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INTERGRANULAR FLOW VELOCITY THROUGH SALMONID REDDS: SENSITIVITY TO FINES INFILTRATION FROM LOW INTENSITY SEDIMENT TRANSPORT EVENTS[†]

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ABSTRACT

This paper presents results from a novel technique allowing continuous monitoring through multiple storm events of interstitial flow in salmonid redds. Previous studies have shown that long-term increases in fine sediment inputs into rivers can silt up spawning beds, reduce intergravel flow and threaten egg survival. Not enough is known, however, about the temporal and spatial scales of the physical processes affecting spawning habitat. The short-term sensitivity of intergravel flow through salmon nests to low-intensity sediment transport events has not been documented. Furthermore, it is unclear if the egg pocket flow vital to incubation is principally controlled by the hydraulic conductivity of the redd patch or by that, generally lower, of the ambient riffle substrate. The purpose of this study was to determine if individual runoff events could affect intergravel flow in salmon nests and to investigate the sensitivity of interstitial flow to the fines content and conductivity of the redd patch.

During the summer and autumn of 2001, a new intergravel velocity sensor based on the hot wire principle made it possible to continuously monitor, over five months, interstitial velocities in artificial redds in four tributaries of the Cascapedia River, Quebec. Fifteen low and moderate intensity runoff events (up to 50% bankfull) were monitored. Data were obtained for each storm on suspended sediment transport as well as sand infiltration rates in sediment collectors emplaced in redd zones. It was found that redd interstitial velocities were reduced whenever a runoff event deposited more than 7 kg/m^2 of sands in infiltration traps. In addition, redd interstitial velocities were reduced four out of the five times that the event-integrated suspended sediment dose exceeded 7 mg l^{-1} day (dose is defined as the area under the concentration time curve). In the study conditions, where ambient riffle sediment has relatively moderate permeability and localized groundwater upwelling is negligible, our data suggest that significant intergravel flow (0.1–0.6 mm/s) can be triggered through 2 m long redd patches, in response to the redd-scale water surface gradient and the relatively higher conductivity of the redd patch, after spawner activity.
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KEY WORDS: salmonid spawning habitat; intergranular circulation; sediment infiltration; salmon redds; hyporheic flow

INTRODUCTION

Throughout North America there is concern for the health of salmonid populations that support major sport and commercial fisheries. The declining quality of in-stream habitat is a major concern for salmonid species, in particular, the habitat used for spawning and rearing purposes (Meehan *et al.*, 1969). One human impact has been an increase in fine sediment supply often associated with agriculture and logging (Meehan *et al.*, 1969). Fine sediment build-up in streams is believed to reduce intergravel flow by decreasing the hydraulic conductivity of the gravel, as fines in-fill the pore spaces and reduce both the interconnectedness and size of pores (Chapman, 1988; Copper, 1965; McNeil and Ahnell, 1964; Moring, 1982; Peterson, 1978). The flow velocity of water through the redd has been considered a key factor controlling the survival of incubating salmonid eggs as it brings dissolved oxygen to the eggs and removes metabolic waste (Chapman, 1988). Thus, both the hydraulic conductivity (Mason *et al.*, 1992; McNeil and Ahnell, 1964; Moring, 1982) and the amount of fine sediment in spawning beds are frequently measured to determine spawning habitat quality (e.g. Everest *et al.*, 1985; Payne and Lapointe, 1997; Coulombe-Pontbriand and Lapointe, in press).

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The very act of spawning, however, significantly reduces fines content and increases permeability in salmonid redds (Kondolf *et al.*, 1993). To what extent does localized redd cleaning ensure sufficient intergravel flow for incubation success, even if the river substrate surrounding the redd is badly silted-up? For example, if spawners remove fines from only a metre-scale patch of substrate, is there enough hydraulic gradient across such a patch to cause interstitial flow sufficient to sustain incubation? Important questions remain concerning the temporal and spatial scales of the physical processes affecting spawning habitat quality. In terms of spatial scale, how large does the higher permeability redd zone need to be in order to significantly enhance flow near egg pockets? In temporal terms, how long can it take, after spawning, for enough fine sediment to infiltrate into redds to significantly decrease intranest flow? How sensitive is intranest flow in new redds to repeated, low intensity runoff and sediment transport events?

In principle, the effectiveness of sediment infiltration events in reducing intergravel flow depends partly on the flow path controlling interstitial circulation through the redd. In the spawning habitat and contaminant and nutrient transfer literatures (e.g. Boulton *et al.*, 1998; Baxter and Hauer, 2000; Packman and Bencala, 2000) four distinct flow scales and associated controls have been described that may, in various combinations, affect intergravel flow through salmon nests.

Figure 1 illustrates intergravel flow at three different scales; a fourth, valley-flow scale is discussed later. These flow models are not mutually exclusive; rather they highlight different factors that may, in combination, drive shallow intergravel flow. The flow paths illustrated are based on conceptual models previously introduced in the literature.

(1) At the scale of bed micro-topography, the movement of water over a bedform can cause a high-pressure zone upstream of the bedform and a low-pressure zone downstream of the bedform, causing water to flow through the bedform (Figure 1a; Copper, 1965; Savant *et al.*, 1987; Thibodeaux and Boyle, 1987; Worman *et al.*, 2002). This process has been called ‘pumping’ and has been observed in the laboratory within bedforms with shapes and sizes similar to redds. The pumping flow model is supported by Stuart’s (1953; cited in Chapman, 1988) observation of a dye moving downward and longitudinally through a redd.

(2) At the same scale as pumping flow, but in the absence of a bedform, redd-scale flow can also occur, driven by the downstream hydraulic head drop associated with the drop in water surface over the redd cell (Figure 1b; Savant *et al.*, 1987). One can hypothesize that such redd-scale flow may dominate when redd substrate is much more

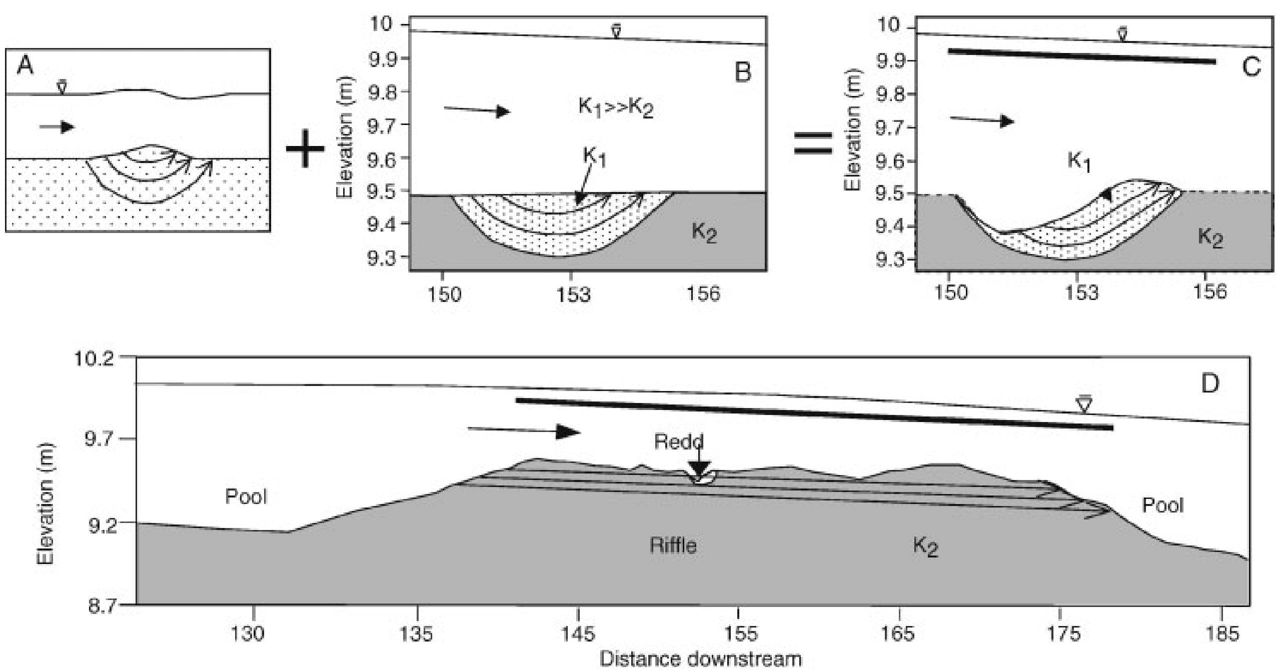

Figure 1. Multi-scale hydraulic processes potentially controlling intergravel flow near redds (see text for discussion)

permeable than surrounding, undisturbed riffle gravel. By definition, intergravel water flow driven by both redd-scale and pumping-induced forcing would obey Darcy's law and be affected by the hydraulic conductivity K_1 of the redd gravel (rather than the lower conductivity K_2 of the ambient substrate). Figure 1c illustrates that when a bedform occurs where the water surface is sloped (i.e. there is a general, head gradient resulting from bed friction losses) intergravel flow is driven by both redd-scale and pumping flow (Elliott and Brooks, 1997b; Thibodeaux and Boyle, 1987).

