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Sediment transport along lower Fraser River
1. Measurements and hydraulic computations

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Abstract. A comprehensive program of sediment transport measurements was conducted along lower Fraser River, British Columbia, between 1966 and 1986. The data yield a detailed sediment budget. Annual total suspended loads at three stations are virtually identical, averaging 17×10^6 tonnes/year (t yr^{-1}). The suspended sand load is about 5.5×10^6 t yr^{-1}, about one third of the total. In the gravel bed reach of the river the sand behaves as wash load. Significant transport of gravel begins at Agassiz at a discharge of about 5000 m^3 s^{-1}. The annual gravel transport was estimated to be about 0.23×10^6 t yr^{-1}, only 1% of the total load. All of this material is deposited in the reach upstream of Mission. At Mission, sands finer than 0.177 mm make up more than 50% of the suspended sand load but are virtually absent from the sand bed. Therefore a portion of the sand load at Mission is wash load. The total bed material load here was estimated to be 3.0×10^6 t yr^{-1}, about 18% of the total sediment load. Virtually all of the bed material load was transported in intermittent suspension near the bed, less than 5% occurring as bed load. In the long term the suspended sand load upstream is approximately equal to the total sand load at Mission. However, within individual years some of the sand is stored within the reach temporarily and then reentrained later.

1. Introduction

Between 1965 and 1987, the Water Survey of Canada (WSC) conducted a comprehensive program to measure the sediment transport at several locations on Fraser River in British Columbia (Figure 1). Unusually, for a river of the size, the program included bed load measurements at three sites on the lower course of the river: at Port Mann and Mission in the distal sand-bed reach, and over a gravel bed near Agassiz. During part of the period, suspended load was measured also at Hope, near the upstream limit of the alluvial reach. Early results from the program were reported by *Tywoniuk* [1972], and a detailed analysis was presented by *McLean and Church* [1986]. The purposes of this paper are to present an overall assessment of the measurement program and to make more widely available the results from one of the most comprehensive programs of sediment transport measurements made on a major river. Particular attention is given to the problem of distinguishing the wash load and bed material load at each station. The reliability of the measurements and the precision of the estimates of annual load are also assessed. The total annual sediment load by grain size fraction is established at Agassiz and Mission. Since Agassiz is located in the gravel-bed reach, and the bed at Mission consists of sand, arriving at the result entails a discussion of assumptions and integration methods suitable for sediment transport measurements in a large river.

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In a companion paper [*McLean and Church*, this issue], long-term gravel budget estimates are derived for the reach between Agassiz and Mission from a study of morphological changes in the reach. Those results are then compared with the results of the conventional measurements described in this paper, and conclusions are drawn about the usefulness and general applicability of the various approaches.

2. Definitions

Fluvially transported sediment customarily is categorized and reported according to the method by which it is measured. Accordingly, it is divided into suspended load and bed load. Suspended load is carried in the water column because momentum imparted to the sediment grains by upward directed water currents equals the settling effect of submerged particle weight. It is measured by taking a sample of the water column and determining the particulate content. Bed load, comprising particles too heavy to be suspended, moves by rolling and sliding over the bed, its weight being borne primarily by contact with the bed. It is measured by deploying some form of sampler or trap on the bed. Saltating material, particles which leave the bed and then return to it via a ballistic trajectory, is practically measured with the suspended or bed load. Ultimately, what constitutes measured suspended or bed load is determined by sampler performance.

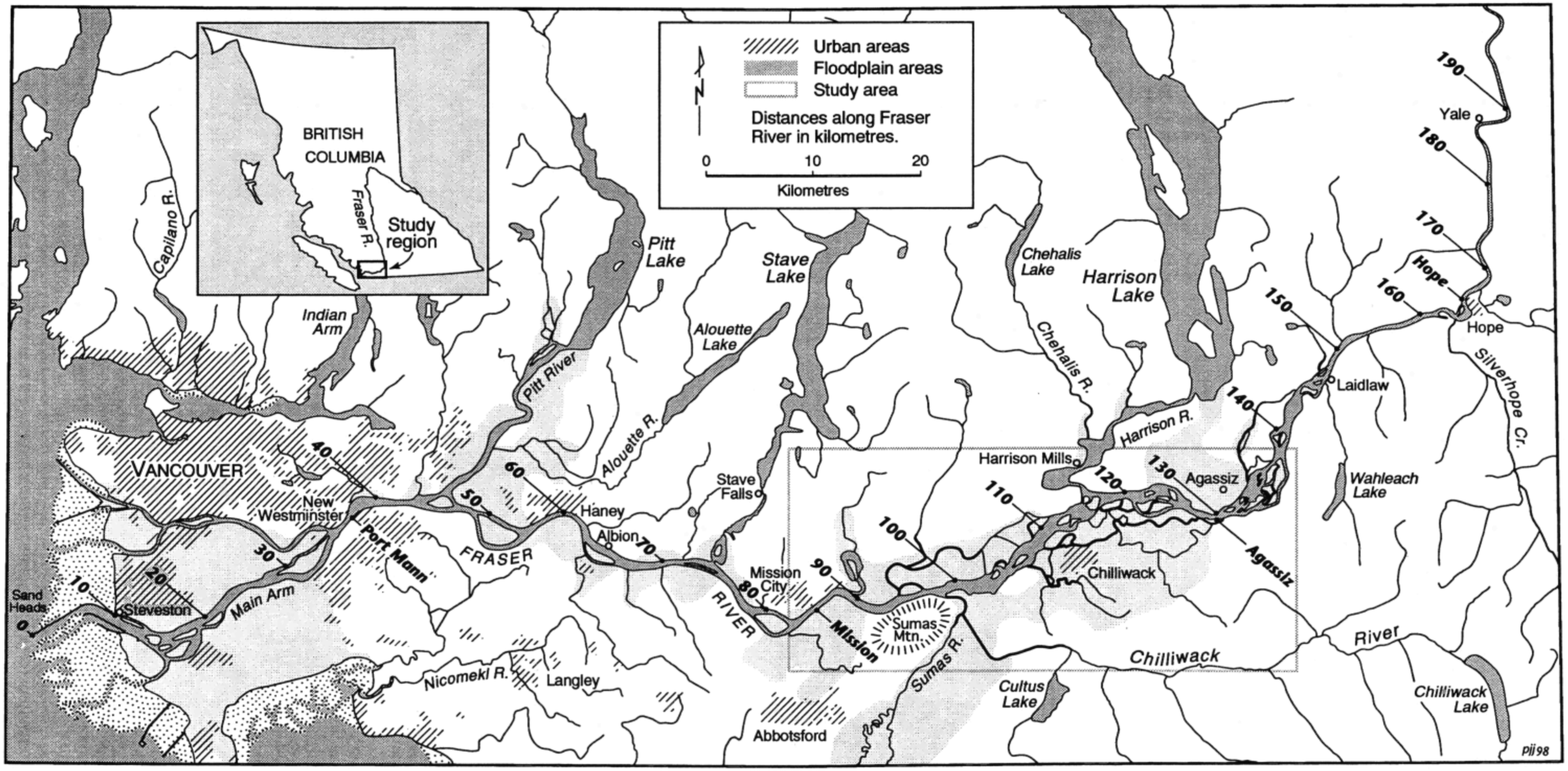

Figure 1. Lower Fraser River, showing principal gauging stations and river kilometers from Sand Heads, the mouth of the river in the Strait of Georgia.

To relate sediment transport to the development of river morphology and to long-term considerations of sediment storage and transfer, a different division of the total load is more appropriate. Material which forms the bed and lower banks of the channel is largely responsible for determining river channel form: this is the bed material of the river reach. Material finer than that found in the bed and lower banks normally is transported directly through the reach by the river, although it may constitute a significant or dominant element of the upper banks where it is deposited during floods. This material is referred to as wash material. What constitutes bed material and wash material varies along a river according to its competence during significant sediment transporting flows.

We are interested in distinguishing bed material and wash material in Fraser River because we are interested in studying the morphology and stability of the channel [*McLean and Church*, this issue]. In this paper, we first analyze the sediment transport, following the measurements, in terms of suspended and bed load. We then present results for bed material transport and wash material transport. In the upstream, gravel-bed reach this presents no great complication because the bed material consists in the main of material >2 mm in size, which is transported as bed load. However, in the sand-bed reach, bed material moves in intermittent suspension. Here the suspended load must be divided to determine the bed material load and the wash load. This is accomplished by observing the size distribution of material resident on the bed and comparing that with the grain size distribution of the suspended load. In making this comparison, it must be recognized that a small proportion of wash material is trapped in bed material due to the filter effect of the bed on water circulating into it. *Einstein* [1950] proposed that D_{10} of the bed material size distribution would approximately indicate the wash material content of a sand bed, but there seems to be no reason why this would be a general result. We have considered Einstein's criterion as a guideline but have used other physical criteria in making our division. We give specific details at the appropriate places in the text.

