11 The Physical and Biological Influence of Spawning Fish on Fine Sediment Transport and Storage

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Introduction

The successful migration of Pacific salmon stocks back to their natal streams for spawning has long been known to be of economic importance, but only more recently has it been documented as being ecologically significant due to the contributions of organic nutrients to the aquatic ecosystem (Wipfli *et al*., 1998; Gende *et al*., 2002; Johnston *et al*., 2004). The return of adult Pacific salmon to their spawning streams results in a transfer of oceanic biomass and nutrients to these freshwater systems. This semelparous species invests all their reproductive energy in this one season to dig a nest (redd) to deposit and fertilize their eggs after which they die, in the vicinity of their redd. While there is a nutrient contribution of excretion products from live fish and the decaying of dead eggs and sperm, the most significant contribution is from the decomposition of the fish carcasses (Johnston *et al*., 2004).

In building a redd the fish rework the gravel bed streams to a depth of approximately 30 cm. In this process the finer sediments stored in the gravel matrices (e.g. Soulsby *et al*., 2001) are resuspended into the flowing water and moved downstream (Chapman, 1988). The gravel stored sediment which is available to be released to the water column during redd building has been observed to be a combination of both sand and sand-sized aggregates comprised of silts, clays and organic matter (Petticrew, 1996). The settling rate of some of these larger aggregates is similar to that of fine sands (Petticrew and Droppo, 2000), indicating that the fine sediment (silts and clays) and the organic matter constituting the aggregates are not directly advected out of the system as hydrodynamic models would predict for these constituent grain sizes.

Terrestrial nutrients delivered from the watershed spiral down through the aquatic system (Vannote *et al*., 1980; Webster and Meyers, 1997), but it is not clear what portion of the nutrients delivered from salmon carcass decay are retained in the system and for what length of time. Algae, periphyton and benthic insects as well as sediment-associated nutrients are potential retention pools within the stream system. While natural stream and mesocosm investigations of the effect of salmon nutrients on primary productivity and insects have been undertaken (Ritchie *et al*., 1975; Schuldt and Hershey, 1995; Wipfli *et al*., 1998), the retention by sediment has not been assessed directly.

Salmon die-off in productive spawning streams has been documented as contributing in excess of 250 g C/m^2 (Johnston *et al*., 2004). These salmon carcass nutrients are readily bioavailable, as much of the decay process occurs within the stream. These nutrients drive instream bacterial activity, which has been linked to the development of sediment flocs and aggregates (Droppo, 2001; Leppard and Droppo, 2005). Therefore, as a means of clarifying if these nutrients have the potential to be retained in the stream, it is of interest to determine the magnitude of the suspended and gravel stored sediment compartments and if they contain salmon nutrients.

Stable isotope analysis (SIA) of nutrients (C and N) was adopted by ecologists as a method of tracing the flux of materials through food webs (Peterson and Fry, 1987). More recently it has been valuably employed to track fluxes through aquatic systems (Bilby *et al*., 1996; France, 1997; Bouillon *et al*., 2000). SIA has been used to characterize estuarine seston (Cifuentes *et al*., 1998; Bouillon *et al*., 2000), but its ability to distinguish organic source materials in freshwater stream suspended sediment has only recently been utilized (McConnachie, 2003; McConnachie and Petticrew, in press). The ratios of carbon isotopes ($^{13}C/^{12}C$) are usually very distinct between terrestrial sources and adult salmon, allowing the differentiation of source material of two potentially important pools of organic matter supply to stream sediments (McConnachie, 2003).

Some of the world's largest salmon stocks return to streams of the Pacific northwest, where the ecological effects of high numbers of semelparous fish on the flux of nutrients to the terrestrial and freshwater ecosystems have been investigated (Naiman *et al*., 2002). However, the impact of the physical act of spawning and the die-back of the carcasses on the flux of inorganic sediment from watersheds has not been addressed in an ecological or geomorphic context. In order to assess the physical and biological effect of spawning salmon on fine sediment transport and storage, two objectives were identified, to determine: (i) if the digging of salmon redds modifies the transport and storage of fine sediments; and (ii) if salmonid nutrients are associated with the transported and stored fine sediment.

Study Area and Methods

The three study creeks, O'Ne-eil, Gluskie and Forfar, have small watersheds (36–75 km^2) located in the Stuart-Takla experimental forest in the central interior of northern British Columbia. These mountain tributaries of the larger Fraser River basin have highly productive sockeye salmon (*Oncorhynchus nerka*) returns which have been enumerated annually by the Canadian Department of Fisheries and Oceans since the 1950s. The streams are located in the Hogem Range of the Omenica Mountains, and have mouths at 700 m above sea level (m asl) and drainage divides at approximately 1980 m asl. The channels are all approximately 20 km in length and are straight with coarse bed and bank textures (Macdonald *et al*., 1992). Each system has a steep upper reach which drains well developed cirques, a steeper middle reach that passes through a rock-walled canyon and a gentle, low gradient depositional reach (Ryder, 1995). In the lower 2 km of the streams the channel bed is comprised of clean gravels suitable for salmon redd construction. These spawning reaches are underlain by glaciolacustrine sediments and the only anthropogenic disturbance at the time of sampling consisted of a gravel road, constructed in 1980, that cuts through this fine-grained material. This work is part of the larger Stuart-Takla Fish–Forestry Interaction Project (MacIsaac, 2003).

Sampling took place in the creeks during 1995, 1996, 1997, 1998 and 2001. Active spawn, salmon die-off, spring melt and summer storms were sampled in the first 4 years respectively, while the 2001 sample period incorporated all of these hydrological and biological events of interest.

Suspended sediment analyses

Suspended sediment was collected and filtered for a range of analyses as well as photographed directly in the water column or in a settling column. Filtered sediment was used for estimates of suspended particulate matter (SPM), absolute particle size distribution (APSD) and isotopic carbon analysis. Photographic images were used to determine the effective particle size distribution (EPSD).

