Hydrological and biological event based variability in the fine-grained sediment structure of a small undisturbed catchment

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Abstract In 2001 a study in an undisturbed, highly productive salmon bearing stream (O'Ne-eil Creek) was undertaken in the northern interior of British Columbia, Canada. The aim was to determine if the structure and settling characteristics of the aggregated sediments varied significantly over the different hydrological and biological regimes of an open-water season. Sampling regimes included the hydrological conditions of the rising limb of spring freshet, falling limb flows of snowmelt and summer rainstorms, while biological conditions included sampling during spawning and die-back of 13 580 sockeye salmon. A negative relationship between shear stress and effective particle size diameter, D_{50} is evident for the hydrological regimes, while the largest flocs occur when live and dead salmon are present in the stream. Increased organic matter quality and biological resuspension of gravel-stored material attributed to spawning salmon, reflect their physical and chemical influence on the change in size and density of aggregated fine sediment in this stream system.

Key words aggregation; Canada; effective density; floc factor; flocculation; image analysis; organic matter quality; shear stress; spawning salmon; suspended sediment

INTRODUCTION

Downstream transport of fine-grained sediment (<63 μm diameter) in river channels is assumed to be efficient, according to conservative hydrodynamic theory, such that yield models should accurately predict sediment fluxes from catchments. However, field studies indicate conveyance losses in longitudinal fine sediment flux attributed to storage on flood plains as well as within channel beds (Owens *et al.*, 1999), which renders yield models inadequate. This difference is largely due to the misconception that particles are transported as single grains with very slow settling rates.

Recent research indicates that suspended sediment is commonly transported in a flocculated form (e.g. Petticrew, 1996, 1998; Droppo *et al.*, 1997; Woodward *et al.*, 2002), whereby single sediment grains (inorganic and/or organic) combine together to form larger units. The composite particles have been further categorized by Petticrew & Droppo (2000), who visually identified two populations: (a) fast settling, compact aggregates, and (b) slow settling, amorphous flocs.

Particle structure is a major factor in regulating the behaviour of suspended material in aquatic environments (Nicholas & Walling, 1996). Flocculation alters the hydrodynamic properties of sediment by changing particle density, shape, porosity and composition through increases in effective size and internal complexity of particles (Petticrew & Biickert, 1998; Droppo, 2001). Petticrew & Biickert (1998) suggest that these alterations to the suspended particle population should increase storage of fine-grained sediment in gravel beds compared to what is currently predicted by hydrodynamic models.

While the magnitude and duration of fine-grained sediment storage depends mainly on sediment supply and hydrological conditions, the stored load may comprise a significant portion of a system's annual sediment budget (Owens *et al.*, 1999). However, even small quantities of fine-grained sediment stored on or in the gravel bed for short (weeks) periods could be significant for streams that support salmon-spawning habitat because of the potential for decreased oxygen flow through interstitial spaces that house salmon eggs, and degradation and/or loss of aquatic habitat for food species (Newcombe & MacDonald, 1991). The purpose of this study is to evaluate the temporal variability in suspended fine sediment structure and settling properties over a full field season of hydrological (snowmelt and rain storms) and biological (salmon spawning and die-off) events in an undisturbed salmon stream.

METHODS

Field site and sampling design

The O'Ne-eil drainage basin is a small (75 km^2), relatively undisturbed (one approximately 20-year old access road) system at the most northerly extent (55°N, 125°50′W) of the Fraser River catchment in British Columbia, Canada (Petticrew, 1996). The main channel is about 20 km in length with the lower 2 km exhibiting excellent conditions for sockeye salmon (*Oncorhynchus nerka*) spawning. A 10-m riffle in the main channel, approximately 1500 m upstream of the mouth, was sampled during the period of 18 May to 21 August 2001. Samples were collected to evaluate the seasonal changes in fine sediment structure and morphology over a range of hydrological and biological events (Fig. 1(a)). Hydrological events included: (a) the rising limb of the freshet, (b) the falling limb of snowmelt, and (c) five rain events sampled at a range of times relative to the start of each storm (displayed as points in Fig. 1(a)). Biologically important periods were: (a) active spawning upon the return of migrating salmon (return date 21 July), and (b) the post-spawn die-off. The spawn regime includes the period of active digging of redds (nests for eggs) as well as the start of post-reproductive die-off, while post-spawn is devoid of live fish but incorporates a greater presence of decaying fish carcasses. In this year, 13 580 sockeye salmon returned to the lower reaches of O'Ne-eil Creek to spawn with an approximate density of 0.7 fish m^{-2}.

