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The importance of temporal changes in gravel-stored fine sediment on habitat conditions in a salmon spawning stream.

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Abstract Sediment (<2 mm and <75 μm) was collected in a productive sockeye spawning stream in northern British Columbia, Canada, using infiltration gravel bags from the pre-spawn through to the post-spawning period of 2002. As much of the gravel-stored fine sediment (<75 μm) exists as larger, aggregated particles composed of inorganic and organic matter, their quantity, structure, composition and settling behaviour were assessed. The goal was to evaluate the temporal changes in the gravel-stored fine sediment in the context of: (a) fish activity (i.e. active spawning and die-off) and (b) inter-gravel oxygen concentrations which reflect the habitat quality. Infiltration rates of <2 mm sediment increased with stream discharge and fish redd construction. The finer (<75 μm) sediment exhibited lower infiltration rates during the peak of fish spawning activity indicating successful reduction of this sediment fraction. Inter-gravel oxygen concentration decreased 18% over the period of active spawning and salmon die-off, but recovery occurred later. Aggregate particle size and density changes were explained by the physical action of spawning fish and the inter-gravel microbial activity associated with increased high quality organic matter (fish decay products) which reduced inter-gravel oxygen concentrations.

Key words aggregates; dissolved oxygen; fine sediment; flocculation; gravel beds; organic matter; redds; salmon habitat

INTRODUCTION

The deleterious accumulation of sediment in fish spawning gravels is most often estimated using only the inorganic portion of the sediment and generally reported for relatively large size fractions (i.e. <2 mm) which have been noted to block gravel pore spaces (Chapman, 1988; Lisle, 1989; Soulsby *et al.*, 2001). The importance of the organic content and type has been overlooked until recently when Petticrew & Arocena (2003) suggested that the presence of salmonid detrital material was responsible for changes in gravel-stored sediment structure and composition in a northern British Columbian stream. In the same stream McConnachie & Petticrew (2006) found that the organic composition and size structure of suspended sediments changed over the summer as organic source materials varied from detrital terrestrial through to salmonid inputs. In a controlled laboratory study, Arkinstall (2005) identified that dissolved organic carbon from salmonid decay generated larger and faster settling flocs than headwater stream and algal-based carbon sources. The

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implication of these results is that both the quantity and quality of the organic matter present in a stream play a significant role in the generation, transfer and storage of aggregated sediment in stream systems. While the total mass of gravel-stored organic material may be small relative to the <2-mm inorganic fraction, it has the potential to decrease the quality of the inter-gravel habitat as these organic-laden sediments are mineralized by aerobic bacteria which use oxygen required for the incubating fish eggs. The objective of this work was to evaluate the temporal changes in the gravel-stored fine sediment in the context of: (a) fish activity (spawning and die-off) and (b) inter-gravel oxygen concentrations which reflect the habitat quality.

METHODS

Study site

O'Ne-eil Creek is located in the Hogem Range of the Omenica Mountains in the central interior of northern British Columbia, Canada. This tributary of the larger Fraser River basin has highly productive sockeye salmon (*Oncorhynchus nerka*) returns which have been enumerated annually at a fish fence near the stream mouth by the Canadian Department of Fisheries and Oceans (DFO) since the 1950s. The lower 2 km of the streambed is composed of clean gravels suitable, and used, for salmon redd construction. The 500-m pool and riffle study reach, located 1000–1500 m upstream of the mouth had independent fish counts taken on each date that infiltration bags were collected. DFO also monitors discharge in a number of Takla area streams and local precipitation.

