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Sediment aggregation and transport in northern interior British Columbia streams

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Abstract Fine-grained sediment moving in headwater, gravel-bed streams of northern British Columbia (Canada) generally comprises only a small portion of the transported load. This small mass can be significant if stored in the stream, as it has the potential to both modify aquatic habitats and act as a vector for sediment-associated contaminants. A preliminary study of the grain-size structure of suspended sediment was undertaken in three salmon bearing streams. These small watersheds (36-75 km^2) represent the most northern extent of the Fraser River watershed and exhibit high relief and straight channels with coarse bed and bank textures. The concentration and structure of the suspended load both before, and following, channel bed disturbance were sampled and analysed by filtration and Coulter particle counting techniques. *In situ* aggregates of fine-grained sediment in suspension were photographed and sized before and after disturbance using an underwater silhouette camera and an image analysis program. This preliminary study indicates that aggregates up to 1290 μ in diameter are stored in and on the gravels. In each of the streams sampled, the maximum size of the constituent inorganic material comprising these aggregates is less than 130 μ. This storage of aggregates indicates that the settling rate of the fine sediment has been altered, therefore modifying its transport through the stream network.

INTRODUCTION

The delivery of large amounts of fine-grained sediment to mountain streams by either natural processes (landslides, debris torrents) or anthropogenic activity (road-building, logging) can result in a variety of in-stream effects on the receiving reaches of the system (Bilby *et al.*, 1989). The response to the delivery of sediment will depend upon the volume of material delivered, the grain size of the particles, the hydraulic properties of the channel and the flow at the time it enters the channel (Bilby, 1985). One of the more obvious effects is the accumulation of sediment in the channel reaches where conditions amenable for particle settling or trapping exist. The magnitude and, therefore, the significance of channel storage of suspended sediments is highly variable both within a system and over time. Lambert & Walling (1988) suggest evaluating a range of fluvial environments to assess the potential importance of channel storage in the sediment budgets of rivers.

The impact of increased loadings of fine-grained sediment on fish and aquatic life has been studied intensively. Specific effects on salmonids and aquatic invertebrates have been shown to include interference with the development of eggs and larvae (Platts *et al.*, 1989) and the reduction of abundance of food organisms available (Newcombe & MacDonald, 1991). Concern regarding habitat degradation associated with increased sediment delivery to channels has resulted in several large Canadian studies on forestry-fisheries interactions which have been, or are, investigating the Carnation Creek, Queen Charlotte Islands and Stuart-Takla regions (Macdonald *et al.*, 1992). The effects of channel storage of fine-grained sediment is an important component of these studies. Several different methods of estimating suspended loads, sediment stored in the gravels and sediment stored in pools and riffles have been used in these fisheries-forestry studies but what has been overlooked is the process and significance of aggregation or flocculation of fine materials in the headwater streams.

The distribution and residence time of fine-grained (also termed cohesive) sediment in channels will be modified by the process of aggregation or flocculation of fines. Flocculation of materials (organic and inorganic) in freshwater systems has been identified as a factor which increases the settling speed and deposition of fine-grained materials in natural systems (Burban *et al.*, 1990; Droppo & Ongley, 1994). The flocs or aggregates settle at rates completely different from those of their constituent primary particles (Kranck *et al.*, 1993). Lau & Krishnappen (1992) show from annular flume studies that the effective settling velocities of natural river sediment (silts and clays, less than 63 μm in diameter) in freshwater increased due to the process of flocculation. Prediction of settling rates using standard numerical models, which impose conditions of single grain settling, would incorrectly indicate the absence of fine-grained deposition in environments where flocculation or aggregation is occurring.

The process of flocculation of suspended sediment is enhanced by high concentrations of suspended material in the water column (Kranck *et al.*, 1993) but it is also mediated by the chemical composition of the water, especially the dissolved organic material which appears to act as a substrate for bacteria, which produce exudates that serve to bind the particles as stable and larger aggregates (Muschenheim *et al.*, 1989). While flocculation has been studied in larger, sand-bed river systems (Droppo & Ongley, 1994) the process has been overlooked in turbulent, productive headwater streams. This oversight may be a function of there being a relatively small portion of fine-grained sediment moving in these systems. However, it is this small mass of material which, if stored, may significantly affect the biological and chemical functioning of the aquatic habitats. In the lower depositional zones of gravel bed streams, where salmonid productivity is high, there is a need for predictive models which link sediment supply and storage to changes in aquatic habitats (Lisle & Hilton, 1992).

An investigation of the structure of the fine-grained sediment in biologically rich headwater streams would address this research gap. The objective of this paper is to present preliminary findings on the size and concentration of suspended sediment to determine if the process of aggregation is occurring in salmon bearing headwater streams.