(3) At a larger spatial scale, interstitial flow at the riffle scale occurs when stream water flows into riffle gravel at the tail of the upstream pool and emerges at the head of the downstream pool (Figure 1d; Baxter and Hauer, 2000; Dahm, 1996; Harvey and Bencala, 1993; Vaux, 1966). Riffle-scale flow is thus driven by the concentrated drop in water surface level across riffles, from pool to pool, a drop which is marked at all but the highest flow stages. Assuming that redd zones are small with respect to the volume of the riffle substrate, this flow system is mainly controlled by the hydraulic conductivity of the overall riffle gravel. In systems where only a small portion of the riffle gravel is cleaned by spawning, a conceptually clear distinction can thus be made between redd-scale and riffle-scale flow since the two flow domains will have very different hydraulic conductivities and may respond to different hydraulic gradients. When numerous salmon spawn over the entire riffle area the distinction can become blurred.

(4) At the scale of the valley bottom, intergravel flow through redds can also be driven by local groundwater effluent discharge into the stream and/or influent seepage (groundwater recharge) out of the stream bottom. Flow at this scale is driven by differences in head (elevation and pressure potentials) between the water under valley sides and that under stream bottom; these differences reflect infiltration, runoff and evaporation patterns, depth to bed-rock, hydraulic conductivities and consequent variations in the storage of groundwater across the whole valley bottom including riverside terraces and the floodplain (Baxter and Hauer, 2000; Harvey *et al.*, 1996; Malcolm *et al.*, 2003; Packman and Bencala, 2000).

Due to scale effects, short-term sediment transport events may reduce intergravel flow driven by pumping or redd-scale processes more than flow driven by riffle-scale or channel-scale processes. Pumping and redd-scale flow occurs within the top 20–30 cm (depth of the redds) of the gravel, which can be significantly clogged by individual sediment depositing events. Intergranular flow at the riffle or valley-bottom scale has longer flow paths and larger-scale controls and is less likely to be affected by individual suspension events or infiltration of fines into the redd zone. Under riffle-scale or groundwater flow processes, channel migration and scour and fill events (e.g. Carling and Glaister, 1987) probably affect intergravel flow much more than would minor suspension events.

The objectives of this study are three-fold.

1. To quantify the difference in hydraulic conductivity and interstitial flow rates within fresh redds compared to conditions in ambient, fines-rich, undisturbed riffle substrate.
2. To quantify the sensitivity of interstitial redd flow to repeated summer and autumn runoff events that cause fines infiltration into the redds.
3. To investigate the hypothesis that, where redds are embedded within ambient riffle substrate with relatively lower conductivity, interstitial circulation at redd scale can ensure sufficient flow for egg incubation (at least in the early stages of embryo development).

STUDY AREA

The study was conducted in four tributaries to the upper reaches of the Cascapédia River in the Gaspe peninsula, Québec. The Cascapédia River is a north–south flowing sixth-order river, which drains the Chic-Choc Mountains of the Appalachian geological province into Chaleur Bay (Figure 2). The river is over 150 km long and supports a world class Atlantic salmon sports fishery. At study sites, fines content in riffle substrate ranges between 12 and 21% (by weight, fraction under 2 mm). However, because of the friable mudstone lithology that outcrops in the upstream study areas, the interstitial matrix is compact and relatively rich in the lowest permeability, finest fractions: silt (on average 1.1%, finer than 64 µm) and fine sand (average 3%, fraction 64–250 µm). Interstitial flow through undisturbed (unspawned) riffle substrate is believed to be hindered by these relatively high silt-loadings

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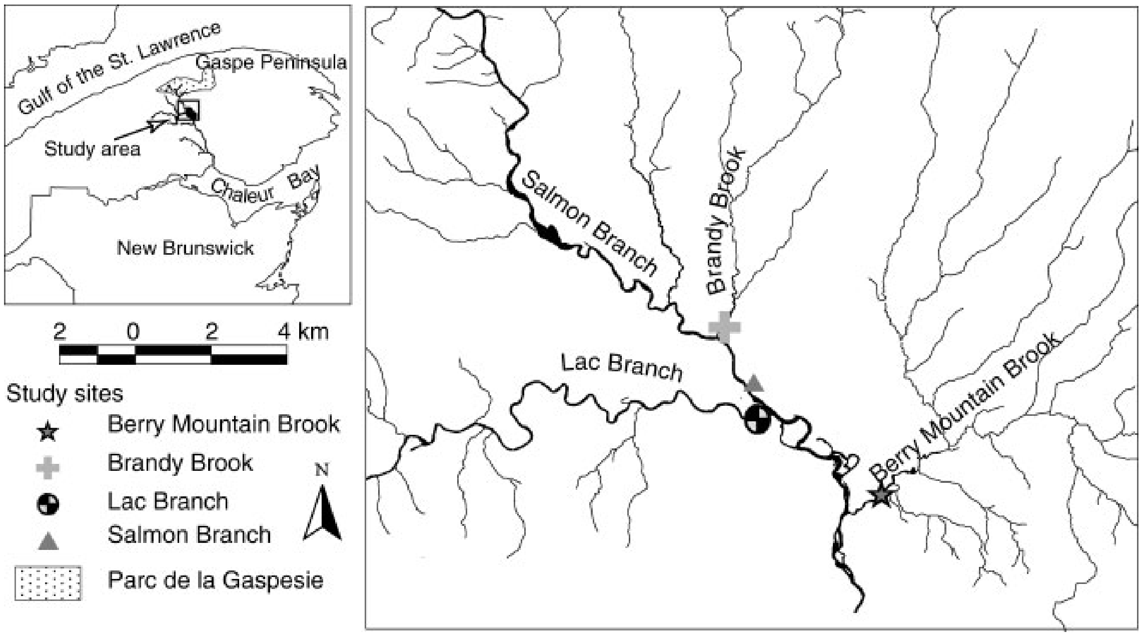

Figure 2. Map of study area with location of study sites

(Lapointe *et al.*, 2004). In addition, in the Cascapédia river system salmon only spawn over a small portion of the riffle gravel and the spawned redd gravel contrasts with the more compact, silt-rich, ambient riffle gravel.

Study sites consisted of riffles that were potential spawning beds located on four fourth to fifth order tributaries of the Cascapédia River: the Salmon Branch, Lac Branch, Brandy Brook and Berry Mountain Brook (Figure 2). The bankfull width at the study sites ranged between 7 (Brandy Brook) and 50 m (Salmon Branch) and reach-scale slopes from 0.3 to 0.7%. The range of median diameters of riffle substrate was 95–130 mm for the pavement and 25–30 mm for the subpavement. Pavement layer thicknesses ranged from 125 to 170 mm. The study sites were all located within 10 km of each other, in an area approximately 60 km from the river mouth. The selected riffles were considered suitable as Atlantic salmon spawning grounds, based on overall substrate size and sand content criteria and on the opinion of local salmon fishing guides. During the study, salmon could not migrate to the spawning beds on Brandy and Berry Mountain Brook, as there were obstructions to fish passage on these two streams. Atlantic salmon did spawn at the Lac Branch study riffle in 2000 and 2001.

