berry and (to a lesser extent) Salmon, at all of the sites there was no significant change ($p > 0{\cdot}05$) in the percentage of sand, sand index (Peterson and Metcalfe, 1981) or in the hydraulic conductivity of the riffle substrate.

Despite the observed deposition of fine sediment in collectors buried in redds (Figures 7 and 8), our bulk sample data fail to reveal significant changes in redd fine sediment content during the study period (Figure 11; analysis of variance (ANOVA), $p > 0{\cdot}1$, three freshly created redds compared with three 3-month-old redds, at two sites). Repeat *in situ* hydraulic conductivity tests conducted on the redds also failed to reveal significant differences (ANOVA, $p > 0{\cdot}1$) between the hydraulic conductivity of new and old redds.

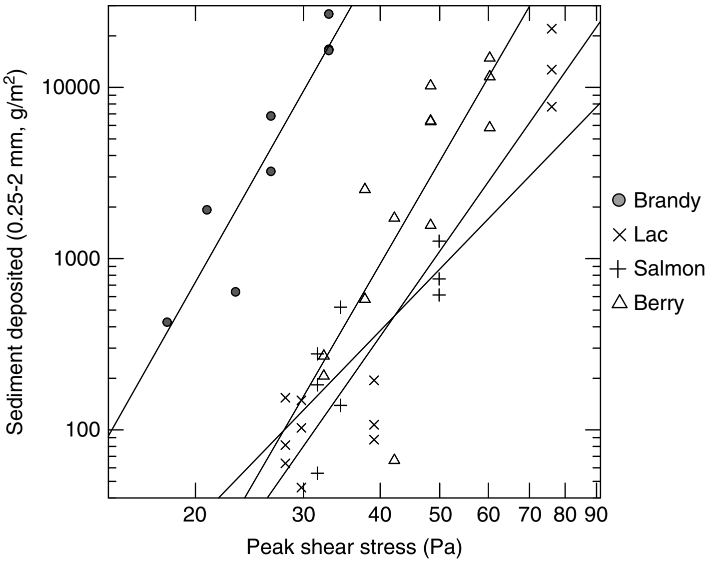

Figure 8. The relationship between the amount of bedload sized sediment (0·25–2 mm) deposited in the collectors and peak shear stress during storm events at the four study sites

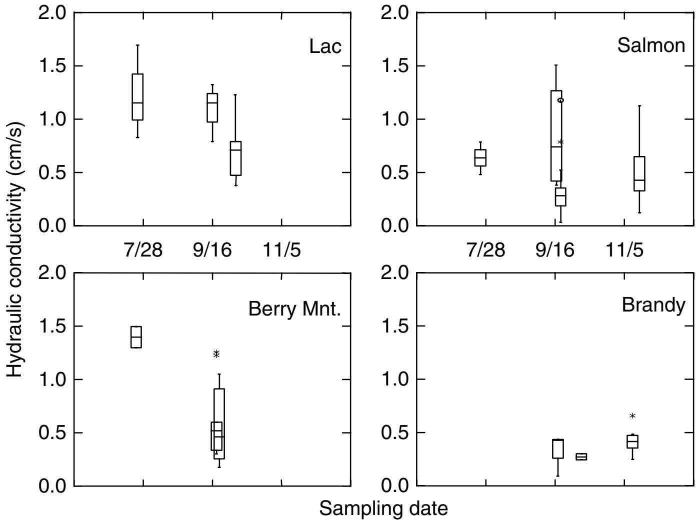

Figure 9. Box plots illustrating the hydraulic conductivity of riffles during the study. The middle line represents the median, the box splits the remaining halves again, the whiskers are 1·5 times the interquartile range, and stars are less than three times the interquartile range (Wilkinson *et al.*, 1992)

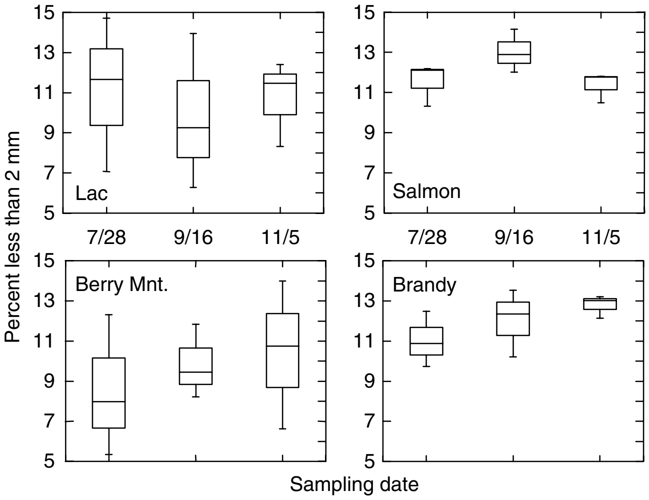

Figure 10. Box plots illustrating the amount of sediment finer than 2 mm in riffles during the study. The middle line represents the median, the box splits the remaining halves again, the whiskers are 1·5 times the interquartile range, and stars are less than three times the interquartile range (Wilkinson *et al.*, 1992)