3. Fraser River

Fraser River drains 250,000 km^2 of south-central British Columbia, comprising part of the very humid Coast Range, the subhumid Interior Plateaux, and the Columbia and Rocky Mountains. The annual pattern of runoff is dominated by a snowmelt freshet beginning in April, with high flow occurring throughout late May, June, and early July, receding in August and September. The mean annual flow at Mission is 3410 m^3 s^{-1}, the mean annual flood is 9790 m^3 s^{-1}, and the flood of record (1894) is estimated to have reached 17,200 m^3 s^{-1}. The measured flood of record was 15,200 m^3 s^{-1} (1948) at Hope, which would have been between 16,200 and 16,500 m^3 s^{-1} at Mission, and the largest flood at Mission during the period of sediment transport measurements was 14,400 m^3 s^{-1} (1972).

Upland areas of Fraser basin are not prolific sediment sources. The region was glaciated in the Pleistocene epoch, and thick fills of glacial deposits have been left in the trunk valley and its major tributaries. The rivers have incised into these Quaternary sediments, which supply the main sediment load directly from erosion of river banks and terraces [*Church*, 1990]. The bulk of the source material is glacial till, glaciolacustrine silt, earth flow, and silty debris flow deposits, so that most of the sediment load is fine grained. Major lakes on several principal tributaries intercept part of the sediment load. The total sediment yield is not considered to be large in comparison with that of other major river systems (see data of *Milliman and Meade* [1983]).

Lower Fraser River extends 190 km from Yale to the sea (Figure 1). From Yale, where it emerges from its rock canyon, to Laidlaw, the river flows in a single channel that is confined nearly continuously by Pleistocene terraces, landslide material, or bedrock. The 55 km reach between Laidlaw and Sumas Mountain, including the Agassiz gauge section, displays a "wandering" gravel-bed channel [*Neill*, 1973; *Desloges and Church*, 1989], with frequent midchannel islands and low-order braiding (Figure 2a). The island stratigraphy consists of channel gravel and sand overlain by 1–3 m of sand or silty sand floodplain deposits.

In the channel, prominent gravel bars are displayed at low water, including lateral bars that are attached to the shore or to islands, point bars at bends, and midchannel bars in areas of flow expansion. In addition to these relatively stable features, transient gravel "waves" migrate along the channel until they become attached or incorporated into the bars (Figure 2b). These wave-like features form when upstream bank erosion or channel shifting transfers material from islands and banks into the active channel. The growth of the bars diverts flow to produce strong flow impingement on adjacent banks, which initiates new episodes of erosion and channel instability along the river.

The subsurface channel deposits are strongly bimodal with a coarse fraction consisting of gravel (median diameter typically 25–30 mm), and a fine fraction consisting of medium sand (see texture curves in Figure 10). The sand fraction typically comprises 10–20% of the bed material and occupies the voids in between the gravel clasts. Surface material exposed on bars is typically unimodal gravel, similar in composition to the subsurface material except that the sand sizes are absent. Surface deposits of sand are found on the downstream side of and in the shallow channels behind bars, and along some of the secondary channels.

At Sumas Mountain (Figure 1), near the town of Mission, the river changes abruptly to a single-thread, sand-bed channel. Virtually all of the river's gravel-bed load is deposited upstream of Sumas Mountain. The transition from gravel to sand is accompanied by a reduction in gradient, from 2×10^{-4} in the Chilliwack reach to 6×10^{-5} at Mission (Figure 3). The sand-bed reach continues for 50 km to the head of the alluvial delta at New Westminster, below Port Mann. From there, it is 35 km to the sea. Below Sumas, the river is tidally influenced. The tidal range at Mission varies from a few centimetres in freshet to over 1 m during the highest winter tides. However, salt water does not penetrate beyond the head of the delta at New Westminster.

Hydraulic and sedimentological data for Hope and Agassiz in the gravel-bed reach and for Mission, at the head of the sand-bed reach, are given in Tables 1 and 2. Because of the lack of a well-defined stage-discharge relation in the tidal reach, data from Port Mann have not been analyzed systematically. Between Hope and Agassiz, the discharge remains virtually constant, and there are few locations along the river where significant quantities of fine sediment are stored. Hence data from these two stations present an opportunity to study the precision of the measurements of suspended sediment load. Between Agassiz and Mission, Harrison and Chilliwack Rivers (Figure 1) add about 4.6% to the drainage area, increasing mean flow by about 18% and typically increasing flood

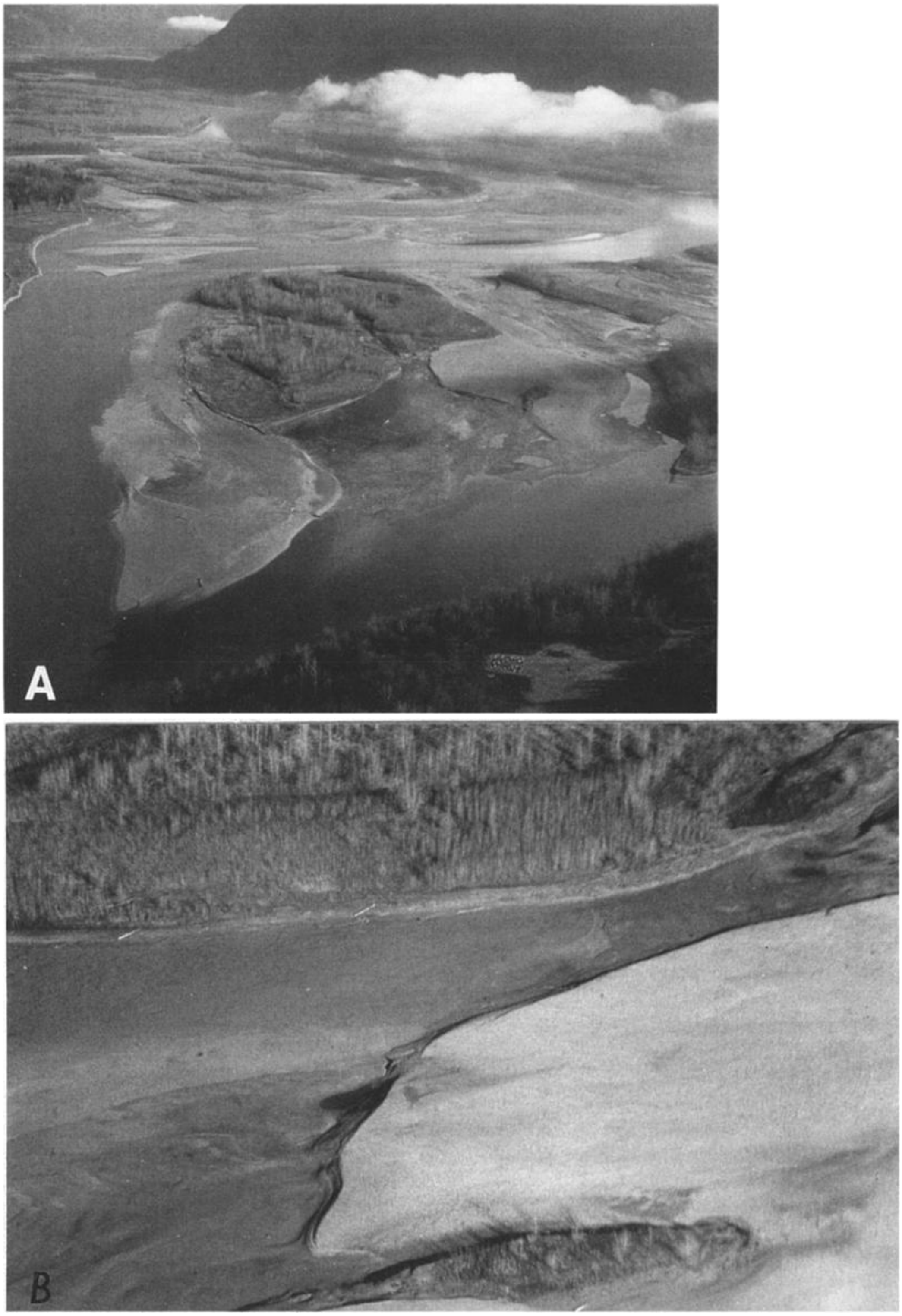

Figure 2. Channel pattern in the wandering, gravel-bed reach: (a) view upstream at km 130 (near Agassiz gauge) and (b) gravel wave moving along a lateral bar.

flows by 10–15%. Harrison River drains through a large lake. In 5 years of measurements it delivered an average of 0.12×10^6 tonnes/year (t yr^{-1}) of suspended clastic sediment to Fraser River. Chilliwack River delivers on average 0.13×10^6 t yr^{-1} of sand and finer material [*Church et al.*, 1989]. The combined load of these two rivers constitutes about 1.5% of the load at Mission.