Much of the main-stem Cascapédia River is a moderate energy gravel-bed river, with many valley sections controlled by bedrock, which outcrops in many places along the bed and banks of the river. The four tributary study sites are typical riffle–pool channel reaches formed within a relatively thin layer of silt-rich, gravel-cobble alluvium over bedrock. While there were no bedrock outcrops at any of the study riffles, some sites had bedrock close to the channel perimeter. In all study reaches bedrock outcropped within a few pool–riffle sequences of each study riffle.

Malcolm *et al.* (2003) and Soulsby *et al.* (2001) have shown that groundwater effluent seepage in and around redds causes distinct differences between the temperature and/or dissolved oxygen concentration measured in stream water and interstitial redd water. Water temperature and dissolved oxygen data showed that groundwater effluent seepage was negligible at all chosen field sites during the summer and autumn study periods. The water temperature in 20–30 cm deep redds and that in the water column differed by no more than 1°C at any of the sites during the study period. There was also no significant difference between the daily temperature fluctuations measured in the water column and in redds. In addition, the concentration of dissolved oxygen measured in the redds did not differ from the concentration measured in the water column. Thus, at the four selected study sites, local groundwater circulation at the valley-bottom scale was considered to be negligible during the summer–autumn measurement period. However, groundwater seepage was found to be important at other sites: at one riffle site not used in this study, the groundwater seeping into the river had a distinct temperature and dissolved oxygen concentration.

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METHODS

At each site, to assess the effect of sediment deposition on intergravel flow, we installed an optical backscatter sensor to track suspension transport as well as a sensor that continuously monitored intergravel water velocities in artificially constructed redds. Infiltration traps were also installed in redds to assess low-intensity sand-granule bedload transport. The grain size distributions, *in-situ* substrate hydraulic conductivity as well as surface water gradients over redds and riffles were also measured. Methods are described herein.

Measuring suspended sediment concentrations

Suspended sediment concentrations were continuously monitored in order to determine how much fine sediment was being transported in the streams during rain–runoff events over the period from the end of spring high flows (mid-June) to freeze-up (mid-November) 2001. An optical backscatter sensor (OBS) was used at each of the study sites to monitor turbidity over the five-month period. Turbidity was related to suspended sediment concentration by taking 2-litre or larger water samples under varying flow conditions. A relationship between turbidity and suspended sediment (s.s.) concentration was developed and used to predict the peak suspended sediment concentration and the total s.s. dose (area under the concentration time plot) for each storm event (Figure 3). A transport event was defined based on exceeding a 3 mg/l backround s.s. concentration. Zimmermann (2003) describes the calibration and installation of the OBS sensor in greater detail.

Construction of artificial redds

Two sets of artificial redds were constructed on the study riffles. The first set was constructed in June and abandoned in October 2001, while the second set was constructed in mid-October and abandoned in April 2002. In an attempt to mimic salmon spawning activity, the artificial redds were excavated in the coarse cobble substrate under 30–80 cm of water using a shovel assisted by gasoline powered water pump with a 2 cm spray nozzle to help wash finer sediments downstream. A 30 cm deep pit was scoured out to form an egg pocket in the pit and covered by sediment from another 20 cm deep pit dug upstream. The redd zones thus created were approximately 1.5 m wide by 2 m long, as illustrated in Figure 4. Based on the description of Kondolf *et al.* (1993) and White (1942) and field observations, the topography of the artificial redds was similar to a wild salmon's redd. At the Lac Branch site, Atlantic Salmon spawned in three of the artificial redds in October 2001.

Measuring sediment deposition in redds

Sediment collectors were used to measure the amount of sediment deposited in artificial redds. The sediment collectors were filled with clean, 16–32 mm sediment and installed into the instrumented artificial redd on the

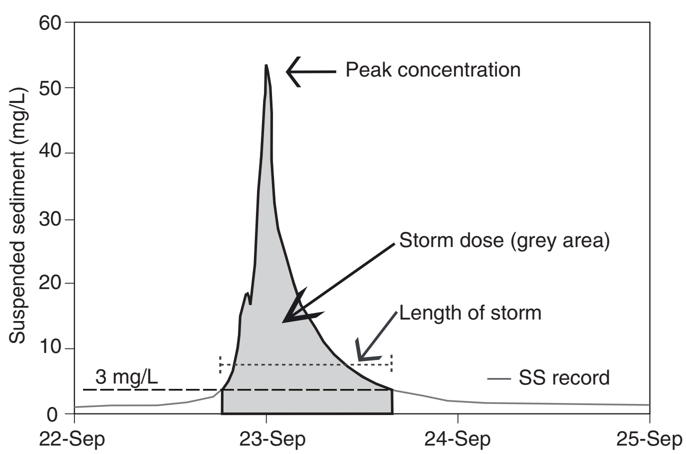

Figure 3. Typical suspended sediment (SS) record for a runoff event with definition of integrated suspended sediment dose for the event (area under curve in mg l^{-1} day^{-1}). Between-event background concentration was approximately 1 mg l^{-1}

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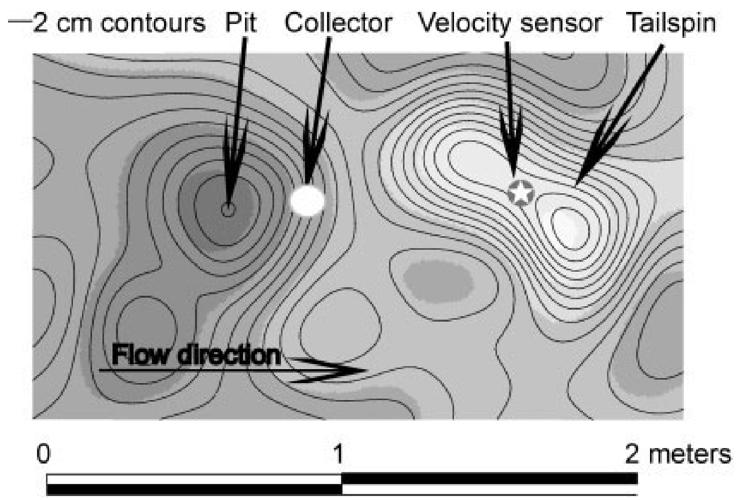

Figure 4. Topographic map of artificial redd indicating relative locations of TVM sensor and collector for infitrating sand/granule sediment

downstream side of the pit (Figure 4) and covered by some coarse gravel. After each suspension event, the collectors were removed and clean ones were installed. The amount of sediment less than 2 mm deposited in the collectors was weighted.

The collectors (SEDIBAC^{TM}; details at www. bio-innove.ca; see also Lachance and Dube, 2004)) are constructed from two 1-litre buckets set one inside the other. The buckets have multiple matching holes that enable water and sediment to pass through them from the sides as well as from the top when the holes are open, ensuring the collectors efficiently capture sediment (Carling, 1984). To avoid loss of fines when the collectors are retrieved, rotation of the outer bucket before extraction closes the side holes and a third, plastic outer enclosure completely seals the inner buckets before extraction from the bed.