For determination of SPM, water samples were collected in the thalweg, just below the water surface, in large-mouthed 1-l bottles. The water was filtered through pre-combusted and pre-weighed 47 mm diameter, 0.7 μm pore size glass-fibre filters for gravimetric determination of suspended particulate matter. Water was collected in the same manner for APSD, but was returned to the laboratory and filtered through pre-weighed 8 μm SCWP Millipore cellulose-acetate filters. The weighed, dried filters were burned in a low-temperature asher (< 60°C) and wet digested with an excess of 35% H_2O_2 before analysis on a Coulter Counter (Milligan and Kranck, 1991). A Coulter Multisizer IIE was used to determine the inorganic, disaggregated or absolute particle size distribution (APSD). Results are expressed as a volume/volume concentration in ppm and are plotted as smoothed histograms of log concentration versus log diameter (Milligan and Kranck, 1991). Surface grab samples of water and suspended sediment were filtered through pre-ashed glass-fibre filters, freeze-dried and analysed for ^{12}C and ^{13}C by stable isotope mass spectrometry at the University of British Columbia, Oceanographic Stable Isotope Laboratory (see below).

Suspended sediment sizing

During the active spawn sampling in 1995 an underwater silhouette camera was used to photograph the particles as they moved in the water column. The camera was moved to various locations in the creek over the sampling period to collect images representing the background, or ambient, suspended sediment as well as the direct effect of fish digging their redds. Photographs were taken every 5 s of the volume of water (7.4 cm diameter by 4 cm thickness) passing through the camera aperture and grab samples of the water photographed were collected behind the camera aperture for APSD analyses. *In situ* or effective particle size distributions (EPSD), from the photographic negatives of the silhouette camera, were obtained by image analysis using Jandel Scientific's MOCHA program. The equivalent spherical diameters of the detected particles were counted and grouped into size classes which correspond to the same intervals as the Coulter Counter. The Multisizer has a lower detection limit of 0.63 μm and an upper detection limit of 1200 μm, while the silhouette camera has a lower detection limit of approximately 100 μm.

Effective particle size distributions of larger populations of suspended sediment were obtained using a rectangular plexiglass settling box ($1.5 \times 0.14 \times 0.06$ m) with two removable end caps, which held approximately 13 l of water. A scale, mounted on the outside back wall of the settling chamber using white adhesive paper, aided in photographing and sizing particles. The settling chamber was aligned into the stream flow such that water and suspended sediment passed through it. When a sample was required the ends were capped and the box carried in a horizontal position to the side of the creek, where it was placed vertically on to a stable platform 20–30 cm in front of a 35 mm single lens reflex (SLR) camera mounted on a tripod. After a period of several minutes, during which fluid turbulence decayed, a series of timed photographs were taken. Pairs of sequential images were then projected on to a large surface and examined to identify individual flocs. The particle size, shape and position in the two images were determined using image analysis packages (Mocha and/or Bioquant). Population means and other size statistics were derived from these data.

In the spring of 1997 the same settling chamber was used to collect suspended sediment samples from the snowmelt flood events in O'Ne-eil Creek. Due to the high overbank flows at this time, the box was lowered and returned to the bridge platform using a winch system. The box was filled and capped by persons standing in the stream. The photographic system employed in the field at this time was a video capture system. A black and white digital camera (a charged-coupled device – CCD), with a resolution of 512×512 pixels, was connected to a personal computer running Empix Imaging's NORTHERN EXPOSURE software. This field setup allowed an automated image grabbing system, which recorded the current time (accurate to 10^{-2} s) on each image. The resultant images had individual pixel resolution of 55 μm ± 10 μm. The images were then analysed using a custom-developed (Biickert, 1999) settling rate measurement program.

In 2001 a procedural change occurred mid-June, where the analog CCD was replaced by a Retiga 1300 digital CCD (resolution 1280×1024 pixels). At the same time the software was upgraded to Empix's NORTHERN ECLIPSE. These two changes were not found to bias the particle image collection. Dimensions (e.g. diameter, area, perimeter and shape) of 500–1500 particles for each sample date were measured and recorded using the NORTHERN ECLIPSE package with a detection minimum of 42 µm. D_{50} particle sizes were determined from linear interpolation of cumulative per cent volume data for both EPSD and APSD. While the lower resolution of particle diameters using these techniques was regulated by the pixilation, the upper limit was defined by the field of view of the cameras, which given the distance from the settling chamber allowed a photographic image of a particle with a long axis in excess of 10,000 µm.

Gravel stored fine sediment

As a means of characterizing the size and composition of the gravel stored sediments during the salmon die-off period in 1996, a resuspension technique was used that aimed to rework the surface gravels with approximately the same energy expended by spawning salmon. Photographs, water grab samples and settling column images were obtained following physical mixing of the top layer (0.04–0.06 m) of gravels by a field assistant, positioned 4–5 m upstream of the collection site. This distance provided sufficient travel time for the resettling of heavier sand particles, thereby allowing the collected material to comprise the aggregated and non-aggregated fine sediment stored within the surface gravel matrix. This material is referred to here as resuspended gravel stored fines.

Infiltration bags were used to collect gravel stored fine sediments over the summer season of 2001. On 13 July, prior to the return of the spawning fish, 12 infiltration gravel bags were installed in two riffles approximately 1500 m upstream of the mouth of O'Ne-eil Creek. Gravels were removed to dig a hole approximately 25 cm in depth and cleaned through a 2 mm sieve. Infiltration bags, modified from the design of Lisle and Eads (1991), consisting of a watertight sack with a maximum volume of 10,000 cm^3 clamped on to a 20 cm diameter iron ring, were used to collect gravel stored sediment. The bag was folded down on itself at the bottom of the hole, while straps attached to the ring were placed along the sides of the hole and left at the gravel–water interface. The cleaned gravel, all > 2 mm, was placed on top of the folded bag, filling the hole, and left for a known period of time to accumulate fine sediments in the intergravel spaces. The bag traps were retrieved over a 71-day period following installation. The six retrieval dates represent: (i) the period before the fish return to the river to spawn (17 July); (ii) the early spawn (28 July); (iii) mid spawn (3 August); (iv) two dates during the major fish die-off (12 August and 16 August); and (v) a sample when there was no visual evidence of live or dead carcasses in the stream, termed post fish (22 September). Upon retrieval a lid was placed over the surface gravels between the emergent straps and pulled up, moving the iron ring and the bag up through the gravels ensuring a minimal loss of fine sediment. The gravels and water collected in the bags were washed through a 2 mm sieve such that all of the infiltrated sediment was collected in a calibrated bucket. This material was returned to the laboratory, dried, disaggregated in a mortar and sized using sieves of 1180, 500, 150 and 63 µm.