4. Fraser River Sediment Program

In 1965 the Sediment Survey Section of the Water Survey of Canada began measuring the suspended load and bed load on Fraser River and some of its tributaries. The sampling program was established to provide reliable data for making decisions about the need for engineering works on the navigable portion

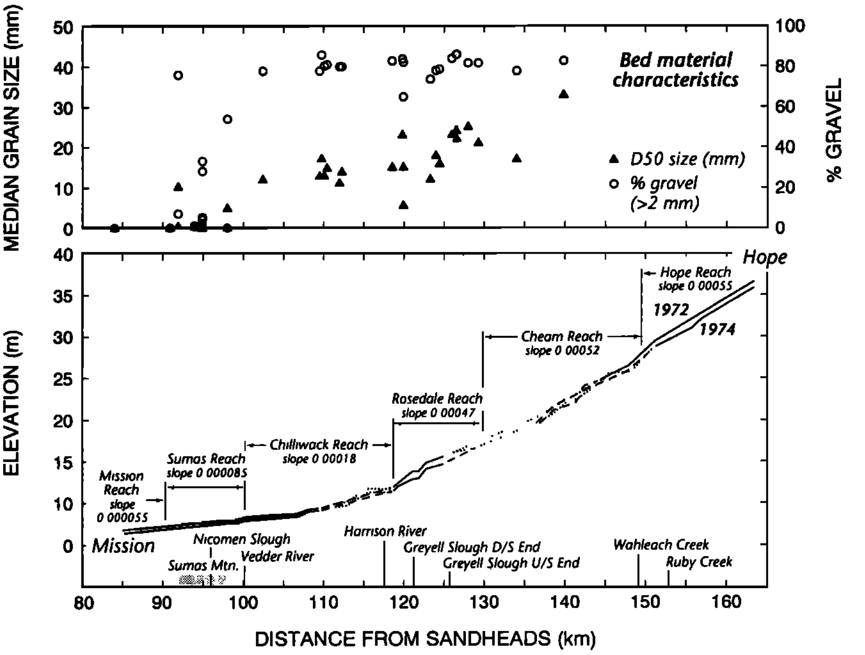

Figure 3. Water surface profile and longitudinal variation in bed material texture.

of the river downstream from Port Mann. Daily discharges, suspended sediment concentrations, and sediment loads have been published annually for each station. Table 3 summarizes published annual suspended loads between 1966 and 1986 for Agassiz and Mission, and until the end of observations in 1979 for Hope. In addition to these data, miscellaneous measurements, including particle size analyses of bed material, bed load, and suspended load were compiled. Following a program review in 1984 [*Kellerhals*, 1984], the measurement effort was reduced greatly. All measurements were discontinued at Port Mann and Agassiz, and only suspended sediment measurements were continued at Mission.

Table 1. Hydraulic Characteristics at Gauging Stations

Flow Condition	Q, $m^3 s^{-1}$	V, $m s^{-1}$	D, m	W, m
Hope (S = 6.0 × 10⁻⁴; Cobble-Gravel Bed, Confined by Rock on One Bank)				
LTM	2,830	1.5	7.9	240
June	7,030	2.8	9.7	258
MAF	8,766	3.2	10.1	268
5 year	10,200	3.5	11.1	270
10 year	11,500	3.7	11.5	270
1972 peak	12,900	4.0	11.7	275
Agassiz (S = 4.8 × 10⁻⁴; Gravel Bed)				
LTM	2,880	1.4	4.1	500
June	7,180	2.3	6.1	509
MAF	8,760	2.6	6.6	512
5 year	10,300	2.8	7.1	513
10 year	11,600	3.0	7.5	515
1972 peak	13,100	3.2	7.9	516
Mission (S = 5.5 × 10⁻⁵; Sand Bed)				
LTM	3,410	0.7	9.4	518
June	8,140	1.3	12.0	530
MAF	9,790	1.5	12.6	540
5 year	11,500	1.6	13.2	550
10 year	13,000	1.7	13.7	552
1972 peak	14,400	1.9	14.1	555

S, average water surface slope at the gauging section; LTM, long-term mean value; June, average monthly value in June; MAF, mean annual flood value.

5. Suspended Load

5.1. Measurements

Determination of suspended sediment load at the Fraser River stations typically has been based upon analysis of 150–220 depth integrated water samples each year collected at single vertical sections. Samples were obtained using USP-61 samplers at the Hope and Agassiz-Rosedale highway bridges and a P-63 sampler installed on the railway bridge at Mission [*Stichling and Smith*, 1968]. Daily sampling was conducted during the freshet, when most of the annual load is transported (Figure 4). In contrast, sampling occurred infrequently between October and March, when the river transports less than 6% of its annual suspended load. Ten to 15 times per year, five verticals were sampled by point integration to estimate the "true" average suspended sediment concentration in the river. The single vertical daily samples were corrected by WSC ac-

Table 2. Bed Material Size at Gauging Sites

	Cumulative Percent Finer				
	90%	75%	50%	25%	10%
Hope					
Surface	180	130	100	75	40
Subsurface	128	60	30	8	2
Agassiz					
Surface	80	56	42	30	20
Subsurface	80	50	25	8	2
Mission					
Surface	2	0.50	0.38	0.20	0.15
Subsurface	2	0.50	0.38	0.20	0.15

Values are in units of millimeters.

Table 3. Annual Suspended Sediment Transport by Grain Size Fraction

Year	Hope Published Total	Agassiz Published Total	Agassiz Clay	Agassiz Silt	Agassiz Sand	Mission Published Total	Mission Clay	Mission Silt	Mission Sand	Mission >0.177 mm[a]
1966	19,746					19,273	3,193	9,687	6,393	3,190
1967	23,437	25,333	4,035	12,611	8,687	26,071	3,742	11,591	10,738	6,737
1968	23,626	21,359	3,533	11,040	6,786	20,927	3,353	10,218	7,356	4,144
1969	13,171	12,769	2,190	6,844	3,735	13,928	2,286	6,898	4,744	2,373
1970	12,003	12,392	2,098	6,557	3,737	11,499	1,897	5,954	3,648	1,382
1971	16,308	18,023	2,977	9,302	5,744	17,531	1,774	6,031	9,725	3,139
1972	29,061	28,029	4,323	13,510	10,196	30,954	4,204	13,104	13,645	8,461
1973	16,151	13,839	2,361	7,377	4,101	12,220	2,055	6,365	3,800	1,653
1974	23,230	24,134	3,904	12,202	8,028	24,938	3,825	11,735	9,378	5,362
1975	12,031	11,238	1,905	5,955	3,378	11,975	1,967	5,967	4,041	2,409
1976	27,637	25,808	4,160	13,002	8,646	24,883	3,966	12,023	8,894	4,889
1977	12,415	12,745	2,184	6,826	3,735	14,535	2,666	8,016	3,853	1,224
1978	8,993	10,651	1,861	5,817	2,973	12,297	2,194	6,675	3,428	1,129
1979	15,539	14,721	2,533	7,917	4,271	15,008	2,648	8,415	3,945	1,280
1980		9,497	1,672	5,223	2,602	10,908	2,064	6,072	2,772	1,144
1981		12,048	2,046	6,395	3,607	12,366	2,127	6,573	3,667	1,567
1982		23,329	3,749	11,714	7,866	25,562	4,125	12,633	8,804	4,106
1983		8,735	1,572	4,804	2,358	8,093	1,360	4,081	2,651	1,710
1984		15,074	2,783	8,698	3,593	12,345	2,130	6,289	3,926	2,121
1985		15,000	2,540	7,936	4,524	15,576	2,389	7,489	5,698	2,700
1986		16,000	2,590	8,094	5,316	17,316	2,615	8,118	6,583	3,269
Mean	(18,100)	16,500	2,750	8,590	5,190	17,100	2,690	8,280	6,080	3,050

Values are in units of 10^3 t yr^{-1}.
[a]Bed material load carried in suspension.

cording to the ratio $K = C_5/C_1$, wherein C_5 is the mean concentration of suspended sediment determined from a five-vertical sample and C_1 is the mean concentration determined at the same time from the usual single-vertical section. The results formed the basis to estimate daily sediment transport. Between five-vertical samples, values of K were interpolated by assuming that the value changed systematically according to the hydrograph. On days with no sample the load was interpolated between adjacent measurements.

Given the distributions of suspended load and of the number of measurements throughout the year, the technique appears to be reasonable. However, the variation of K is of considerable importance to evaluate the possibility of bias in the results. At Hope and Agassiz, where the streambed consists of cobbles and turbulence intensity is relatively high, K appears to vary randomly about 1.0 with a coefficient of variation ranging from 0.1 to 0.15. At Mission, K varies systematically with discharge. The systematic variation was not explicitly incorporated into the analyses reported here, but subsequent work by M. A. Hassan and M. Church (unpublished data, 1998) demonstrates that small biases in the estimation of individual daily loads are offsetting and have no significant effect on the evaluation of the annual load.

