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SEDIMENT SOURCES, TRANSPORT PROCESSES, AND MODELING APPROACHES FOR THE FRASER RIVER

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A thorough understanding of sediment sources and transport processes in rivers is essential to assessing the impact of pollutants from industrial, agricultural and urban sources on the aquatic ecosystem. Sediments interact with a large number of contaminants and serve as carriers of these contaminants through the river system. This is especially true for fine-grained sediments because of their large specific surface area and high affinity for contaminants. Unlike sand-sized sediments, fine clays and silts are also cohesive, which further complicates their behaviour. Hence, knowledge about the transport and cohesive characteristics of fine sediments is required to better understand their role in contaminant transport and in shaping riverine habitats.

In a number of investigations of contaminant concentrations in Fraser River sediments (*e.g.* Mah *et al.* 1989, Derksen and Mitchell 1994, and Sekela *et al.* 1995), concentrations of a suite of chemicals in suspended and bed sediments, including dioxins, furans, polycyclic aromatic hydrocarbons and chlorophenolics, were observed to be higher in river reaches downstream of pulp mills than those at the reference sites upstream of the pulp mills. The transport of the contaminated sediment, then, determines to a large degree the fate of the contaminants and their interactions with benthic organisms in the riverine environment. For example, deposition of contaminated sediment in sections of the river, where the bed shear stress and turbulence level are low, results in a temporary storage of the contaminants on the riverbed and could expose bottom-dwelling aquatic life and the other organisms connected by the food chain to these contaminants.

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. In order to improve our ability to predict the impact of these contaminants on the river ecosystem, it is important that we have a better understanding of the cohesive sediment transport behaviour under different hydraulic conditions of the river.

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 EcoFate (Gobas *et al.* 1999). Unfortunately, these models do not include cohesive sediment transport sub-models. However, even if these were available, the data requirements are large and include settling velocity, shear stress and flow relationships, erosion and deposition rates, and critical shear stresses for erosion and deposition of the cohesive sediments. Reliable quantitative estimates of these parameters are not currently available for Fraser River sediments.

For the past two decades, sediment studies in the Fraser River system have been concerned with the transport of cohesionless coarse-grained sediment (see for example: McLean and Mannerstrom 1985; Church *et al.* 1989; Church and MacLean 1994; Kostaschuk *et al.* 1989, 1992; Kostachuk and Church 1993). The work described in this chapter begins to address the data gaps on cohesive sediment and incorporates aspects of coarse-grained sediment dynamics, which influence the processes controlling the erosional and depositional environments for both kinds of sediment. The chapter first considers the sources and annual regime of fine sediment transport in the river. It then reviews historical data collected by Water Survey of Canada on sediment concentrations, load, and some limited characterization of sediment types. It continues with a description of field and laboratory observations of the behaviour of Fraser sediments, and concludes with a discussion of the possibilities for predicting sediment transport and fate.

SEDIMENT SOURCES AND LOADING

The quantity and timing of sediment delivered to a river are determined by the distribution of runoff to the river and the location and character of sediment sources in the drainage basin. As most of the Fraser drainage basin is alpine or plateau country, with elevations near or above 1,000 m, snowmelt in spring gives rise to the major hydrological event, locally called the "freshet." Figure 1 illustrates the dominance of the freshet on the annual discharge pattern, with the river starting to rise in early April and peaking anytime in June. The average sediment concentration tends to peak earlier than the discharge and the loading curve peak occurs between the concentration and discharge peaks.

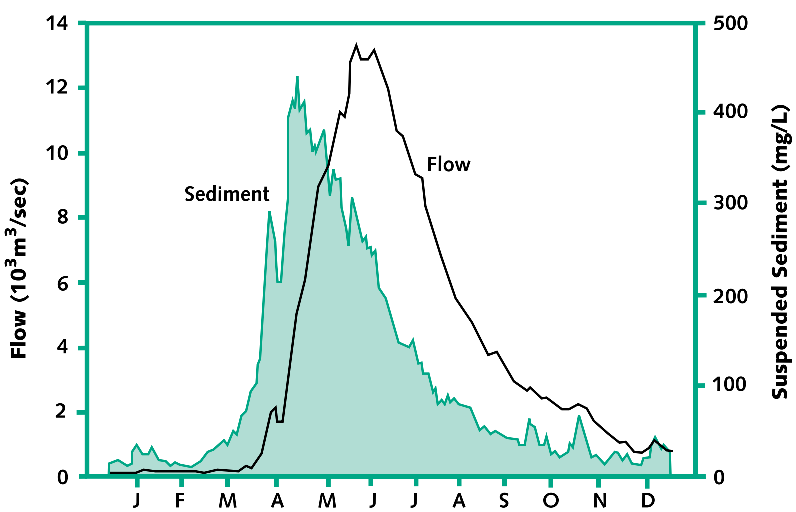

Figure 1. Hydrograph and suspended sediment concentration graphs for Fraser River at Agassiz (Water Survey of Canada Stn. 08MF035), 1972 daily observations. This was an unusually large freshet. The peak of sediment concentration leads the peak flow as a consequence of seasonal exhaustion of readily available sediment along the stream channels as flow increases toward its highest level.

Upland areas in the drainage basin are not prolific sediment sources today. In the high mountains, the main points of sediment production—alpine glaciers, rockfall cliffs and avalanche slopes—are poorly connected with the river channel network. Many alpine streams, which do carry significant sediment loads, drain to lakes in the Fraser headwaters that trap most of the material. In such a large and thinly populated basin, land use is unlikely to have affected overall sediment yield significantly. Thick valley fills of glacial deposits along the Fraser River and its principal tributaries supply the main sediment load of the river directly from the river banks. It is expected, then, that annual sediment yield should reflect the size of the main spring runoff and the amount of bank scour along the main channels, so that long term variations in sediment yield should follow a pattern similar to that for flows. The relation is confirmed by observations at Mission, the lowermost long-term gauge on the river (Fig. 2). The total sediment yield of the basin averages 18.5 million tonnes per year. In comparison with some other large rivers, this is only a modest yield (Table 1). The limited distribution of sources and modest erosion activity are reasons for the low yield.

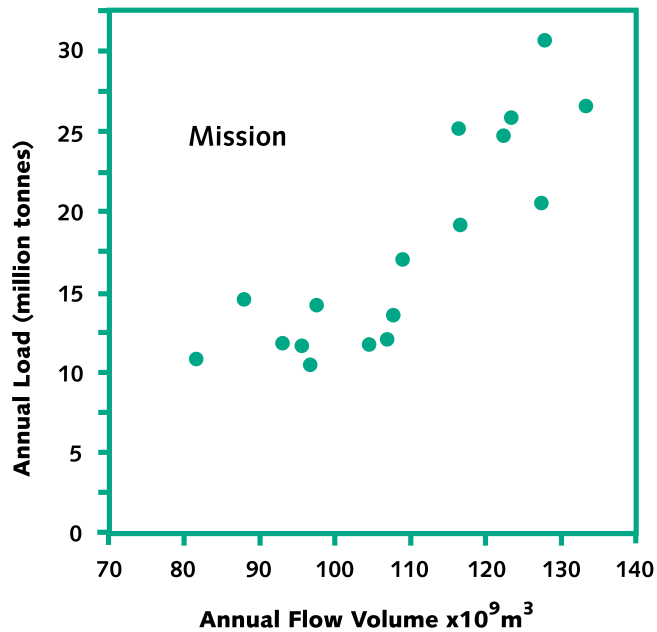

Figure 2. Correlation between annual suspended sediment load and annual flow volume, Fraser River at Mission (Water Survey of Canada Stn. 08MH024).