Stable isotopes

Suspended sediment collected in the three streams during: (i) the post spawning period of 1996; (ii) the spring melt discharges of 1997; and (iii) five summer storms in 1998 were used for analyses of isotopic carbon. The carbon isotope ratio of suspended sediment filters and potential source materials were measured and expressed relative to conventional standards as δ values defined as:

$$\delta X\,(‰) = (R_{sa} / R_{std} - 1) \times 1000$$

where X is ^{13}C determined as parts per thousand (‰), R_{sa} is the isotopic ratio of the sample ($^{13}C/^{12}C$), and R_{std} is the isotopic ratio of the standard (PeeDee Belemnite for carbon). The source materials represented terrestrial vegetation, salmon and free-floating algae. Multiple tissue samples from riparian vegetation comprising spruce needles, willow, alder and birch leaves, algae and salmon tissue were collected and stored in 1.2 ml centrifuge tubes and subsequently freeze-dried. Isotopes of carbon as well as the δ values of each were determined and reported in McConnachie (2003). This technique enables assessment of organic matter sources in

Table 11.1. Stuart-Takla Creek sampling schedule. Conditions and variables for 5 sample years.

Year	Stream	Date	Event type	Conditions sampled	Cumulative fish return	SPM (mg/l)	Figure number
1995	O'Ne-eil	1–8 Aug	Active spawn	Ambient average	20,648–26,456	14.12	na
1995	O'Ne-eil	8 Aug	Active spawn	Fish digging	26,456	241.07	Fig. 11.1
1995	O'Ne-eil	8 Aug	Active spawn	Post digging	26,456	24.81	Fig. 11.1
1996	O'Ne-eil	26 Aug	Die-off	Ambient	10,772	0.93	Fig. 11.4
1996	O'Ne-eil	26 Aug	Die-off	Resuspended gravel stored fines	10,772	7.22	Fig. 11.4
1996	Forfar	26 Aug	Die-off	Ambient	9,076	0.41	Fig. 11.4
1996	Forfar	26 Aug	Die-off	Resuspended gravel stored fines	9,076	15.45	Fig. 11.4
1997	O'Ne-eil	28 May	Spring melt rising limb	Ambient	0	8.38	Fig. 11.4
1997	O'Ne-eil	30 May	Spring melt rising limb	Ambient	0	6.79	Fig. 11.4
1997	O'Ne-eil	1 Jun	Spring melt rising limb	Ambient	0	8.70	Fig. 11.4
1997	Forfar	29 May	Spring melt rising limb	Ambient	0	3.92	Figs 11.4 and 11.6
1997	Forfar	1 Jun	Spring melt rising limb	Ambient	0	1.58	Figs 11.4 and 11.6
1997	Gluskie	29 May	Spring melt rising limb	Ambient	0	3.57	Fig. 11.4
1997	Gluskie	1 Jun	Spring melt rising limb	Ambient	0	1.57	Fig. 11.4
1998	Forfar	14 Jun	Summer rain storm	Ambient	0	3.08	Figs 11.4 and 11.5
1998	Forfar	18 Jun	Summer rain storm	Ambient	0	3.85	Figs 11.4 and 11.5
1998	Forfar	21 Jul	Summer rain storm	Ambient	0	0.32	Figs 11.4 and 11.5
1998	Forfar	8 Aug	Summer rain storm	Ambient	770	0.47	Figs 11.4 and 11.5

1998	Forfar	16 Aug	Summer rain storm	Ambient	956	0.29	Figs 11.4 and 11.5
1998	O'Ne-eil	14 Jun	Summer rain storm	Ambient	0	1.97	Fig. 11.4
1998	O'Ne-eil	18 Jun	Summer rain storm	Ambient	0	1.17	Fig. 11.4
1998	O'Ne-eil	21 Jul	Summer rain storm	Ambient	2	0.80	Fig. 11.4
1998	O'Ne-eil	8 Aug	Summer rain storm	Ambient	2,020	3.38	Fig. 11.4
1998	O'Ne-eil	16 Aug	Summer rain storm	Ambient	2,268	0.46	Fig. 11.4
1998	Gluskie	14 Jun	Summer rain storm	Ambient	0	0.51	Fig. 11.4
1998	Gluskie	18 Jun	Summer rain storm	Ambient	0	2.47	Fig. 11.4
1998	Gluskie	21 Jul	Summer rain storm	Ambient	0	0.17	Fig. 11.4
1998	Gluskie	8 Aug	Summer rain storm	Ambient	749	1.35	Fig. 11.4
1998	Gluskie	16 Aug	Summer rain storm	Ambient	812	4.26	Fig. 11.4
2001	O'Ne-eil	24 May–21 Aug	All event types	Ambient	0–13,893	0.87–18.09	Fig. 11.3A
2001	O'Ne-eil	17 Jul	Pre fish arrival	Gravel stored fines	0	na	Fig. 11.3B
2001	O'Ne-eil	28 Jul	Early spawn	Gravel stored fines	8,211	na	Fig. 11.3B
2001	O'Ne-eil	3 Aug	Mid spawn	Gravel stored fines	10,931	na	Fig. 11.3B
2001	O'Ne-eil	12 Aug	Die-off	Gravel stored fines	13,757	na	Fig. 11.3B
2001	O'Ne-eil	16 Aug	Die-off	Gravel stored fines	13,892	na	Fig. 11.3B
2001	O'Ne-eil	22 Sept	Post fish	Gravel stored fines	13,893	na	Fig. 11.3B

the suspended sediment at different times of the year by comparing isotopic ratios from source material contributed to the stream to those in suspended sediment samples.

Physical measurements

Stream flows were determined using a Swoffer current meter at the time of sample collection, while discharge on the three streams was monitored and calibrated over the open water season for each year by the Canadian Department of Fisheries and Oceans.