Intergravel flow sensor: temperature velocity meter

We designed a novel instrument called a temperature velocity meter (TVM; Figure 5) to continuously monitor interstitial flow at redds and detect minor changes that might be associated with runoff and sediment transport

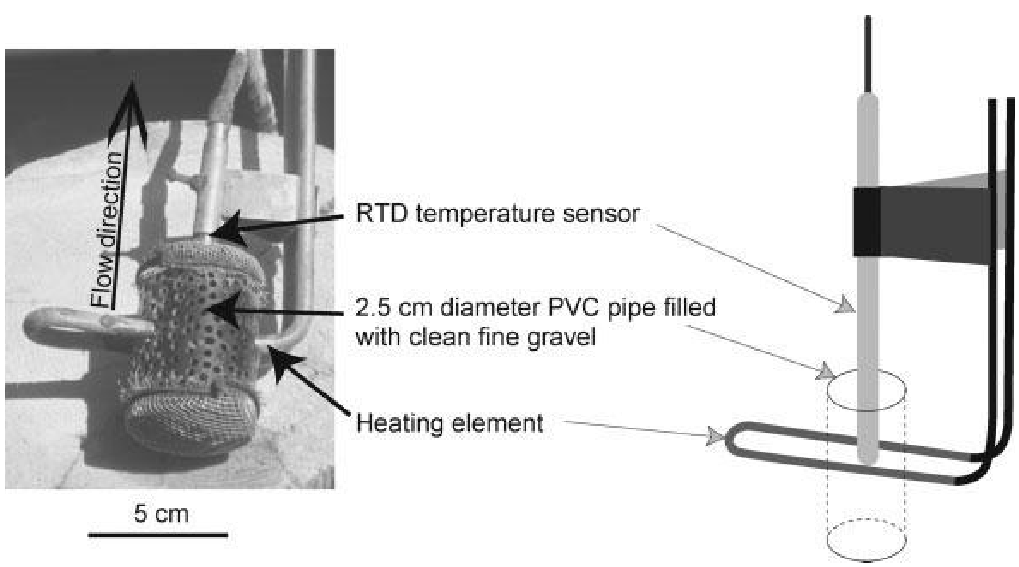

Figure 5. Thermal velocity meter (TVM) unit, custom designed to continuously monitor interstitial flow and transmit records to remote data logger. Design is discussed in text

events. The TVM is, in concept at least, broadly similar to a hot wire anemometer used in hydraulics and fluid mechanics labs. To survive deployment in stream gravels during runoff events, it is designed to be much more massive and robust than laboratory units and, because of higher thermal intertia, is much less sensitive to short-period (scale of $<$ tens of minutes) flow fluctuations. To operate the sensor, a 30 W heating element buried in the gravel was turned on by a data logger for 7 min every 4 h. During this period, the interstitial water temperature was measured with a resistance temperature device (RTD; 0.1°C accuracy) located a few millimetres from the heating element. The data logger recorded the water temperature every second and the total change (ΔT) over the 7 min. Laboratory calibrations show that the ΔT value is related to intergranular velocity, as larger changes in temperature are measured because slower water velocities transport heat away from the sensor less efficiently. One TVM was installed at each of the four sites in a redd as illustrated in Figure 4. These sensors provided a 5 month record of interstitial redd flow, measured every 4 h. When the redds were re-built in November the TVM was transferred to a new redd and flow velocities were recorded until the end of November. Since TVM installation modifies substrate conductivity in its surroundings, the device could not be used to measure flow in ambient, undisturbed substrate.

As long as the arrangement of the TVM sensor and surrounding substrate remains constant after installation, qualitative or relative changes in the velocity of water around the sensor can be directly interpreted from the ΔT signals (without calibrating the sensor), as a larger ΔT corresponds to a slower flow velocity. Knowing the actual intergranular velocity within redds is, however, desirable. Equation 1 illustrates a simple sensible heat balance model that can be used to relate mean interstitial velocity to the power supplied to the heating element (P_{elem}), the change in temperature (ΔT) detected by the RTD, and the cross-sectional area (A) affected by the heat of the element:

$$\Delta T = P_{\mathrm{elem}}/(\rho_{\mathrm{w}} A S_{\mathrm{h}} V) \tag{1}$$

where ρ_{w} is the density of water, S_{h} is the specific heat of water and V is effective 'bulk or apparent' water velocity, equal to substrate porosity multiplied by mean interstitial velocity (cf. Freeze and Cherry, 1979). Area A will depend in a complex way on V as well as ambient grain size distributions and pore geometry. In any given installation, assuming these last two factors remain constant, A thus varies only with V (Equation 1) so that ΔT is functionally related to V. In laboratory calibrations with varying gravel mixtures and flow velocities, the effective cross-sectional area was estimated to vary between 5 cm^2 and 65 cm^2 (see sample laboratory calibrations in Figure 6A).

To calibrate the TVM in the field, at each riffle site, 20–25 direct heat trace measurements of interstitial velocity were conducted. Boiling water was injected into the gravel 7–35 cm upstream of the sensor and the time delay (ranging from 1 to 15 min) for the hot water to move downstream past the temperature sensor was measured on the logged RTD signal (sampled at 1 Hz). Injecting a sufficient volume of hot water into the bed took 20 s on average. Logged RTD signals reveal clear phases of rising temperature, followed by more protracted falling phase: the peak time was determined (usually to 30 s precision) as the average between time to stabilization at peak and start of fall. Time delay to peak was better defined with hotter water and shorter travel distance. Individual heat trace estimates of mean interstitial flow velocity typically had 10% uncertainty. Experimentation showed that travel time for such heat traces was much easier to interpret than alternative techniques that relied either on salt water dilution or the movement of salt water through the gravel from an injection point to a downstream point where a conductivity meter was buried in the redd.

To reduce error in field calibrations, five replicate heat trace measurements were made at each site. Heat trace velocity estimates at each site were then regressed against the TVM velocity taken at the same time. Data from all four streams combined are illustrated in Figure 6B, which also gives the overall best-fit line between all predicted and observed velocities. The mean cross-sectional area (in Equation 1) producing the best-fit line closest to 1:1 was 13.79 cm^2, which is similar to the cross-sectional area determined in the laboratory for redd-like gravel.

A number of outliers are evident in Figure 6B, where anomalously high TVM velocities are calculated based on the single, best-fit area (A) value (Equation 1). Most of these anomalies occurred in the first two to three weeks after the sensors were installed for the second time in the study redds in late October. They appear to reflect atypically porous, ambient grain fabrics (thus higher effective A values than average for the deployments). A few weeks after these sensors were re-installed all the velocities dropped to the 0.1–0.8 mm/s range. Note also that the bulk of data shown in Figure 6B appear to curve slightly. This may reflect gradual changes in effective exchange area A with

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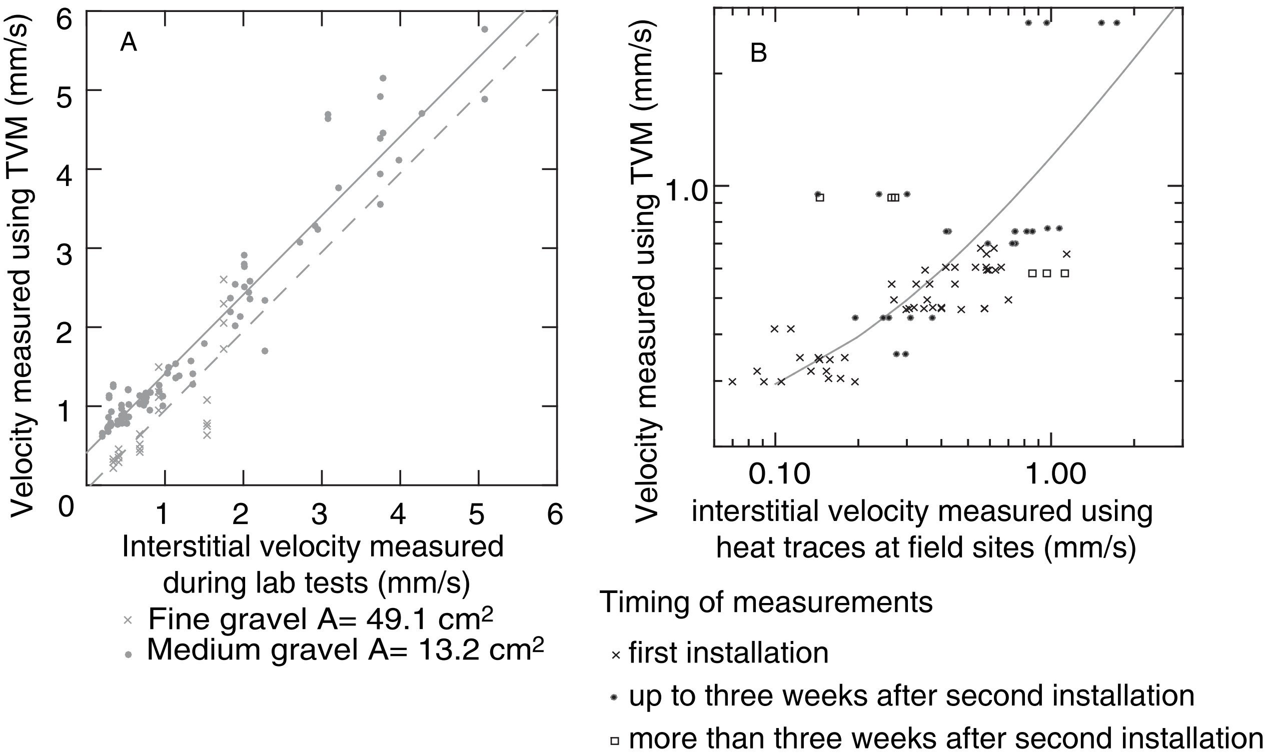