Table 1. Sediment yield of some large rivers.

RIVER	DRAINAGE AREA (10^3 km²)	ANNUAL FLOW VOLUME (10^9 m³/yr)	ANNUAL SEDIMENT YIELD (10^6t/ yr)	SPECIFIC SEDIMENT YIELD (t/km².yr)	MEAN SEDIMENT CONCENTRATION (mg/L)
Fraser R. at Mission	214	112	18.5	86.4	165
Chilliwack R.	1.23	2.33	0.130	106	55.8
Columbia R. at Birchbank[1]	88.1	69.5	7.07	80.3	101
Peace R. at Peace River	186	58.6	44.1	237	753
Liard R.	277	75.1	42.5	153	566
Mackenzie R.	1,810	306	100	55.2	327
Rhone R.	90	49	10	111	204
Amur R. (Asiatic Russia)	1,850	325	52	28.1	160
Amazon R.	6,150	6,300	900	146	143
Huang Ho R.	770	49	1,080	1,400	22,000

[1] *Before dam construction.*

The majority of sediment transported in large rivers consists of fine particulate materials suspended in the water column, as opposed to material moving over the bed. The Fraser River is quite typical. At Mission, the lowermost hydrometric station on the river, 99.4 per cent of the sediment load consists of suspended sand, silt and clay, the balance being sand moving on the bed. The division of the load at Mission, in terms of the primary particle sizes, is about 16 per cent clay (very fine material less than 0.002 mm in diameter), 49 per cent silt (material up to 0.063 mm in diameter), and 35 per cent sand. All the gravel and cobbles are deposited in the river before it reaches Mission but constitute only one per cent of the load upstream. The predominance of silt in Fraser River is a bit unusual; most large rivers carry a relatively larger proportion of clay. The reason is the character of the source sediments along the river, which consist of rock grains that were mechanically broken under the influence of freezing and glacial grinding.

Because direct bank erosion constitutes the major source of sediment to the river, its mobilization is related to flows in the river. Hence there is a reason to expect regular behaviour of the sediment regime—perhaps predictably regular. The ability to predict the fine sediment transport in the river would be a substantial advantage in any water quality model.

The set of observations available to study the sediment transport regime of the river consists of regular measurements of suspended sediment concentration undertaken by the Water Survey of Canada at six principal observing stations along the river (Fig. 3) between 1966 and the present day. Records at individual stations vary from 16 to 30 years (Table 2). This represents a remarkably detailed record in comparison with that available for most rivers—the Fraser is one of the best-monitored major rivers of the world. It is the object of the following sections to present an analysis of the relation of flow to sediment transport and to evaluate its potential usefulness in contaminant transport and fate models, such as that developed for the Fraser and Thompson rivers (Gobas *et al.* 1999).

Table 2. *Principal hydrometric and suspended sediment observing stations on the Fraser River, with the period of record for various measurements.*

STATION (WSC[1] NO.)	DRAINAGE AREA (km²)	DISCHARGE RECORDS	SEDIMENT YIELD	SUSPENDED SEDIMENT LOAD PARTICLE SIZE		BED MATERIAL PARTICLE SIZE
				P1	D1	
Hansard (08KA004)	18,000	1952–1996	1972–74	1972–74	1972–74	1973–74
			1976–86	1976–78	1976–81	1979
					1984–86	
Marguerite (08MC018)	114,000	1950–1996	1971–86	1971–79	1971–86	1973–79
				1983–84		
Hope (08MF005)	217,000	1912–49 MC	1965	1965	1965	
		1950–96 RC	1966–69	1967–68	1966–69	
			1970–79	1970–78	1970–79	
Agassiz (08MF035)	217,870	1949–50 MS*				
		1951–55 RC*				
		1956–64 MC*	1966		1966	
		1965 RC*	1970–79	1968	1967–69	
		1966 RS	1970–79	1970–79	1970–78	1970–79
		1967–86 RC	1980–84	1981–84	1980–84	
Mission (08MH024)	228,000	1876–1935 MS*	1965	1965	1965	1965
		1936–64 RC*	1966–71	1966–68	1966–71	1966–71
		1965–96 RC	1972–80	1972–79	1972–80	1972–80
			1981–96	1981–96	1981–96	1982
Port Mann (08MH054)	232,000	1956–71 RC*	1965	1968	1966	
			1966–72	1970–79	1967–78	1965–78
				1981–84	1980–84	

M = manual observations
R = recorded observations
S = seasonal operation
C = continuous operation
** = stage data only*
PI = point-integrated samples
DI = depth-integrated samples
Miscellaneous additional samples have been taken in other years.
[1] WSC denotes Water Survey Canada (Environment Canada)