Results

Suspended sediment

Four hydrologically or biologically important periods, which comprised spring melt, summer rain storms, active spawning and fish die-off, were sampled for suspended sediment in the Stuart-Takla streams. Table 11.1 displays surface water concentrations of suspended sediment sampled during each of these event types over the 5 sample years. Measurements taken during the 1995 active spawn in the immediate vicinity of digging fish exhibit the highest suspended sediment concentrations (241 and 25 mg/l). The absolute and effective particle size distributions of these two fish-suspended sediment samples are shown in Fig. 11.1. The EPSD spectra were determined from analysis of the Benthos underwater camera images (triangles), while the APSD was measured using a Coulter Counter (circles). The solid symbols represent samples taken 0.5 m downstream of a fish digging its redd, while the open symbols represent samples collected approximately 4 m further downstream. The mode and maximum of the APSD in the immediate vicinity of fish digging are 294 and 512 μm, representing medium sands, while the EPSD of the same volume of suspended sediment has a mode and maximum of 588 and 1024 μm. Given that the EPSD comprises a large number of particles greater than the maximum size of the constituent particles (APSD), it is clear that the physical action of digging fish resuspends aggregated fines as well as sands. Images from the Benthos camera just preceding, during and following the sampled fish resuspension are shown in Fig. 11.2. Comparing the image on the right to the central one indicates an abrupt change in sediment concentration due to the fish digging, while the image on the left demonstrates the rate at which the water clears. The spectra for fish-suspended sediment sampled 4 m downstream of redd construction has modes of 169 μm for the EPSD and 16 μm for the APSD. Note that all of the aggregates moving in the water column at this time are smaller than 400 μm and are comprised of inorganic sediment less than 85 μm, indicating the loss, by settling, of the sands and larger aggregates.

The average suspended sediment concentration observed in O'Ne-eil Creek during the 1995 active spawn was 14 mg/l. This value does not include samples such as those mentioned above that directly tracked the plumes of fish-resuspended sediment, but rather represents the ambient water conditions in reaches of this stream, where by 8 August up to 24,000 salmon had returned to spawn. This ambient average suspended sediment concentration is higher than 1997 spring melt concentrations of 7–9 mg/l (Table 11.1) but less than the maximum of 18 mg/l observed in spring melt of 2001 (Fig. 11.3A). Note in 2001 the significant ($P < 0.05$) elevation of suspended sediment concentrations during the active spawn when compared to the pre spawn lower flow concentrations. These ambient average values ($n = 3$) are taken over 5 days following the midpoint of the fish returns (Fig. 11.3C) reflecting large numbers of active spawners in this reach.

Size characteristics of the suspended sediment populations from spring melt, active spawn and fish die-off are shown in Table 11.2. These results were obtained from image analysis of particles in the settling column and in all but 1996 represent the ambient or background conditions at that time. Aggregates moving during spring melt are smaller than those of active spawn, while the largest particles are observed in the sediment resuspended from on and within the gravels during salmon die-off in 1996.

Gravel stored fine sediment

Figure 11.3B shows the amount of sediment infiltration into the gravel bed before, during

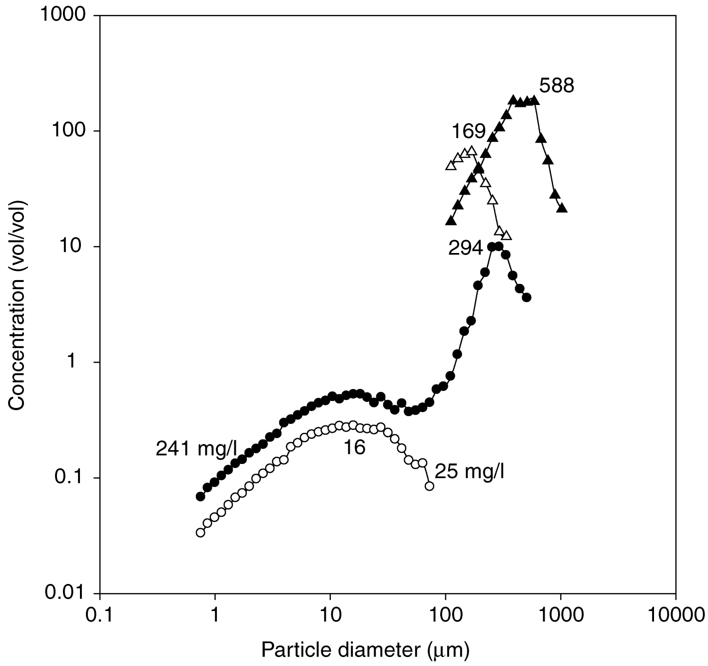

Fig. 11.1. Particle size spectra for sediment resuspended by a redd-digging fish (solid symbols) and 4 m downstream (open symbols). The circles represent the disaggregated inorganic component of the suspended sediment (APSD), while the triangles represent the *in situ* or effective particle size distribution (EPSD). The suspended sediment concentrations of the APSD samples are noted (mg/l) along with the mode size of each sediment spectra (µm).

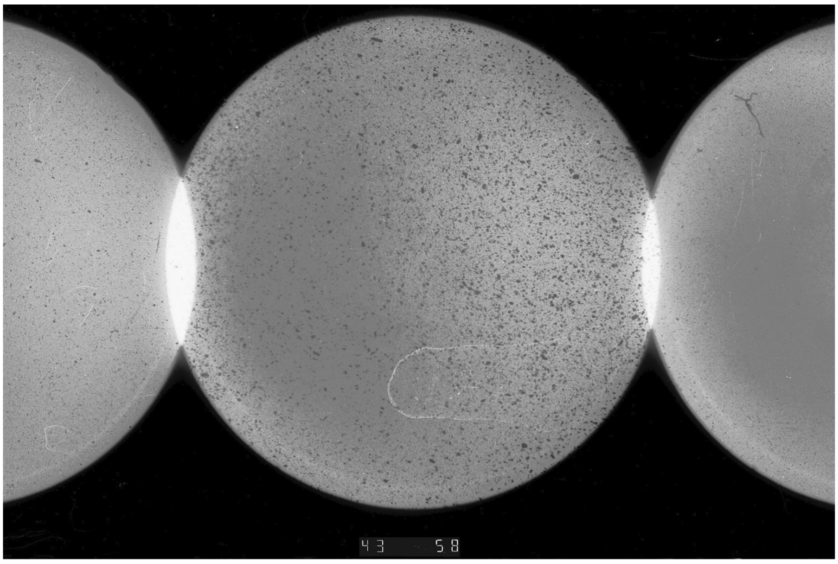

Fig. 11.2. Silhouette images of suspended sediment taken in sequence from right to left at intervals of 5 s. A fish digging its redd resuspended sands, aggregates and fine sediment 0.5 m in front of the Benthos camera in the central image. Ambient water column conditions are represented in the right image, while clearing rates of the water column can be assessed in the left image. The diameter of each image is 7.4 cm.