DISCUSSION

Intersite comparison of sediment deposition rates

When comparing sediment deposition rates from the four watersheds based on collector data with uniform clean gravels, clear intersite differences in average sediment infiltration rates were observed. On average, Berry Mountain and Brandy brooks had more sediment finer than 2 mm deposited in the collectors during the 5 months of deployment, compared with the other two sites (8·4 and 8·1 kg m^{-2} versus 4·5 and 0·58 kg m^{-2}). In addition, more suspended-sediment-calibre sediment (<0·25 mm) was deposited per suspended sediment

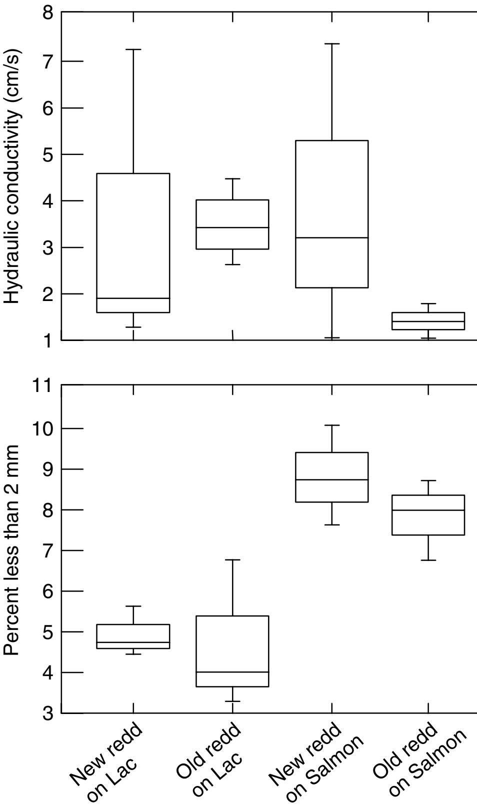

Figure 11. Box plot illustrating the amount of sediment finer than 2 mm and hydraulic conductivity of redds. One set of redds ($n = 6$) was constructed days before being sampled, and the other set ($n = 6$) was constructed 3 months earlier and subject to sediment infiltration events. The middle line represents the median, the box splits the remaining halves again, and the whiskers are 1·5 times the interquartile range (Wilkinson *et al*., 1992)

dose unit in Brandy Brook and (to a lesser degree) Berry Mountain Brook than at the two other sites (see Figure 7). Likewise, per unit of peak bed shear stress for each event, more fine bedload (2–0·25 mm) was deposited in the collectors at Brandy Brook than at the other sites (see Figure 8).

Although the number of sites is too small ($n = 4$) to test whether the elevated amounts of fine sand and silt deposited in the Brandy Brook infiltration traps are due to lateral transport of fine sediment from the surrounding silt–fine-sand-rich riffle substrate, the association is clear. At Brandy Brook the greater proportion of silt–fine sand in the riffle substrate may have caused more silt and fine sand to be deposited in the collectors than at the other sites.

The elevated rates of fine bedload (0·25–2 mm) infiltration at Brandy Brook (see Figure 8) could possibly be due to a greater availability of fine bedload in the channel, particularly in the pools and channel margins. Fine bedload and suspended sediment may be more available at the Berry Mountain Brook and Brandy Brook sites due to the very recent logging within the watersheds (Table I), where 11·4% and 7·4% of the watersheds respectively were logged during the 3 years prior to the study. In comparison, for both the Lac and Salmon watersheds, only 2·5% of the watersheds were logged during the same period. Other logging-related data, such as the percentage of the watershed logged in the preceding 5 and 10 years and the road density, do not correlate with the infiltration rate data (Table I). Clearly, based on our four sites, the relationship between logging and sediment depositions is inconclusive. The average slope of the basins and the amount of the watershed covered by the Lake Branch Formation, a particularly erodible lithology, also do not correlate well with sediment deposition rates. Although four sites are sufficient to show intersite differences, in this study the four sites do not clearly illustrate a correlation between sediment infiltration and land use, geology or physiography. Others have more clearly demonstrated that interbasin differences in deposition rates of fine sediment are related to logging (Lisle, 1989; Davies and Nelson, 1993).

In principle, by relating the infiltration of sediment finer than 0·25 mm to suspended sediment dose, differences in sediment transport and sediment availability between streams are accounted for in Figure 7. The scatter in Figure 7 suggests that additional factors may also affect deposition. These factors may include grain vibrations (Brasington *et al.*, 2000), flow hydraulics (e.g. velocity, Froude number) and intergravel flow (Schalchli, 1995).

In summary, clear intersite differences in sediment deposition rates were evident between the four sites. The different sediment infiltration rates correlate with the amount of silt in the subsurface substrate, but do not obviously correlate with land use, basin physiography or geology.