5.2. Precision of the Measurements

Daily sediment loads g_i are computed as $g_i = KQ_iC_i$, wherein Q_i is daily mean flow and C_i is the measured or estimated mean sediment concentration for the same day. A measure of relative precision is given by the coefficient of variation of the daily load estimates (CV_g), which can be expressed as

$$CV_g = [(s_K/K)^2 + (s_Q/Q)^2 + (s_C/C)^2]^{1/2} \quad (1)$$

wherein s indicates the estimated standard deviation of the sampling distribution and s_K/K, s_Q/Q, and s_C/C represent the relative error terms for the K value, discharge, and concentration measurements, respectively.

A first-order estimate of precision was made using values of s obtained by analyzing concentration estimates derived from replicate single-vertical samples taken at all three stations in 1968 and 1972, by estimating the rms deviations of streamflow measurements from stage-discharge rating curves, and by computing the standard deviation of the observed K values at Hope and Agassiz. In 1968 the freshet was close to mean annual flood, and 1972 experienced the highest flood during the period of sediment transport measurements (second highest measured flow). The results yielded estimates CV_K $(=s_K/K) = 0.10$, $CV_C = 0.10$, and $CV_Q = 0.05$, so the relative precision of a single daily load would be $CV_g = 0.15$.

This study is primarily concerned with estimating annual sediment loads. The annual load G_a can be expressed as

$$G_a = K_1 \sum Q_iC_i + K_2 \sum Q_iC_i + \cdots + K_j \sum Q_iC_i \quad (2)$$

wherein K is constant for each sum. The precision of the annual suspended load can be estimated by propagating the errors in K_j, Q_i, and C_i through this relation. This involves compounding the sampling variances of daily sediment concentration and discharge measurements and of individual determinations of K. Results are pooled over the number of such determinations made in each year (i.e., the number of five-vertical concentration measurements, each leading to an individual value of K_j) and weighted by the proportion of the annual load transported during the period between each full measurement. On the basis of the number of K values determined in 1968 and 1972, and on the distribution of the sediment load in those years, the relative precision of an annual load is estimated to fall within the range $0.04 < CV_{Ga} < 0.06$; i.e., annual suspended load is measured to within about ±10% when a $2s$ confidence range is adopted. The precision is governed mainly by the number of determinations of K that were made during the freshet season.

Sediment load estimates can also be affected by systematic errors at each station. In particular, flow approaches the measurement section obliquely at Hope, and hydrometric engineers have supposed that this might affect measurements of both flow and sediment concentration by biasing the estimates of downstream flux. More generally, suspended sediment samplers customarily miss a portion of the load near the bed [*Chien*, 1952; *Nordin and Richardson*, 1971]. Although methods have been devised to approximate this missing load [*Colby*, 1957], no adjustments were made in this study. If such errors exist, they will influence the interstation comparison made below. Thus insight regarding unsampled sediment load may be gained from that comparison.

5.3. Patterns of Suspended Sediment Transport at Agassiz

The seasonal variation in suspended sediment load is illustrated in Figure 4. Within each year, there is a well-defined clockwise hysteresis (Figure 5) [*Kidd*, 1953; *Whitfield and Schreier*, 1981], indicating that the supply of suspended sediments becomes limited during the freshet. The fraction of the annual load transported by various discharges was calculated, and the results for Agassiz are illustrated in Figure 6, the other stations being very similar. The largest fraction is carried by flows between 7500 and 8000 m^3 s^{-1}, which corresponds to a value near the 1.5-year flood. In comparison, flows above 10,000 m^3 s^{-1} (5-year return period) account for only about 12% of the annual suspended sediment load. These results are

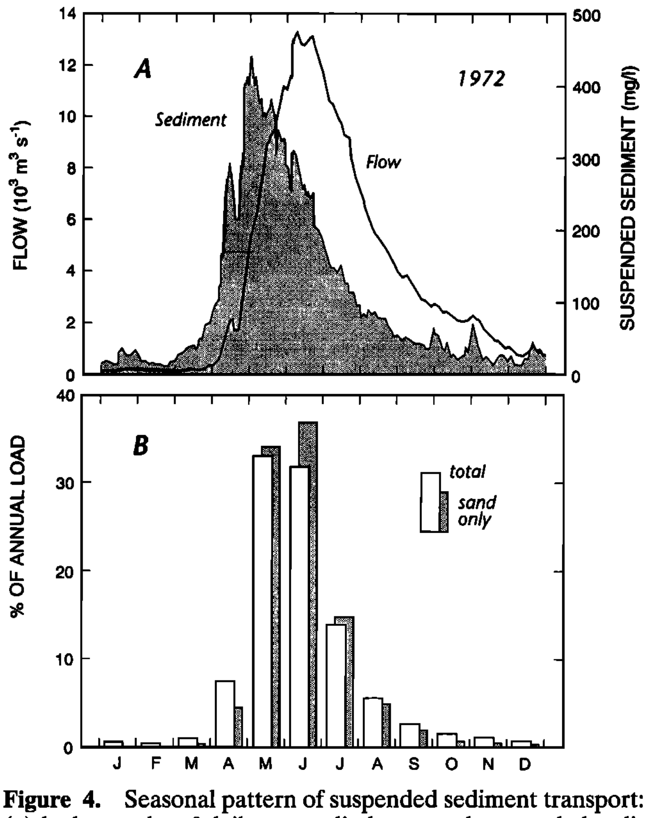

Figure 4. Seasonal pattern of suspended sediment transport: (a) hydrographs of daily water discharge and suspended sediment concentration at Agassiz 1972 and (b) proportional distribution of average suspended load by month at Agassiz (1966–1982).

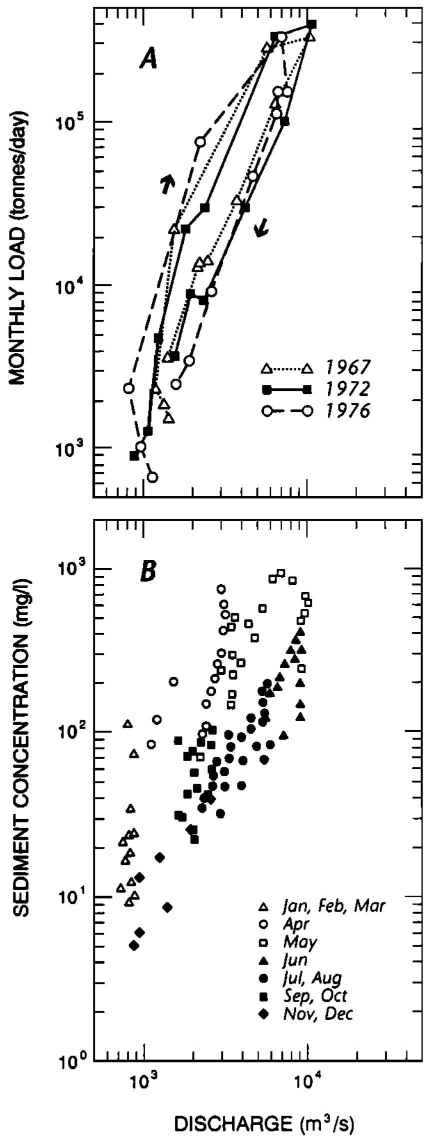

Figure 5. Suspended sediment ratings at Agassiz (a) based on monthly averaged data in several years, 1972 emphasized (note the systematic hysteresis), and (b) 1972 observations, to illustrate the seasonal variation.

in accordance with findings on many other large rivers [*Wolman and Miller*, 1960].

Suspended particle size data were obtained when more than about 150 mg was contained in a sample. Analysis was by bottom withdrawal tube at 1 ϕ intervals. Results indicate that the suspended load consists typically of 35% sand, 50% silt, and 15% clay during freshet conditions. Nearly half the suspended sand load consists of very fine sand (0.063–0.125 mm), while the coarsest material in suspension seldom exceeds 1.0 mm. At Agassiz and Hope, clockwise seasonal hysteresis occurs in all size fractions of the suspended sand load (Figure 7a). Sand-sized sediments generally account for less than 10% of the channel bed material in the reach between Hope and Agassiz, all of it sequestered within the interstices of the dominant gravel mode. We conclude that all of the suspended sediment load at Hope and Agassiz can be considered "wash load" in this reach. Its transport rate evidently is governed not by hydraulic conditions in the channel but by the rate of sed-