Field sampling

The seasonal hydrograph was reconstructed from stage height data logged by the Department of Fisheries and Oceans at a gauge within the study reach. Bottle samples were removed at the thalweg for (a) suspended particulate and organic matter concentrations (SPM and SOM), (b) carbon and nitrogen content, and (c) absolute particle size distributions (APSD). Composite 20 L samples were collected for effective (*in situ*) particle size and settling analysis. Samples were withdrawn near the water's surface and thus do not reflect depth integrated values. Shear velocity and stress was calculated as per Gordon *et al.* (1992) from

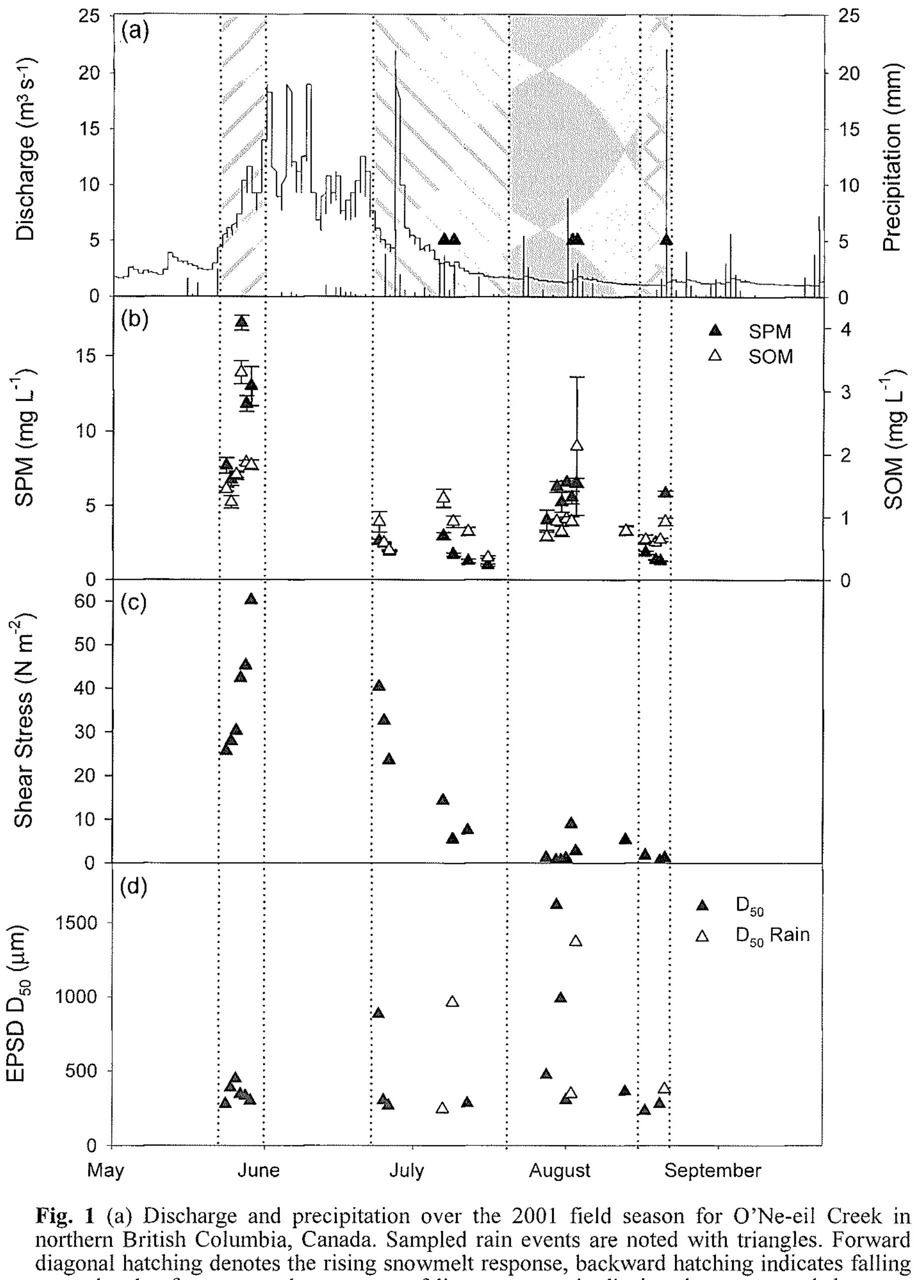

Fig. 1 (a) Discharge and precipitation over the 2001 field season for O'Ne-eil Creek in northern British Columbia, Canada. Sampled rain events are noted with triangles. Forward diagonal hatching denotes the rising snowmelt response, backward hatching indicates falling water levels after snowmelt, presence of live spawners is displayed as grey, and the post-spawn period is crosshatched. (b) SPM and SOM (mg l^{-1}) values from triplicate samples of suspended sediment. Error bars represent ± 1 SE. (c) Shear stress (N m^{-2}) calculated from vertical velocity profiles. (d) D_{50} particle diameters calculated from cumulative percent volume effective particle size distributions (EPSD).

vertical profiles of velocities measured at 5-cm depth intervals with a Swoffer Model 2100 current meter.

Laboratory analysis

Water samples were filtered through triplicate pre-combusted and pre-weighed 47 mm diameter, 0.7 μm pore size glass-fibre filters for gravimetric determination of SPM and SOM. A second set of these filters was freeze-dried and analysed for carbon and nitrogen content using a Carlo Erba NC2500 elemental analyser with an AS 128 autosampler. C:N ratios were calculated from the resultant percentages. Sediment was also filtered for analysis using a Coulter Multisizer (detection range of <1 to 111 μm) to size and count the inorganic constituent particles in the manner of Petticrew (1998). All particles for each sample were grouped into classes defined by their equivalent spherical diameters as per Kranck *et al.* (1993) yielding APSD.

