TRANSPORT CHARACTERISTICS OF FINE SEDIMENT IN THE FRASER RIVER SYSTEM

DOE FRAP 1998-15

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June 1998

Acknowledgements

The authors wish to acknowledge the logistical support for the field work provided by the B.C Ministry of the Environment and the Environment Canada, Pacific and Yukon Region. The financial support by the FRAP is gratefully acknowledged. The critical review of the manuscript by Dr. Jiri Marsalek, Project Chief, Non Point Sources of Pollution Project, Aquatic Ecosystem Protection Branch, NWRI and by Dr. Jim Maguire, Acting Director of the Aquatic Ecosystem Protection Branch of the National Water Research Institute is very much appreciated.

Abstract

In this report, the sediment transport studies undertaken in the Fraser river system as part of the FRASER RIVER ACTION PLAN are described. The studies consisted of field surveys and laboratory investigations. In the field surveys, the in-situ size distributions of the suspended sediments of the Fraser and Thompson rivers were measured using a laser device and were compared with the size distribution of the dispersed primary particles. From such comparisons, the flocculation state of the sediments was assessed. The laboratory investigations involved measurement of deposition and erosion rates of the river sediment under controlled conditions in the rotating circular flume of the National Water Research Institute. In addition, the influence of the pulp mill effluent on the flocculation mechanism of the sediment was also investigated in the laboratory. Based on the results of these investigations, a new mathematical model of the fine sediment transport was formulated for the Fraser river system.

Résumé

Dans ce rapport, on décrit, des etudes sur le transport des sédiments entreprises dans le bassin hydrographique du fleuve Fraser dans le cadre du PLAN D'ACTION DU FRASER. Ces études étaient composées de relevés sur le terrain et d'études en laboratoire. Au cours des relevés sur le terrain, on a mesuré a l'aide d'un appareil laser la distribution granulométrique *in situ* des sédiments en suspension du fleuve Fraser et de la rivière Thompson et on a comparé les résultats à la distribution granulométrique des particules primaires dispersées. Ces comparaisons ont permis d'évaluer le degré de floculation des sédiments. Les études en laboratoire, effectuées avec le canal jaugeur rotatif annulaire de l'Institut national de recherche sur les eaux, portaient sur la mesure des vitesses de sédimentation et d'érosion des sédiments des cours d'eau dans un milieu à conditions contrôlées. On a également étudié en laboratoire l'influence de l'effluent des usines de pâtes sur le mécanisme de floculation des sédiments. Les résultats de ces études ont permis de formuler un nouveau modèle mathématique du transport des sédiments fins pour décrire le bassin hydrographique du Fraser.

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Introduction

Sediment transport processes in rivers are governed by both the flow and the sediment characteristics. Among the sediment characteristics, the size distribution plays a major role. If the sediment is in the size class of sand and gravel, it is classified as non-cohesive sediment and its transport is characterized by discrete particles moving either as bed load or as bed load superimposed by the suspended load depending on the transport capacity of the river flow. The transport characteristics of such sediment had been studied extensively in the literature and a large body of knowledge exist to make predictions such as the critical flow condition for initiation of sediment motion, sediment transport rate, the characteristics of bed forms that are likely to form on the river bed and the energy drop over a section of a sediment transporting river flow. On the other hand, if the sediment is in the size classes of silt and clay, it is classified as cohesive sediment and its transport is characterized by the interactions among the sediment grains and the formation of sediment flocs depending on the flow turbulence and physical-chemical processes of sediment water mixture. The transport characteristics of the cohesive sediment were not very well studied and there are no generally accepted formulations for predicting the cohesive sediment transport behaviour in a river flow.

A thorough understanding of sediment transport processes in rivers is an essential prerequisite for assessing the impact of pollutants from industrial, agricultural and urban sources on the river ecosystem as the sediments interact with a large number of hydrophobic contaminants and serve as carriers of these contaminants through the river system. This is especially true for cohesive sediments because of their large specific surface area and high affinity for contaminants. In fact, a number of studies that examined the contaminant concentrations in Fraser River sediments (e.g. Mah et.al. 1989, Derksen and Mitchell 1994 and Sekela et al. 1994) have found concentrations of a suite of chemicals including dioxins, furans, PAH's and chlorophenolics in suspended sediments and the concentration values were higher in river-reaches downstream of pulp mills than those at the reference sites selected upstream of the pulp mills. Therefore, the transport of the contaminated sediment determines the fate of the contaminants and their interactions with the benthic organisms in the riverine environment. For example, deposition of the contaminated sediment in sections of the river, where the bed shear stress and turbulence level are low, could result in a temporary storage of the contaminants on the river bed and could impact on the bottom dwelling aquatic life and the other organisms connected by the food chain. The storage of the sediment and consequently the contaminants can either be short term or long term depending on the temporal changes in the transport capacity of the river flow. Therefore, it is important that we have a better understanding of the cohesive sediment transport behaviour under different hydraulic conditions of the river in order to improve our ability to predict the impact of these contaminants on the river ecosystem.

Predictions of contaminant impacts on the ecosystem of river and other environments are often carried out using contaminant transport models such as WASP5 (Ambrose et.al., 1991) and Simon Fraser University Model (Gobas, 1991) etc.. These models include a cohesive sediment transport component and require cohesive sediment transport parameters such as the settling velocity, the erosion and deposition rates and the critical hydraulic conditions for erosion and deposition of sediment. The quantitative and reliable estimates of these parameters are not currently available for the Fraser River sediments in spite of the fact that there has been an extensive research and monitoring efforts in the Fraser River system for the past two decades (McLean and Mannerstrom, 1985; Church et al., 1989; Church and Collett, 1993; Church and MacLean, 1994; Kostaschuk et al. 1989, 1992; Kostachuk and Church, 1993). The majority of these works were concerned with the transport of cohesionless coarse grain sediment and hence the cohesive, fine sediment transport processes in the Fraser River system remain largely unknown.

Under the FRASER RIVER ACTION PLAN (FRAP), a new sediment transport study was initiated to examine the transport characteristics of cohesive sediments of the Fraser and Thompson River system. The study consisted of both field measurements and laboratory investigations. Based on the results of these studies a new cohesive sediment transport model was formulated and implemented in the Simon Fraser University's food chain model that was calibrated for the Fraser River system under FRAP. Main conclusions of the sediment transport studies and the salient features of the new sediment transport model are summarised here.

Field Study

Four field surveys were carried out over a period of three years (October 1993 to October, 1996) and the sampling sites in each of these surveys and the survey dates are listed in Table 1 and are illustrated in Figure 1.

Table 1. Spatial and temporal coverage of the field study.

Sampling sites	October, 1993	October, 1994	April, 1995	October, 1995	October, 1996
Fraser at Northwood Bridge	X	X	X		X
Fraser at 30 m d/s NW outfall		X			X
Fraser at 100m d/s NW outfall		X			X
Fraser at 300m d/s NW outfall		X	X		X
Fraser at 1000m d/s NW outfall		X			X
Nechako at Prince George	X	X			
Fraser at Stoner	X	X			
Fraser u/s Quesnel	X	X			
Quesnel River at Quesnel		X			
Fraser d/s Quesnel		X			
Fraser at Margarette		X			
Fraser at Lilloet		X			
Fraser at Hope		X			
Fraser at Mission		X			X
North Thompson at Kamloops				X	
South Thompson at Kamloops				X	
Thompson u/s of Weyerhauser				X	
Thompson d/s Weyerhauser				X	
Thompson d/s STP outfall				X	
Thompson at Savona				X	

The sampling sites spanned from an upstream station at Northwood bridge to a downstream station at Mission. The objectives of the field study were twofold: 1) to measure the size distribution of the sediment in suspension and to determine if these sediments were transported in a flocculated form and, 2) to determine the influence of the pulp mill effluents on the flocculation of the river sediment. The size distributions were measured using a new laser instrument that was assembled at the National Water Research Institute in Burlington, Ontario, Canada (Krishnappan et al.1992). This instrument was capable of measuring the in-situ distribution of sediment in suspension without disrupting the flocs, unlike the traditional sampling method, which is often associated with the floc disruption due to sampling and/or analysis in laboratories. To assess the state of flocculation of the suspended sediment, the in-situ