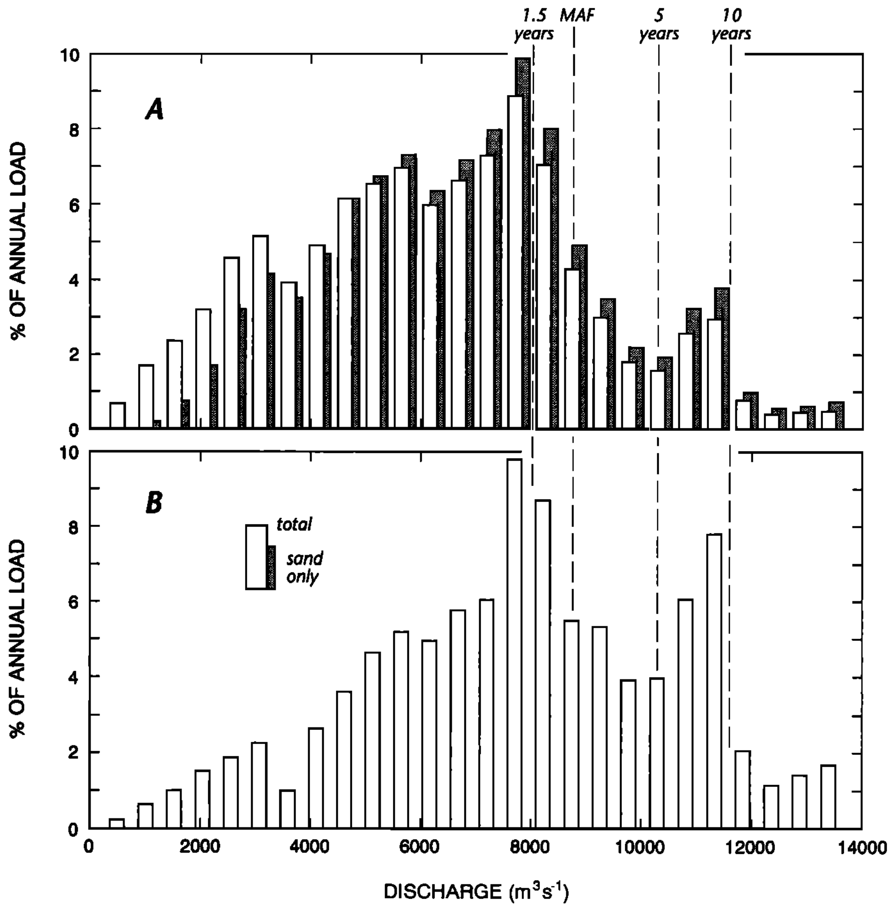

Figure 6. Proportional distribution of (a) daily suspended sediment load and (b) bed load at Agassiz by discharge, 1966–1982.

iment supply, and its presence in the channel bed is limited to interstitially trapped material.

Particle-size measurements of the suspended sediment load were analyzed to determine the variation in size fractions by month and by discharge. The average composition of the suspended load was then estimated in each month, and the total load by size fraction computed. Results of this analysis are summarized in Table 3.

5.4. Patterns of Suspended Sediment Transport at Mission

Conditions are different in the sand-bed reach. The D_{10} bed material size at Mission is around 0.177 mm; thus wash load includes only very fine sand, silt, and clay, while medium and coarse sands constitute bed material load. The proposed division point at 0.177 mm (2.5 ϕ) is near the size at which entrainment velocity equals suspension velocity for grains of usual density [*Sundborg*, 1967]. For smaller grains, suspension velocity is smaller than entrainment velocity and declines rapidly. We expect that such grains, once entrained, would be carried a long way, as is characteristic of wash load. Particle sizes of suspended sediment samples were analyzed at 1 ϕ intervals (Figure 8); thus only the 0.125 and 0.250 mm size fractions are available. Again, virtually one half of the suspended sand is finer than 0.125 mm, and about 65% is estimated to be finer than 0.177 mm. Rating curves of sand >0.125 mm are notably less hysteretic in seasonal occurrence than are those for the total sand load (Figure 7b) or the total suspended sediment load, suggesting that the medium and coarse sand loads are determined by hydraulic conditions in the channel governing entrainment rate from the bed, rather than by the upstream sediment supply.

The daily suspended load coarser than 0.177 mm was estimated from the regression equation

$$\log_{10} C_{0.177} = -8.46 + 2.60 \log_{10} Q \qquad (3)$$

standard error of estimate $\pm 0.18 \log_{10}$ units; $R^2 = 0.86$.

Concentration values for sediments coarser than 0.177 mm grain size were interpolated between the published 0.125 and 0.250 mm size fractions. Table 3 summarizes the estimated annual suspended load by size fraction at Mission. The mean annual suspended bed material load (coarser than 0.177 mm) averaged 2.8×10^6 t yr^{-1} over the period 1966–1986, ranging from a high of 8.5×10^6 t yr^{-1} in 1972 to a low of 1.1×10^6 t yr^{-1} in 1980. On average, suspended bed material is about 15% of the total suspended load.

6. Bed Load

6.1. Measurements

Between 1968 and 1976, 110 sets of bed load measurements were made at the Agassiz-Rosedale bridge, of which 62 were made under freshet conditions. The measurements were made with a basket sampler when flows exceeded 7000 m^3 s^{-1} and a

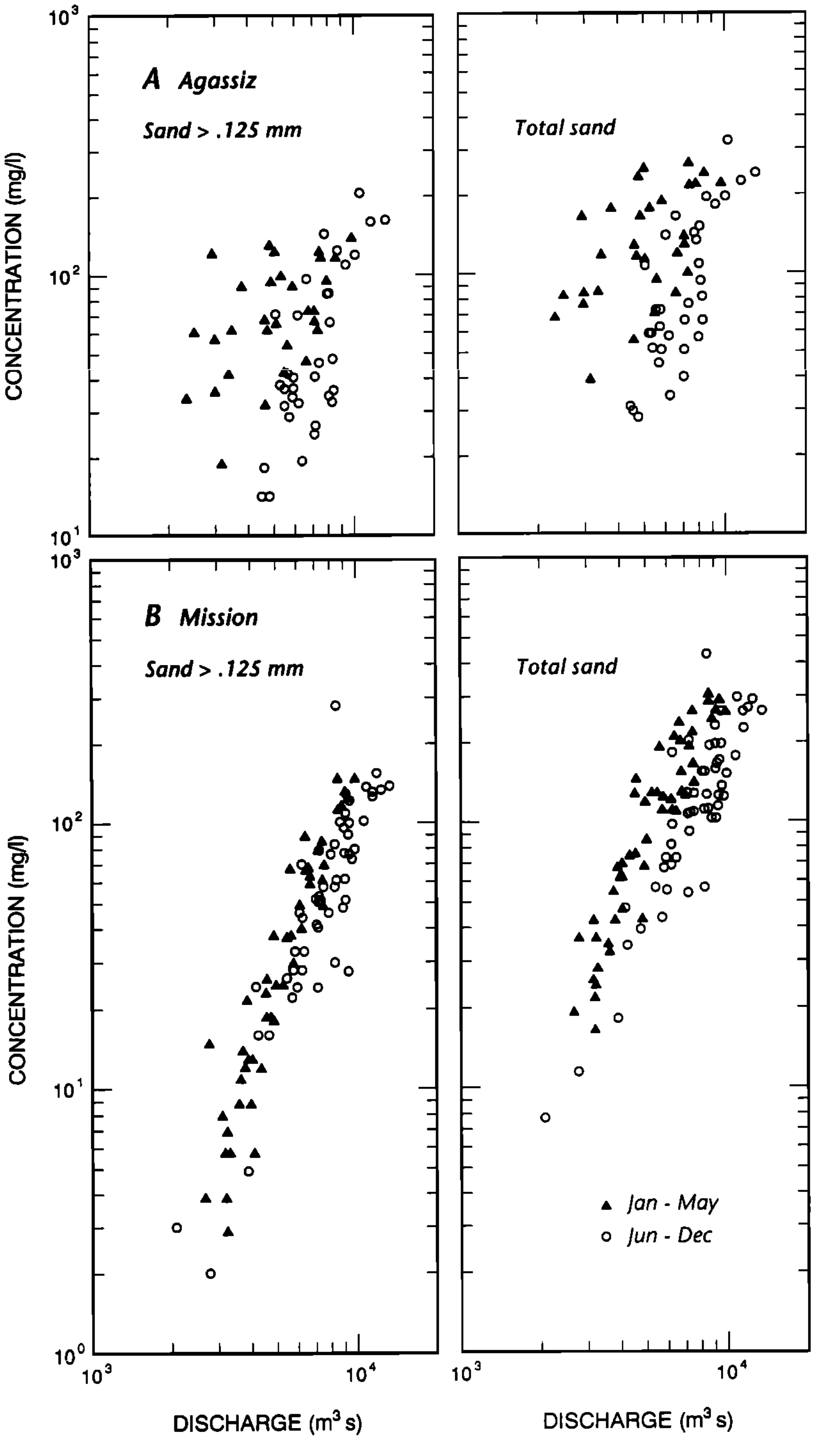

Figure 7. Sand concentration ratings at (a) Agassiz and (b) Mission in 1968.

half-size VuV sampler [*Novak*, 1957] for lower flows. The VuV sampler had a mouth 225 mm wide and 115 mm high. The basket sampler had a mouth 610 mm × 255 mm and a wire mesh gap of 6 mm. The measurements were conducted from a boat at six or fewer verticals. Sampling durations for both the VuV and basket samplers were usually 2 or 3 min, and sample catches typically ranged from a few hundred grams up to 2 kg in the VuV sampler and up to 20 kg in the basket sampler. Normally, the measurements were repeated two or three times to estimate the average transport rate at each vertical. These results were integrated across the channel to estimate the total transport.