Gravel-stored <2 mm sediment

Fourteen gravel-filled infiltration bags were installed on 9 July 2002 to measure sediments <2 mm accumulating in two riffles within the study reach of O'Ne-eil Creek. Infiltration bags, modified from the design of Lisle & Eads (1991), were placed in the bottom of a 0.25-m hole and covered with the displaced gravels following cleaning through a 2-mm sieve. The bags were retrieved over a 57-day period to determine the mass of sediment <2 mm accumulating in the inter-gravel spaces. On each of the seven retrieval dates, two bags were removed to represent: (a) the pre-spawn period before the fish return to the river (17 and 24 July); (b) the early-spawn (2 August); (c) mid-spawn (9 August); (d) two dates during the major fish die-off (15 and 21 August); and (e) a sample when there was no visual evidence of live or dead carcasses in the stream, termed post-fish (5 September). Upon retrieval, a lid was placed over the channel bed and the bag pulled up through the gravels, ensuring a minimal loss of fine sediment. As 13 of the bag retrievals were successful, gravimetric results for all but the first date are duplicated. The gravels collected in the bags were washed through a 2-mm sieve and all of the infiltrated sediment was collected in a calibrated bucket. After sub-sampling in the field for aggregated fine particles, this material was returned to the laboratory, dried and weighed.

Gravel-stored aggregated sediment

Each sample bucket containing <2 mm sediment was gently resuspended and, after 10 s, two 250-ml sub-samples representing material which settled slower than sands were collected from the top 5 cm. These were later analysed for sediment concentration, organic matter content, effective particle size distribution (EPSD) and settling velocity. This sub-sampling technique allows the incorporation of larger flocculated particles or aggregates of mineral and organic matter which may be larger but less dense than sand grains >63 µm. Particle size analysis of the constituent inorganics comprising sub-samples collected in this manner indicate no particles >75 µm are left in suspension; therefore, all observed particles exceeding this size are aggregates or organic debris (Petticrew *et al.*, 2006).

Inorganic and organic concentrations were determined gravimetrically following filtration and ashing at 550°C. For comparative purposes, each bag's mass of <75 µm sediment was normalized to 10 kg which was the maximum mass of gravel contained in the infiltration bags. Effective particle size distributions of the population of aggregated sediment were obtained using a settling box combined with a digital video camera. Details of the set-up are provided in McConnachie & Petticrew (2006). Aggregated sediment was introduced into the settling chamber, which was filled with particle-free water of known temperature. After a period of several minutes, during which fluid turbulence decayed, a series of video images was collected. The size, shape and position of particles were determined in two sequential images using Empix's Northern Eclipse image analysis software, allowing estimates of settling velocity and calculations of particle density. Size statistics were determined for each aggregate population, which comprised in excess of 590 measured particles.

Gravel dissolved oxygen

During the spawn and post-spawn periods a dissolved oxygen probe (Point Four Systems, Model 420, accuracy +2%) was buried in the riffle gravels in a stainless steel tube, which was sealed off to surface air but had openings along the shaft to allow inter-gravel water to pass through it. The probe, which had a wiper system to ensure adequate water flow over the sensor, recorded temperature and dissolved oxygen concentrations at a depth of ~0. 25 m at 15-min intervals.

RESULTS

Infiltration rates of <2 mm sediment

Net infiltration rates for pre-spawn through to post-spawn periods are shown along with the daily discharge and the cumulative daily fish returns to O'Ne-eil Creek (Fig. 1). In 2002 a total of 2353 sockeye returned to the stream between 30 July and 16 August. Infiltration rates of sediment <2 mm nearly doubled between early (2 August) and peak (9 August) spawning dates with values of 18.0 and 35.5 g day^{-1}, respectively. Values fell significantly, to ~12 g day^{-1}, for the two later sample dates in August, but rose