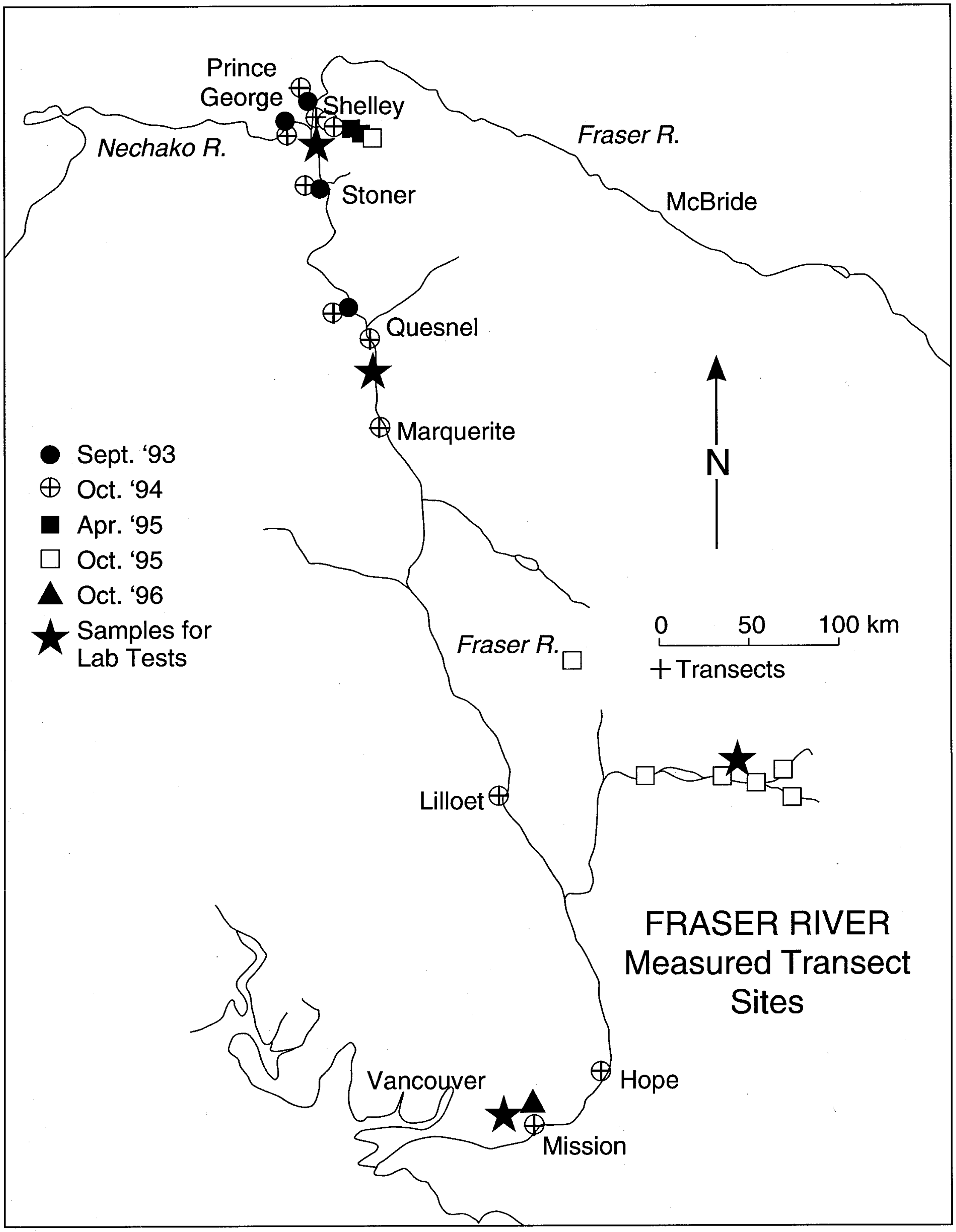

Figure 1. **Sampled transects in Fraser and Thompson rivers.**

distributions measured in the field were compared with the distributions of the primary particles measured by collecting samples and analyzing for size distribution using a laboratory particle size analyzer that operated on the same principle as the field instrument. The samples were sonicated to ensure total disruption of flocs for this analysis.

Comparisons of the in-situ and primary particle distributions are shown for some selected transects in Figures 2 to 9. Figure 2 is for the transect at Shelley, upstream of the Northwood pulp mill outfall. From this figure, we can see that the in-situ distributions and the primary particle size distributions are very close to each other, which is an indication that the sediment particles are not flocculated. In other words, the suspended sediment at this transect is transported as individual particles and the traditional theories of sediment transport that were formulated for the cohesionless sediments are applicable for this section of the river.

A very different result was obtained for the transect below the Northwood pulp mill outfall. Figure 3 shows the comparison of the two size distributions for the transect at 300 metres downstream from the pulp mill effluent outfall. From this figure, we can see that the in-situ distribution is coarser than the primary particle size distribution. The in-situ distribution consists of particles in the size classes of 205 and 384 microns, whereas the primary particle size distribution does not contain particles larger than 134 microns. On the finer end of the size spectrum, the in-situ distribution contains only about 12% of the particles in the size class of 3 microns, whereas the primary particle size distribution contains as high as 33% of particles in this size class. This is a clear indication that the sediment at this transect is flocculated and the flocculation is triggered by the presence of pulp mill effluent. To ascertain that this is not due to the presence of solid particles (bio-solids) in the effluent, the size distribution of the solids in the effluent was measured and is shown in Figure 4. From this figure, we see that the size distribution of the solids in the effluent is slightly coarser than the primary particles, but not as coarse as the distribution measured for the 300 m transect. Furthermore, the percentage of the coarser fractions is also small in comparison to the floc sizes in Figure 3. Therefore, the passive presence of the solids in the effluent alone would not account for the increased floc sizes measured at 300 m transect. The river sediment had to flocculate to produce large size fractions in such quantities (>200 microns at about 10% by volume of solids). Therefore, it was hypothesized that the pulp mill effluent had played a role of a coagulant and triggered the flocculation of the river sediment. This hypothesis was later tested in the laboratory.

Figure 5 shows the comparison of the in-situ and primary particle size distributions for the Nechako river at Prince George. The Nechako river is a tributary to the Fraser River and from Figure 5, it can be seen that the suspended sediment in this river is transported in the flocculated form. A relatively high organic content in the river is suspected to have contributed to the formation of sediment flocculation in this river. Figures 6 and 7 show the comparisons for the transects of the Fraser River at Stoner and at Quesnel and indicate that the sediments in these transects are also flocculated. Figures 8 and 9 show the comparisons for the transects at Lilloet and Mission respectively. Figure 8 shows only small differences between the two distributions and it is due to the fact that the flow velocities at this transect are very large and the that the flocs are unable to withstand the high shear stress associated with the high velocities in this transect and are broken up into constituent primary particles. The situation at Mission is just the opposite. The flow velocities are slow due to tidal effects and the flocs formed at this transect are much larger.

The results shown in Figures 2 to 9 are summarized in Figure 10, where the median sizes of the distributions are plotted for all the transects. From this figure and from the above discussion, we can draw the following conclusions:

1. The suspended sediments in the Fraser River upstream of pulp mills were transported as primary particles.
2. The suspended sediments in the Nechako River at Prince George were flocculated.
3. The pulp mill effluents promoted the flocculation of the suspended sediment in the river.
4. The size of the flocs was a strong function of the bed shear stress of the river flow.

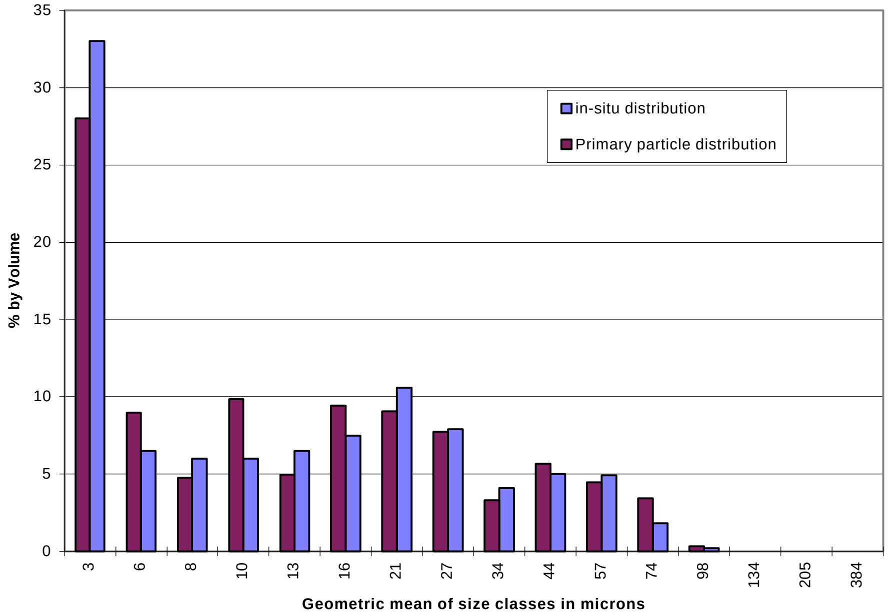

Figure 2. Comparison of *in-situ* and primary particle size distributions in the Fraser river near Shelley.