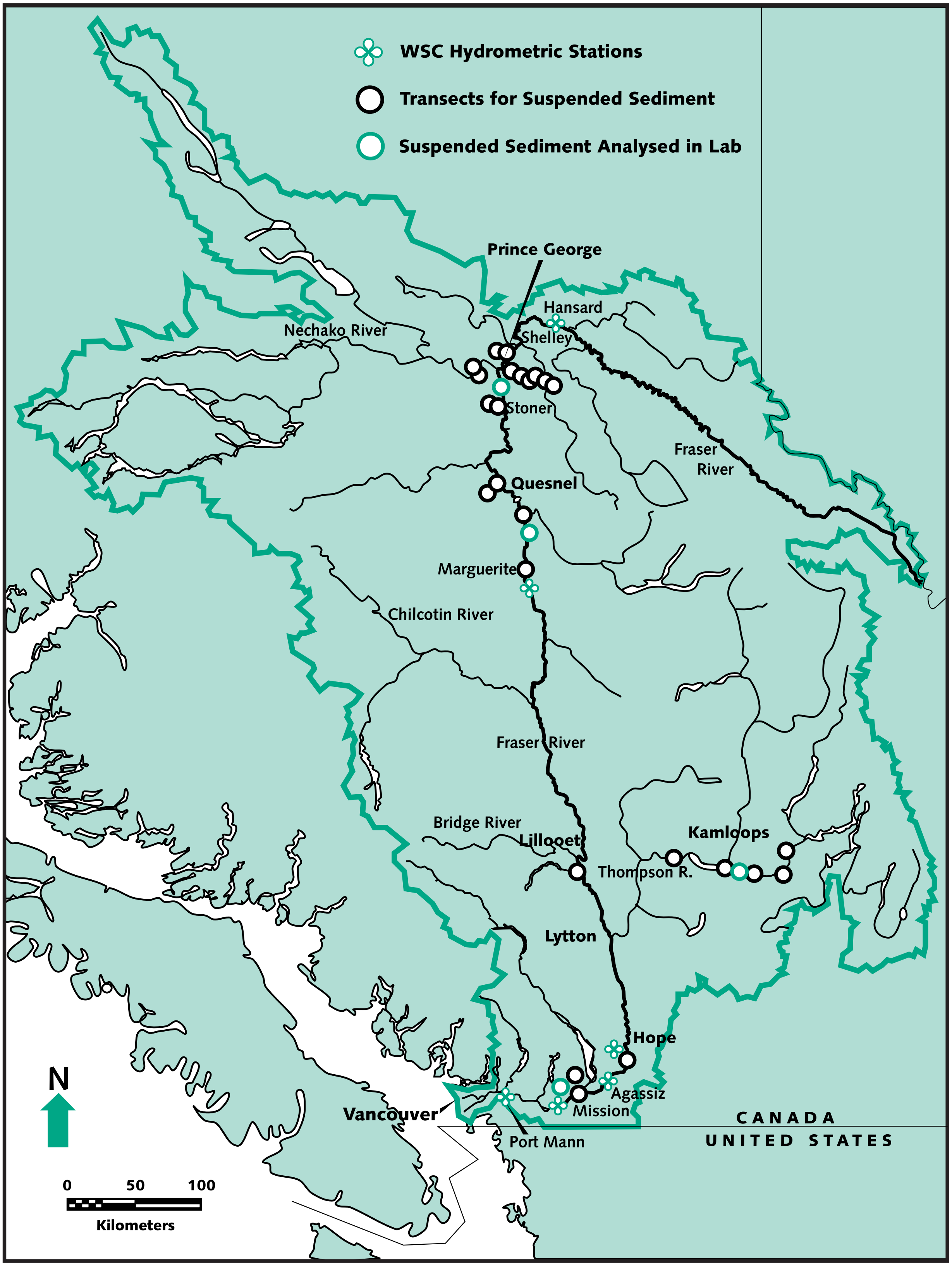

Figure 3. Location of hydrometric stations with suspended sediment monitoring along Fraser River, and of the field observations undertaken for this study.

The Data

Samples were taken from bridges (and from the cable ferry at Marguerite) on a near daily basis through all the months of elevated flows (April through October), and a small number of additional samples were taken during winter low flows. Standard floc-disrupted grain-size analysis was conducted on the sampled material when a sufficient amount was caught, mainly during freshet flows. A daily sample normally consisted of one vertical traverse of the water column at a single location.

Of course, suspended sediment concentration varies across the river channel. On up to 10 or 15 occasions in the year, traverses or multiple point samples were taken in a number of verticals, usually five. The single-vertical observations were subsequently adjusted to represent the average concentration of suspended sediment across the entire channel according to the results of the complete samples. To correct single-vertical samples when no complete sample is available, it is necessary to estimate K, the ratio of the average sediment concentration in the river cross-section to that in the usually measured vertical. This can be accomplished if K varies systematically with some known quantity. An obvious candidate is river discharge, Q. Accordingly, regressions of K on Q were examined.

Figure 4 illustrates a typical result. There is substantial scatter in the values of K, but there is also a systematic trend, and the value of K typically departs from 1.0 (that is, the single-vertical samples are biased). Adjustments were also investigated for size-specific fractions of the suspended sediment load. The pattern of results was similar, although individual regression relations were different. In general, sands are apt to be overestimated by the single-vertical samples, whilst silts and clays are more apt to be underestimated. There is no obvious reason for this pattern other than that the single vertical is customarily located in a part of the river with strong flow, where sand movement is most vigorous.

Predicting the Fine Sediment Load

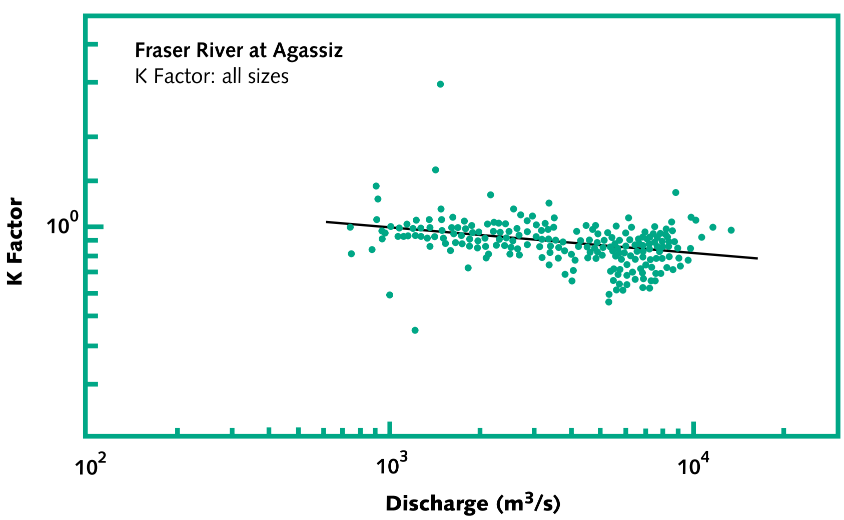

Figure 4. Variation of the adjustment factor, K (ratio of average sediment concentration in a river cross-section to that measured in a single vertical), with discharge.

If measurements are sufficiently frequent, load can be estimated as C_iQ_i where C_i is the observed mean concentration of sediment in the water column and Q_i is the corresponding discharge. Then, either by direct summation of successive measurements, or by interpolation of additional estimates between measurements (usually guided by the hydrograph), the load can be estimated for an arbitrary period. This method was used by the Water Survey of Canada to compute the suspended sediment load in the Fraser River at observing stations during the period of measurements. However, it cannot be used to project estimates beyond the period when measurements are taken.

A second approach is to find a predictive functional relation between sediment concentration and some other measured variate, almost always streamflow. So long as the relation—termed a rating curve—remains stable, it can be used to predict sediment load given the continuing record of flows. Our object is to find a prediction model for fine sediment in the Fraser River for continued use beyond the period of measurements.

Suspended sediment rating relations have frequently been presented in the form

$$C_i=C_0Q_i^{m}$$

in which C_0 is the concentration when Q=1 m³/s and m is an exponent, often in the range 1.5<m<2.5, which indicates the sensitivity of concentration to changing discharge. The pattern of variation of suspended sediment concentration in the Fraser is more complex than this (Thompson *et al.* 1987). Figure 5 illustrates a typical pattern that exhibits seasonal hysteresis. The best general description of this pattern is

$$C_i=C_0Q_i^{m1}(Q_i/Q_c)^{m2}Q_{i-7}^{m3}$$

in which Q_c is a critical flow level on the rising limb at which the rating sensitivity changes, and Q_{i-7} is the flow seven days before. The term Q_i/Q_c allows us to model the hysteresis; when $Q_i<Q_c$, it is ignored. Physically, the inclusion of this term covers the reduced sensitivity of concentration to changing discharge near the peak of freshet, when the availability of additional fine sediment for entrainment is declining. The term Q_{i-7} reflects the influence of the recent history of flow in determining the continued addition of fine sediment to the water column. The seven-day lag is the time scale of synoptic weather spells.

The rating function was fit to data of individual years at all stations. In addition to data of total suspended sediment concentration, ratings were computed for silt + clay (*i.e.* material finer than 0.063 mm), for fine sand (*i.e.* material with 0.063 mm<D<0.125 mm), and for coarse sand (*i.e.* material coarser than 0.125 mm). The division at 0.125 mm is predicated on the fact that finer material ("wash material"), once entrained, goes immediately into suspension (Sundborg 1967) and may travel a long distance, whereas the coarser material is only intermittently suspended and forms the normal bed material in the lower course of the river (that is, at and below Mission). Ratings were also calculated for all material finer than 0.125 mm, which can be called the "wash load" of the river; it is this material, as will be discussed later, that is apt to form flocs and interact with contaminants.