Figure 6. Calibration data for TVM output against *in-situ* heat trace measurements of interstitial flow rate. Calibration procedures discussed in text. (A) Laboratory calibration data for two different gravels. (B) Best-fit field calibration across all study sites

increasing velocity. Given all the other sources of variation, these secondary changes in the cross-sectional area could not be resolved precisely with the methods used in this study. To generate a 5-month-long redd flow record, the single best-fit cross-sectional area of 13.79 cm^2 was used in Equation 1 for calibration.

Although there is uncertainty in TVM calibration because of gravel settling over the first weeks after installation, the instrument efficiently detected any rapid changes in velocities occurring over periods of a few days, after the stabilization period. Figure 6B shows that, beyond the stabilization periods, this single overall calibration is reasonably accurate to within 0.2 mm/s in the range 0–0.7 mm/s.

In this paper, replicate heat-trace measurements are relied on for accurate spot estimations of flow velocity during stable, interstorm periods. The overall calibration of TVM output described above was used mainly to yield insight on relatively rapid temporal changes in interstitial flow associated with sediment transport events (because such events occur at any time of day or night these changes cannot easily be monitored by manual, heat trace measurements). In future studies, to generate a more accurate, long-term record of interstitial flow, we suggest modifying the TVM unit by adding a second RTD, approximately 10–20 cm downstream of the first one, and employing for velocity estimation the more robust time of heat travel approach rather than a heat balance calibration (Equation 1). The heat balance approach is more useful in laboratory hot wire anemometry of turbulent, open channel flows, where flow Reynolds numbers are much higher and, in the absence of a granular phase, A is a more predictable function of V around the instrument.

Measuring hydraulic conductivity

A Mark VI standpipe was used in order to estimate the hydraulic conductivity of the gravel within redds and riffles. The standpipe, originally designed by Pollard (1955) and modified by Terhune (1958) and Barnard and McBain (1994), samples the hydraulic conductivity of the gravel around a 6 cm diameter steel core tube that is pounded into the substrate, with its openings 20 cm below the gravel surface. The core tube used in this study

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was identical to that of Barnard and McBain (1994) apart from the addition of a 1 m diameter foam and rubber skirt which fits tightly around the steel core at the bed surface (Terhune, 1958). The operator stood on the skirting during sampling to reduce the possibility of water flow to the openings 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), Terhune (1958) and other literature on salmonids (e.g. Chapman, 1988; Peterson, 1978) use the term permeability to describe the measurements with the Mark VI standpipe; this terminology is incorrect as the pumping test results have the units of velocity and depend on temperature and viscosity of the fluid in addition to the permeability of the sediment. To conform to modern groundwater nomenclature, the term hydraulic conductivity is used to describe these data.

Measurement of water surface slopes over riffles and redds

Given insignificant groundwater effluent seepage at the study sites, the main head gradients driving redd interstitial flow relate to the water surface slope patterns at various scales over the bed. To measure water surface slopes at redd and riffle scales, a longitudinal series of five or six water level pins were surveyed at each site. Pins were positioned to determine the water surface slope in the upstream pool, the transition between the tail of the pool and the riffle crest, where redds were installed, and the upper and lower portion of the downstream riffle. At all sites, water levels were recorded at the pins at a range of flow conditions.

RESULTS

Hydraulic conductivity of riffle versus redd substrate

The grain size distribution and in-situ hydraulic conductivity of newly created redds and of ambient, undisturbed riffle substrates were sampled to quantify changes due to redd building. Grain size analyses were based on 100 kg bulk samples collected with a flow isolation chamber. A minimum of 12, *in-situ* hydraulic conductivity tests were also done over the field season at each site. In October, the hydraulic conductivity of three recently constructed artificial redds and three three-month-old artificial redds on both the Lac and Salmon Branches were also measured.

Figure 7 compares the fines content and hydraulic conductivity of riffles and redds on Lac and Salmon Branches. Riffle substrate contained significantly more fine sand and silt and had lower hydraulic conductivity than redd substrate ($p < 0.01$). On average 41% of the fine sediment under 2 mm was washed out of redds when they were built, which is consistent with the findings of Kondolf *et al.* (1993). Table I summarizes, for all four sites, *in-situ* hydraulic conductivity measured with the Mark VI standpipe and conductivity values inferred from grain size data. The *in-situ* measurements of hydraulic conductivity of the riffle substrate at the four sites ranged from 0.38 to 0.83 cm/s (Table I), which was slightly higher than the lower range of hydraulic conductivities quoted for gravels (0.1 cm/s; Freeze and Cherry, 1979) but not as low as some hydraulic conductivity values reported in other streams (Chapman (1988): 0.11 cm/s; Peterson (1978): 0.14–1.5 cm/s).

In contrast, the average measured hydraulic conductivity of artificially constructed redds was 3.0 cm/s (Table I), consistent with Chapman (1988) who found the hydraulic conductivity in Chinook salmon redds was 2.9 cm/s. The hydraulic conductivity of artificially constructed redds was the same as that of recently built Chinook salmon redds along the Columbia River, and greater than the hydraulic conductivity found in artificial redds created only with a shovel (Chapman, 1988). Clearly not all redds have the same hydraulic conductivity. For example, Gustafson-Greenwood and Moring (1991) found that the hydraulic conductivity of natural and artificial redds was 0.27 cm/s, an order of magnitude smaller than the hydraulic conductivity measured in the artificial redds created in this study.

TVM signals: installation transients and seasonal evolution

Intergravel velocities in redds were monitored with the TVM, calibrated with *in situ* heat trace velocity measurements. To better describe the performance limitations of this new sensor, the sensitivity of TVM signals to

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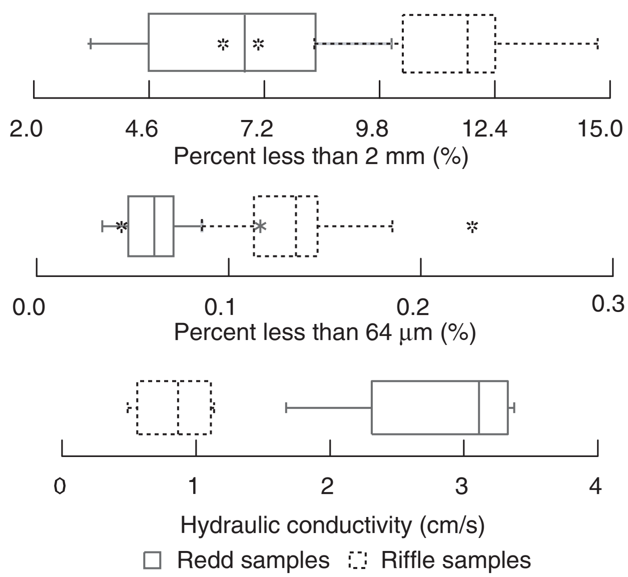

Figure 7. Box plots showing differences between fines content (total sand at top, silt fraction in middle) and between *in-situ* hydraulic conductivity (bottom) in redd and ambient riffle substrate at Lac and and Salmon Branch sites

disturbances of various sources are described next, based on the seasonal record in Figure 8. First, intergravel velocities inferred via TVM always markedly slowed within the first two to three weeks after TVM installation, whose timing is marked by squares in Figure 8. This apparently reflects a period of initial gravel settling (as discussed under Methods) after installation. Beyond these settling periods, Figure 8 also reveals six highly conspicuous peaks, highlighted by circles (periods marked by ovals will be discussed later). These peaks all correspond precisely with gravel disturbances that we triggered near the redds while trying to calibrate the velocity sensors, using (unsuccessful) salt dilution measurements. While attempting to get the dilution tests to work, 20-cm-deep holes were dug within the redds, 30–60 cm away from the TVM, to install a 2.5 cm PVC pipe as a dilution chamber. These peaks (Figure 8, circles), associated with clear human disturbance, confirm that the flow of water through redds was very sensitive to disturbance of the substrate within the redd zone, 30–60 cm away from the velocity sensor. Finally, Figure 8 also shows two main stable sections, highlighted by ovals, which will be used below for between-site comparisons of mean intergravel velocities over periods between storm events.