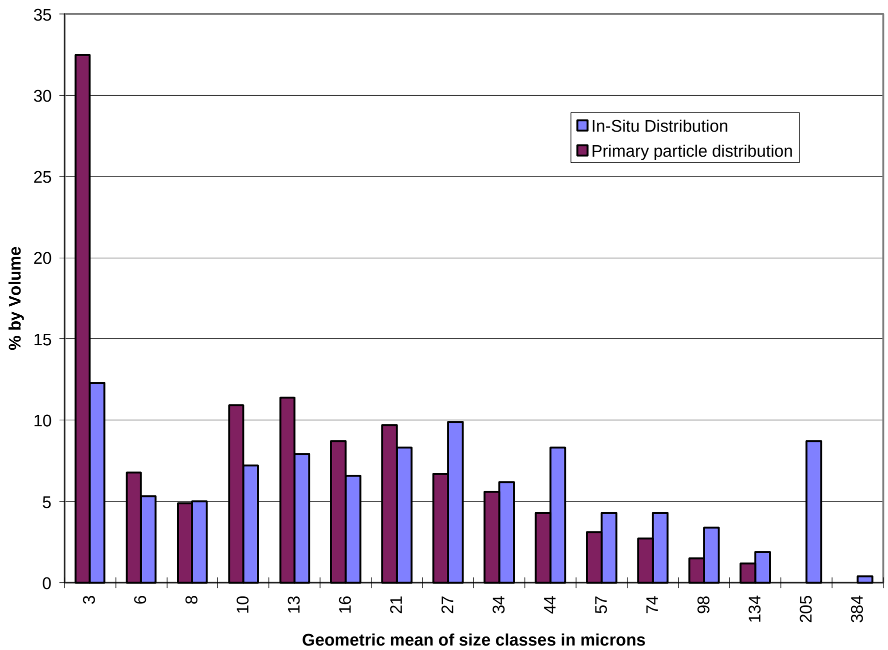

Figure 3. Comparison of *in-situ* and primary particle size distributions in the Fraser river at the Northwood pulp mill-300m downstream of outfall.

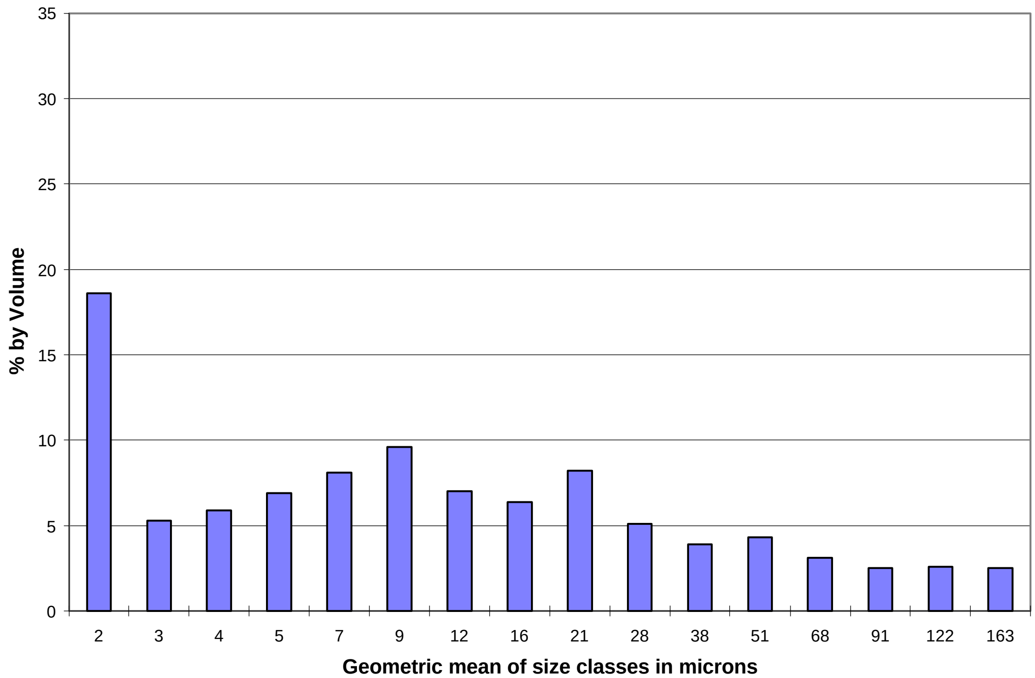

Figure 4. Size distribution of Northwood pulp mill effluent.

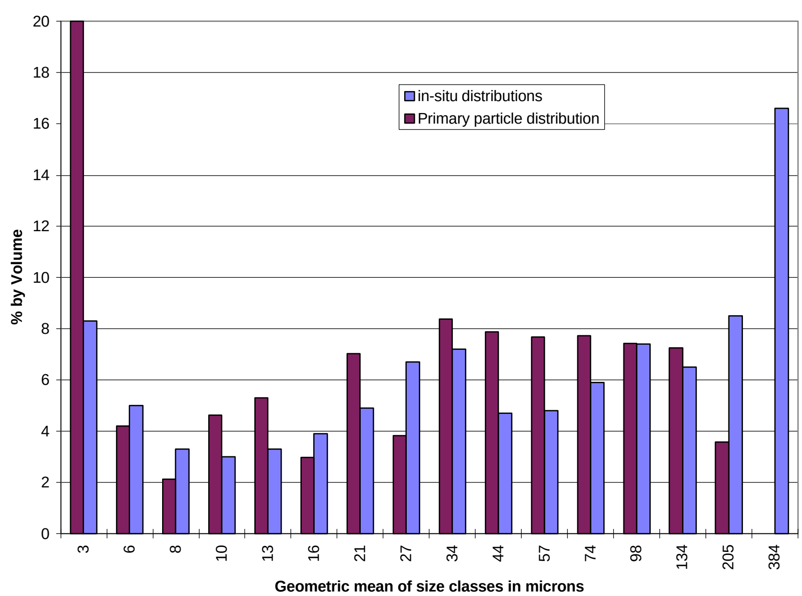

Figure 5. Comparison of *in-situ* and primary particle size distributions in the Nechako river at Prince George, B.C.

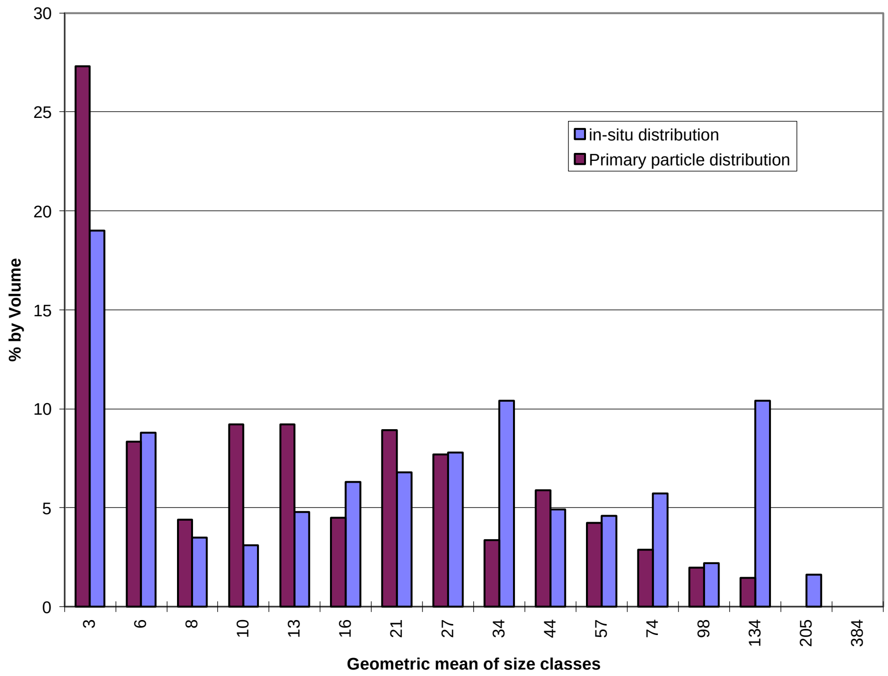

Figure 6 Comparison of *in-situ* and primary particle size distributions in the Fraser river near Stoner.

