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Characterization of sediment transport and storage in the upstream portion of the Fraser River (British Columbia, Canada)

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Abstract Several techniques to determine the *in-situ* size, morphology, settling and storage characteristics of fine grained sediment have been used in the Fraser River at Prince George. The river was sampled both upstream and downstream of the effluent outflow of a major pulp mill (Northwood) to determine the role of this effluent in modifying the transport and storage of sediments. Both the natural suspended sediment load (upstream) and the effluent-sediment mix (downstream) were characterized by concentration, organic/inorganic ratios and image analysis to identify the presence and size of aggregates or flocs in the water column. Preliminary analysis of the data from the first eight months of 1997 indicates seasonal changes in floc size of the natural sediments but no significant difference between sites upstream and downstream of the effluent pipe. Buried gravel traps were used to quantify and characterize the amount of fine grained storage in the gravel bed during the post flooding period. Over short periods (four days) abundant fine grained (<63 μm) material was collected. The modal size of the constituent particles in the size class below 150 μm was 40–60 μm. This storage of silts and clays in the gravel bed is important in the context of both habitat quality and sediment associated contaminant transfers.

INTRODUCTION

Temporally and spatially the suspended sediment transport in large river systems can be quite variable due the natural fluctuations in both flow and sediment supply. In the last decade research on riverine sediment transport has emphasized that fine grained sediments in most river systems are not moving as individual particles but rather that aggregates or flocs are forming (Droppo & Ongley, 1994; Petticrew, 1996; deBoer, 1997). The formation of these larger particles should modify both the transport and storage of fine grained sediment and also any sediment associated contaminants in river systems. Storage of these aggregates or flocs on the surface of the gravel bed or in the interstitial gravel spaces should be increased. The environmental significance of the storage of fines, and their associated contaminants, in the gravel beds of rivers will depend on their residence time. In large fast flowing systems, channel bed deposition zones of fines can be difficult to find, yet during increased discharge events fine material is mobilized. While this storage may only be a short-term phenomena (days) the literature indicates that gravels need to be physically moved to clean smaller particles from interstitial spaces (Kondolf *et al.*, 1987). If gravel entrainment velocities or physical disturbance is necessary to dislocate the fines, then longer term storage (weeks to months) could result.

The factors which have been noted to regulate floc formation and structure include suspended sediment mineralogy and concentration, organic matter supply, temperature, ionic concentrations and shear velocities. Increases in suspended sediment concentration increase the probability of collision and therefore aggregation (Hill, 1992) while various types of organic material (bacterial exudates, fibrils) increase the stickiness of the particles (Droppo *et al.*, 1997) enhancing floc formation. The temperature has been noted to be associated with both changes to the electrical double layer in clay particles and the activity level of biological processes in water (Lau, 1990). Ionic concentrations affect the binding of the charged clay particles and observations along estuaries indicate increased floc formation with increased ionic content (Eisma, 1993). Lau & Krishnappen (1992), working in a flume environment noted that increased shear resulted in decreased D_{50}'s of the particles that settled while Milligan and Hill (in press) found the role of shear in regulating floc size and settling rate interacted with both particle mineralogy and suspended sediment concentration.

The results presented in this paper are the preliminary findings from the first eight months of a year long study on the Fraser River (British Columbia) at Prince George. The objective of the study was (a) to determine the extent of natural flocculation or aggregation in the system on a weekly basis over the year long period, and (b) to determine the downstream effect of the addition of pulp mill effluent. We were testing the hypothesis that pulp mill effluents increase the size and structure of suspended sediments. The potential for aggregated sediments to be transported and stored in the gravel bed matrix is also being evaluated.