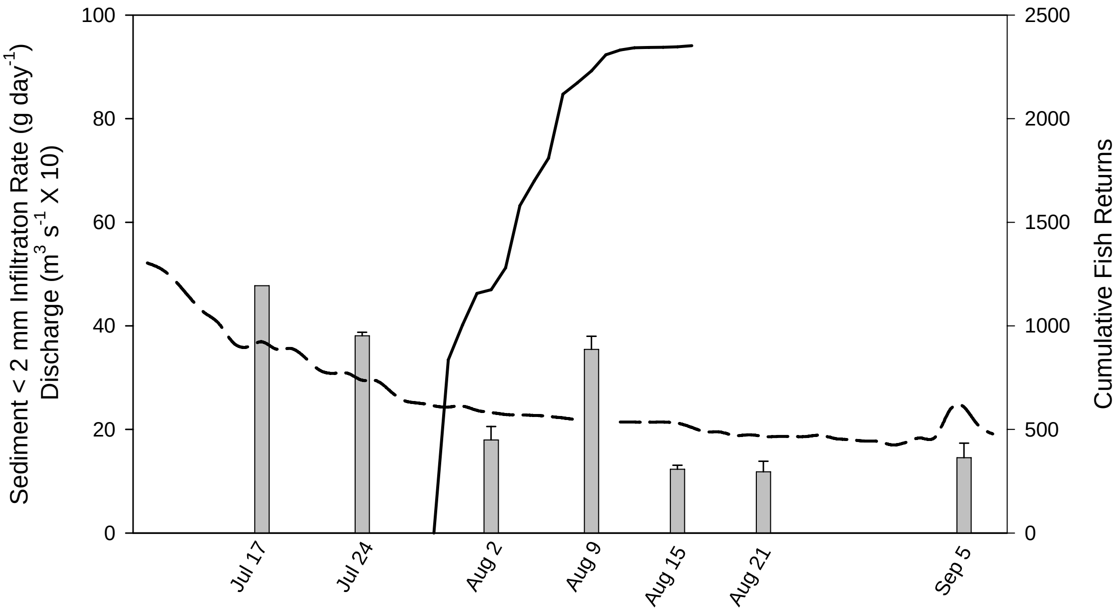

Fig. 1 Infiltration rates of <2 mm sediment for the sample period in 2002. Cumulative counts of fish returns to O'Ne-eil Creek are shown as a solid line, while stream discharge (× 10) is represented by a dashed line. One standard error is plotted with infiltration rates.

slightly to 14.5 g day^{-1} in the 5 September post-fish sample which was preceded by a rainstorm event. Pre-spawn infiltration rates for <2 mm sediment in July were high, as were streamflows comprising the falling limb of the mid-June peak snowmelt discharge.

Gravel-stored sediment < 75 µm

Normalized infiltration rates calculated for the finer sediment fraction are presented for both the inorganic and organic portion of <75 µm sediment (Fig. 2, Table 1). Seventy-two percent (n = 13) of the variance in mass of organic matter is explained by the mass of the inorganic component of the infiltrated fine sediments indicating a relatively consistent ratio of the two components over the sample period. Maximum infiltration rates occur on 2 August when 176 live fish were observed within the sample reach. Significantly lower infiltration rates were observed in the die-off and post-spawn period following 21 August. Note that on 9 August, the peak spawning period, when 294 live fish were observed in the sample reach, the infiltration rate was lower than the week before (early-spawn) and the week following (late-spawn and die-off).

The predicted density of an aggregated 500 µm particle for each sample population is also shown in Fig. 2. These values are calculated from their observed settling velocity. The aggregates increase in density up to early-spawn but decrease at peak-spawn. The gravel-stored aggregates increase in density again towards the end of the season, when spawning activity has stopped but die-off and carcass decay prevails. Note the increased density of particles and infiltration of fines at early-spawn, the reduction of both density and infiltration rates during peak spawn and a later increase in density when very little mass of new material was added to the sediments after 21 August.