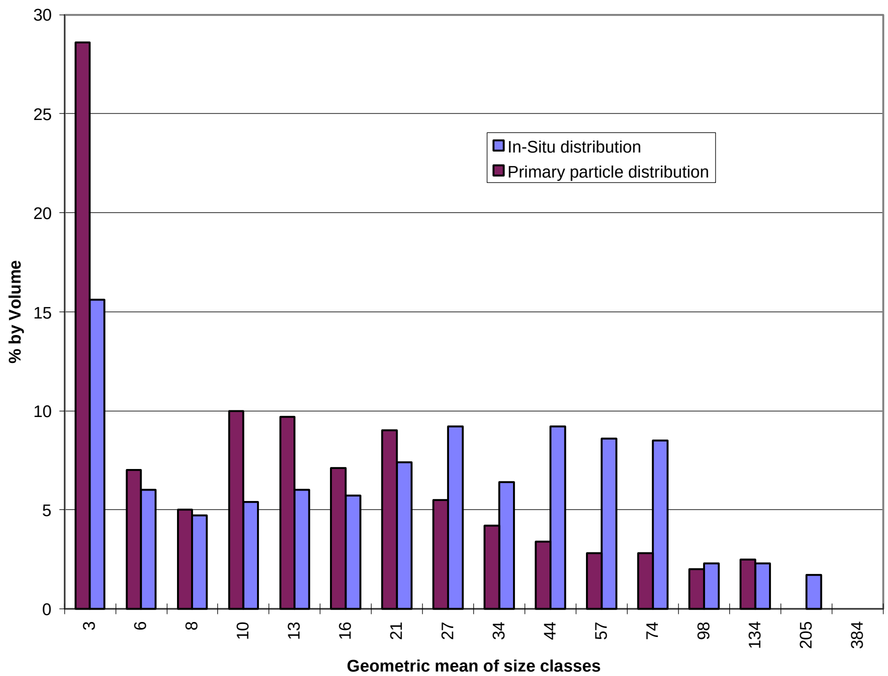

Figure 7. Comparison of *in-situ* and primary particle size distributions in the Fraser river near Quesnel.

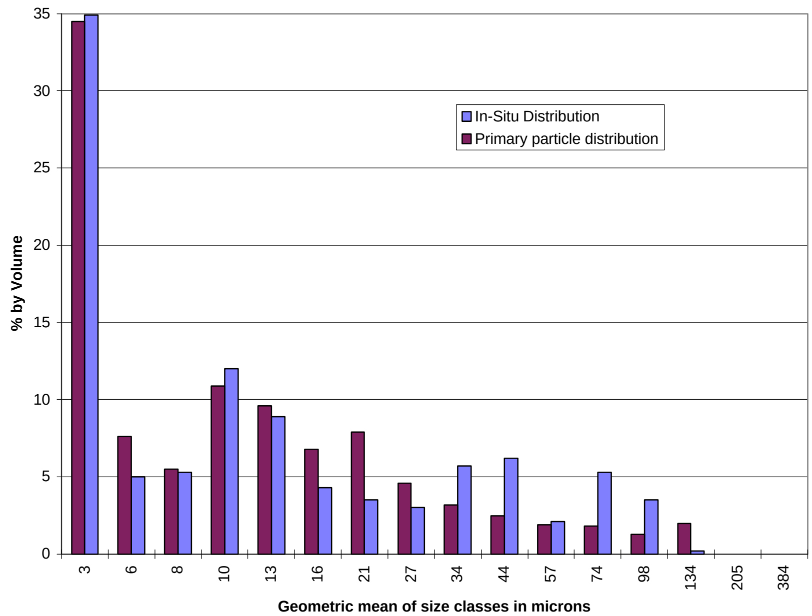

Figure 8. Comparison of *in-situ* and primary particle size distributions in the Fraser river near Lilloet.

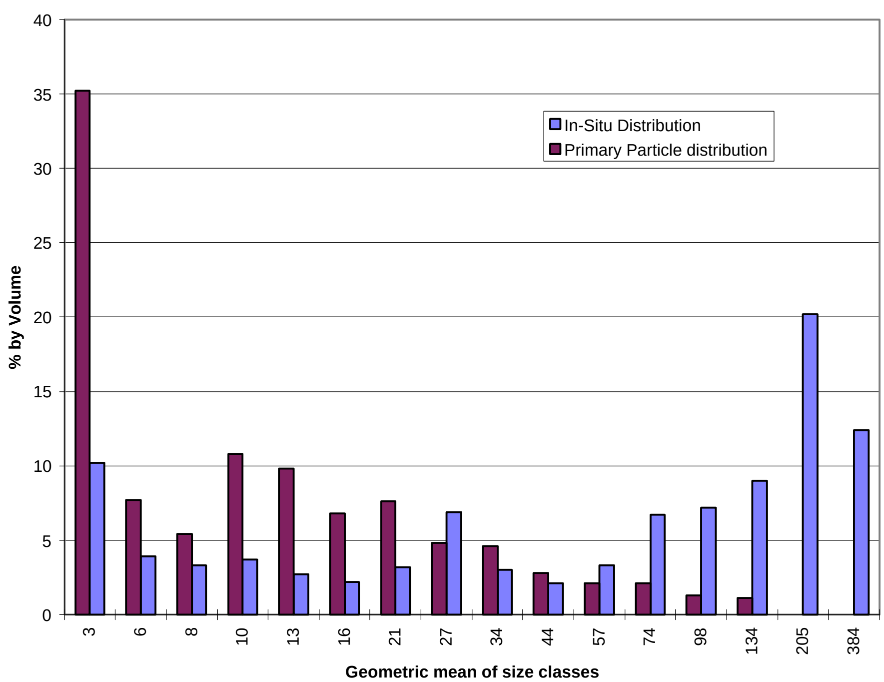

Figure 9. Comparison of *in-situ* and primary particle size distributions in the Fraser river near Mission.

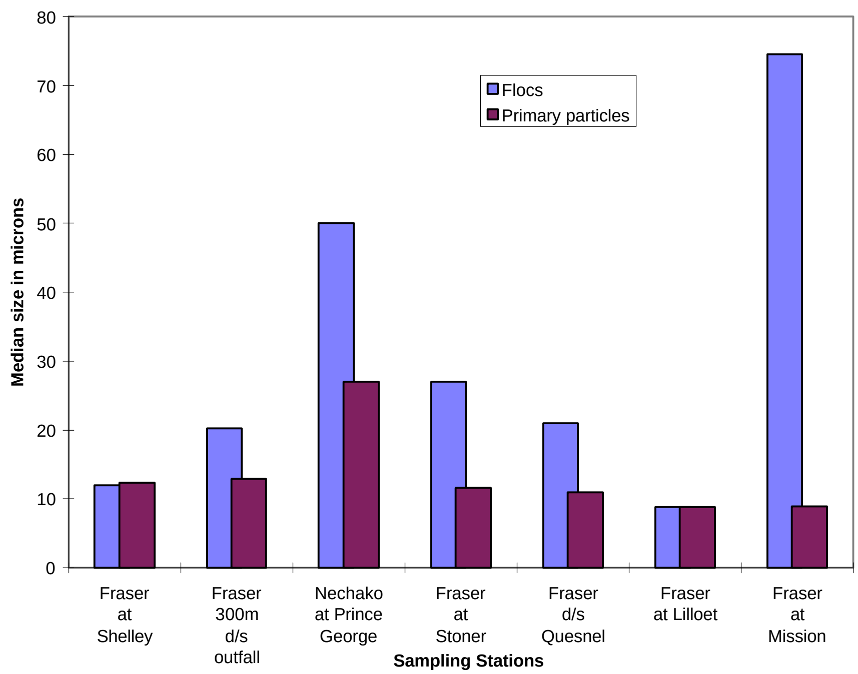

Figure 10. Floc and primary particle sizes in the Fraser river.

From the field surveys, it became apparent that the suspended sediments of the Fraser River downstream of Northwood pulp mill are transported as flocculated sediment and behave in a manner similar to cohesive sediments and hence the traditional cohesionless sediment transport theories are not applicable for these sediments. Their transport characteristics, therefore, have to be determined in the laboratory using special flumes such as a rotating circular flume and site specific sediments.