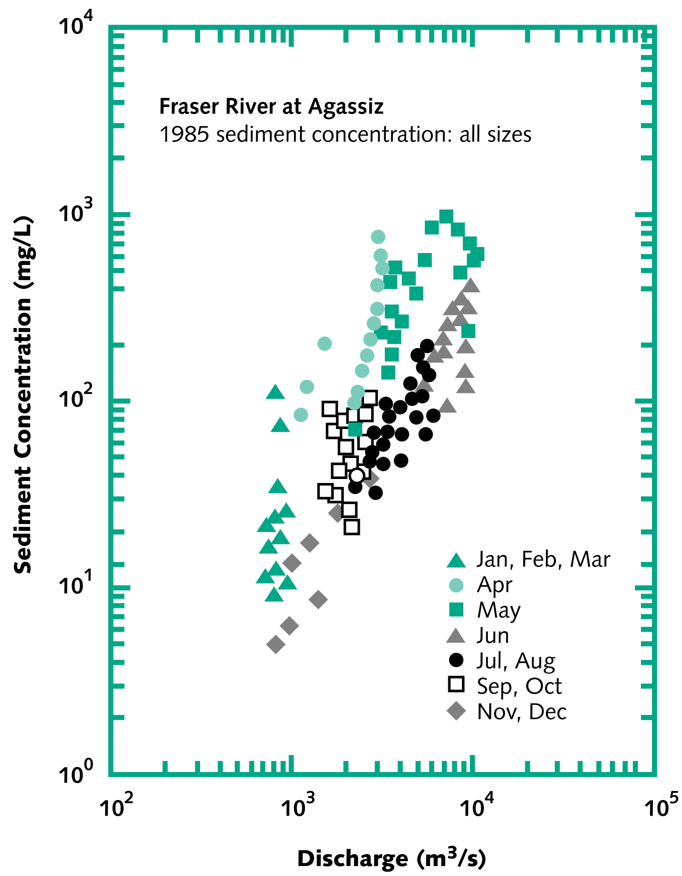

Figure 5. A typical annual rating function of suspended sediment concentration in relation to river discharge, showing the customary hysteresis.

Not all of the terms of the general rating function are always significant. At some stations and in some years, this lack of significance is possibly the consequence of insufficient observations to define the rating function in adequate detail. On the falling limb, neither the m2 nor the m3 terms are significant, so the falling-limb ratings are of classical form. In a few cases, the regression is not significant at all. This outcome usually appears in the silt + clay size range and, occasionally, in fine sand. These are the components of the sediment load that are strongly influenced by sediment supply limitations, so the outcome is not entirely surprising.

More problematically, the rating functions at the same station do not, in general, coincide from year to year. This means that sediment concentration in the Fraser River cannot be predicted on a continuing basis from flow. This is a serious handicap for systematic water quality modeling. Interannual variation presumably is related to the variable character of winter weather, which influences preparation and release of fine materials by weathering along the streambanks, and to the rate of the spring rise in flow, which influences the rate at which material is mobilized. If, as seems probable, a significant amount of these fine materials is stored on the streambed in flocculated form, the history of flows in the preceding autumn and the period of winter-time settling of the material may also be significant. Altogether, these conditions significantly affect the fine sediment mobility.

An implication of this result is that, to assure appropriate input data for a sediment transport and water quality model, observations must be continued at some sites along the river, which will become model input values. To decide how many sites should be monitored will depend upon how well correlated down-stream sediment loads are in the short term and how precisely the load needs to be known. Considering the water quality concerns along the river, it would be prudent to maintain one station upstream of significant development on the river, and one upstream and downstream of the Thompson River confluence. Initial choices would be Hansard, Marguerite Ferry and Mission, where historical records already exist.

In comparison with the daily ratings, annual total-suspended-sediment load is well predicted at each gauging station by the annual volume of water passing the gauge. Variance reduction is in the range 83–93 per cent, and the standard error of an annual estimate is about ±10 per cent in the upper river and about ±15 per cent at Agassiz and Mission, but only ±6 per cent at Hope. The high errors in the lower mainland are related to large transient storage of sand in the reach between Hope and Mission.

The change in load between stations is predicted by water volume at the downstream station plus the load of the preceding year at the upstream station. The latter presumably indexes the volume of fine sediment stored in the reach during the low water season. Between Hansard and Marguerite, precision is ±10 per cent, but between Marguerite and Hope it is only ±18 per cent; this probably results from the addition of the large but variable volume of the Thompson River, which carries very little sediment. Between Hope, Agassiz and Mission, predictability is apparently poor because the change in fine sediment load, on average, fluctuates about zero. Absolute precision is of the order ±1 million tonnes, which is comparable with the value in the next reach upriver. This should be compared with a total annual throughput on the order of 18.5 million tonnes.

Sediment Dynamics

On the basis of loads derived from the model equations, changes in sediment transport along the river can be predicted and studied. Average annual-fine-sediment pickup in successive reaches is given in Table 3. Major sediment recruitment occurs in the reach between Hansard and Hope (in fact, nearly all of it upstream of Lytton, where the Thompson River joins the Fraser). There is a near balance of the load below Hope, with deposition of fine sediment occurring along the Hope-Mission reach in most years and net erosion in years with high floods. There are, therefore, substantial swings in the transient storage of sediment, mostly sand, in this reach, but with a balance of accumulation. This is expected in this distal reach of the river, where a substantial floodplain has been constructed within the last ten thousand years. The situation emphasizes the significance of the

Table 3. *Average annual fine sediment recruitment along Fraser River.*

REACH	ANNUAL RECRUITMENT (million tonnes/yr)	STD. DEVIATION
Above Hansard	2.720	0.671
Hansard-Marguerite	7.041	2.820
Marguerite-Hope	7.743	1.640
Hope-Agassiz	-1.095	1.964
Agassiz-Mission	-0.217	1.742
Hope-Mission	-1.261	2.852

Because the rating curves upon which the results are based are optimised at individual stations, there are small discrepancies amongst the various sums that can be formed.

Hope gauge as a reference station for considering sediment transfers. Year-to-year variations in sediment recruitment are shown in Figure 6.

A significant amount of fine sediment is seasonally stored along the river. Most of the storage sites are on the open riverbed or in sandbars along the main channel bank. There are few backwaters for longer term storage. As discussed below, a mechanism exists for flocculated sediment to be seasonally deposited and entrained on the riverbed. The effect is evident by the film of fine sediment which coats the emerging cobble riverbed as the annual flood recedes in late summer (soon washed off exposed rocks by rain).

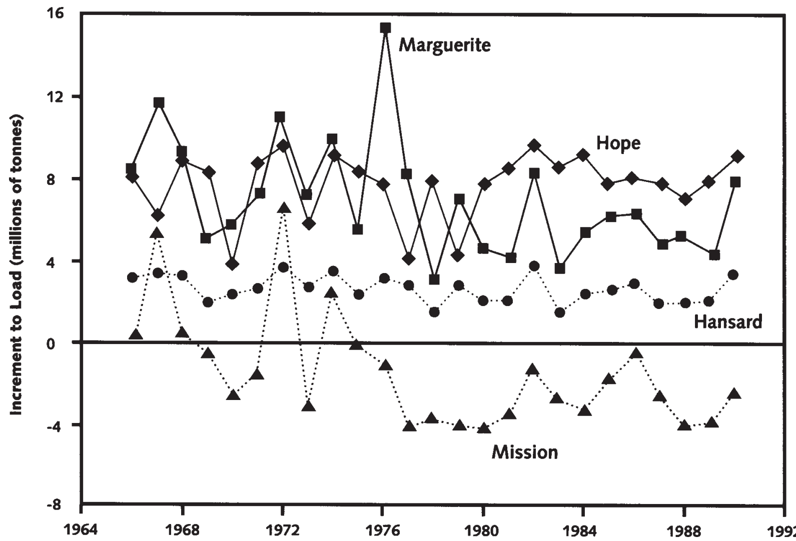

Figure 6. Annual fine sediment recruitment in four major reaches of Fraser River (millions of tonnes). The material is derived from stream banks and from tributary inflows.