METHODS

Site characteristics

The Fraser River basin drains approximately 234 000 km^2, of which 14% (32 400 km^2) is upstream of the city of Prince George (Fig. 1). The Fraser is one of Canada's largest rivers with the second greatest mean annual flow (3972 $m^3\ s^{-1}$) (Dorcey, 1991). The Environment Canada monitoring record from Shelly, a site 20 km upstream of Prince George, indicates a mean annual base flow of approximately 150 $m^3\ s^{-1}$ while the springtime peak is of the order of 2400 $m^3\ s^{-1}$ (Vine, 1996). The first major point source of industrial effluent on the upper Fraser is the Northwood Pulp Mill. This mill releases 1.47×10^5 m^3 of effluent into the Fraser on a daily basis (Marks, 1996). Analysis indicates this material is 85% organic material.

Study design

The Northwood Pulp Mill site was selected as a suitable location to test effluent effects on the flocculation of fine particles in the Fraser River due to its upstream location relative to the other major effluent producers on the river system. Suspended sediment and trapped sediment was measured at three sites. The first was 50 m upstream of the Northwood diffuser, the second was 300 m downstream, and the third was approximately 600 m downstream (Fig. 1). The upstream site provides a control, having no mill effluent. The first downstream site was chosen to reflect the mixture of effluent and natural sediment under hydrodynamically similar conditions. It is assumed that the only difference between the sites is the effluent and that the other factors such as flow velocity, sediment concentration and sediment chemistry are common to the three sites. To test the effect of the effluent the first downstream site needed to be far enough from the effluent outfall to provide space for the anticipated flocculation and deposition phenomena, yet close enough to exclude confounding factors. The second downstream site was added in late May as evidence indicated that the first downstream site was only periodically within the effluent plume. This site is located at the downstream cutbank which has been reinforced with riprap. There is no control for hydrodynamic similarity between it and the previous two sites, yet water conditions indicate that it is constantly bathed in the effluent-water mix.

Sample methods

Weekly water column characteristics consisted of grab samples of suspended sediment and *in situ* measurements of temperature, velocity and conductivity. Conductivity and temperature was obtained using a Hach TDS combined conductivity and temperature meter, which was accurate to ±0.1 μS and 0.1°C respectively. Velocity profiles were obtained using a Swoffer current meter.

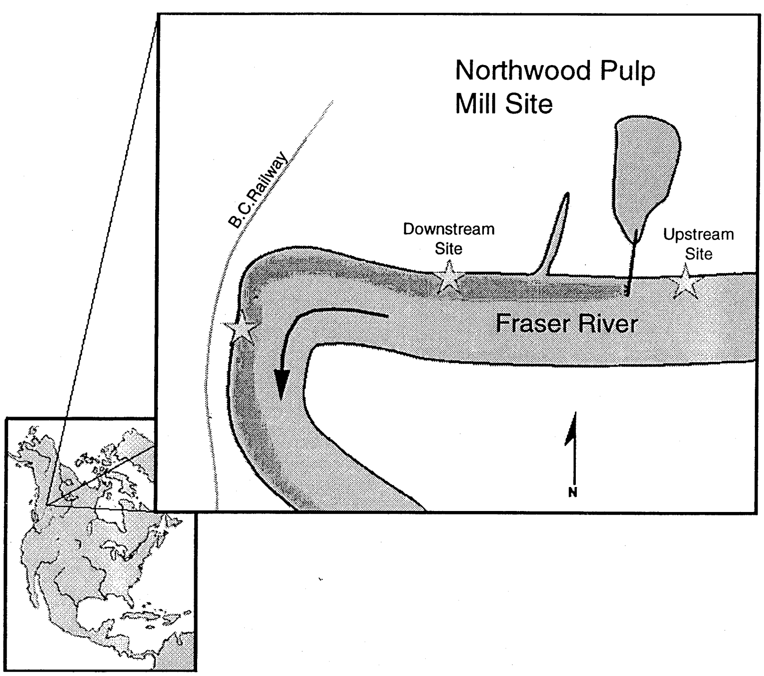

Fig. 1 Three sampling locations (identified by stars) along the Fraser River near Prince George, British Columbia.