Effective particle size distributions (EPSD) were collected from analysis of images obtained from experiments using a Plexiglas settling tube (cf. Petticrew & Droppo, 2000). A charge-coupled device (CCD), with a resolution of 512 × 512 pixels, interfaced with an Intel-based PC running Northern Exposure (Empix Imaging, Mississauga, Ontario, Canada) was used to capture sequential images of particles as they settled due to gravity. A procedure 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 (detection minimum of 42 μm). Population particle distributions were obtained in the same manner as APSD. D_{50} particle sizes were determined from linear interpolation of cumulative percent volume data for both EPSD and APSD, and the ratio of the two was calculated as the floc factor (degree of particle aggregation). Settling velocities were determined from the distance travelled by the particle divided by the time interval between images, and particle densities were calculated from these measurements as per Namer & Ganczarczyk (1993).

RESULTS

The hydrograph is shown along with the results of the suspended particulate matter, suspended organic matter, shear stress and the median size of the suspended EPSD (D_{50}) (Fig. 1). As expected, the SPM and SOM increase on the rising limb of the snowmelt flood and decrease on the falling limbs of the large floods. The EPSD D_{50} also rises at the start of the snowmelt, but only for three consecutive days after which it begins to decrease. Shear stresses increase consistently over this six day period, indicating that higher shear conditions are able to entrain more material but potentially disaggregate, or inhibit the aggregation of particles. Alternately, the channel and/or terrestrial supply of aggregates could be smaller in size during the latter part of the rising limb of snowmelt.