Another mechanism augments seasonal storage and creates longer term storage as well. Upstream from Bridge River rapids, much of the river has a cobble bed, which may scour during freshet. Data to study this phenomenon are available only at the Marguerite gauge, where soundings made during flow gauging permit changes in bed elevation to be studied. Hickin (1995; see also Carson 1988) has studied the data and shows up to two metres of bed scour during the highest freshets (see Fig. 7). This creates a scour volume of up to 300 m^3 in the channel bed per metre of channel length. It is probable that such a zone could harbour up to 40 m^3 (or 100 tonnes) of fine sediment (*i.e.* material smaller than 2 mm in diameter), stored in the interstices of the larger material. There is a potential, then, to store as much as 100,000 tonnes per kilometre of scour-prone channel if the Marguerite scour figure is representative. Much of this material would be sequestered for many years, because full scour would occur only occasionally. Furthermore, extensive reaches probably experience much more limited scour. Nonetheless, there appears to be a potentially large capacity here to sequester and release fine sediment, even if only a small fraction of this storage potential is realized.

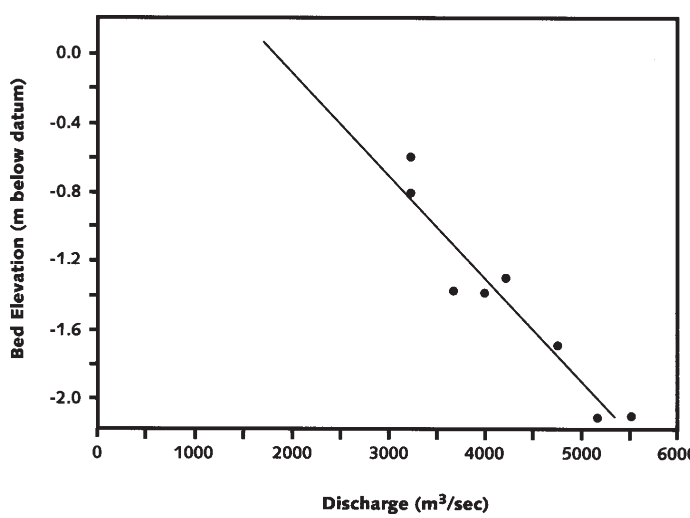

Figure 7. Relation between river discharge and bed elevation at Marguerite, based on the maximum scour observed in each year of record (modified from Hickin 1995; figure 8.6c).

In a small number of subsurface bed material samples from Marguerite analyzed by Carson (1988), about 10 per cent of the material was finer than 0.05 mm. However, almost no material finer than 0.062 mm was found. It is not known whether finer material was lost in the sampling procedure, or was not present. The sequence of years in which significant exchange occurs between the sub-bed storage and the mobile sediment load, juxtaposed on the sequence of transient additions of contaminants to the river, creates the possibility for certain "pools" of contaminated fine sediments, specifically silts and clays, to remain in the riverbed for many years. Episodic release of such stored material would significantly affect the observed variance of contaminant occurrence in the river and could complicate both trends and compliance monitoring.

SEDIMENT TRANSPORT PROCESSES

Transport of the coarse-grained sediments, which behave as individual particles when transported by a river flow, has been studied extensively and a large body of knowledge exists in the literature. With this existing knowledge it is possible to make reasonable predictions of transport parameters such as the critical flow condition for initiation of sediment motion, the sediment transport rate, the characteristics of bed forms such as dunes and ripples and the friction factor of sediment transporting flows. Transport processes of fine sediments, on the other hand, are not very well studied and there is a lack of generally accepted theoretical formulations for treating fine sediment transport in river flows. The reason is that the fine sediments in the size classes of silt and clay, classified as cohesive sediments, exhibit a strong interaction among the sediment grains and form sediment flocs. The interaction depends on the flow turbulence and the physical, chemical and biological properties of the sediment-water mixture. To improve our understanding of fine sediment transport processes in the Fraser and Thompson River system, we initiated a field and a laboratory study to formulate a new fine sediment transport model (FINESED). The main conclusions of the sediment transport studies and the salient features of FINESED are summarized here.

Field Evaluation of Cohesive Sediment Transport

The purpose of the field evaluation was to measure the size distribution of the sediment in suspension in its natural environment and to determine if these sediments were transported in a flocculated form or not. Five field surveys were carried out between September, 1993 and October, 1996. The four fall and one spring dates of these surveys were selected to coincide with low flow periods so that the effects of effluents from pulp mills and other sources on the suspended sediment in the river could be examined (see Krishnappan and Lawrence 1999). Transects were located at 12 stations along the Fraser main stem and on the Nechako and Thompson rivers (Fig 3). Size distributions were measured using an instrument assembled from components of a commercially available laboratory laser particle size analyzer (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 and analysis methods, which are known to cause floc disruption. To assess the state of flocculation of the suspended sediment, the *in situ* distributions measured in the field were compared with the distributions of the primary particles in concurrently collected samples that were subjected to sonic vibration to ensure total disruption of flocs. The particle size distributions were obtained with a laboratory particle size analyzer operating on the same principle as the field instrument.

A comparison of the median sizes of the particles measured in the field and the primary particles after disruption in the laboratory were made for a number of sampling stations as shown in Figure 8. From this figure, it is evident that at the transect at Shelley (a station upstream of all pulp mills), the median sizes of the *in situ* and primary particles are nearly equal, which implies that the particles at this transect are transported as individual particles rather than as flocs. At a downstream transect, which is located at about 300 m downstream of the Northwood Pulp and Timber Ltd. pulp mill outfall at Prince George, the condition of the particles' state is very different. Here, the median size of the *in situ* particles is higher than that of the primary particle size distribution, which implies that the particles at this transect are transported as flocs. This flocculation phenomenon could have been caused by the presence of the pulp mill effluent. An experimental verification of this hypothesis had been provided by a set of controlled experiments using the

Fraser and the Nechako River water and the Northwood pulp mill effluent (see Krishnappan and Lawrence 1999).

Figure 8 also shows the comparison of the median size of *in situ* and primary particles for the Nechako River, as well as the Fraser River at Stoner, Quesnel, Lillooet and Mission. The Nechako River data show that the particles in this river are also flocculated. The agent responsible for the flocculation of these sediments could be effluent from sewage treatment plants that contain organic matter and bacteria. The presence of bacteria has been found to cause flocculation of sediments by way of secretion of polysaccharides, a glue-like substance that promotes bonding among particles (Van Leussen 1988). The data for the Lillooet transect show that the flow velocities and turbulent shear stresses are high enough in the canyon to break up the flocs into individual particles. Farther downstream at Mission, where the flow becomes much less turbulent, the flocs appear to reform.