Table I. Hydraulic conductivity (K) of redd and riffle gravel at each study site

K (cm/s)	Formula*	Brandy Brook	Berry Mnt. Brook	Salmon Branch	Lac Branch
Riffle gravel					
Predicted (based on bulk/freeze-core samples)[a]	Hazen	0.25	0.95	0.23	0.11
	Slichter	0.55	2.1	0.52	0.53
Mean measured		0.38	0.67	0.47	0.83
Number of tests		12	20	33	18
Coefficient of Variation (%)		12	61	74	42
Redd gravel					
Predicted (based on adjusted bulk samples)[a]	Hazen			2.8	1.7
	Slichter			8.86	3
Mean measured ($n = 6$)				2.68	3.32
Coefficient of Variation (%)				93	63

*The hydraulic conductivity of redd and riffle gravel was estimated with the Hazen and Slichter formulas, which require porosity. Porosity was estimated based on V.S. Istomina's data (Vukovic and Soro, 1992).
[a] See Zimmerman *et al.* (in press) for more details.

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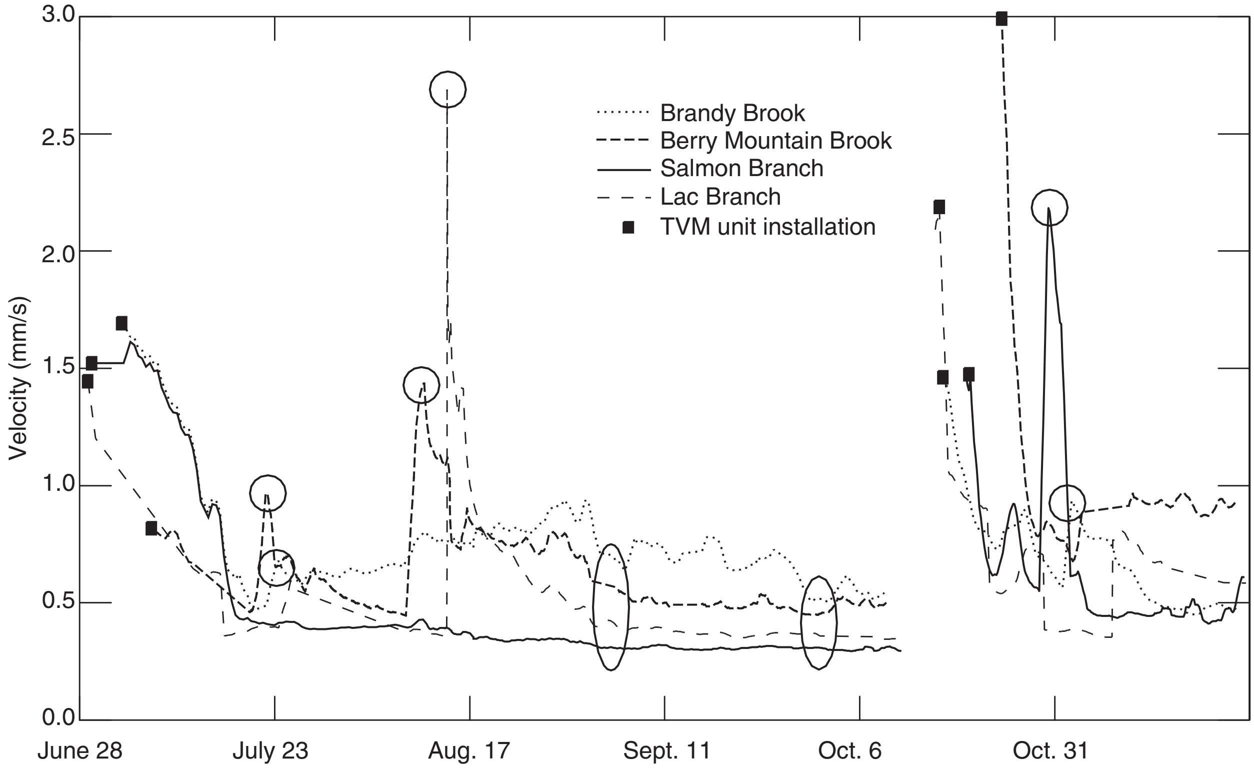

Figure 8. Intergravel flow records at all four redd sites over summer and autumn 2001. Solid squares denote times of TVM unit installation; circles and ovals are discussed in the text

Sediment transport events and effects on redd circulation

Intergravel flow, suspended sediment exposure and sediment deposition in collectors at the redds were monitored at all sites over the period June to November. During the five months of monitoring, six to ten freshets producing suspension events occurred per stream (a significant event was tallied at any given study site when suspended concentrations rose above a 3 mg/l background level; see Figure 3). In general, these events lasted one day. Based on the Water Survey of Canada historical gauge records, the largest events were approximately 50% smaller than the mean annual flood, while the smaller freshets were 10% of the mean annual flood. The flood frequency distribution was determined using a log-normal distribution and a 34-year record of annual peak flows on the Cascapédia River. The smallest events monitored occur on average 3.5 times per year while the largest events occur 1.4 times per year.

Although many of these events affected the four streams simultaneously, some rain events caused a suspension event in one stream but not in another. In total, 15 site-specific transport events were tallied. Based on painted pavement stones, none of these events was powerful enough to mobilize the coarser pavement fractions on the study riffles, i.e. to produce phase 2 sediment transport (*sensu* Jackson and Beschta, 1982). Relations among peak flow, suspended sediment and observed sand and fine gravel (phase 1) transport rates are subject to another paper (Zimmermann and Lapointe, in press).

TVM records reveal that intergravel flow was notably reduced in the 24–48 hour period immediately succeeding the five strongest transport events. Figure 9 illustrates the time traces of intergravel velocity and sediment suspension records for these five events. Note that for two of these events (Figure 9d and e), the storm event occurred within the first three weeks after redd creation and TVM installation and before the TVM output had stabilized. On these two occasions, velocities were already decelerating before the sediment-depositing events occurred, but the transport event is associated with a faster deceleration of intergravel flow. Detailed inspection of the TVM records detected no reduction in redd flow for the other ten site/event combinations.