Bed load measurements over the sand bed at Mission were made with a BTMA Arnhem sampler [*de Vries*, 1973], a pressure difference sampler with an intake opening 85 mm wide and 50 mm high. The samples were collected at five verticals from a boat on the gauging line upstream of the Mission Railway Bridge. Typically, three samples were collected at each vertical.

The efficiencies of the VuV and basket samplers were cali-

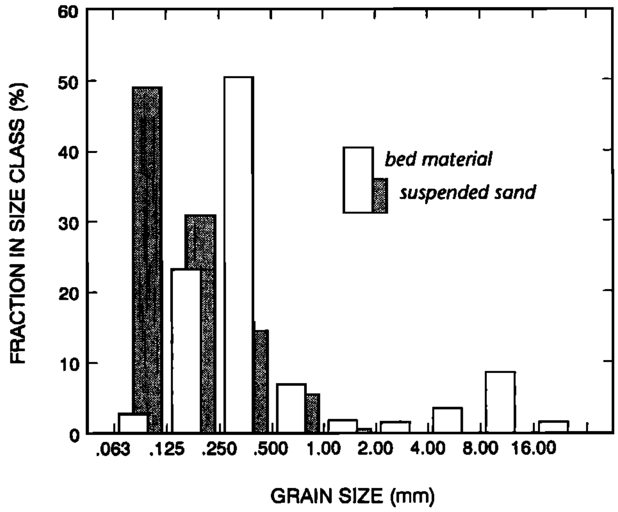

Figure 8. Size distribution of suspended sand (high flow samples) and of bed material at Mission.

brated in laboratory tests conducted at the Canada Centre for Inland Waters [*Engel*, 1982, 1983]. The efficiency of the half-size VuV varied between 30% and 60%, which is much lower than previously reported values [*Novak*, 1957]. For the deployment conditions at Agassiz, a correction factor of 3.0 is applied. A similar correction factor was prescribed for the basket sampler, but in Fraser River it is necessary to apply a further adjustment for the proportion of bed material finer than 6 mm that escapes the sampler. Assuming that the bed load size distribution at high flow is similar to that of the subsurface bed material [*Einstein*, 1973; *Parker et al.*, 1982] (a reasonable assumption based on the texture of bed load samples observed in this study), a factor of 1.18 is applied to account for the 15% of −6 mm material in the bed. We therefore applied an adjustment factor of 3.5 to basket sampler data in order to estimate the total transport of material found in the local bed. It is apparent from a small number of occasions when both the VuV and basket samplers were deployed that, at flows above about 6000 m^3 s^{-1}, the VuV sampler fails to trap the largest material that is mobile. However, we have no basis upon which to apply a correction for this effect.

The efficiency of the Arnhem sampler was determined by *Meyer-Peter* [1937] to decrease as it filled, from 90% to about 50%. Hence an efficiency correction should be applied to each individual measurement according to the catch size. Analysis of 2600 Fraser River samples indicates an overall sampling efficiency of 70–75% for the total bed load rate, values close to ones previously reported by *Novak* [1957] and *Hubbell* [1964]. WSC estimated an efficiency of only 23% after comparing catches at Mission with computations of bed load movement based on dune tracking. In most of those comparisons, dunes moved only 2 or 3 m, which is comparable to the resolution of the measurements. Subsequently, much better measurements of dune progression in the Main Arm of Fraser River at Steveston (Fraser delta) have shown that a substantial proportion of the material transfer associated with dune progression actually occurs in suspension or saltation [*Kostaschuk and Ilersich*, 1995]. On the basis of these findings, we decided to use the original Meyer-Peter calibration results rather than the WSC estimates. Consequently, we assumed a catch efficiency of 70% for the Arnhem bed load measurements and applied a correction factor of 1.4 to the sampler data.

6.2. Precision of the Measurements

Because of the sporadic nature of bed load movement near threshold conditions [*Wilcock and McArdell*, 1993], its tendency to move in "clumps" at all flows [*Hubbell*, 1987; *Gomez et al.*, 1989], and the physical difficulties involved in sampling, measurements of bed load usually are less reliable than measurements of suspended load. Bed load sampling reliability has been examined by several investigators, generally by collecting replicate samples at a single vertical and then comparing the load determined from only a few samples with the presumed average load determined from all the samples. The most thorough study was provided by *Hamamori* [1962] and *deVries* [1973], who investigated fluctuations in bed load rates caused by the passage of dunes and ripples along a sand-bed channel [see also *Gomez et al.*, 1989]. On the basis of those investigations, deVries recommended that a minimum of 10 samples be collected at each vertical. *Einstein* [1936] had earlier described the distribution of bed load movement by assuming that individual particles move in a sequence of steps and rest periods. He applied his concept to the related problem of the distribution of sediment volume caught in a sampler after a specified time. The probability density function for the volume of sediment trapped in a given period implies that the distribution of observed transport rates depends upon both the intensity of transport and the duration of sampling. Measurements of *Csoma* [1973] in the gravel-bed Danube River were consistent with this model. Hence Einstein's model appears to be appropriate for estimating the precision of measurements in a gravel-bed river.

Special observations were made at Agassiz in 1985 to assess the precision of the bed load measurements there. We collected 20 repeat samples at each of two verticals and 14 samples at a third location to estimate the variance in transport rates. We observed large fluctuations in bed load catches during apparently steady flow conditions, with individual measurements reaching as much as 6 times the overall mean transport rate. The distribution of estimated transport rates was highly skewed, nearly 70% of the samples being smaller than the mean. Following the approach of *Csoma* [1973] and *Hubbell* [1987], we conducted a series of Monte Carlo simulations to assess the precision of WSC's sampling program [*McLean and Tassone*, 1987]. On the basis of the simulation results, we calculated that the coefficient of variation of the mean sediment transport rate in a three-sample estimate would be 0.84. The sources of the variability are believed to be both actual fluctuations in gravel transport and operational effects caused by misalignment of the sampler on the river bottom and sampler dragging during raising and lowering.

Repeat measurements made by WSC in 1972 and 1974 at Mission varied between 0.1 and 4 times the mean transport rate. The data reasonably fit the Hamamori distribution [*McLean and Tassone*, 1987], and the three-sample CV was found to be 0.50.

In order to estimate the error of the total bed load transport rate, information is required on the spatial variability of transport across the channel. Adequate field assessment in a river the size of Fraser River would be very onerous. Instead, the Monte Carlo simulations were extended by assuming various smoothly varying distributions of bed load rate across the channel. We found that when the spatial variability of the transport