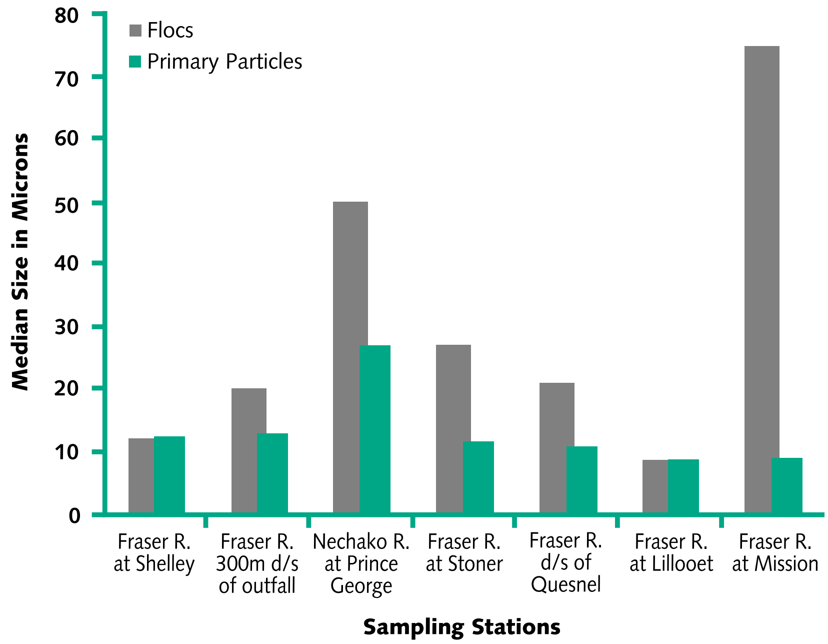

Figure 8. *Floc and primary particle sizes at several locations in the Fraser and at one location in the Nechako River.*

From the field surveys, it became apparent that the suspended sediments of the Fraser River system should be treated as cohesive sediments. Therefore, their transport characteristics cannot be predicted theoretically (Krishnappan and Ongley 1989). With the current state of knowledge on cohesive sediment transport, the transport parameters of cohesive sediment can only be obtained through direct measurements in special flumes such as a rotating circular flume. Such an approach was adopted for the present study.

Laboratory Evaluation of Fraser River Cohesive Sediment Behaviour

The Rotating Circular Flume (RCF) located at the National Water Research Institute was used to evaluate depositional and erosional process parameters of sediment-water mixtures from the Fraser River at Prince George, Quesnel and Mission, the South Thompson River at Kamloops and the Nechako River at Prince George. A brief discussion of the testing procedure and the results are outlined below.

The RCF consists of a circular flume, 5 m in mean diameter, 30 cm wide and 30 cm deep, resting on a rotating platform, 7 m in diameter, with a rotating lid that 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 flows with characteristics similar to straight and uniform channel flows. Complete details of the flume can be found in Krishnappan (1993).

The deposition characteristics of 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. Concentrations of sediment in suspension and the size distributions were monitored as a function of time during the course of the experiment. The concentration results from a typical deposition test are shown in Figure 9. This figure shows that for a particular bed shear stress, the concentration drop is steep in the beginning and levels off gradually, leading to an eventual steady state concentration. Earlier studies demonstrate that the attainment of a steady state concentration during the 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 riverbed (Partheniades and Kennedy 1966).

The deposition experiments also revealed that the steady state concentration was a function of the initial concentration, and the ratio between these two concentrations was constant for a given shear stress. This implies that when a known amount of cohesive sediment enters the river, a fraction of the sediment will deposit and the remaining sediment will stay in suspension indefinitely. The fraction that stays in suspension indefinitely is a function of the bed shear stress for a particular type of sediment. It is interesting to note here that in the case of cohesionless sediment (sediment that behaves as individual particles), the steady state concentration is a function of only the bed shear stress and does not depend on the initial concentration. This is one of the important differences between the transport characteristics of cohesionless coarse-grained sediment and those of cohesive fine-grained sediment.

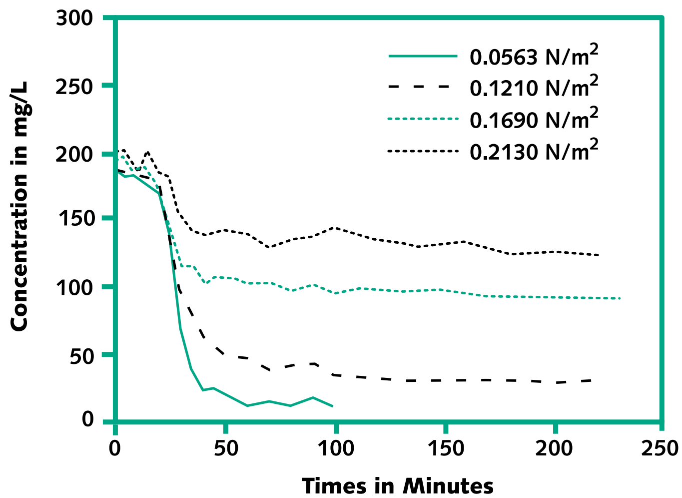

Figure 9. *Variation of suspended sediment concentration over Fraser River sediments with different shear stresses. Shear stress expressed as Newtons/m².*

The deposition experiments provide quantitative estimates of the amount of sediment that would deposit under a particular bed shear stress given the initial amount and kind of sediment that had entered the river reach. The shear stress at which all of the initially suspended sediment would deposit is termed the critical shear stress for deposition. For Fraser River sediment, an average critical shear stress for deposition of 0.05 Newtons (N)/m^2 was obtained. The variation of this parameter at the different sampling locations was within 15 per cent of the average value. Similar measurements carried out in the Athabasca River near Hinton, Alberta, yielded a value of 0.085 N/m^2 (Krishnappan and Stephens 1995). A lower value of the critical shear stress for deposition means that Fraser River sediment stays in suspension more readily and has lower settling velocities than sediments in some rivers on the east side of the Rocky Mountains.

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 at a shear stress slightly below the critical shear stress for deposition, 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 its size distribution were measured as a function of time. A typical result from an erosion test is shown in Figure 10. From such results, we can estimate the shear stress at which the sediment begins to erode, *i.e.* the critical shear stress for erosion. An average critical shear stress for erosion of 0.120 N/m^2 was obtained for Fraser and Thompson River sediments. The variation of this parameter with the sampling locations was within 15 per cent of the average value. In comparison, for Athabasca River sediments, a critical shear stress for erosion of 0.170 N/m^2 was obtained (Krishnappan and Stephens 1995). A lower value for critical shear stress for erosion means that Fraser River sediment is more mobile and can easily be brought back into suspension.

From the deposition and erosion experiments, we observe that the values of critical shear stresses for deposition and erosion are different, which is typical for cohesive sediments. In contrast, for non-cohesive sediments, the two values merge into one and the critical condition for deposition is equal to the critical condition for erosion. A single value for the critical conditions means that these sediments can undergo deposition and erosion simultaneously.

For the Fraser and Thompson River sediments, the ratio between the critical shear stress for erosion and the critical shear stress for deposition is 2.4, which is not too far off from the value of 2 that was obtained for Athabasca River sediments (Krishnappan and Stephens 1995). Nevertheless, the transport characteristics of these two sediments are very different. As pointed out earlier, the Fraser sediments are much more mobile than the Athabasca sediments because the former have lower values for the critical shear stress for deposition and erosion. Further details of the deposition and erosion experiments using the Fraser River sediments can be found in Krishnappan and Engel (1997).