Laboratory Study

With the current state of knowledge on the cohesive sediment transport, the transport parameters of the cohesive sediment can only be obtained through direct measurements in special flumes such as a rotating circular flume. The Fraser River sediments, therefore, were tested in the Rotating Circular Flume of the National Water Research Institute at Burlington, Ontario, Canada. For these tests, sediment-water mixtures from different reaches of the Fraser River system were brought to the National Water Research Institute and the deposition and erosion processes of the sediment and their interaction with the effluent from the pulp mills were studied in the flume. A brief discussion of the testing procedure and the results are outlined below:

The Rotating Circular Flume of the National Water Research Institute consists of a circular flume, which is 5.0 m in mean diameter, 30 cm wide and 30 cm deep resting on a rotating platform, which is 7.0 m in diameter and a rotating lid which fits inside the flume with close tolerances. By rotating the flume and the lid in opposite directions at different speeds, it is possible to generate different flows with characteristics similar to flows in straight, uniform channels. Complete details of the flume can be found in Krishnappan (1993).

The deposition characteristics of the Fraser River sediment were studied by placing the sediment-water mixture in the flume and operating the flume at different speeds to simulate different flow conditions. At each speed, the flume was operated for a period of about four hours. During this time, the concentration of sediment in suspension and the size distributions were monitored as a function of time. The concentration results from a typical deposition test is shown in Figure 11.

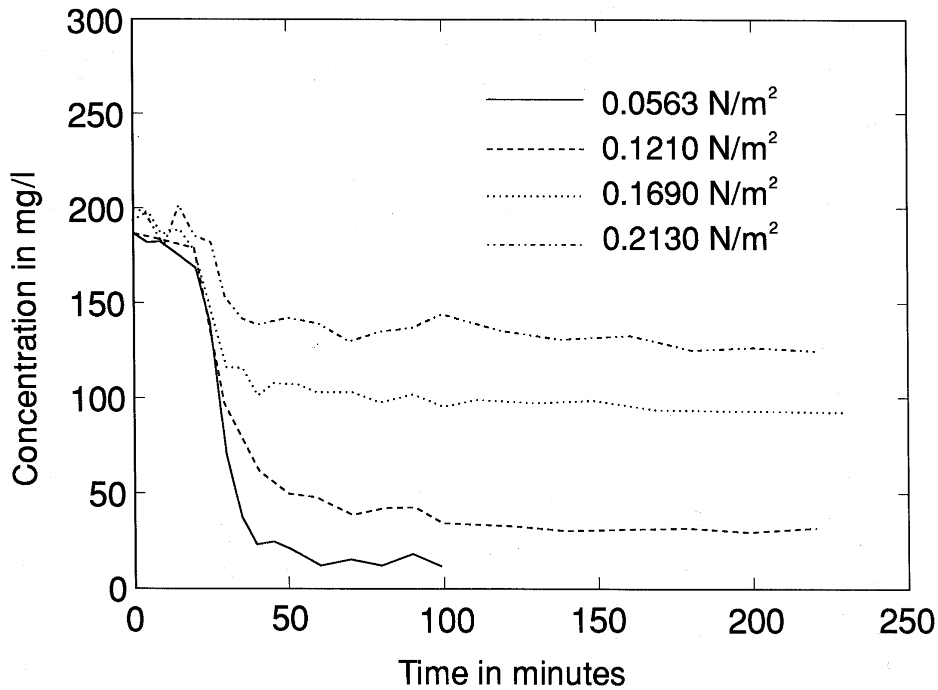

Figure 11. Variation of concentration for different shear stresses.

This figure shows that for a particular bed shear stress, the concentration drop is steep in the beginning and it levels off gradually leading to an eventual steady state concentration. It has been demonstrated by earlier studies that the attainment of a steady state concentration during a deposition of a cohesive sediment is due to the fragility of the flocs and their inability to penetrate the high shear stress region near the bed and reach the river bed. This implies that when a known amount of cohesive sediment enters the river, a fraction of that sediment will deposit and the remaining fraction will stay in suspension indefinitely. The fraction that will stay in suspension indefinitely is a function of the bed shear stress of the river flow. The deposition experiments, therefore, provide quantitative estimates of amount of sediment that would deposit under a particular bed shear stress given the initial amount of sediment that had entered the river reach.

The re-suspension potential of the deposited sediment was also studied using the rotating flume. For these tests, the sediment was allowed to deposit on the flume bottom over a known period of time and then the erosion characteristics were studied by applying the bed shear stresses in step increments. At each step, the concentration of the eroded sediment and their size distributions were measured as a function of time. A typical result from an erosion test is shown in Figure12.

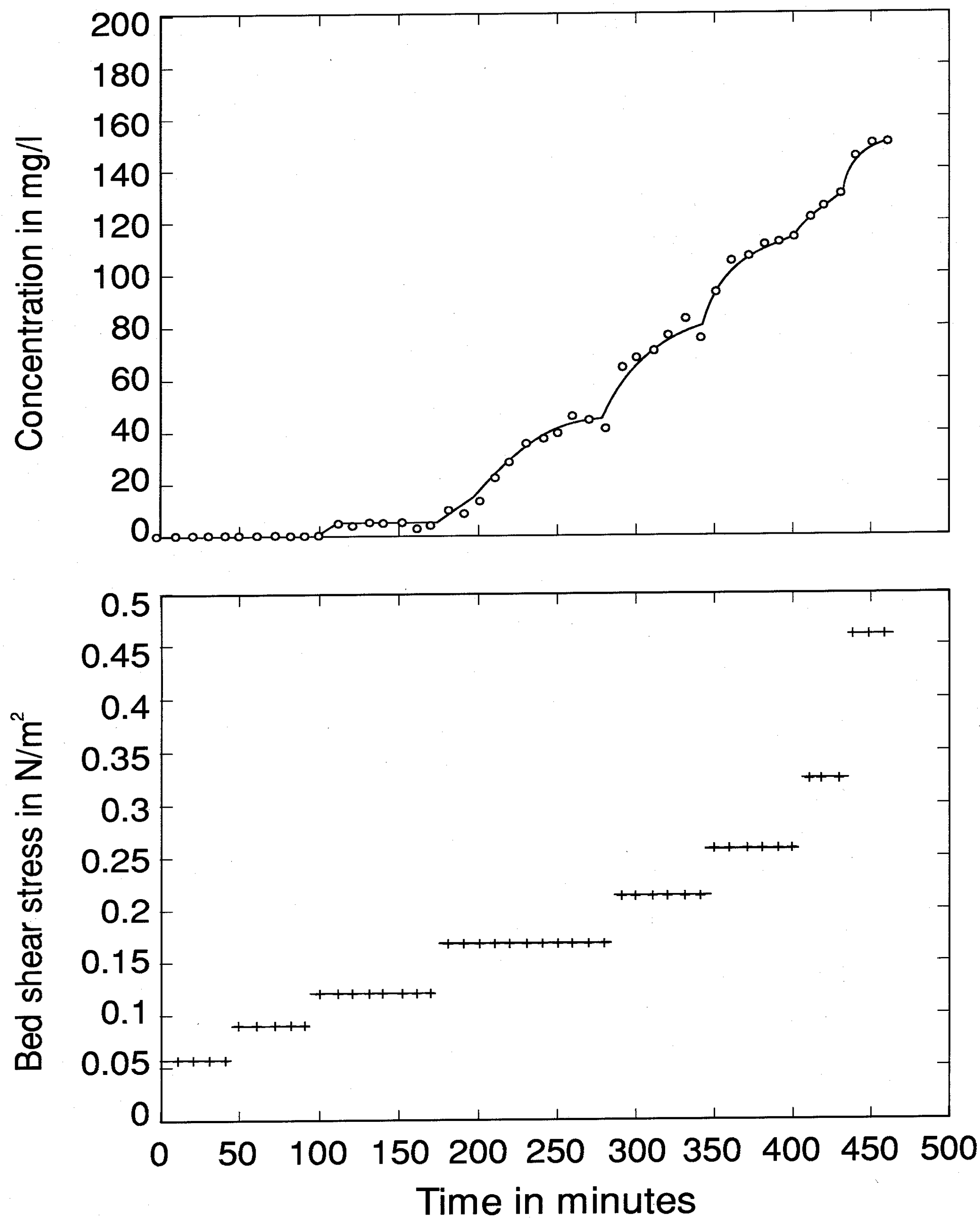

Figure 12. Erosion characteristics of the Fraser river sediment.