Table II presents suspended sediment dose estimates and infiltration rates in bed collectors (for sediment under 2 mm) for all 15 runoff events monitored over the period 20 June to 15 November. These results illustrate that the

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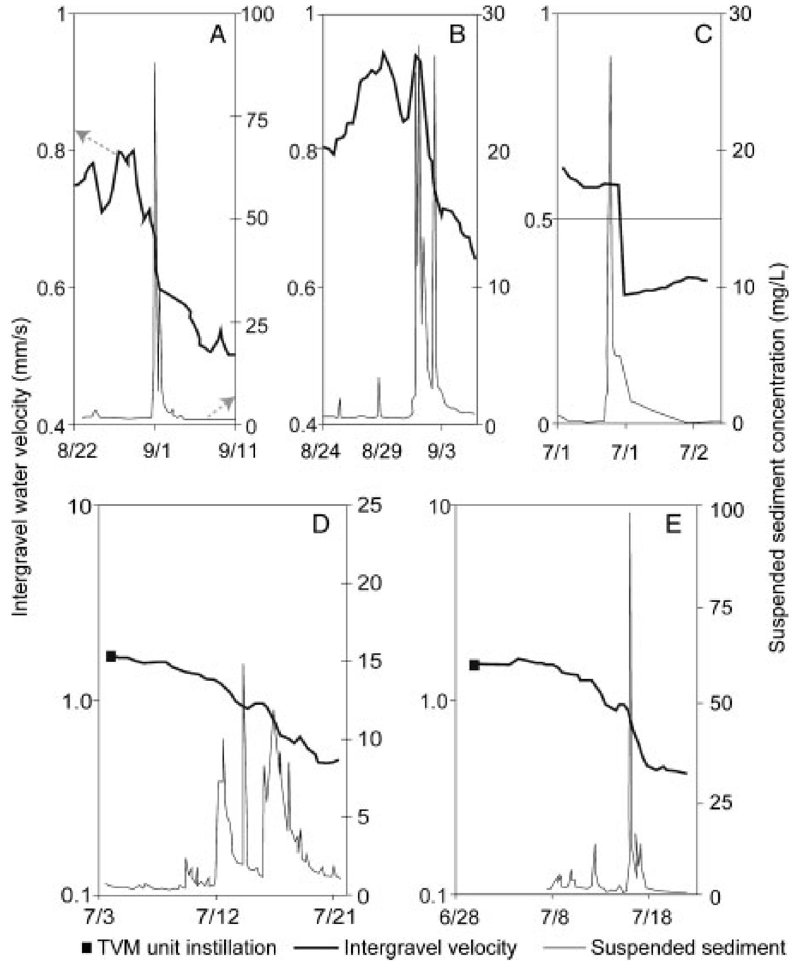

Figure 9. TVM records showing reductions in intergravel flow (thick lines) associated with significant suspended sediment events (thin lines): (A) Berry Mountain Brook; (B) Brandy Brook; (C) Lac Branch; (D) Brandy Brook; (E) Salmon Branch. Note that in (D) and (E) the velocity scales are log transformed and the suspension events occurred within the stabilization period soon after TVM installation

Table II. Relationship between observed velocity reductions, suspended sediment storm dose and sediment (<2 mm) deposited in collectors for all summer and storm events ($n = 15$)

Velocity change?	Sediment deposited (kg/m^2)	Suspended sediment (mg l^{-1} day^{-1})
No	0.3	2.30
No	0.64	3.02
No	1.2	6.80
No	1.57	0.37
No	2.1	1.85
No	2.4	6.53
No	3.14	13.4
No	N.A.	0.11
No	N.A.	1.09
No	N.A.	0.78
Yes	7.4	7.17
Yes	20.1	N.A.
Yes	23	24.2
Yes	28	153
Yes	38	7.4

NA, not available.

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occurrence of distinct TVM velocity reductions was dependent, as expected, on both the dose of the suspension events and the amount of fine sediments deposited in the collectors. Based on detailed TVM records from these 15 events, intergravel water velocities were reduced by 0.2–1 mm/s within one to two days after all five transport events causing over 7 kg/m^2 of sediment (<2 mm) deposition. Four of these five events deposited over 20 kg/m^2 of sediment in the collectors (Table II). In addition, on four of five occasions when the suspended sediment dose was larger than 7 mg l^{-1} day^{-1}, there was a clear velocity reduction. There was no obvious velocity reduction for the fifth event, which had a suspended sediment dose of 13.4 mg l^{-1} day^{-1} but a collector deposition rate of only 3 kg/m^2.

Predicting intergravel water velocities in artificial redds

Intergravel velocity and hydraulic head fields are complex and three-dimensional within riffles (Soulsby *et al.*, 2001), given the heterogeneity and geometry of substrate layers (with distinct geometries and hydraulic conductivities within redd zones, ambient riffle and underlying bedrock or non-alluvial layers). Notably, in this study the mean hydraulic conductivity of redds (K_1) is about six times larger than that of ambient riffle substrate (Table I). In the absence of the detailed information on subsurface layering needed to construct three-dimensional flow nets, we use velocities and hydraulic conductivities measured within redds to test inferences, in the context of Darcy's law, about the likely intensity and origin of the hydraulic gradients driving the observed interstitial flow. More precisely, we test whether redd-scale or riffle-scale interstitial circulations (as defined in Figure 1c and d) can explain the observed redd flow velocities. As discussed in the Introduction, the physical scale of the flow net of which the redd is part has potential implications with regards to the susceptibility of redd circulation and incubation habitat to storm disturbances.

Two stable, interstorm sections of the TVM record (ovals in Figure 8; early September and early October) were selected in order to compare intergravel water velocities between sites. In addition, during these periods, intergravel water velocities were directly measured using the heat trace technique. For each stream, the average TVM and heat trace velocities for these periods are presented in Table III (under 'Observed data'). Reported heat trace velocities are based on the average velocity measured with two to four separate hot water injections. The TVM velocities are based on the average velocity from six samples before and six samples after the heat trace sampling was completed.

The bottom part of Table III compares observed velocities to rough predictions of interstitial circulations at both scales. To generate the latter, the mean interstitial velocity through the redd at each site during the summer and autumn was predicted with Darcy's law (Equation 2), using alternately either the redd- or riffle-scale hydraulic gradients and mean substrate conductivities and finally assuming that mean interstitial velocity equals bulk velocity V divided by substrate porosity (taken here as 0.3 on average):

$$V = -K\Delta H/\Delta X \tag{2}$$

where ΔH is the head difference over streamwise distance ΔX, and K is the hydraulic conductivity of the substrate.

Table III. Comparing interstitial flow velocities through artificial redds with predicted velocities based on redd- and riffle-scale flow

Velocity (mm/s)	Brandy Brook	Berry Mnt. Brook	Salmon Branch	Lac Branch
Observed				
Sept. heat trace velocity	0.59 (±0.1)	0.35 (±0.04)	0.16 (±0.02)	0.15 (±0.03)
Oct. heat trace velocity	NA	0.36 (±0.06)	0.12 (±0.02)	0.12 (±0.03)
Sept. TVM velocity	0.70	0.55	0.30	0.34
Oct. TVM velocity	0.51	0.46	0.31	0.31
Average of all observed velocities	0.6	0.42	0.22	0.23
Predicted				
Redd scale	0.72	0.80	0.63	0.50
Riffle scale	0.12	0.20	0.11	0.10
Overall channel gradient (1/1000)	7.7	5.5	3.0	1.7
Basin area (km^2)	69	118	585	877

NA, not available.

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Table IV. Average water surface slopes at different scales

Slope (‰)	Brandy Brook	Berry Mnt. Brook	Salmon Branch	Lac Branch
Over redd	7.4	8.1	7.0	4.6
From redd to end of riffle	10	9.0	6.9	3.8
Number of samples	29	26	23	23

Since, irrespective of bar geometry, mean pressures within the water column are hydrostatic over any vertical in all but the steepest channels (Dingman, 1984), the mean hydraulic head at any point along the gravel surface is the same as the elevation of the water surface above this point. In the absence of vertical groundwater effluent seepage at our study sites, we further assume that vertical head gradients were essentially nil in the top 2–3 dm of gravel where salmon eggs incubate. In such conditions, within the few-decimetre redd layer below the gravel surface, the driving head gradient ($\Delta H/\Delta X$) in the downstream direction is equal to the local water surface slope above the bed. This approach in effect assumes that, at least within a thin, decimetre-scale layer below the gravel surface where redds are located, interstitial flow lines are to a good approximation parallel to the substrate surface and water surface. This assumption is essentially that the Dupuit–Forchheimer approximation applies to the flow net. This is considered a good approximation (Freeze and Cherry, 1979) in cases when the gradient of a free water surface is small (here less than 1%) and interstitial flow is essentially parallel to this water surface. Clearly this approximation becomes less valid the deeper one goes below the substrate surface, especially in the case of riffle-scale flow.