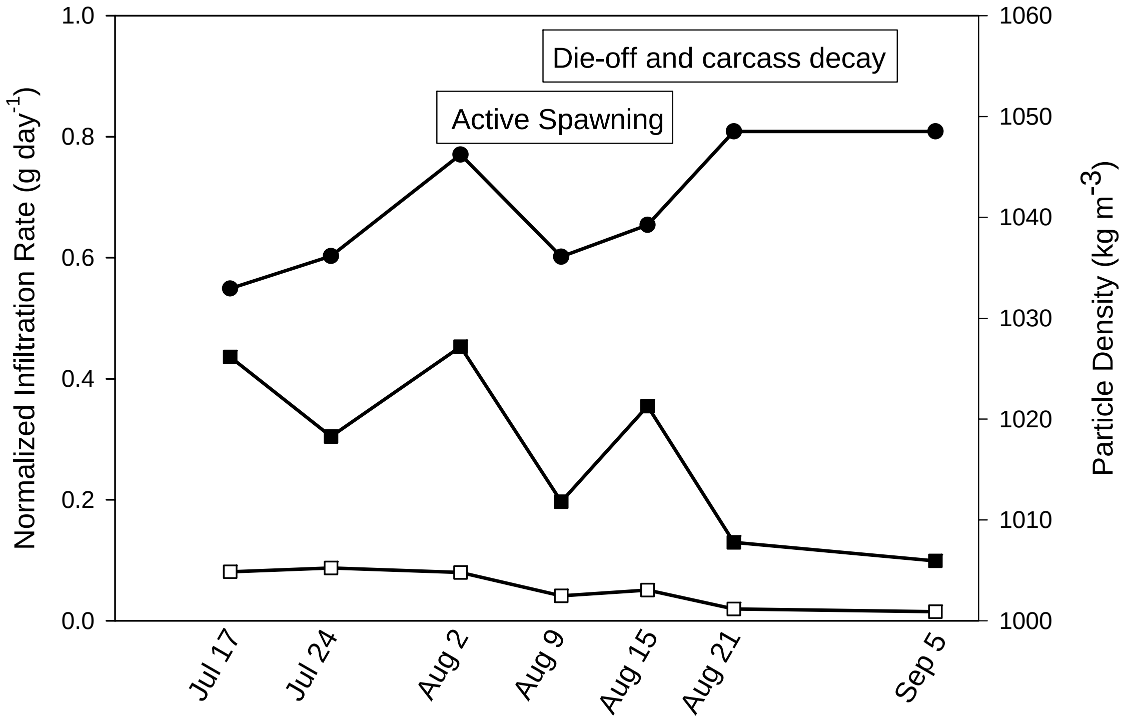

Fig. 2 Infiltration rates of <75 µm inorganic (filled squares) and organic sediment (open squares) shown with calculated particle densities of a 500 µm aggregate (circles). The timing of fish spawning, die-off and decay is shown to overlap.

Table 1 Results of <75 µm sediment collected in infiltration bags in spawning reach. Infiltration rates are normalized to a 10 kg total weight and include both organic and inorganic sediment.

Date (2002)	Days after bag installation	Event type	No. fish in sample reach	Infiltration rate (g day^{-1})	500 µm particle settling velocity (cm s^{-1})	500 µm particle density (kg m^{-3})	% aggregate pop'n <500 µm	D_{50} of aggregate pop'n
17 July	8	Pre-spawn	0	0.518	2.27	1032.95	75.2	386
24 July	15	Pre-spawn	0	0.392	2.67	1036.17	82.5	336
2 August	24	Early spawn	176	0.533	3.76	1046.22	91.6	274
9 August	31	Peak-spawn and die-off	294	0.238	2.80	1036.10	96.4	241
15 August	37	Late-spawn and die-off	110	0.406	3.04	1039.24	91.6	272
21 August	43	Die-off	14	0.149	3.53	1048.52	95.6	251
5 Sept	57	Post-fish	0	0.114	3.85	1048.52	94.6	251

Cumulative particle size curves were plotted for the aggregate populations obtained via image analysis. The two largest-grained samples were for the pre-spawning dates (17 and 24 July), while the finest grained populations were observed at peak spawn and die-off (9 and 21 August) when <75 µm infiltration rates were also low. To allow comparison to Fig. 2, the proportion of aggregates <500 µm in each of these populations was determined (Table 1). During pre-spawn this size range increased from 75 to 83%; on 2 August (early-spawn) it increased to 92%, while at peak-spawn on 9 August, 96% of the aggregate population was finer than 500 µm. The same pattern was exhibited in the D_{50} values of these aggregate populations (Table 1).