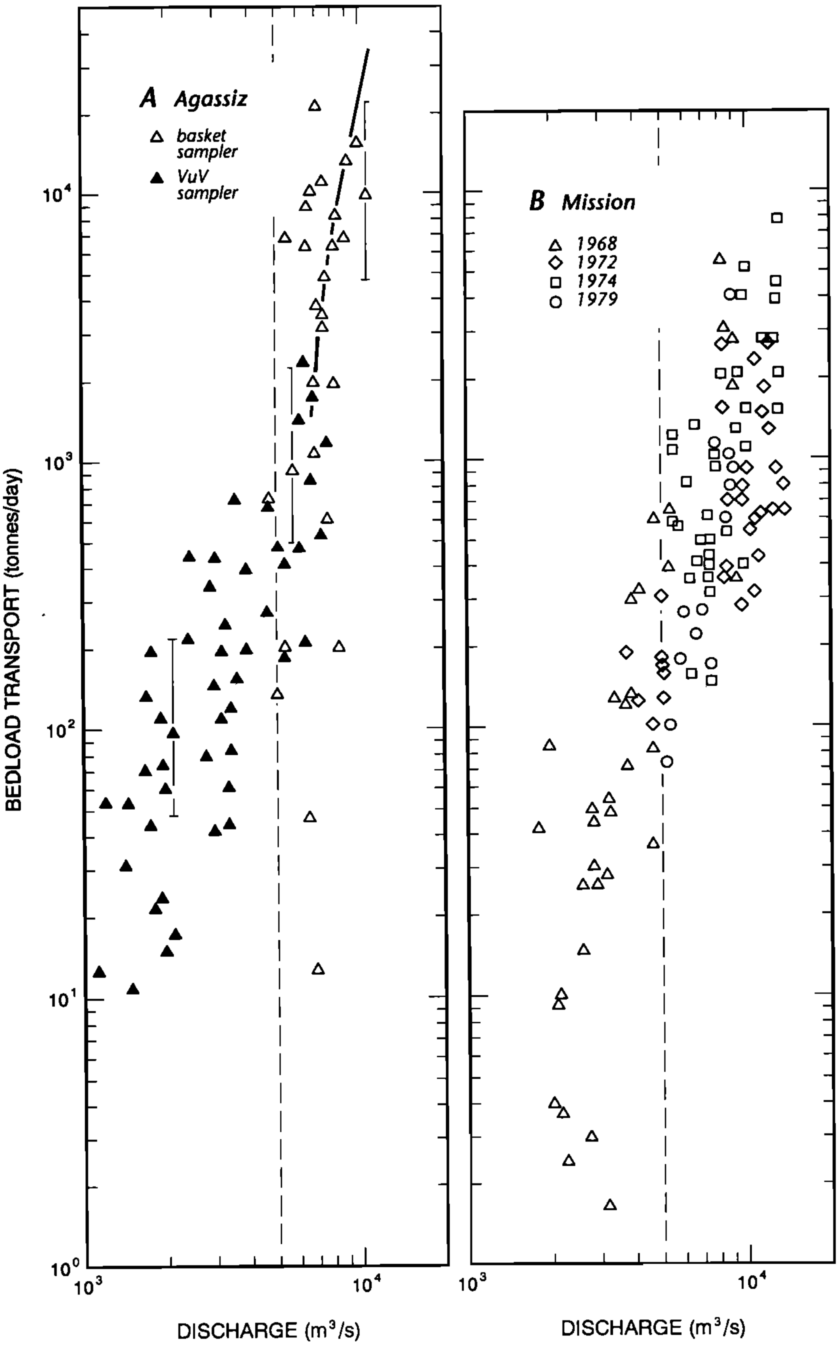

Figure 9. Bed load transport rating curves: (a) Agassiz: superimposed, modified Ackers-White equation. Error bars are two-standard error ranges based on the estimated CV. See text for further discussion. (b) Mission. Vertical dashed line indicates the onset of significant bed load transport.

rate is smaller than the temporal variability, the relative error in the total bed load transport rate is smaller than the relative error in the average transport rate estimated at a single vertical section. If the bed load transport rate were uniform across the channel, the normal WSC sampling procedure would suffer relative errors (CV) in the total transport rate of 0.40 at Agassiz and 0.26 at Mission. We have no information on the actual cross-channel variation in transport. To gain a nominal basis for assessment, we may suppose that it is similar to the temporal variability observed in our special observations, reported above. Most of the catches fell within a factor of 3× the mean. For a skewed distribution with a ratio of maximum rate/mean rate of 3, the relative errors are 0.58 at Agassiz and 0.34 at Mission (see *McLean* [1990] for further details). In comparing the skewed results with the unrealistic uniform case, it appears that the errors are not excessively sensitive to the (unknown) spatial distribution of transport and are in the range of 50% of the estimated load.

6.3. Patterns of Bed Load Transport at Agassiz

Figure 9a shows that there is only a poorly defined relation between bed load transport rate and discharge in the gravel-

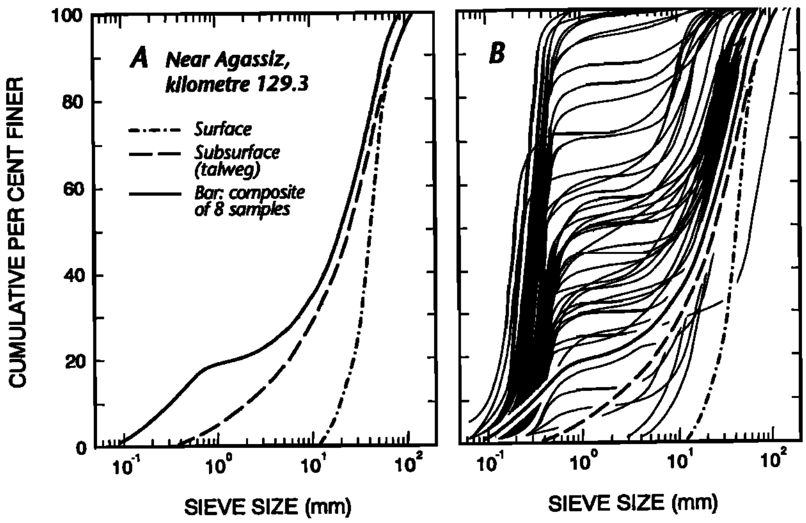

Figure 10. Sediment grain size distributions at the Agassiz gauging station for (a) surface and subsurface bed material and (b) bed load cumulative grain size distributions (bed material superimposed for comparison). Bed load size distributions are from samples taken at flows between 2326 $m^3 s^{-1}$ (fine extreme) and 10,679 $m^3 s^{-1}$ (coarse extreme). Only the two bed load samples with no indicated sand component were taken in the basket sampler. The introduction of significant amounts (>5%) of material >1 mm occurs near 5000 $m^3 s^{-1}$, and the sand/gravel proportion continues to change until the size distribution of the load approximates that of the bed near 10,000 $m^3 s^{-1}$. However, the set of displayed sample grain size distributions does not simply reflect increasing flow. Differential mobility is also affected by recent flow history, which influences sediment sources, bed surface conditions, and the size distribution of mobile material at the time of sampling.

bed reach near Agassiz. The error bars about the individual measurements show that a large portion of this scatter may be attributed to the low precision of the bed load measurements. Significant gravel transport commences at flows near 5000 $m^3 s^{-1}$, which represents the threshold condition at which the armoured surface of the channel bed is mobilized. Most VuV bed load samples collected below this flow consisted mainly of sand, with some fine gravel in the range 2–8 mm (see Figure 10). Above 5000 $m^3 s^{-1}$, the grain size distribution of the bed load approaches that of the subsurface bed material as flows increase to about 10,000 $m^3 s^{-1}$ (Figure 10) and the data from the basket sampler and the VuV sampler both follow the same general transport relation. Most of the mixed sand/gravel distributions represent situations in which moving pebble and cobble gravel is sampled in some verticals, while sand and granule gravel are sampled in others; that is, the bed gravels are mobile over only a part of the bed.

The transport rate of the gravel remains low throughout the entire range of flows experienced on the river. For example, based on the hydraulic properties measured during bed load sampling, the Shields parameter reached 0.07–0.09 during flood conditions. These values are about twice that commonly adopted for incipient motion of bed material but may not be very much in excess of the threshold for clasts locked by imbrication and other structural effects [*Church et al.*, 1998]. Under these conditions, even minor fluctuations in mobility resulting from particle imbrication and sheltering induce large variations in transport rates. Consequently, the local bed load transport rate is affected by flow history and the limited supply of mobile sediments along the channel as well as by local channel hydraulics. As a result, a simple equilibrium relation between transport rate and flow hydraulics may not exist.

Because the measurements are sparse, estimates of monthly and annual bed loads nevertheless were made by rating curve techniques. Inspection of the rating curve in Figure 9a shows that the slope of the bed load–discharge relation changes abruptly near 5000 $m^3 s^{-1}$, corresponding with the onset of gravel transport. For flows greater than 5000 $m^3 s^{-1}$, gravel bed load was estimated from a simple log linear regression equation based on VuV and basket measurements:

$$\log_{10} G = -17.7 + 5.41 \log_{10} Q \qquad (4)$$

standard error of estimate $\pm 0.43 \log_{10}$ units; $R^2 = 0.53$. After reviewing the individual bed load particle-size data and bed material samples, the size distribution of the load was estimated from the average subsurface bed material size distribution. For flows <5000 $m^3 s^{-1}$ it was assumed that gravel transport was zero and only sand (<2 mm) was moving over the immobile gravel clasts. The <2 mm fraction is only nominally "bed load," representing in fact, that portion of wash material that is trapped in the interstices of deposited gravel. Sand transport over the bed for flows <5000 $m^3 s^{-1}$ was estimated on a daily basis by fitting a line through the VuV measurements as follows:

$$\log_{10} G = -4.23 + 1.83 \log_{10} Q \qquad (5)$$

standard error of estimate $\pm 0.47 \log_{10}$ units; $R^2 = 0.51$. Monthly and annual loads were then estimated by summing the daily estimates.

The extreme sensitivity of the gravel-bed load relation to variation in Q is another indication that the transport is occurring very near threshold conditions, where the rapidly changing spatial extent of the phenomenon produces sensitivity [cf. *Wilcock and McArdell*, 1997]. The standard error of estimate reported above translates into a 2s error range of 0.14× to 6.9× the nominal result for an individual load estimate. This is a much larger range than indicated by the preci-

Table 4. Annual Bed Load Transport by Grain Size Fraction

	Mission[a]			Agassiz[b]			
Year	0.177–2.00 mm	2.0–8.0 mm	Total >0.177 mm	0.177–2.00 mm	2.0–8.0 mm	8.0–128 mm	Total Gravel >2.0 mm
1966	165	nil	165				
1967	320	1	321	100	115	576	691
1968	209	nil	209	58	45	222	267
1969	124	nil	124	37	11	56	67
1970	73	nil	73	27	11	55	66
1971	161	nil	161	38	28	137	165
1972	397	2	399	133	168	841	1009
1973	89	nil	89	31	13	65	78
1974	263	1	264	69	77	385	462
1975	126	nil	126	34	18	92	110
1976	247	1	248	60	66	334	400
1977	69	nil	69	33	6	27	33
1978	63	nil	63	31	4	20	24
1979	70	nil	70	27	9	44	53
1980	65	nil	65	33	2	10	12
1981	86	nil	86	37	13	67	80
1982	207	nil	207	61	64	320	384
1983	92	nil	92	32	7	35	42
1984	112	nil	112	40	19	93	112
1985	136	nil	136	47	38	189	227
1986	162	nil	162	51	44	217	261
Mean	154		154	49.0	37.9	189	227

Values are in units of 10^3 t yr^{-1}.
[a]All material is also bed material load.
[b]All material >2 mm is considered bed material load.

sion of the measurements, confirming that real variability in the transport at a given discharge is important. Stratifying the data into rising and falling limb components, or including other variables in the regression model, did not significantly improve the precision of the estimates.