From such results, we could conclude that the critical shear stress for erosion of the sediment was larger than the shear stress at which the deposition of that sediment occurred. This can be explained on the basis of cohesion between the depositing sediment and the sediment that is already on the bed and the consolidation process. The erosion tests also provide quantitative estimates of the amount of sediment that can be re-suspended knowing the deposition history of the sediment. The details of this study can be found in Krishnappan and Engel (1997).

Interaction with Pulp Mill Effluent

The effect of pulp mill effluent on the transport characteristics of Fraser and Thompson river sediments was studied using the flume as follows: Large volume samples of sediment-water mixtures (500 litres) from the Fraser and Thompson rivers and effluents from Northwood and Weyerhauser pulp mills were brought to the laboratory and deposition experiments were performed with and without the pulp mill effluents. A typical deposition experiment involved placing a known concentration of the sediment in the flume and operating the flume at high speed (flume speed = 2 rpm and ring speed = 2.5 rpm) for twenty minutes to thoroughly mix the sediment-water mixture. The flume speed was then lowered to the desired value and was operated at this speed for about three to five hours. During this time, the concentration of the suspended sediment and the size distributions were monitored as a function of time. In addition, samples of the sediment were collected for microscopic analysis. The experiment was then repeated with a known amount of effluent added to the flume. For the Fraser river water, 15 litres of Northwood effluent was added to give a volume concentration of 3% and for the Thompson river water, 25 litres of Weyerhauser effluent was added to give a volume concentration of 5%, which are the representative concentrations in the field during low flows.

Figure 13 shows the variation of suspended sediment concentration in the water column as a function of time during the deposition of the Fraser River water-sediment mixture with and without the North wood pulp mill effluent. The operating shear stress for these tests was 0.056 N/m^2.

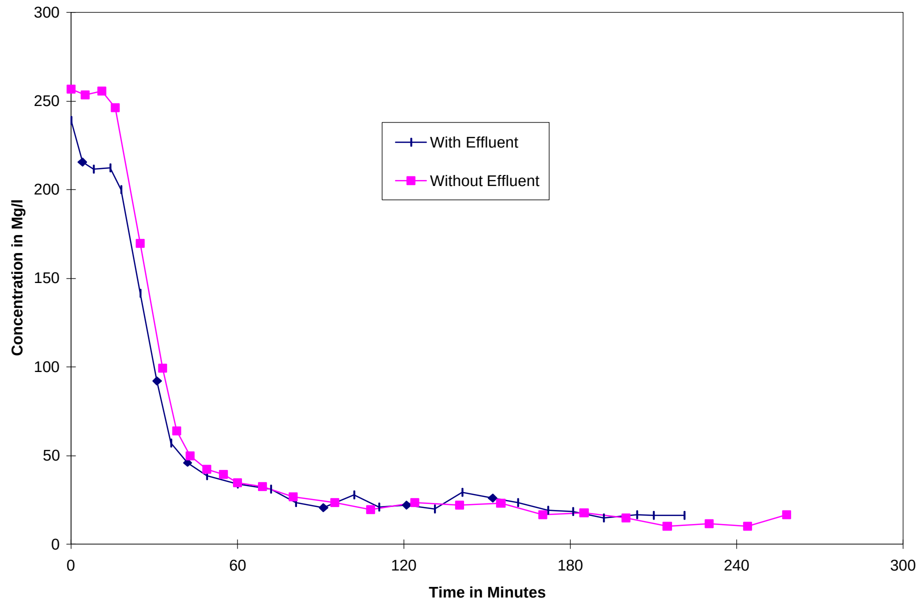

Figure 13. Concentration vs time during deposition with and without effluent. Fraser river sediment; Shear stress=0.056 N/m^2.

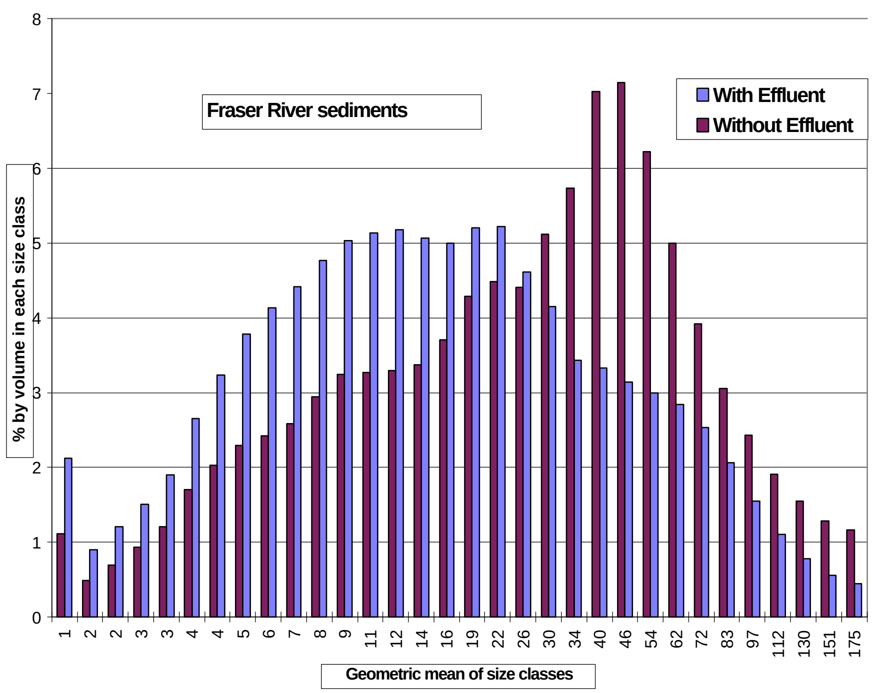

Figure 14a. Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time=50 minutes.

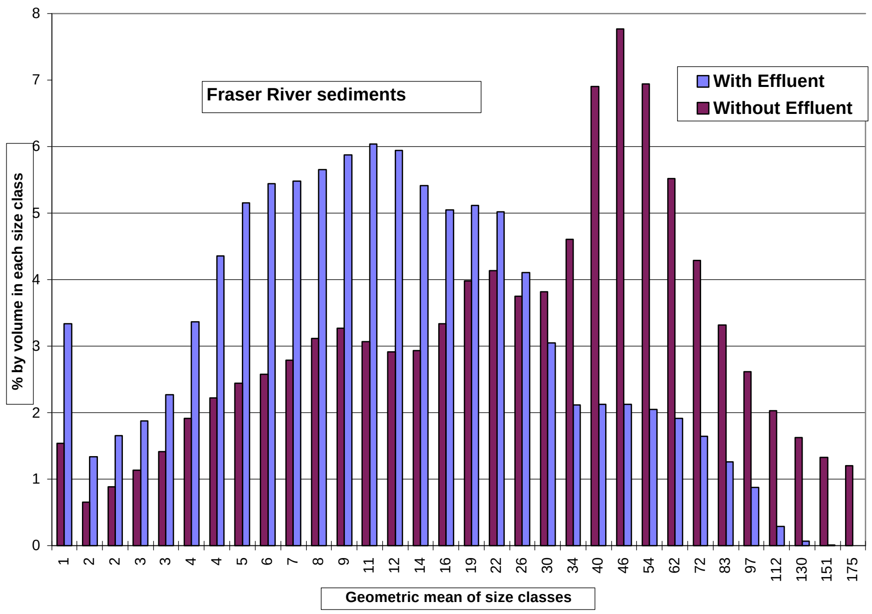

Figure 14b. Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time = 100 minutes.