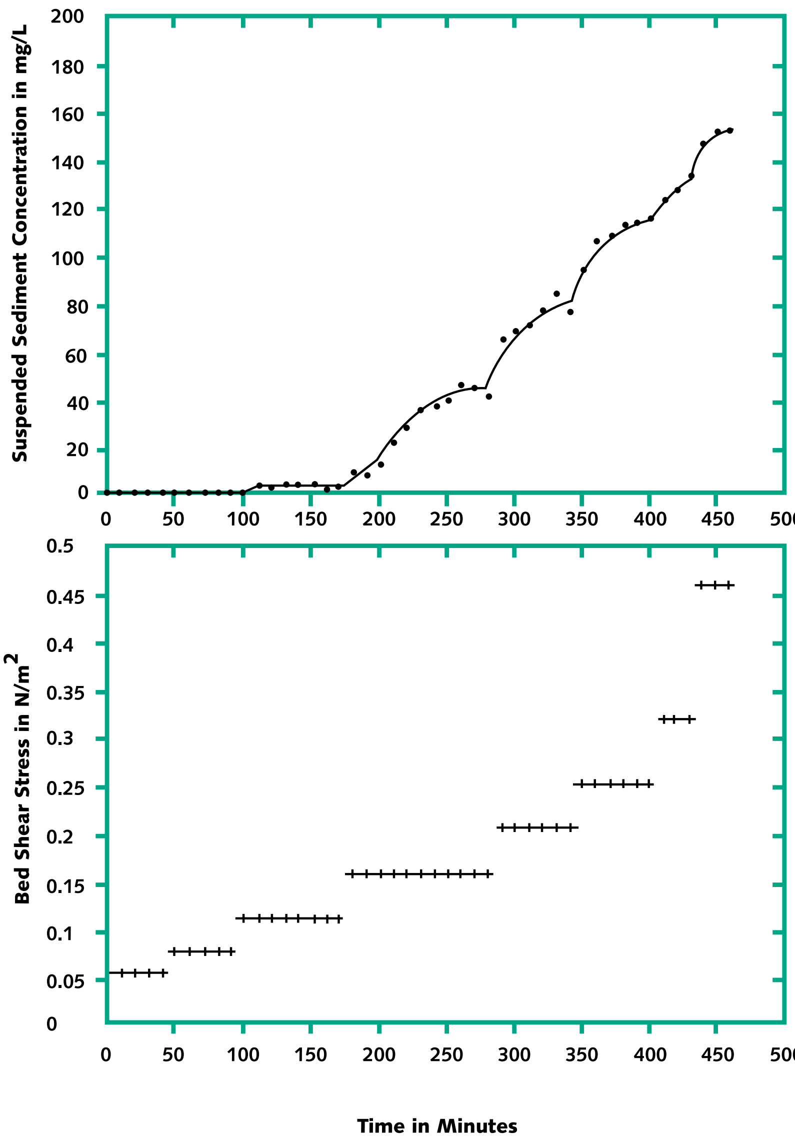

Figure 10. Erosion characteristics of Fraser River fine sediment demonstrated by the increase in suspended sediment concentration with time in response to a series of step-wise shear stress increases starting below the critical shear stress for erosion.

MODELING THE TRANSPORT OF COHESIVE SEDIMENTS IN THE FRASER RIVER SYSTEM

Existing models of cohesive sediment transport (*e.g.* SERATRA and FETRA by Onishi and Thompson [1984], the University of California model by Ziegler and Lick [1986], Finite Element Hydrodynamic and Cohesive Sediment Transport Modeling System by Hayter [1987], TABS-2 by U.S. Army Corps of Engineers [Thomas and McAnally 1985] and WASP5 by US Environmental Protection Agency [Ambrose *et al.* 1991]) assume that the transport characteristics of fine sediment are analogous to those of coarse sediment and treat the fine sediment transport using sediment transport theories developed for coarse-grained sediments.

As indicated above, our study has found a sizeable difference between the shear stress for deposition and erosion for fine sediments in the Fraser suggesting that the theories of coarse-grained sediment behaviour are not adequate for modeling fine sediment transport. These theories give equal critical shear stresses for erosion and deposition. In the case of fine, cohesive sediment, however, the two critical shear stresses demarcate three sedimentary regimes. In the first regime, under low flow conditions below the critical shear stress for deposition, only deposition occurs. In the second regime, under higher flow conditions between the critical stress for deposition and erosion, the fate of a sediment floc depends on whether it is in the bed sediment or suspended in the water and on its specific behaviour with respect to the average critical shear stress for deposition and erosion measured for the whole sediment population. A suspended floc will remain in suspension in this stress regime unless it is denser (a floc with higher settling velocity) than the "average" floc, in which case the floc will deposit at a stress above the average critical stress for deposition. Once attached, however, this floc will not re-suspend until, or if, the critical stress for erosion is exceeded. A floc attached to the bed sediment, on the other hand, will stay attached in this stress regime unless it is more fragile (a floc that is weak and easily broken up) than the average floc in which case it could become suspended below the critical stress for erosion for the average floc. In this regime both erosion and deposition can occur, but they happen at different stresses and to different flocs. In the third regime, under high flow conditions, above the critical shear stress for erosion, only re-suspension occurs.

Accordingly, a true representation of the erosion and deposition behaviour of cohesive sediments at different shear stresses is important for contaminant transport models, as the fate of the adsorbed contaminants will be strongly influenced by the shear stresses occurring over the calculation period. A model that assumes erosion and deposition are occurring simultaneously, although at different rates depending on the shear stress, will predict accumulation and dispersion outcomes that differ from a model that accounts for the behaviour of the sediments in the three shear stress regimes discussed above. Hence, for stresses below the critical stress for deposition, a model incorporating the cohesive sediment assumption will predict deposition only, while a model incorporating a non-cohesive sediment assumption will predict both deposition and erosion. The cohesive model would predict a higher contaminant concentration in the bed sediment than the non-cohesive model if the suspended sediment load was more contaminated than the bed sediment, or vice versa if it was less contaminated.

For stresses between the critical levels for deposition and erosion two general outcomes are possible. For example, the cohesive model would predict no dispersion of bed sediments and greater dispersion of suspended sediments than the non-cohesive model as the river flow and associated stress increased past the critical stress for deposition. However, as a high river flow declined past the critical stress for erosion the cohesive model would predict a cessation of bed sediment dispersion and a higher dispersion of suspended sediments. The impact on contaminant concentrations in the suspended and bed sediments under these two scenarios would vary dramatically depending on the modeled inventory of accumulated bed sediment and contaminant burden in the bed and suspended sediments.

Lastly, at stresses above the critical level for erosion, the cohesive model would predict no deposition and the beginning of the dispersion of contaminated sediments deposited earlier which, depending on their contaminant content, could decrease or increase the contaminant concentration in suspended sediments and water. The non-cohesive model, on the other hand, would still predict exchange of contaminated sediments between the water column and the bed sediments, which would effectively slow down the rate of bed sediment dispersion even though the model would undoubtedly predict a net erosion of the accumulated sediments.

While the theoretical implications of these different model outcomes have been stated here, there is a need to examine the practical implications of this modeling approach over different time and spatial scales as well as hydrological regimes. To fulfill this need, a new sediment transport model called FINESED was formulated for Fraser River sediment based on the results of the laboratory experiments.