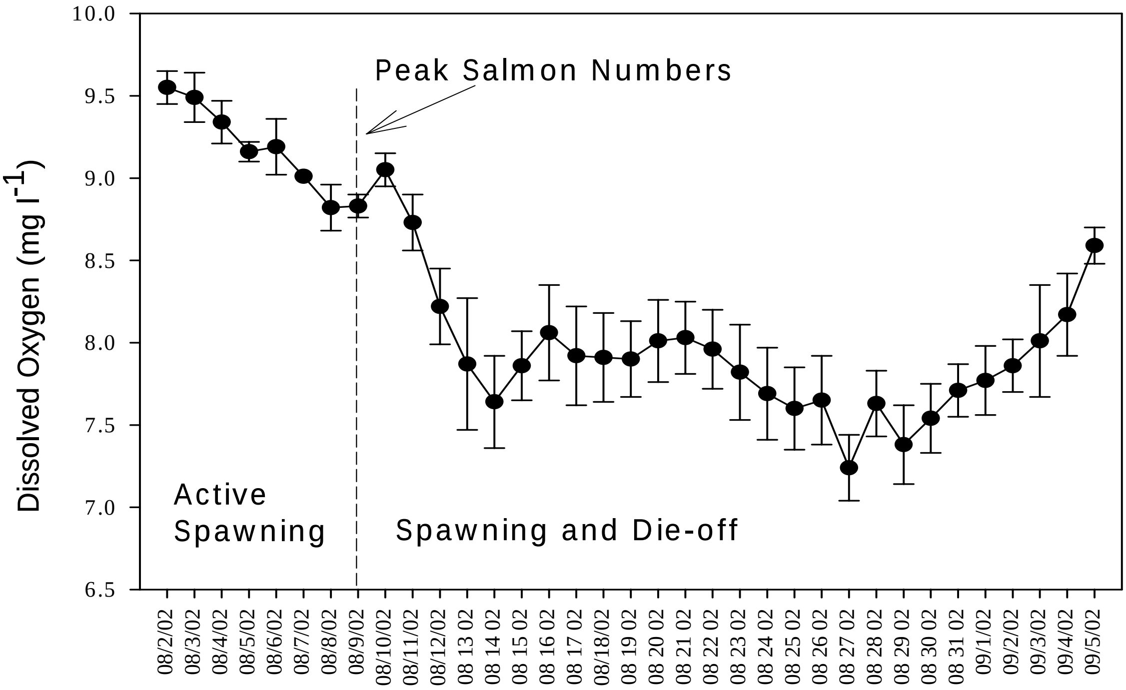

Fig. 3 Temperature-corrected, inter-gravel oxygen concentrations in O'Ne-eil Creek in 2002. One standard deviation is shown around daily average values.

Gravel dissolved oxygen

Dissolved oxygen concentrations (Fig. 3) decreased 18% from ~9.5 to 7.5 mg L^{-1} from early spawn (2 August) through to late spawn (14 August). The concentrations fluctuated between 7.5 and 8.0 mg L^{-1} during late spawn and die-off, while a trend of increasing oxygen began on 29 August when the creek approached the fish-free period.

DISCUSSION

Infiltration rates of <2 mm sediment

The infiltration of <2 mm sediment into the riffle gravels shows a relationship that clearly relates to both the river discharge and the activity of returning sockeye. The infiltration sample bags were installed at a discharge of 4.95 $m^3 s^{-1}$, which decreased to 2.55 $m^3 s^{-1}$ by 27 July. The higher early discharges combined with fresh reference gravels explain the elevated pre-spawn infiltration rates. Note that equipment failure from 27 July to 10 August resulted in discharge data for O'Ne-eil Creek being generated from stage values correlated to records from an adjacent stream (r^2 = 0.98). Both sites experienced equipment failure on 9 and 10 August, although no precipitation was recorded during this data gap. Therefore the doubling of infiltration rates from early to peak-spawn can be explained by the reworking of the gravels by the 294 fish active in the sample reach. The cleaning of gravels for redds, resuspends the sands (Chapman, 1988) and aggregated fines (Petticrew, 2006) into the flow for transport short distances downstream. During the week of 2–9 August, when the greatest intensity of gravel cleaning occurred, the <2 mm sediments would have been very mobile, as reflected by the increased mass in the infiltration bags. Low infiltration rates during the less active periods of late-spawn and die-off are associated with low flows of ~2.00 $m^3 s^{-1}$. The small increase in the infiltration rate of 5 September, when fish are no longer present in the stream, indicated the significance of local rain events in moving material of this size.