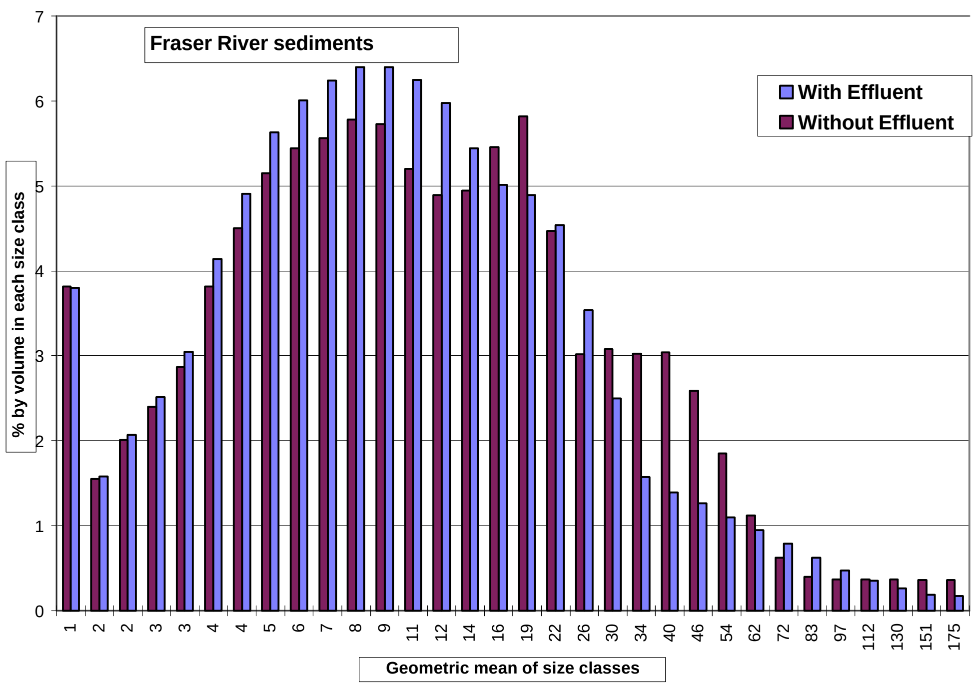

Figure 14c. Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time = 150 minutes.

From this figure, we can see that the sediment deposition had been enhanced by the addition of the pulp mill effluent to the system. The suspended sediment concentration for the test with the effluent was lower than that for the test without the effluent. The difference was the largest at the beginning of the experiment and as the steady state concentration was approached, the difference decreased and practically vanished. However, the net effect of the effluent was to increase the amount of deposited sediment. This increase was computed from Figure 13 as 15% including the solid fraction of the added effluent. It should be noted that the pulp mill effluent was added to the flume prior to the high speed operation of the flume. The high shear stress generated during the high speed operation was unable to maintain in suspension as much sediment as it did for the test without the effluent because of the enhanced flocculation due to the effluent.

The size distributions measured during the two tests are shown in Figures 14a, 14b and 14c. Figure 14a shows the distributions for the elapsed time of 50 minutes. Figs14b and 14c are for elapsed times of 100 min and 150 min respectively. From these figures, we can see that the deposition characteristics of sediment in different size classes are affected by the addition of the pulp mill effluent. At 50 and 100 minute marks, the size distribution of the sediment in suspension is finer for the test with effluent in comparison to that without the effluent. The coarser fractions have settled when the effluent was added, which suggests that the flocculation in the presence of pulp mill effluent had produced stronger flocs that were able to penetrate the high shear region near the bed and deposit to the bed. Sediment without the effluent, on the other hand, contains larger, but weaker flocs in suspension and requires longer duration to deposit to the bed.

Similar results were obtained for the Thompson river sediments. These results are shown in Figures 15 and 16a, 16b and 16c.

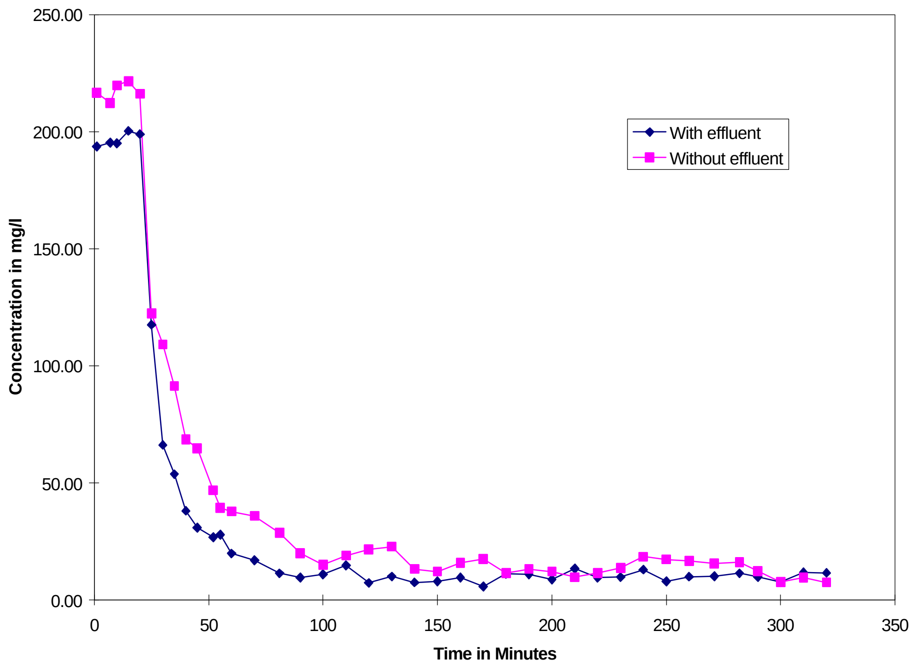

Figure 15. Concentration vs time during deposition with and without effluent: Thompson river sediment. Shear stress = 0.121 N/m^2.

Figure 15 shows the variation of suspended sediment concentration in the water column as a function of time during the deposition with and without the pulp mill effluent. The operating shear stress for this case was 0.121 N/m^2. From this figure, we again see that the sediment deposition had been enhanced by the addition of the pulp mill effluent to the system and the effect is very much similar to that observed for the Fraser river sediment shown in Figure 13. In this case, however, the amount of increased deposition was higher. The net deposition computed from Figure 15 showed an increase of 30% due to the effluent addition. The size distributions measured during the deposition tests are shown in Figures 16a to 16c. Again the effect of the pulp mill effluent is apparent and the behaviour of the sediment fractions were similar to those of the Fraser sediments.

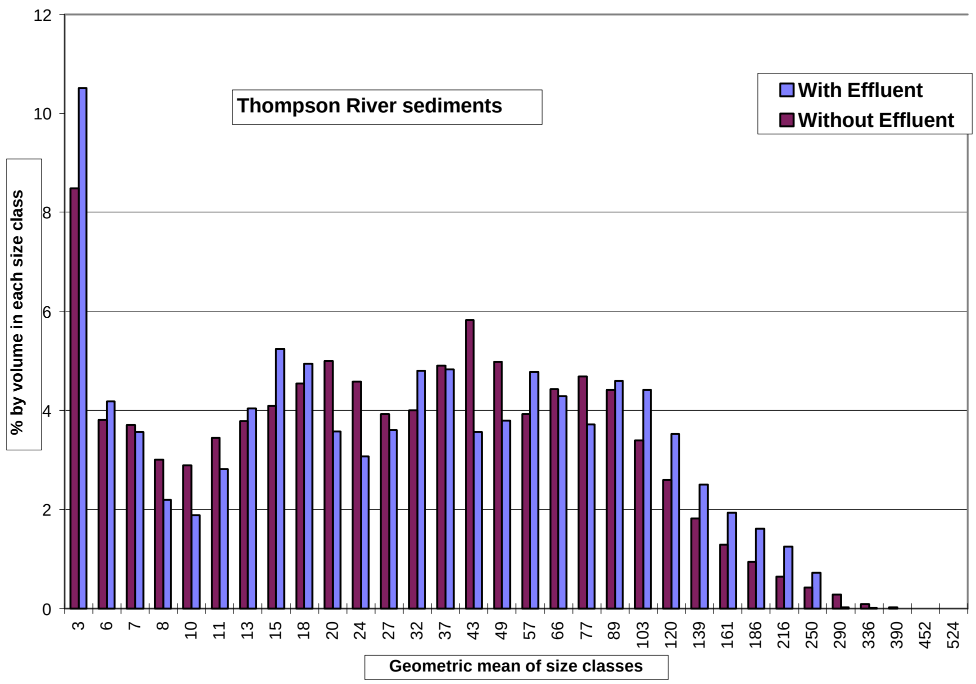

Figure 16 a. **Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time= 50 minutes.**