METHODS

Field location The watersheds of Gluskie, Forfar and O'Ne-eil Creeks are in the Stuart-Takla Lakes region, which is located in the Hogem Range of the Omenica

Mountains in northwestern British Columbia (Canada). They represent the most northern extent of the Fraser River watershed (55°N, 125°50'W) and exhibit relief ranging between 700-1980 m. The channels are relatively straight and each is approximately 20 km in length. In their upper reaches, the creeks flow through glacial tills which are interspersed with extensive deposits of lacustrine clays (Macdonald *et al.*, 1992). The last 2-3 km of each creek cuts through a lowland area which is underlain by a belt of fine-grained glaciolacustrine sediment (clays, silts and fine sands), a few metres thick (Ryder, 1994). The lower stream reaches exhibit low gradients (0.5-2%) and gravel sizes favourable for spawning habitat. Each stream supports an extensive sockeye salmon (*Oncorhynchus nerka*) spawning stock (Macdonald *et al.*, 1992).

Field sampling The lower reaches of the three streams were sampled in August 1994. The sample period followed the peak of sockeye salmon spawning in these watersheds. Suspended sediment was sampled at stream cross sections located upstream of the salmon counting gates in order to reflect natural transport conditions. Mid-depth suspended sediment samples were obtained downstream of the aperture of the underwater silhouette camera while it was photographing the water column. At two second intervals the camera photographed a 7.4 cm diameter by 4 cm wide volume of water at the mid-point of the water column. A Marsh-McBirney current meter was used to measure stream velocities at the camera site. The initial sampling was termed pre-disturbance and reflected normal flow conditions in the stream during the investigation. A second sampling at the same stations occurred several minutes later. This was termed post-disturbance and was an attempt to simulate the degree of natural resuspension of sediment that occurs during salmon spawning or the digging of redds. Physical mixing of the gravels 4-5 m upstream of the camera was performed by a field assistant. This "dance of the spawning salmon" resuspended several centimetres of gravel and the associated fines. Suspended sediment was sampled in the water column and photographed following this staged disturbance.

Laboratory analysis The water samples were filtered on triplicate preweighed 8 μm SCWP Millipore cellulose-acetate filters and were used for gravimetric and disaggregated inorganic grain size analysis. Suspended particulate matter (SPM) was determined gravimetrically on the dried filters and reported in mg l^{-1}. The weighed, dried filters were ashed 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 & Kranck, 1992). A Coulter Multisizer IIE was used to determine the constituent or disaggregated inorganic grain size distribution. Results are expressed as a volume/volume concentration in ppm and are plotted as smoothed histograms of log concentration *vs* log diameter (Figs 1 and 2) (Milligan, 1995). The *in situ* size distribution and concentration of the flocculated particles were obtained by image analysis of the photo negatives obtained from the silhouette camera. The images were transferred to CD-ROM and imported into Jandel Scientific's Mocha image analysis program. The equivalent spherical diameters of the detected flocs were counted and grouped in size classes which correspond to the class intervals from the Coulter counter. They are plotted in the same fashion and on the same plots as the constituent particles. In the configuration used, the Multisizer has a lower detection limit of 0.63 μm and an upper detection limit of 1200 μm while the floc camera has a lower detection limit of approximately 60 μm.

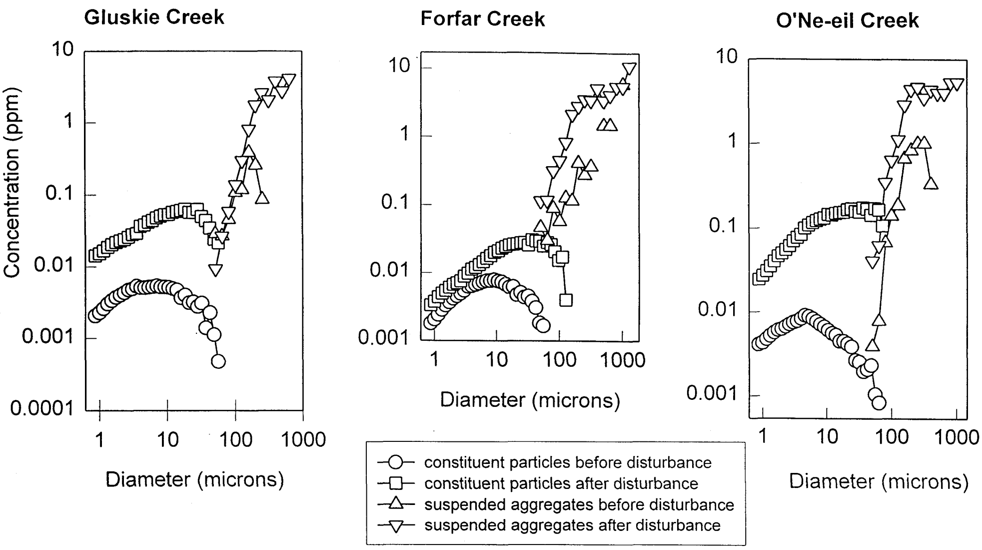

Fig. 1 The particle size composition of suspended material in three northern interior British Columbia streams. The sediment spectra of constituent material represent the inorganic particles, which comprise the suspended aggregates mechanically disaggregated before analysis.