Suspended sediment One litre grab samples were collected at approximately one third of the water column depth which varied between 1.0 and 1.2 m. These samples were filtered to obtain: (a) total suspended sediment (TSS) and organic percentage, (b) constituent inorganic composition (by Coulter counter) (Petticrew, 1996) and (c) representative floc morphology (by microscopy and image analysis). Flocs, being delicate structures, required care to filter and measure. Small amounts (4–70 ml) of river water were poured over Sartorius 0.45 μm millipore filters. The negative pressure on the filter was regulated to 80 kPa so as not to stress the flocs unduly. To analyse the floc filters, they were viewed using a trinocular microscope with a 4× lens and 10× ocular. Images from a charge-coupled display (CCD) camera, attached to the microscope were stored in a BioQuant image analysis system. Analysis consisted of thresholding the images to delimit the flocs, and then automated measurement of several shape parameters including area, longest dimension and perimeter.

Gravel traps Two different trap designs were constructed to characterize the composition and quantity of sediment settling onto/into the gravel bed of the river. Each consisted of washed, sized, Fraser River bed materials. A gravel bag design (Lisle, 1991) which exhibits a minimum of disturbance on natural flow (and therefore deposition) was selected. This trap consisted of a metal ring, 20 cm in diameter, to which was attached a non-permeable nylon bag approximately 25 cm deep. This bag was compressed and placed in a shallow excavation in the bed of the Fraser River. It was then covered with gravel which had previously been taken from the bed and washed of all clasts smaller than 6350 μm. Thus the ring is at the base of an inverted cone of washed gravel, through which it was pulled, by means of attached ropes, at the end of the study period. The material trapped in the bag was then washed to separate particles <6360 μm which were then sieved and weighed to determine the net settled or infiltrated sediment.

The second trap was designed to allow the sediment and the interstitial water to be returned to the laboratory with a minimum of disturbance. It consisted of a 45 cm length of 7.5 cm block plastic pipe, closed at both ends by 0.64 cm wire mesh and filled with cleaned gravel. It was positioned on the bed parallel to the flow. Following the immersion period, the ends of the trap were sealed, and the tube was lifted from the bed, removing both the gravel and water. The mass of sediment within the tubes was poured into containers in the laboratory and then sub-sampled for organic percentage and constituent size spectra.

Particle analysis The particle data for each filter were binned on 1/5 phi intervals based on their equivalent spherical diameter. The counts in each bin were then normalized to 100% of particles counted. The resulting distributions were compared using the multi-group Kolmogorov-Smirnov (K-S) test, which tests for significant differences between sample distributions.

Supplementary to this, a measure of the changes in floc form or complexity is also valuable. Measures of fractal dimension have been used to test for differences in floc form over time and space. DeBoer (1997), found that differences in source material and/or river conditions were reflected in values of the fractal dimensions of particles. In this work, three discrete measures of fractal dimension, D, D_1 and D_2, were calculated to look for changes between sites and over time.

RESULTS AND DISCUSSION

Over the period of this study, changes occurred in many of the Fraser River's flow characteristics in response to the changing seasons. Variations in discharge or stage, TSS, temperature, and the organic/inorganic ratio in the suspended sediment were observed (Fig. 2). Each of these variables has been shown to affect flocculation in either the laboratory or natural environment. The spring flood of 1997 was approximately a 1 in 20 year event, resulting in high stages and a high peak discharge. Total suspended sediment varied in response to discharge with the highest concentrations at the onset of the spring flood. Water temperature was steady at 0.5°C over the winter months. At ice-off, the temperature increased to a peak in late July at around 16°C. The organic/inorganic ratio of the suspended sediment remained fairly constant throughout the study period, with the exception of an organic peak coinciding with ice-off. This flush is theorized to be a result of organic material on or within the ice.