Infiltration rates into collectors versus rates in redd and undisturbed riffle substrate

During the time period between the first set of bulk samples (July) and the last set of bulk samples (November) an average 30 kg m^{-2} of sediment finer than 2 mm was deposited in the clean collector gravel (max. 43 kg, min. 14 kg, across all sites and replicates). During the same time period, no statistically significant change (at the 5% level) was detected in the amount of fine sediment or the hydraulic conductivity of redd or riffle gravels (Figures 9–11). Indeed, temporal trends in conductivity and sand content vary insignificantly across sites. This, in part, reflects the difficulty in detecting temporal changes in fine sediment content and permeability of *in situ* river substrate. The very same substrate patches cannot be monitored through time, and spatial variation reduces the power of the temporal comparisons.

Broadly, two hypotheses can be entertained to explain the discrepancy between collector results and ambient redd or riffle data. Assuming that fine sediment infiltration was spatially uniform over the sampled riffle area, it remains possible that the addition of approximately 30 kg m^{-2} of sediment finer than 2 mm to the substrate translates into a change in sand content that is undetectable in bulk sample data. Conversely, as hypothesized in the Introduction, sediment infiltration rates may differ between collectors and *in situ* gravels, as the collectors contain clean 16–32 mm gravels and thus have much more open pore spaces than *in situ* river substrate.

Back-of-the-envelope computations shed light on this. On average, bulk samples consisted of 140 kg of sediment extracted from a surface area of approximately 0·34 m^2 (porosity: 0·30; $\rho_s = 2650$ kg m^{-3}; sample depth: 20 cm). Assuming the infiltration of 30 kg m^{-2} of fine sediment to a depth of 20 cm in redd or ambient riffle substrate, this represents an addition of approximately 10 kg of fine sediment to the area of a bulk sample during the period July–November. This would correspond to a 40–80% increase in the mass of sediment finer than 2 mm (or roughly an 8% increase in the percentage finer than 2 mm). Such a change is easily detectable using our (140 kg) bulk samples, since the average coefficient of variation of replicate measurements of the percentage finer than 2 mm was about 20%, which is much less than the 40–80% increase that would be expected. We conclude from this analysis that sediment infiltration rates measured in collectors overestimate infiltration rates into redd or riffle gravels. This discrepancy in sediment infiltration rates probably reflects how the effective size of the pore spaces available in the substrate influences sediment infiltration (Meehan and Swanston, 1977; Frostick *et al.*, 1984; Lisle, 1989). These results also support the view that even limited quantities of sand particles in the substrate matrix may be very effective at reducing silt and fine sand infiltration. The modest amount of sand in the riffle and redd gravels appears to have significantly lowered the infiltration rate compared with rates measured with infiltration traps containing only clean, 16–32 mm gravel.

Implications for egg survival predictions

The infiltration collectors that were installed in late fall and left during the winter had an average 9·0 kg m^{-2} of sand (0·25 to 2 mm) and 0·89 kg m^{-2} of silt (finer than 0·065 mm) deposited in them. If we again rely on back-of-the-envelope calculations and assume an infiltration depth into redds of 20 cm, a bulk density of 2650 kg m^{-3} and a porosity of 0·3, this implies an increase of 5·6% sand and 0·6% silt. If we consider that this would be added to the sediment in redds after they are built, which was found to be 6·8% sand and 0·07% silt based on bulk samples of artificial redds, this would imply that a redd, after the winter, but before the spring freshet, would be composed of 12·4% sand and 0·7% silt. Based on Lapointe *et al.* (2004: equation (1)), who explicitly evaluated the effect of silt and sand on egg survival, only 59% of the eggs would be expected to survive to emergence.

$$\text{Survival}(\%) = 103 - 10(\%\ \text{silt}) - 3(\%\ \text{sand}) \qquad (1)$$

In fact, Zimmermann (2003) observed that eggs buried in the same redds that the collectors were deployed in, for the same duration of time, had an average survival rate of 90% to the eyed stage. Emergence was not observed, as it remains impractical to measure emergence in field settings. The discrepancy between the predicted survival (based on all the sediment deposited in the collectors being deposited in the redds) and the observed survival further suggests that less sediment was deposited in the redds compared with the collectors.

CONCLUSIONS

- The continued use of sediment infiltration traps has been illustrated to be appropriate and meaningful if the goal of a project is to examine the type of sediment available to infiltrate into streambeds and how the transport regime of infiltrating fine sediment varies between sites.
- The assumption that one can extrapolate sediment deposition rates measured in collectors to other processes, such as sediment infiltration into salmon nests or riffles, is flawed.
- Despite significant quantities of sediment being deposited in infiltration traps, we observed no significant change in riffle or redd substrate over 5 months during which eight or nine suspended sediment transporting events occurred.
- Effective prediction of sediment infiltration rates into riffles or redds must reflect the grain size distributions found in these gravels and the non-linear deposition processes that likely exist.

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