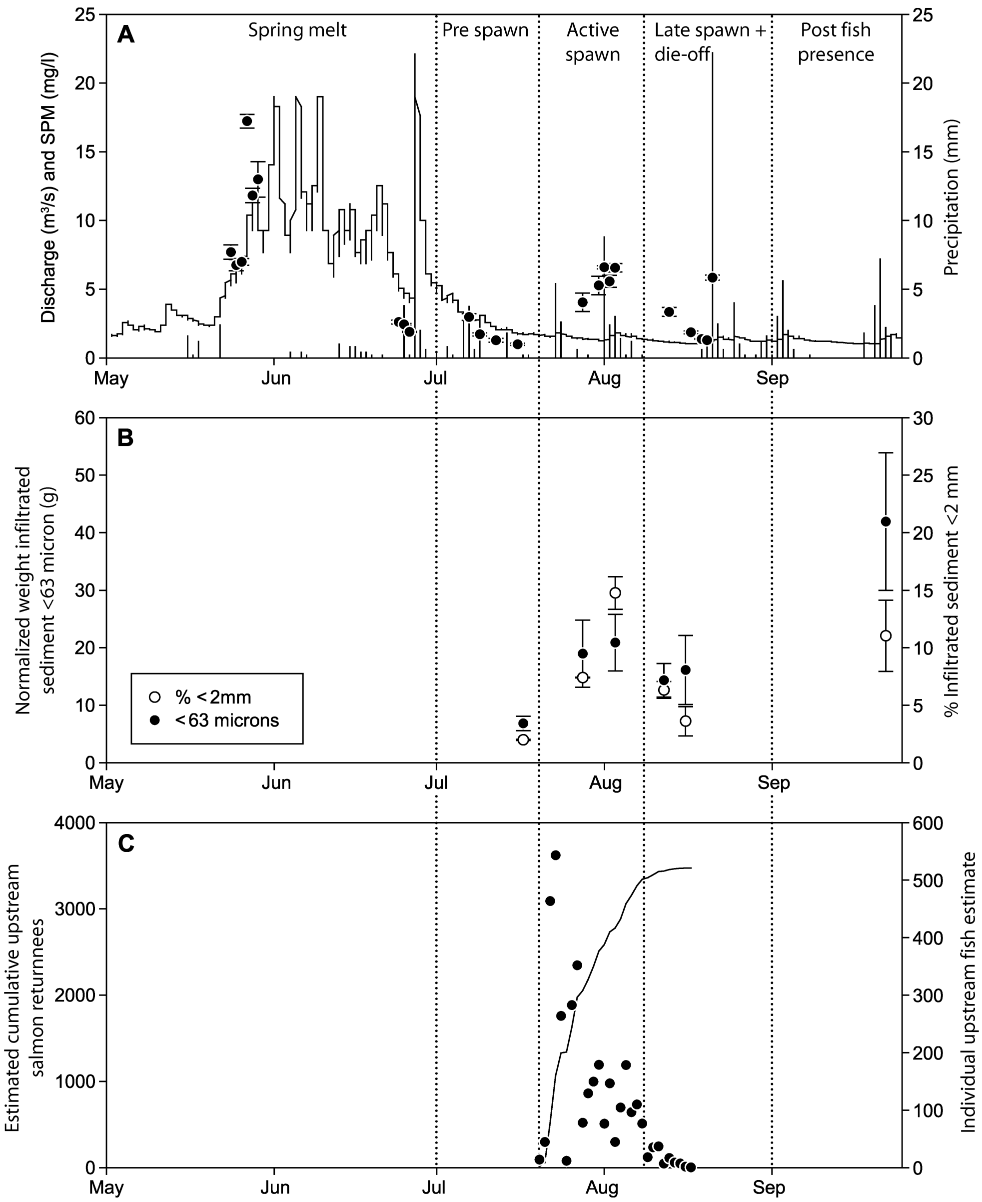

Fig. 11.3. (A) Discharge, precipitation and suspended sediment in O'Ne-eil Creek for periods of spring melt, pre spawning, active spawn and salmon die-off. (B) Weight of fine sediment infiltration into gravels in an active spawning reach and the proportion of material < 2 mm accumulated in the gravels before and following fish presence in the stream. (C) The estimated number of sockeye salmon entering the upstream spawning reach on a daily basis (circles) and the cumulative numbers (line) for the full 2001 spawning season. All error bars represent ±1 standard error (SE).

and following the salmon spawn of 2001. The temporal pattern is similar for both the per cent less than 2 mm and the normalized weight of sediment less than 63 µm. Increases are associated with the period of active spawning, when more than 50% of the returnees to the section of the river upstream of the sample reach are present (Fig. 11.3C). These gravels which had been

Table 11.2. Population particle sizes associated with event type.

Year*	Event	Sample type	Mean diameter and SE (μm)	D_{50} and SE (μm)	Maximum diameter (μm)	Maximum D_{99} (μm)
1997	Spring melt rising limb	Ambient	276 (6.5)		712	
1995	Active spawn	Ambient	514 (58.2)		1,162	
1996	Die-off	Resuspended	897 (107.8)		1,828	
2001	Spring melt rising limb	Ambient		369 (49.4)		894
2001	Active spawn	Ambient		697 (208.5)		2,033
2001	Die-off	Ambient		294 (42.5)		881

*Events are shown in seasonal order not chronological order.