Of interest in Fig. 1 is the statistically significant elevated values of SPM during the period of active spawn that decrease when no live spawners are present in the reach. The EPSD D_{50} also reaches its highest values at this time. Soulsby *et al.* (2001) noted that female fish dig spawning redds to bury eggs exerting enough force on the bed to move the gravels. During this process, finer material stored in the gravels is resuspended; a considerable disturbance when hundreds of salmon are active simultaneously. The data in Fig. 1(b) reflect this biotic resuspension of sediment. The enlarged D_{50} is presumed to be a result of particle resuspension without the accompanying high shear stresses as seen during higher discharges. Although the intermittent shear stresses exerted by salmon activity may also cause particle break up, it does not appear to affect the suspended sediment structure to the extent of the hydrological events.

A contributing factor causing increased EPSD D_{50} during this period could be the introduction of marine-derived organic matter. It is well-established that nutrients, especially nitrogen, released during salmon carcass decay can enhance microbial growth in freshwater ecosystems (Wold & Hershey, 1999) and a connection between microbial activity and flocculation has been suggested by many researchers. For example, Droppo (2001) found flocs coated liberally with extracellular polymeric substances (EPS) typically derived from bacteria. These sticky fibrils act like a glue that improves particle binding capabilities. Thus, it is a possibility that salmon presence has two important implications for flocculation in freshwater systems: (a) particle resuspension, and (b) enhanced particle binding potential.

Three rising limb events comprising early snowmelt, a summer storm and a storm during active spawn are compared in Fig. 2. The increasing D_{50} and floc factor over the season is associated with decreases in shear velocities and C:N ratios. This trend of decreasing floc size with increasing shear is also evident in the larger data set (Fig. 1(c) and (d)) for the hydrological events. Alternately, the largest flocs tend to occur during summer rains and/or in low shears (<10 N m^{-2}) when fish are present, potentially reflecting differences not just in the quantity but also in the quality of organic matter. The seasonal decrease observed in C:N ratios from rising limb events (Fig. 2) reflects the increasing quality of the organic matter in the suspended sediment as low C:N ratios imply higher quality OM for bacterial consumption (Bouillon *et al.*, 2000). These low shear environments, combined with abundant nutrients for bacterial productivity, generate large suspended flocs.

Figure 3 depicts 1186 individual suspended particles, which were characterized by image analysis for size, shape and settling velocity allowing for the calculation of particle density. The five different regimes are plotted separately, and, while the majority of particles

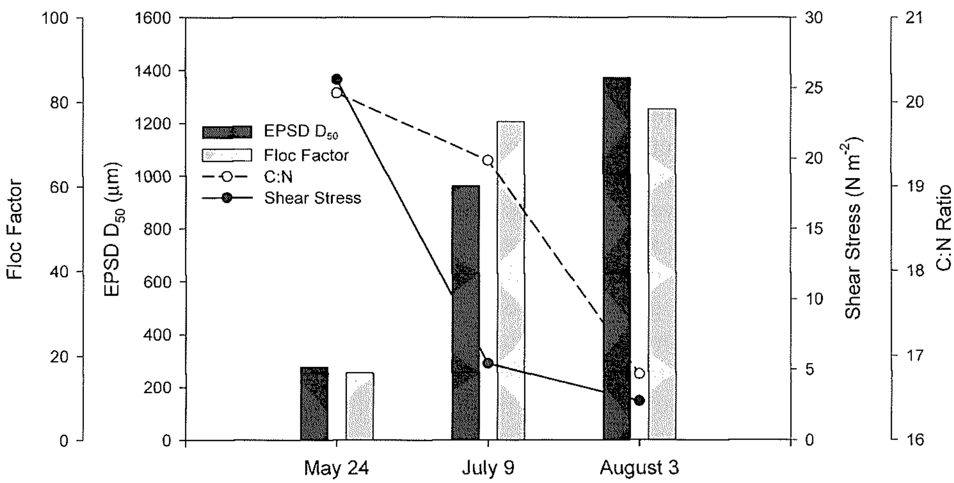

Fig. 2 EPSD D_{50}, floc factor, shear stress, and C:N ratio for three sample days representing rising limb events on the hydrograph for the O'Ne-eil Creek.