Seasonal variation

The seasonal variation in the natural conditions in the Fraser River could be expected to have certain effects on particle structure as (a) there is a documented relationship

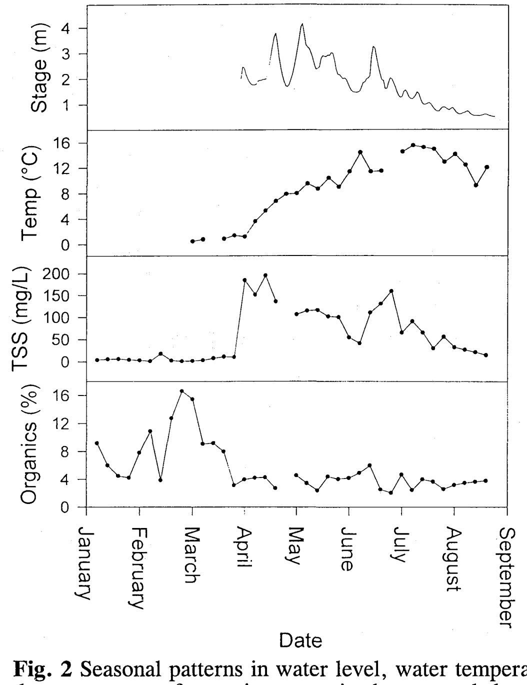

Fig. 2 Seasonal patterns in water level, water temperature, total dissolved solids and the percentage of organic matter in the suspended sediment. Weekly samples from January 1997 to late August are presented.

between increasing temperature and increasing floc sizes due to increased biological activity (Lau, 1990), (b) an increased concentration of suspended sediment associated with spring flows could result in more inter-particle collisions, and potentially increased flocculation (Hill, 1992) and (c) increased spring discharge results in increased shear forces in the water column which breaks flocs, resulting in smaller aggregated structures (Milligan & Hill, in press).

Significant differences ($p < 0.05$) were noted in the upstream (natural) floc size distribution over time. Figure 3 indicates that the particle size mode decreased from February through May when temperatures were warming and sediment concentration was increasing. The warmer temperatures of summer and higher sediment concentrations of the spring flood were associated with greater numbers of smaller particles in the water. This suggests the relationship between shear and floc size is the dominant process in this system. In spring flows shear velocities were measured at 0.062 m s^{-1} while in August well after the freshet it was measured at 0.045 m s^{-1}.

The fractal analysis of the flocs does not reflect the same temporal trend noted in Fig. 3. There is no significant difference noted in any of the three measures of fractal

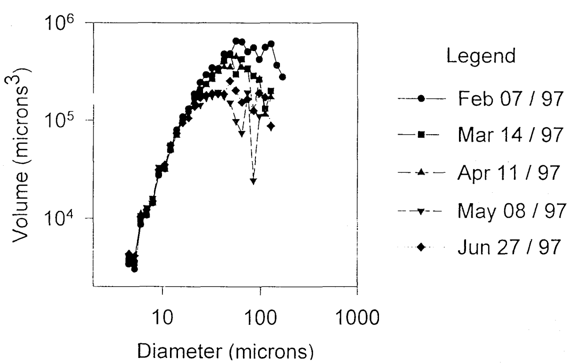

Fig. 3 Floc spectra, obtained from microscopy and image analysis, at the upstream site for five months representing pre, during and post spring melt conditions. Significant differences are seen in the particle structure larger than approximately 15 μm.

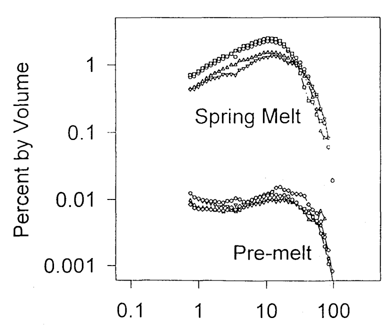

Fig. 4 Particle size spectra of the inorganic constituent materials for two dates during spring melt (2 and 9 May) and two dates preceding the melt (7 and 14 March). For each time period both upstream and downstream sites are presented but no significant difference is observed.

dimensions over time. This means that while we see significant changes in the numbers of particles of given size classes over the season we cannot quantify any change in the morphology (shape complexity) of these particles over the given time period.