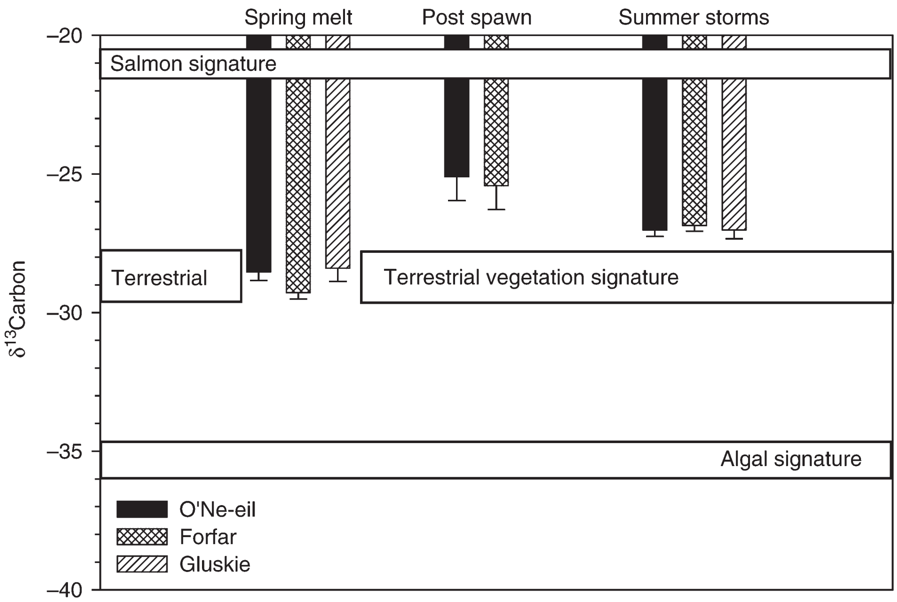

Fig. 11.4. Isotopic carbon results (± 1 SE) for the Takla streams in three periods of hydrologic or biologic interest. The isotopic signatures for the expected organic source material are also shown.

cleaned of sediment < 2 mm, before installation, collected 15% by weight of sediment smaller than this size after a period of 21 days, while up to 20 g of this was < 63 μm. Removal after 71 days indicated the final bags had on average 40 g of silt- and clay-sized particles (< 63 μm).

Stable isotopes

The isotopic carbon content of the suspended sediment was compared to the isotopic signatures for the dominant organic source materials to the creeks (Fig. 11.4). Samples from the 1997 spring melt exhibit values which fall directly within the terrestrial vegetation signature, while post spawn samples of 1996 are significantly different ($P < 0.05$) and are closer to the salmon tissue signature, indicating a dilution of terrestrial organic matter in the samples. Averages of the five summer storms sampled in the three creeks in 1998 reflect a mixture of materials which is due in part to the temporal spacing of the storms. When individual storms are viewed, for example on Forfar Creek (Fig. 11.5), a more interesting pattern emerges, although only single samples are taken for each storm event,

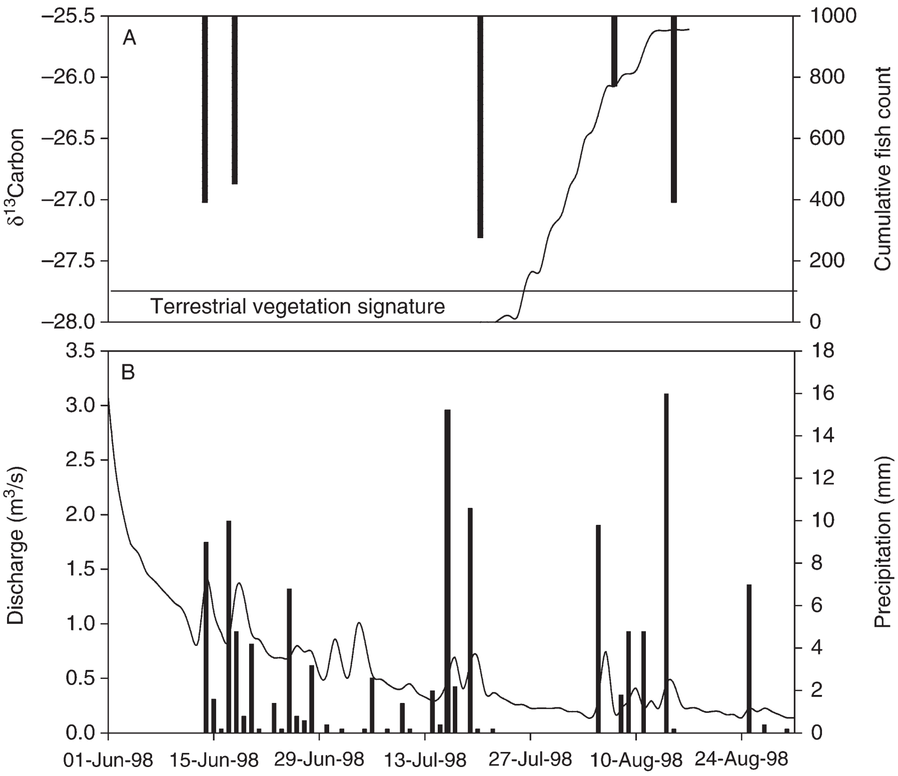

Fig. 11.5. (A) Carbon isotope results of suspended sediment collected for five storms sampled before and during the spawning season in Forfar Creek. Cumulative counts for the 1998 fish return indicate the timing and magnitude of the salmon biomass in the stream. (B) The hydrograph and daily precipitation for 1998 indicate the timing and the stream response of the summer rain events.

thereby restricting statistical comparison. The three storms preceding the return of the fish have values closer to the terrestrial signature, while a sample following a rain storm in the midst of the salmon spawn has a value closer to the salmon tissue signature, indicating the inclusion of fish-based organic matter in the suspended sediment. At the end of spawn the largest summer storm, with 16 mm of rain, has a suspended sediment carbon value that reflects an increased contribution of terrestrial materials.

Both the suspended sediment and the resuspended gravel stored fines were analysed for isotopic carbon at three locations in Forfar Creek in the die-off period of 1996. The upper reaches of stream (1700 and 1500 m from the mouth) exhibit values further away from the salmon tissue signature than the samples taken near the mouth (100 m). It is interesting to note that the isotopic values for the suspended sediment and gravel stored sediment at each site are not appreciably different. In this example, again only single filters were analysed for each $\delta^{13}C$ datum, so statistical tests for significance are not possible.