Gravel-stored fine sediment and habitat conditions

While infiltration rates of <2 mm sediments were high at the peak of spawn, the incorporation of <75 µm material was low. The fining of the gravel-stored population at peak-spawn indicates larger aggregates are broken apart by the digging action, reducing their size and density (Table 1). At these low flows the resuspended sands settle quickly in a short distance while the smaller aggregates, being less dense, are moved downstream resulting in increased local infiltration of <2 mm sediment and decreased local infiltration of <75 µm sediment.

The fifteenth of August represents a mixed period of spawning and die-off as not all of the 110 fish observed in the reach would be actively preparing redds. Given the timing of their return to the stream, about half of these fish would have finished reproducing and, in a physiologically depleted state, would have been guarding their redds for several days as they senesced towards death. The peak die-off period is followed by carcass decay when a massive amount of salmonid breakdown products enter the stream. Johnston *et al.* (2004) observed a flush of soluble nutrients and a concomitant increase in algae following die-off in several other local streams. In O'Ne-eil Creek in 2001, McConnachie & Petticrew (2006) determined that salmonid nutrients (^{13}C and ^{15}N) in the suspended sediment increased from ~10 to 33 to 46% during pre-spawn, active-spawn and post-spawn, respectively, clearly showing the incorporation of carcass breakdown products. The active spawning before and on 15 August will have broken down and resuspended aggregates in the water column that had begun to receive salmonid organic matter. These conditions combined with low flows enhance the production and settling of flocs (Leppard & Droppo, 2005). This process can explain the observed increase in infiltration rate of fine sediment and the modest coarsening of the gravel-stored aggregate population observed on 15 August (Table 1).

The 18% drop in oxygen concentration measured in O'Ne-eil Creek in 2002 is not problematic for the incubation of eggs in this undisturbed river system, but these natural fluctuations correlate well with the observed changes in the composition and structure of the gravel-stored fine sediment. The most extreme reduction in oxygen occurred between 10 and 14 August (Fig. 3), when fine sediment infiltration rates and aggregate density increased (Fig. 2, Table 1). The depletion of inter-gravel oxygen by bacteria mineralizing organic matter at this time would render the resultant aggregates denser, as noted in Table 1. Oxygen levels remained low between 14 and 27 August, when infiltration of new sediment mass was low, but presumably enriched with available salmonid breakdown products. The density of the particles continued to increase as the organics were processed by bacteria. Restoration of higher inter-gravel oxygen concentrations began on 28 August, when the bulk of salmonid breakdown products had entered the stream to be transported away, taken up by primary producers or stored in the gravels.

CONCLUSIONS

Temporal changes in the size, density, settling velocity and infiltration rate of gravel-stored fine sediment was found to relate to the physical activity of salmon preparing their redds, as well as to the change in the quantity and type of organic matter being delivered to the stream during the fish die-off. Oxygen concentrations, which are a good indicator of habitat quality for egg survival, responded significantly to changes in sediment input, although, in this case, the decreases were not critical for incubating eggs. Implications of increased settling and storage of organic-rich sediment are further reductions of inter-gravel oxygen, potentially to critical levels. Therefore the timing and amount of inorganic fine sediment entering the stream should be managed such that minimal <75 μm particles are suspended during the die-back when abundant organic matter enhances flocculation, settling and gravel storage of aggregated organic-rich aggregates.

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