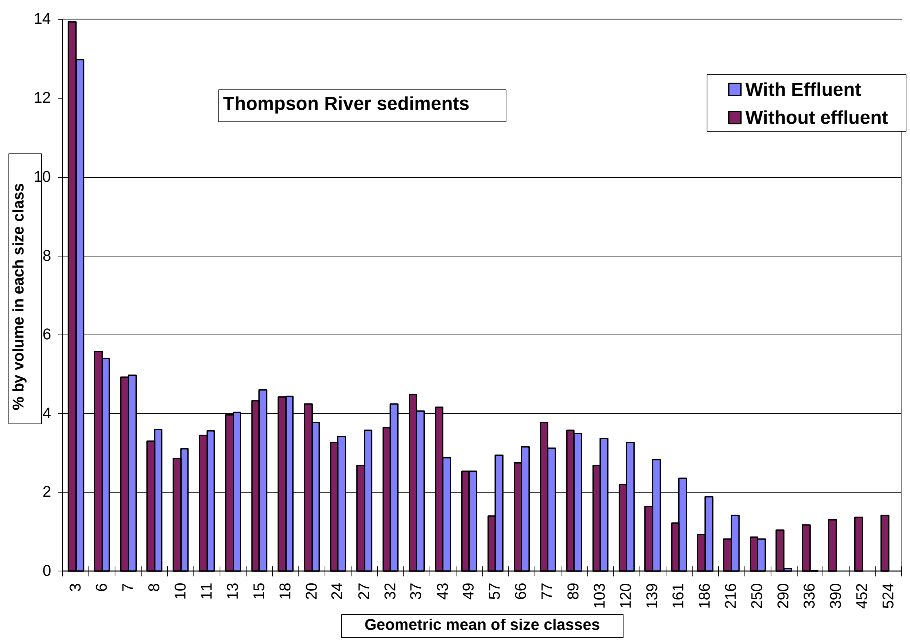

Figure 16 b. **Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time = 150 minutes.**

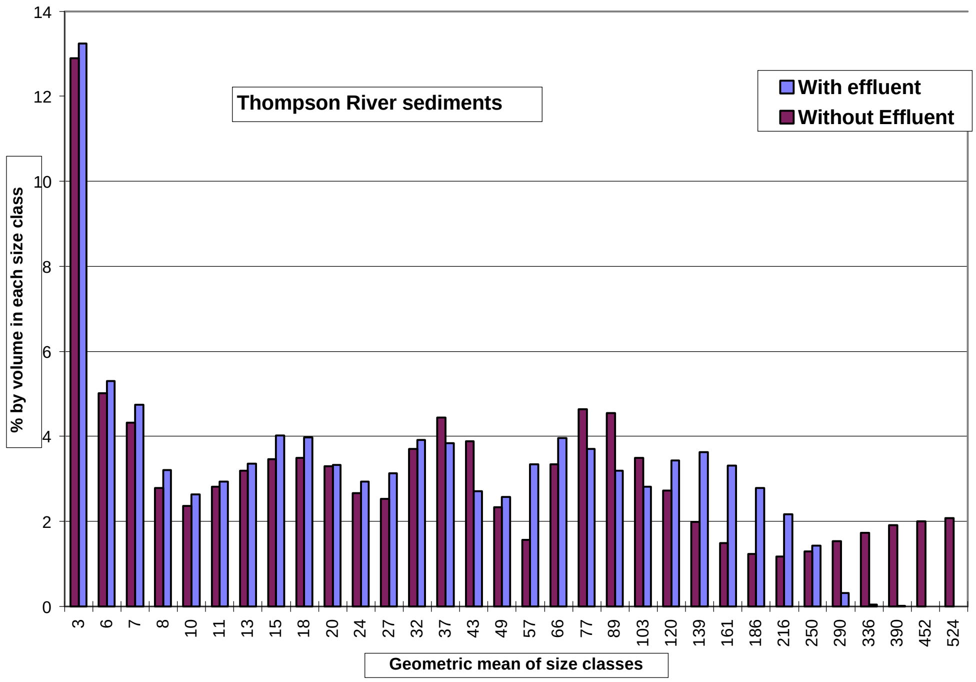

Figure 16 c. **Size distribution of suspended sediment flocs during a deposition experiment: Elapsed time = 300 minutes.**

The microscopic observations provided some insight into the structure of the flocs formed in the presence of effluents. A typical view of a fibrous material in the effluent and a typical floc formed around the fibrous material are shown in Figure 17a and 17b respectively. The fibrous materials that are present in the effluent could carry contaminants and by themselves are not capable of depositing onto the river bed because of their low density and settling velocity. But, when the inorganic particles are attached to the fibres, then they could deposit even under moderate flows in the river. The presence of the fibrous and organic material of the effluent provides the necessary flocculation sites and promotes the flocculation of the inorganic particles constituting the river sediment.

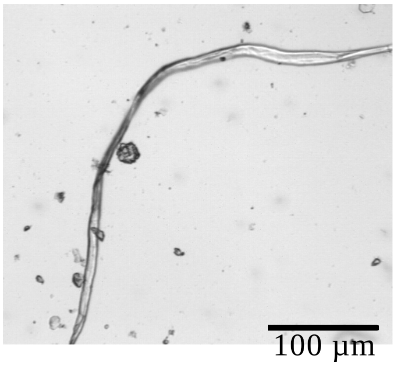

Figure 17 a. Microscopic image of a fibrous material in a Northwood Pulp mill effluent.

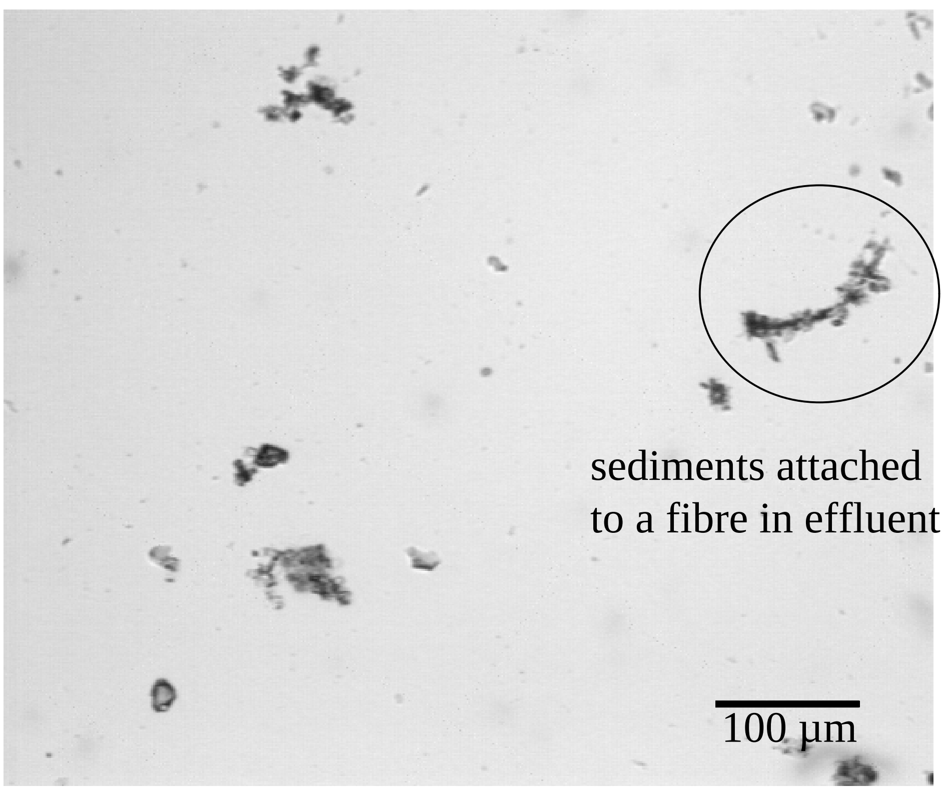

Figure 17 b. Microscopic image of a floc formed around a fibre in the Northwood Pulp mill effluent.

Mathematical Model of Cohesive Sediment Transport

The deposition and erosion experiments in the rotating flume provide quantitative estimates of the fraction of sediment that would deposit and a fraction of the deposited sediment that would re-suspend under a particular flow condition in the river. From these experiments, empirical relationships were developed to quantify these fractions in terms of the bed shear stress and a critical shear stress for deposition (i.e. the shear stress at which all of the initially suspended sediment will eventually deposit). These relationships were then applied for a control reach in the river to establish the mass balance and to route the sediment that is introduced into the river through a number of tributaries and other sources. The details of the model formulation are given in Krishnappan (1997).

Summary

The cohesive sediment transport research initiated under FRAP has shed some new light into the flocculation mechanism of the suspended sediment in the Fraser River. It also has provided quantitative estimates for sediment deposition and erosion processes and thereby facilitated the formulation of a new sediment transport model for the Fraser River system. The effects of the pulp mill effluent on the fine sediments of the Fraser and Thompson rivers were studied in the field and in the laboratories. These studies indicate that the pulp mill effluent has influenced the flocculation behaviour of the river sediments and their deposition characteristics. Laboratory experiments carried out in a rotating circular flume showed that the increased deposition rate can be as high as 30% under certain shear stress conditions.

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