The deposition and erosion experiments in the rotating flume provide quantitative estimates of the fraction of sediment that would deposit and the fraction of the deposited sediment that would re-suspend under a particular bed shear stress. From these experiments, empirical relationships were developed to quantify these fractions in terms of the ratio between the bed shear stress and the critical shear stress for deposition. These relationships formed the basis of the FINESED model. According to the relationship developed for the deposition process, when the ratio between the bed shear stress and the critical shear stress for deposition is less than unity, all of the initially suspended sediment would deposit. When the ratio is between 1.0 and 10.5, only a fraction of the initially suspended sediment would deposit and the amount of the deposited sediment is given by the *deposition function* derived from the laboratory experiments. When the bed shear stress is in excess of 10.5 times the critical shear stress for deposition, none of the initially suspended sediment would deposit. According to the relationship developed for the erosion process, the re-suspension of the deposited sediment was also expressed in terms of the ratio between the bed shear stress and the critical shear stress for deposition. When this ratio is less than 2.4, none of the deposited sediment will re-suspend. When the ratio is greater than 2.4 and less than 25, a fraction of the deposited sediment will re-suspend and the amount of re-suspended sediment can be calculated from the *erosion function* that was determined from the erosion experiments. When the bed shear stress is in excess of 25 times the critical shear stress for deposition, all of the deposited sediment will re-suspend. For complete details of the FINESED model refer to Krishnappan (1997).

To apply the model, the bed shear stresses in each reach to be modeled have to be determined or estimated. This can be done in a number of ways depending on the required precision and the availability of river geometry and hydraulic data.

In the case of the Athabasca River study where a similar model was developed, Golder Associates Ltd. (1996) used a set of "Regime Equations" that related flow velocity, flow depth and slope of the energy grade line to the flow rate. A better approach would be to use a hydrodynamic flow model such as MOBED, which works for non-cohesive sediments (Krishnappan 1981) to calculate the bed shear stresses as a function of distance along the river and time for different flow hydrographs. The spatial and temporal variation of bed shear stress will give rise to different modes of fine sediment transport in different parts of the river. For example, near the banks of the river where the bed shear stress value is close to zero (because of shallower depths), deposition of fine sediment will occur for all flows. Under low flows during winter months, when the flow may be covered with ice, the bed shear stress can be in the range for which partial or full deposition of sediment could occur over the whole width of the river. During high flows in spring, when the bed shear stress can exceed the critical shear stress for erosion, partial or full erosion of the previously deposited sediment could occur. Depending on the magnitude of the flood event, complete erosion of the deposited sediment and subsequent transport of sediment in suspension through the river system is a possibility.

Other required input parameters for the model are the suspended sediment concentration for a chosen time interval at the upstream boundary of the modeled reach, the lateral input of fine sediment from tributary inflows, and the bank erosion in the reach being modeled. As discussed earlier, concentrations must be synthesized from real data and interpolated for the reach in question as no consistent relationship was found between present flow and suspended sediment load. In the absence of real time data, scenarios of expected sediment concentrations could be generated using sediment and flow data from a year with similar hydrograph characteristics to provide the sediment input parameter for modeling contaminant transport.

Recommendation for a Sediment and Contaminant Modeling Strategy in the Fraser River

Since the development of stable sediment rating relationships that would serve as the boundary conditions for the fine sediment transport model was not possible for the Fraser River, an alternate modeling strategy is recommended. This strategy would make use of existing coarse-grained sediment transport models such as MOBED (Krishnappan 1981), the new fine grained sediment transport model, FINESED, developed as part of the Fraser River Action Plan, and continued sediment sampling at a station forming the upstream boundary for the reach. For example, the upstream boundary for the reach from above Prince George to Marguerite would be at Hansard, which also has the benefit of an historical data set of sediment loads.

MOBED solves the flow and sediment mass balance equations and, thus, is capable of calculating the bed shear stresses. It also calculates the transport rates of fine sand, coarse sand and gravel fractions and changes in riverbed elevations due to erosion and deposition of sediment as a function of time and distance along the river for a specified flow hydrograph at the upstream and downstream boundaries. Using the results of the coarse-grained sediment model and the measured sediment data at Hansard as the upstream boundary condition, the new fine sediment transport model can be run to predict fine sediment concentration as a function of time and distance along the modeled river reach. Such predictions can then be used to improve the accuracy of EcoFate (a contaminant fate model developed for the Fraser and Thompson rivers; see Gobas *et al*. 1999). Because the EcoFate model assumes simultaneous erosion and deposition of sediment for all flows, it is possible that it might under-predict the sediment deposition in low flows and over-predict the same in high flows.

By adopting our recommended modeling strategy, a number of issues that were identified in this chapter could be addressed. For example, MOBED allows us to predict the long term storage or erosion of fine sediment due to the aggradation process of the streambed and bank erosion. FINESED, on the other hand, can account for the short term storage of fine sediment due to flocculation and settling on the riverbed during low flow periods. Finally, the lack of a sediment rating relationship can be overcome by using the measured sediment data from an upstream sediment monitoring station; data used should be those acquired in years with hydrological conditions similar to the one being modeled.

SUMMARY AND CONCLUSIONS

The Fraser River is not as "muddy" or sediment-laden as generally believed, especially in comparison to other northwestern rivers. In addition, the suspended sediments are dominated by silt-sized primary particles which, in combination with the relatively low sediment load, may mean that these sediments are not as important in contaminant transport as formerly thought. However, the dynamics of coarse-grained sediment deposition and erosion could provide temporary "refugia" for the fine sediments that become contaminated as they pass point sources or that originate from contaminated sources (*e.g.* particulates in effluents).

The analysis of the existing data showed that fine sediment concentrations cannot be predicted from flow rate in the Fraser River system. There are many possible explanations for the lack of a relationship, chief among them being that the amount of sediment stored on the riverbed during autumn and winter is not determined by the flow rate in the subsequent spring and summer.

New data, which consist of size distributions of fine sediment in the river and transport characteristics of fine sediment measured in a laboratory flume show that fine sediment in the Fraser is transported in a flocculated form and is likely to deposit on the riverbed during low flow periods. These data allow the formulation of a fine sediment transport model that is more realistic than existing non-cohesive sediment transport models. Unfortunately, this model could not be applied during this study because of the lack of predictability of the sediment load and the requirement of reach-specific shear-stress-flow relationships.

A new modeling strategy for the future is proposed that would involve the use of MOBED, an existing coarse grained sediment transport model, and the new fine grained sediment transport model, FINESED, developed during the course of the present study. These models, along with the sediment data from continuous sediment monitoring stations, can be used to predict the fine sediment concentrations in specific reaches. In addition to monitoring suspended sediments in the Fraser main stem at Hansard, Marguerite and Mission, suspended sediment measurements would be required on principal tributaries that deliver significant loads of fine sediment to the main stem.

These results, in turn, can then modify the calculated partition of contaminants between the water column, suspended sediments and bed sediments, which is needed to assess and predict contaminant exposure of fish and benthic invertebrates. Such a modeling strategy will improve the predictive capability of the EcoFate model developed for the Fraser and Thompson River system. Unfortunately, as there are no historical suspended sediment measurements on the major tributaries and monitoring at the main stem stations has recently been terminated, implementing this strategy cannot proceed without new resources.

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