The relative position, on the y-axis, of the inorganic size spectra (constituent particles) of the suspended sediment samples reflects the observed change in concentration between the pre-melt (March) and spring melt samples (May). There is only a slight movement of the modal size downward with the increasing flows, from 18 μm to 12 μm (Fig. 4) and maximum particle size is similar in both sample sets (100 μm). Note that while the modal and maximum particle sizes do not exhibit significant differences between sampling periods, the slope of the fine grained end of the curve (source slope) does change. The relative abundance of particles between 0.5 and 10 μm is increased in spring melt flows. Kranck (1983), identified this portion of the spectra as the source slope and indicated that changes in the slope reflected the contribution of different source materials. While early, pre-melt, flows would move materials from the bed and possibly the banks, the spring melt discharges would carry sediments from both upland and flood plain portions of the basin which may explain this change in spectra source slope.

Effluent effects on suspended sediment

Despite the mixture of the organic effluent and water at the downstream sites, there was not a clear pattern of elevated organics measured. It should also be noted that the floc size spectra do not show a significant difference between the upstream and two downstream sites over this eight month period. Similarly a comparison of fractal dimensions of the flocs between sites did not indicate any significant difference. From this preliminary analysis the influence of pulp mill effluent does not appear to have any significant effect on the size or the morphology of the suspended sediment. While the majority of natural sediments are moving as flocs at all times of the year, the system does not appear to generate very large aggregated particles. Few floc structures are observed with diameters exceeding 150 μm and the constituent inorganic material which comprise these flocs are all particles less than 100 μm, with a mode size around 15 μm (Fig. 4).

Gravel traps

The traps were very successful in collecting fine sediment, both on the gravel beds and in the interstitial spaces. Table 1 indicates that a large amount of sediment can infiltrate into the gravels of the Fraser on a short time scale (4 days). Currently, with only small experimental numbers, a statistical evaluation of difference in sediment storage upstream and downstream of the effluent diffuser is inappropriate. Note (Table 1) that for the two smallest size classes the downstream trap has more than double the mass of sediments than the upstream traps. It is apparent that there is significant deposition of fines within the gravels at all locations and that the gravels

Table 1 Weights (by grain size class) of sediment collected in infiltration bags set into the gravel bed of the Fraser River (August 1997).

Grain size class (μm)	Trap 1 (downstream) (g)	Trap 2 (upstream) (g)	Trap 3 (upstream) (g)
>2000	33.2	82.4	197.3
500–2000	11.0	52.7	137.0
250–499	77.9	51.5	70.9
150–249	122.0	40.5	40.0
<150	164.1	63.1	25.2

act as a short-term storage site for fines and potentially any sediment associated contaminants.

Sediment caught in the tube traps has been analysed for organic percentage and constituent inorganic grain size. Sediment organic matter determined on the material removed from all the traps is low (1.6%–3.0%). Coulter analysis of the smallest size class (<150 μm) captured both in the infiltration bags and in the tubes indicated that the modal sediment grain size was silt (40–60 μm). From the data in Table 1 it is clear that medium and fine sands are also caught by the trap. This is likely to be material that is saltating along the bottom as none of the analyses of suspended matter indicate that medium sands are moving in the water column at the point of suspended sediment grab samples (Fig. 4). The source slope of the inorganic material caught in the gravel traps is steeper than both of the slopes for suspended material shown in Fig. 4. The smallest particles (1–10 μm) are not as abundant whereas the particles at and above the suspended sediments mode size (15 μm) are effectively trapped in the gravels. While this might reflect a winnowing of sediment stored in the gravels, it is unlikely, as the other small particles sizes are maintained in the near bed flows. It more likely reflects a different initial size composition of the material that is settling or moving close to the bottom gravels.

Settling of fine sediment in the gravels is occurring both upstream and downstream of the effluent discharge. More intensive sampling in the gravels is continuing in order to determine if the observed increase in silts and clays downstream of the effluent diffuser is a repeatable and significant observation.

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