RESULTS

The grain size spectra of the aggregated and disaggregated sediment sampled from the three creeks are presented in Fig. 1. The disaggregated or constituent inorganic particles collected from all streams have maximum grain sizes between 56 and 130 μm (Table 1). The suspended aggregates photographed have maximum grain sizes between 256 and 1290 μm. In both sample types, the post-disturbance samples have higher concentrations of particles in equivalent size classes. These data reflect a disturbance of bottom gravels which increases the maximum grain size and the concentration of all grain sizes in suspension. For comparative purposes, surficial sediment samples from an extensive exposure of the glaciolacustrine material in the lower portion of the watersheds were analysed on the Multisizer. This allowed a determination of the grain size structure of materials potentially eroding to the creekbeds during storm or mass movement events. The size spectra for the samples are shown in Fig. 2. Note the high concentrations of clays and silts below 10 μm and the smaller peak in the fine sand size range around 120 μm.

DISCUSSION

Results of this preliminary study in headwater, salmon bearing streams indicate that fine-grained sediment is aggregating. These larger particles are observed both in suspension in the stream during normal low flow conditions and stored in the channel gravel bed matrix. These aggregates are comprised of inorganic particles smaller than 130 μm, with the majority of these constituent particles ranging between 5 and 50 μm.

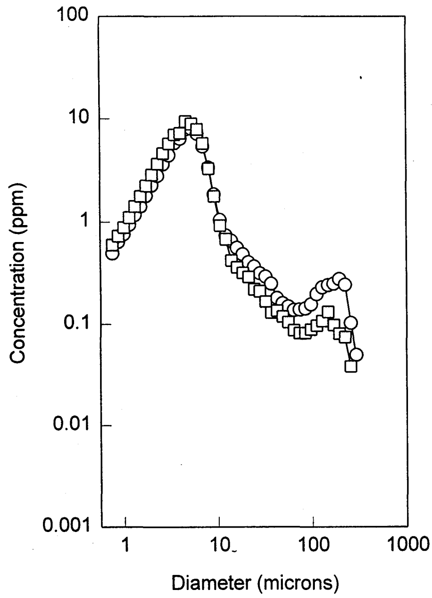

Fig. 2 The particle size composition of duplicate surficial glaciolacustrine sediment samples from the Forfar Creek drainage basin. The material was sampled from an extensive exposure and represents sediment which potentially erodes into stream channels.

The settling rates of individual or disaggregated particles of this size in quiescent water are slow and deposition would not be predicted in flow velocities equivalent to those measured (Table 1). Clearly the storage of fines in the gravel matrix is enhanced by the process of aggregation in these headwater systems.

An earlier investigation of these creeks (Macdondald *et al.*, 1992) reported spawning gravel grain sizes with only 1% of the material by weight smaller than 74 μm. These

Table 1 Characteristics of stream sample sites and suspended sediment.

		Gluskie Creek	Forfar Creek	O'Ne-eil Creek
Water depth (m)		0.42	0.36	0.56
Velocity (m s^{-1})		0.30 (0.02)	0.26 (0.01)	0.14 (0.01)
SPM (mg l^{-1})	pre-disturbance	0.80 (0.22)	0.60 (0.18)	1.33 (0.12)
	post-disturbance	5.80 (1.21)	2.93 (0.69)	11.66 (2.61)
Maximum size of constituent particles (μm)	pre-disturbance	56	56	64
	post-disturbance	56	128	74
Maximum size of suspended aggregates (μm)	pre-disturbance	256	645	406
	post-disturbance	645	1290	1024

SPM = suspended particulate matter
Numbers in brackets are standard deviations

results were obtained from analysis of frozen finger cores. The research reported here clarifies that the proportion of fines stored in the channel in normal conditions is small, but evidence is provided that indicates that the process of aggregation is occurring and could influence the storage, transport and extensive delivery of fine-grained sediment. These systems are currently able to handle the delivery of small loads of fines which aggregate, settle and are moved downstream when entrainment velocities are achieved. Flow conditions in storms, spring melt and gravel disturbances such as occurs during sockeye digging of redds have the potential to transport these stored, aggregated fines.

System response to changes in the watershed, which increase the loading of fines (anthropogenic or natural), will depend upon both the presence and the timing of a number of factors. Both the amount and the size of flocs has been noted to increase with increasing concentrations of suspended sediment (Kranck *et al.*, 1993) and bacterial activity (Muschenheim *et al.*, 1989). These headwater streams are very productive and seasonally experience bursts of bacterial activity (thousands of salmon carcases decaying in a 2-3 km reach of the streams each August). Delivery of high concentrations of fines from the upstream glaciolacustrine sediment (Fig. 2) could be extremely deleterious to the salmon habitat. The timing of such loads would be critical because high sediment delivery in combination with moderate flows and peak bacterial activity would promote aggregation, rapid settling and channel storage resulting in a smothering of eggs and benthic organisms. Given that this paper is reporting on work in progress, the findings suggest that future research in these systems must address:

- the settling rates of the resuspended aggregates,
- the entrainment velocity of aggregated fines stored on the channel bed, and
- the role of bacterial activity in facilitating aggregation in these productive systems.

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