Water levels and water surface slopes at two spatial scales, over redds and riffles, were measured 20 to 30 times during the field season for each stream. These measurements are summarized in Table IV. To model redd-scale flow (Figure 1c), the local mean water surface slope over redds at each site was used in Darcy's law to specify the driving hydraulic gradient. The hydraulic conductivity of the substrate in redds (K_1, Table I) measured at the Lac and Salmon Branch sites in late September was also used for the Berry Mountain and Brandy Brook sites, since the grain size distribution of the sediment at all the sites was similar (Zimmermann *et al.*, in press). To predict potential intergravel water velocities for riffle-scale circulation (Figure 1d) the water surface slope between the water level pin upstream of the redd and the water level pin at the head of the next pool was used as the hydraulic gradient. Since the downstream extent (*c*. 2 m) of the cleaner redd zones at all sites represented only 3 to 13% of the entire length of the riffle, the conductivity of the riffle substrate (K_2; Figure 1c and Table I), which dominates this flow path, was used in combination with the riffle-scale gradient to predict potential riffle-scale flow velocity. Predicted velocities using Equation 2 may in part differ from the observed redd velocities because of the uncertainties associated with the water surface slope and hydraulic conductivity measurements.

Predictions in Table III suggest that, in the study conditions, the redd-scale circulation is potentially more powerful than the riffle-scale one. No clear conclusions concerning the flow paths dominant in redds can be made from these rough predictions of velocity magnitudes for each scenario. Predictions for both redd-scale and riffle-scale flow velocities effectively bracket observed values. Velocity predictions based on redd-scale flow were generally two to three times greater than velocities observed based on TVM and heat trace measurements, while predicted riffle-scale velocities were two to five times too small.

DISCUSSION

Effects of small freshets on intraredd flow

It is well know that moderate intensity rain–runoff events that fail to break up the cobble surface pavement can nonetheless trigger sand/granule (phase 1) bedload transport and suspension transport and, in turn, lead to fines infiltration into clean gravels. This is the first study, however, to directly observe *in situ* a sudden reduction of interstitial redd flow (Figure 9) associated with individual, high recurrence, moderate intensity runoff events. Although the calibration of the TVM sensor is very sensitive to local conditions, the strong association shown in Table II between cases of observed flow reduction and the transport intensity of individual events further supports the observed association between storm infiltration and redd flow data.

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It is difficult to generalize about the potential implications for salmonid embryo development of a sequence of moderate freshets such as observed in this study. These will depend on many other concurrent factors, such as water temperature, stage of embryo development and other oxygen demands, such as decomposing organic matter in the substrate. However, it is noteworthy that, despite the occurrence at each site of between six and ten phase 1 transport events over the period June to November, measured interstitial velocities in all redds remained almost an order of magnitude greater than the 0.01–0.05 mm/s threshold values for embryo survival reported by Wickett (1954) and Copper (1965). Furthermore, a mean of 80% survival to eyed stage was observed for artificially fertilized salmon embryo, installed in multiple egg capsules at all sites during the second phase of redd construction in late October 2001 and recovered five months later (Zimmerman, 2003). During their late autumn and the ice-covered incubation period, these eggs had undergone a few minor freshets, similar to those studied here, with no strong mortality. Note that these eggs were recovered in April 2002, well before fry emergence from substrate, at a time when water temperatures remained close to 0°C and metabolic demands remain low, and well before the June spring flood. These results suggest that, in these northeast American study systems, in which dominant channel-forming and sediment-transport events occur during the spring snowmelt season, the main geomorphic threat to reproductive success may be associated with this spring flood period, which occurs at a time of later embryonic development and before Atlantic salmon emergence. The spring freshet causes much more intense sediment scour and fill than the summer, autumn or winter events monitored in this study.

The importance of redd-scale versus riffle-scale circulation

In the Introduction, four distinct intergravel flow scales and mechanisms were outlined (pumping, redd, riffle and valley bottom). Based on the information summarized under Study area, there was no evidence of groundwater- or valley-bottom-scale flow occurring at any of the chosen sites and intergravel flow past salmon eggs was hypothesized to occur mainly in response to redd-scale or riffle-scale circulations.

The effect of pumping flow was ignored here since its contribution to intergravel flow has not been evaluated for conditions comparable to natural redds. Water surface slopes over redds in this study were an order of magnitude steeper (Table IV) than water surface slopes used in pumping flow research in laboratory flume experiments (e.g. 0.05%; Elliott and Brooks, 1997a). Thus, since water surface slopes drive redd- and riffle-scale flow, the contribution of these gradients to intergravel flow is expected to be larger for salmon redds than previously reported in the flume experiments that evaluated the pumping flow effect. Autumn freshets and small sediment-transport events may also obliterate the tailspin relief, further limiting the effect of the pumping flow mechanism at the time scale of full embryo incubation. At the study sites, a flood 45% smaller than the mean annual flood removed the tailspins of artificial redds. Wu (2000) also ignored pumping flow when he modelled the flow of water through a redd.

Of the two flow models examined using rough estimates in Table III, redd-scale intergranular circulation was potentially at least half an order of magnitude stronger (in terms of predicted velocities) than riffle-scale flow. Observed redd flow magnitudes were halfway between redd- and riffle-scale predictions, suggesting that, within prediction errors, either mechanism might have the potential to drive the observed flow. Redd-scale flow appears, however, to best explain the observed susceptibility to redd disturbance of intergravel water velocities at the study sites. The observations of sudden changes in redd flow, associated with sediment-depositing events (Figure 9 and Table II), as well as other flow responses associated with our disturbances to substrate very near redds (Figure 8, circles), would not be expected to occur if intergravel velocities were controlled by riffle-scale flow, since such disturbances would only affect a minor fraction of the most permeable substrate in a much longer riffle-scale flow path.

This conclusion is also supported by thermal data. Riffle-scale flow enters at the tail of the upstream pool and seeps out at the head of the next pool. Riffle-scale interstitial flow paths are, by definition, much longer than redd-scale ones and should cause diurnal temperature fluctuations in redd interstitial water to be dampened (e.g. Story *et al.*, 2003). At the study sites, where riffle flow paths were measured in tens of metres, no significant differences were observed between the daily amplitude of the water temperatures recorded in the redd gravels compared to the 5–15°C amplitudes recorded in overlying water. This lack of thermal damping of interstitial redd flow in such small streams with open canopies again suggests that significant riffle-scale flow does not dominate circulation in study redds. The flow path of water through redds has not been observed, however, with tracers in this study. Thus, it cannot be definitively confirmed that redd-scale circulation drives intergravel flow through redds.

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CONCLUSION

Our observations suggest that, at least where significant groundwater seepage is absent, intergravel flow in redds may reflect substrate conductivity and head gradients at the scale of the redd zone itself, rather than that of the entire riffle; furthermore, within high silt load riffle substrate, salmonid spawners may, by cleaning off 2–3 m long redd patches, ensure sufficient flow around egg pockets for egg development, at least in the short term. However, moderate intensity freshets producing appreciable fines transport and infiltration triggered detectable, but relatively benign reductions in intergravel water velocities in artificial redds (Figure 9). This directly confirms that the magnitude and frequency of sediment-transporting events that occur when eggs are incubating can be critically important for egg survival. Unfortunately, no data on intergravel flow or embryo development could be collected during the geomorphically dominant spring melt event.

Previous research on Gaspé streams confirms a statistical association between the probability of riffle use by spawners in autumn and fine sediment content of ambient (unspawned) riffle substrate measured at summer low flows (Coulombe-Pontbriand and Lapointe, 2004). The mechanisms underpinning these associations can be complex. Results presented here suggest that ambient substrate fines content may not in the short term directly control reproductive success, because of the effect of redd construction on enhancing circulation in new redds. Rather, ambient fines levels at the reach scale may be a general, longer-term indicator of overall fines transport levels during freshets and, consequently, of the potential for cumulative redd infiltration before the end of the embryo incubation and fry emergence periods.

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