Discussion

Physical influences of salmon

The return of sockeye salmon to their natal streams for spawning results in the digging of a single redd for each salmon pair. The redds are dug to a depth of 25–30 cm, but tend to be much wider due to the subsidence of the gravels, therefore the volume of gravels moved to prepare a single redd can be in the order of 0.03–0.05 m^3. Given the numbers of salmon returning to these streams (approximately 13,000 pairs in 1995), in some years all of the viable gravel bed sites in the lower 2 km of the stream are reworked once, and sometimes more often, over the 3–4 week spawning period. The preparation of the redd results in the short term resuspension of sands and aggregated fines and presumably a longer term resuspension of less dense aggregates and disaggregated silts and clays. Ambient suspended sediment concentrations in these streams were elevated during the active spawning period in both 1995 and 2001, years that had comparatively high fish returns. It is useful to note that the concentration of suspended sediments reported here for spring melt and summer storms are relatively low compared to other streams, reflecting the fact that these mountain creeks are very clean with few anthropogenic disturbances, but also that the samples were surface grabs and not depth integrated samples.

The direct effect of digging fish was documented in 1995 with the images from the Benthos camera. It is clear that sands up to 500 μm in diameter as well as large aggregated particles exceeding 1000 μm are removed from the gravels and introduced into the water column by fish (Fig. 11.1). Comparison of the sample taken 4 m downstream of the digging fish to the sample in the vicinity of the redd indicates that the sands and larger aggregates settle out of the water column in this short distance but that smaller, less dense aggregates are still maintained in suspension.

In papers by Petticrew and Droppo (2000) and Petticrew (2005), the size, settling velocities and densities of the particle populations from these same 1996 artificially resuspended gravel stored fines from Forfar and O'Ne-eil Creeks are presented. The sediment collected 4–5 m downstream of these disturbances comprises two distinct populations of particles: (i) larger, less dense flocs; and (ii) smaller, denser compact aggregates. The settling velocities of a 400 μm floc and compact particle were determined to be 2.4 and 5.5 mm/s respectively. In low flows of 0.2–0.3 m/s, observed during post spawning periods, these particles could be maintained in suspension and advected downstream to the lake for settling. However, in shallow (< 0.25 m) turbulent flows the probability that the particles will make contact with the gravel surface or penetrate into the gravel matrix is high, increasing the likelihood of their instream storage.

The sediment stored on or in the gravels was observed to exhibit the largest particle sizes (Table 11.2), although the ambient active spawn populations in both 1995 and 2001 also had means and maximum sized particles appreciably larger than spring melt and ambient die-off suspended sediments. Given the extensive, continuous digging of the gravels in the spawning period, these larger sizes likely reflect the recently released gravel stored flocs and aggregates which take longer to settle.

Petticrew and Arocena (2003) reported on the size and density of the population of gravel stored aggregate particles (sands had been removed) collected in the infiltration bags discussed in this paper. The median size of the stored aggregates was smallest (244 ± 89 μm) at mid-spawn and exhibited a mean settling velocity of 2.5 mm/s. These particles would be available for resuspension in the water column by fish digging, and due to their density would settle more slowly, thereby increasing the ambient concentration of suspended particles. The larger aggregates from this population of gravel stored sediment would presumably settle back to the gravels in near-field distances (4–5 m) along with the sands. This assumption is supported by the results shown in Fig. 11.1 and in the artificial resuspension exercises of 1996 (reported here and in Petticrew and Droppo, 2000). The data showing that the proportion of sediment < 2 mm, and the mass of fine sediment (< 63 μm) collected in the infiltration bags (Fig. 11.3B) both increase during the active spawning period further corroborates this assumption. The final infiltration bags removed in late September had the highest mass of silt- and clay-sized particles, indicating a continued accumulation of fine sediments in the gravels during the period of salmon egg incubation.

While the observation that spawning salmon temporarily alter the suspended sediment concentrations in their natal streams is not surprising, what is of consequence is that much of the material they clean from their redds is being redeposited in short distances downstream. Silts and clays combined with organic matter as aggregated compact particles are settling out of the water column in the near-field, along with the sands resuspended by digging fish. This transfer of particles back to the gravels implies that both the inorganic sediment and the nutrients associated with the organic matter component of aggregates are being retained in the channel bed at least during the low flow period associated with salmon egg incubation. Presumably these sediments will be flushed out of the system during the high flows of spring melt floods.

Biological influences

Stable isotope analysis of carbon in these stream systems was used as a means of differentiating the source of organic material that contributes to the suspended and gravel stored sediment. The carbon signatures for the source materials of salmon tissue, terrestrial vegetation and instream algae for this region have been reported in McConnachie (2003) and Figs 11.4 and 11.6. As their $\delta^{13}C$ signatures are significantly different, they can be used to evaluate the contribution of the different sources to the organic component of the sediment. The results of this preliminary $\delta^{13}C$ work on suspended and gravel stored sediment indicate that stable isotope analysis is a viable technique to use for differentiating the presence of these organic matter sources in stream sediments. By sampling suspended sediment at several times (Figs 11.4 and 11.5) and locations within the streams (Fig. 11.6), the temporal and spatial influence of the salmon die-off on stream sediment organic matter composition has been determined.

The comparison of suspended sediment from three event types (Fig. 11.4) indicates a shift away from dominantly terrestrial sources in spring melt rising limb samples to a mixture of salmonid and terrestrial sources in a post spawn period. Intuitively this makes sense and is corroborated by Johnston *et al.*'s (2004) modelling of nutrient budgets in Gluskie and Forfar Creeks in 1996, 1997 and 1998. They determined that salmon were the dominant particulate organic carbon source to the streams from late July through October, in all years except 1998 when the fish returns were very low.