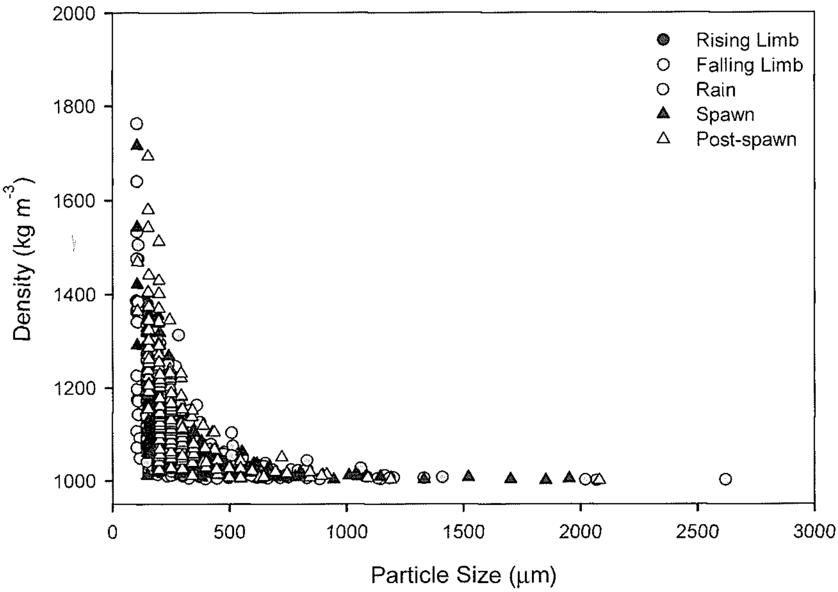

Fig. 3 Effective particle density by diameter differentiated by hydrological and biological response types. An exponential relationship is observed with the majority of the large, low density particles occurring during active salmon spawn and a high number of small, high density particles exhibited post-spawn.

are <500 μm and have densities lower than 1200 kg m^{-3} (or less than an excess density of 0.2 g cm^{-3}), particles in the spawn, post-spawn and rain events exhibit the widest range of particle structure and behaviour. These regimes have the greatest proportion of large, low density particles >1000 μm, as well as the highest proportion of most dense particles (>1400 or in excess of 0.4 g cm^{-3}) which tend to be <300 μm. Large, low density or small, very dense particles are not found in the rising or falling limb samples. A statistical analysis of the full settling data set indicates that the rising limb of the snowmelt flood exhibits significantly smaller particles, while post-spawn consists of the fastest settling and densest particles (all $p < 0.01$). This implies that the potential for gravel-storage of fines is highest when decaying carcasses provide abundant organic material to the stream, which tends to occur when stream flows are low. In fact, Petticrew & Arocena (2003) report increased proportions of gravel stored inorganics, <63 μm, during the die-off and following the decay of all the fish in this same riffle for 2001. Gravel stored fines were at their lowest proportions at mid-spawn when the fish would have both a physical (resuspension) and chemical (decaying OM) effect on the sediment. Infiltration rates from July through September (2001) in this spawning reach were relatively low (<50 g m^2 day^{-1}), but did exhibit a 39% increase following the die-off and rotting of the fish carcasses. As this increase coincides with the period when salmon eggs are incubating, the importance of the timing and the quality of inorganic and organic sediment delivery to the stream on fine particle morphology and behaviour is apparent.

The presence of spawning and decaying fish plays a substantial physical and chemical role in fine sediment dynamics of productive streams. Therefore further examination of the relationship between fine sediment transfers and organic matter source and quality is warranted.

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