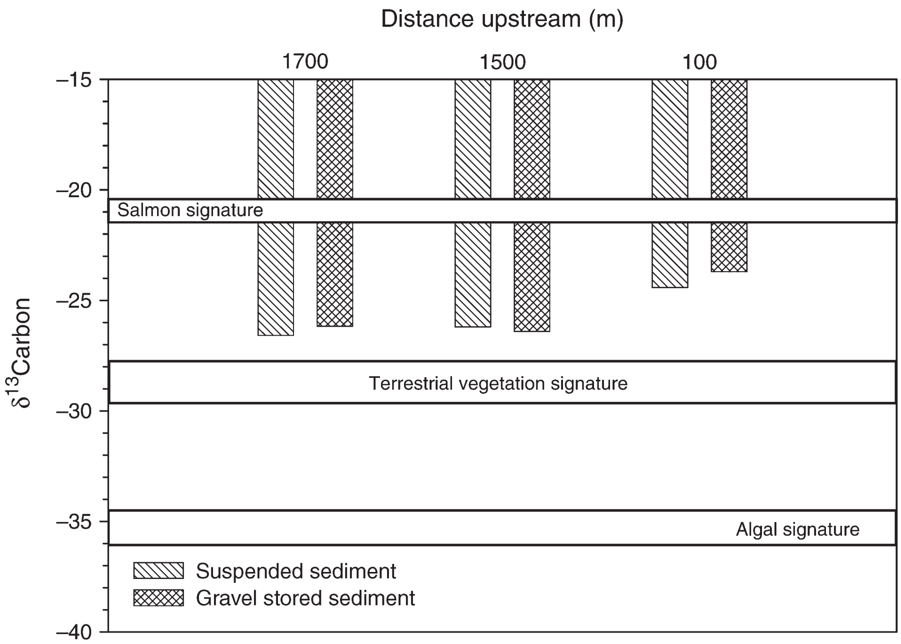

Fig. 11.6. Carbon isotope values for suspended and resuspended gravel stored sediment in three locations in Forfar Creek. Sampling occurred in the die-off period of 1996 when 9076 fish carcasses were contributing nutrients to the stream.

The pattern which emerges from the Forfar Creek rain storm samples also indicates that stable isotope analysis is able to detect temporal differences of organic matter sources in suspended sediments. The suspended sediment sampled from a storm occurring 2 weeks after the return of the fish exhibits a δ^{13}C closer to that of salmon tissue than the three pre-fish return storms. A storm sampled 8 days later, close to the end of the spawning period, exhibited the highest precipitation recorded that season, but its δ^{13}C signal indicated a return towards the terrestrial carbon signature. An analysis of two soil samples from the O'Ne-eil Creek streambank indicated that its carbon signature was –27.04 (SE = 0.16), which is very close to the terrestrial values, indicating the dominant organic source material in the soils is from the riparian vegetation. Therefore this directional change in carbon source dominance associated with high precipitation rates at the end of the fish spawn of 1998 likely reflects the contributions of bank sediments and/or the increased throughflows from the surrounding floodplains and soils. Interestingly as well, the salmon returns for 1998 were the smallest reported here, with only 956 salmon having passed the counting fence at the time of this storm event. Therefore the amount of salmon contributing to the carbon pool was much lower that year, suggesting that the δ^{13}C signals would have been weaker than in other years. This same pattern of results occurred in both Gluskie and O'Ne-eil Creek δ^{13}C data for these five rain storm dates of 1998, supporting the validity of the pattern obtained with only single data points.

Results from a downstream transect of both suspended and gravel stored sediment in Forfar Creek in the post spawn period of 1996 (Fig. 11.6) also reflects the association of fish nutrients with sediments. Samples of both types of sediment taken 100 m upstream of the mouth, where the influence of the 9076 decaying fish would be realized, have δ^{13}C values closer to that of the salmon tissue. Results, not presented here, but again based on single δ^{13}C samples from an O'Ne-eil Creek downstream transect, corroborate these results, exhibiting this same trend in both types of sediment.

The patterns observed in these three creeks over the 3 years where the preliminary isotopic carbon sampling was undertaken indicated that this technique was useful for differentiating source materials of organics in stream sediments and that fish nutrients were associated with both suspended and gravel stored sediment. Changing temporal and spatial contributions of terrestrial vegetation and fish nutrients were detected in the suspended and gravel stored sediment. McConnachie (2003) followed up this approach and sampled O'Ne-eil Creek suspended sediments in replicate, over all event types in 2001. She reported on the ability of stable isotopes of both C and N to differentiate the proportions of salmon nutrients in suspended sediments over the season. Mixing models (Phillips and Gregg, 2001) combined with isotopic results indicated that salmon nutrients comprised 33% of the organic C and N in the active spawn suspended sediment, which increased to 46% during the 2001 post spawn period (McConnachie and Petticrew, in press).

While Johnston *et al*. (2004) identified the importance of salmon carcass decay in the P and N budgets of these streams, they stated that the majority of the nutrients were exported from the study reaches. This was determined from their analyses of reach loadings calculated from water samples and discharge measurements. This approach assumes that all of the material collected in their grab samples of water and suspended sediment for total nutrient analysis remained in suspension until reaching the downstream receiving water body. Given that we have noted the propensity of aggregated fine sediment to settle on to and into the gravels, and that we have detected the influence of salmonid carbon on the gravel stored sediment, it would be relevant for these models to reconsider the importance of storage of aggregated fine sediments as a temporary sink for nutrients.

Conclusion

The physical action of large numbers of spawning salmon digging redds increases the contribution of fine sediment to the water column, enabling the transport and advection of the material that remains in suspension out of the riverine system. However, silt and clay sized particles, combined with organic matter as aggregates, exhibited increased settling velocities and when delivered to the water column, by fish digging redds, settled out of suspension over short distances. The implication of this process is that both aggregated fine sediments and their sediment-associated nutrients readily collect on and in the downstream gravels. Isotopic analyses ($\delta^{13}C$) of the stream sediment indicated that different sources of C were sequestered into the suspended and gravel stored fines of the spring melt flood flows versus post spawning low flows. Active and post spawn sediment exhibited the largest aggregate sizes and incorporated high quality nutrients from instream decaying salmon. This suggests the importance of the biological role that the die-off has on the structure of fine sediment, and therefore the transfers and storage of this material in these fish-bearing streams. While excessive storage of fine sediment and organic matter in the gravels could be deleterious to egg growth, the retention of some nutrients may not necessarily be problematic, as it could enhance stream productivity at both primary and secondary levels.

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