The precision of estimated annual gravel loads was specified by determining the 2*s* confidence range about the regression at 1000 m^3 s^{-1} steps, then determining the fraction of the total annual load that falls within each flow step, thence the sum of the weighted errors. The results indicate that the annual loads are specified to within ±40% [*McLean and Church*, 1986]. Table 4 summarizes the annual bed load transport rates by grain size fraction at Agassiz. The average annual gravel-bed load transport during the period 1967–1986 was estimated to be 227×10^3 t yr^{-1}, ranging from a maximum of 1.0×10^6 t in 1972 to a minimum of 12×10^3 t in 1980.

Figure 6b shows the distribution by discharge of the bed load at Agassiz over the period of record. As with the suspended load, the most significant flows are those near 8000 m^3 s^{-1}. At this flow, the shear stress on the bed is only about 50% greater than the nominal critical stress required to mobilize the armoured surface material. This confirms that the majority of bed load movement takes place when transport is only weakly established, in the "partial transport regime" of *Wilcock and McArdell* [1997].

6.4. Patterns of Bed Load Transport at Mission

Bed load measurements at Mission (Figure 9b) exhibit considerable scatter. In 1974 the transport rate varied more than fivefold under nearly constant discharge conditions. A log linear regression analysis was conducted to develop a rating curve, as follows:

$$\log_{10} G = -10.1 + 3.35 \log_{10} Q \quad (6)$$

standard error of estimate ±0.48 $\log_{10}$ units; $R^2 = 0.76$. The equation was applied on a daily basis, and the annual load was computed by summing the estimated daily loads. The annual bed load transport at Mission (Table 4) averaged 154×10^3 t yr^{-1} between 1966 and 1986, ranging from 399×10^3 t in 1972 to 63×10^3 t in 1978. Nearly all the bed load trapped at Mission consisted of sand between 0.177 and 1.0 mm in size, a range very similar to that of the bed material in the channel. Comparison of individual measurements of bed load and suspended load collected on the same day showed that the ratio of bed load to suspended bed material load ranged typically between 1 and 8%, while the estimated annual bed load transport rate is <5% of the bed material load carried in suspension.

7. Bed Material Load

In the gravel-bed reach at Agassiz, the entire suspended load and the sand portion (<2 mm) of material entrained from the bed can be considered wash load. The true bed material load corresponds to the gravel (>2 mm) fraction of the bed load, even though the performance of the VuV sampler and adjustment factor associated with the basket sampler both introduce a portion of finer material. The bed material load at Agassiz averages 0.23×10^6 t yr^{-1}, which represents only 5% of the total sand load and only about 1% of the total sediment load (Tables 3 and 4). Nevertheless, the transfer of gravel along this reach has a major impact on the channel stability and morphology.

At Mission the total bed material load consists of both suspended bed material load (that portion of the suspended load coarser than 0.177 mm) and the bed load. In the sand-bed reach, most of the bed material probably moves by a combination of saltation and intermittent suspension. The annual bed material load averages ~3.0×10^6 t yr^{-1}, including 2.85 ×

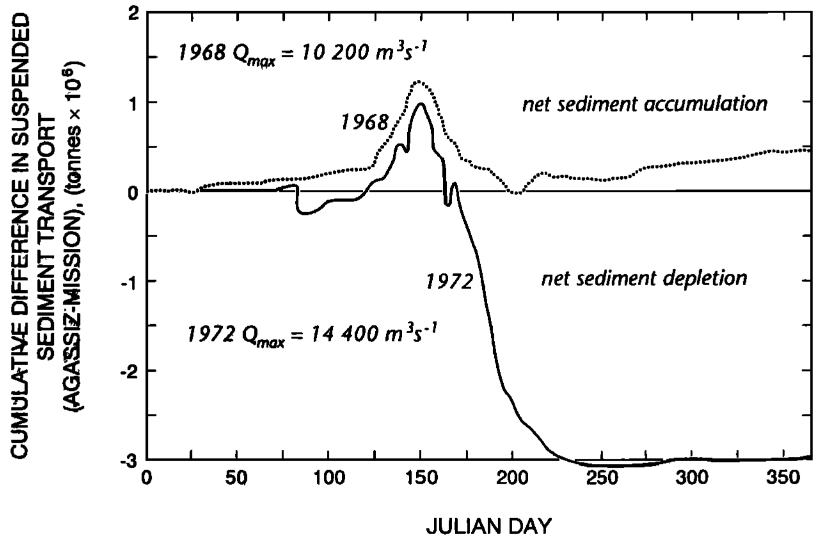

Figure 11. Cumulative differences between suspended loads at Agassiz and Mission in 1968 and 1972.

10^6 t of suspended bed material and 0.15×10^6 t of bed load. The suspended bed material load can be considered to be a near approximation to the total bed material load. Therefore difficulties in sampling bed load in the sand-bed reach are unlikely to have much effect on the overall accuracy of the total bed material load estimate. The suspended bed material load can be measured relatively easily with conventional depth-integrated suspended sediment samplers. Furthermore, the rating curve of suspended bed material load (3) correlates very well with discharge and has relatively little scatter.

8. Interstation Comparisons

From 1967 to 1979, when measurements were made at three stations (including Hope), the mean annual suspended loads were very similar. Given the precision of the measurements, an annual difference of as much as ±14% might be recorded between two stations when the loads are in fact the same. Six of 33 comparisons between adjacent stations exceed this margin, and 10 of 51 comparisons overall do so. There is no consistent pattern in the differences. However, all but one of the significant differences occur in just 4 years, and they are mutually consistent among the stations within each year. These appear, then, to be real differences due to differential deposition and erosion of fine sediment between the stations.

Examination of the pattern of within-season suspended sediment transport confirms the likelihood that real changes occur in sediment storage. Peak loads pass the upstream station early in the season and require some time to pass downstream. Figure 11 shows the cumulative difference between suspended loads at Agassiz and Mission during 2 years. Early in the season, more suspended sediment moves past Agassiz than past Mission; later more material proceeds past the downstream station. However, the cumulative difference does not finish at zero. There is a tendency for net sediment storage to occur within the reach in most years and for net degradation to occur in the years experiencing the biggest floods. Within this pattern there is no indication of a long-term trend. The average loads during the years for which comparisons can be made (13–20 years; Table 3) reveal differences that range from 1.0 to 2.5%, all within the margins of expected error. These results leave no room to suppose that there are peculiar biases present in the measurements at any station. Furthermore, it appears that the bias associated with unmeasured load must either vary randomly from year to year, or that any systematic differences introduced must fall within about 0.1% of the load.

The average annual loads of clay and silt that pass Agassiz and Mission are virtually identical. However, there is a substantial divergence in the sand load transported during the 20 years of common record, indicating that the exchange of fine material in the reach between the two stations involves mainly the sand. Sand >0.177 mm changes from being wash material to bed material between Agassiz and Mission and is most readily deposited on bar tops, in secondary channels, and in flow divergence zones near bar tails. The Hope–Mission reach plays a significant role as a transient store and buffer for sand transport into the more distal reaches of the river.

9. Computations of Bed Material Transport

Measurements of bed load transport are not routine. The currently reduced observing program on Fraser River does not include bed load measurements even though knowledge of bed load is important to determine bed material transport and channel stability. Therefore we were interested to test computational formulae to estimate bed load transport.

Initial trials to estimate gravel transport using bed load equations were described by *Mannerstrom and McLean* [1985]. Various equations that have been recommended for use on gravel-bed rivers were applied to conditions at Agassiz. They yielded a wide range in predictions and were very sensitive to minor changes in input data [cf. *McLean*, 1985]. The high degree of sensitivity results from the hydraulic conditions at Agassiz, where flow is only slightly above the threshold condition for gravel transport even during flood. Such sensitivity has been noted previously on other gravel-bed streams [*Parker et al.*, 1982] and has been analyzed by *Wilcock and McArdell* [1993, 1997]. The Ackers-White equation modified for mixtures [*White and Day*, 1982] provided the best agreement with the average rating curve developed from the measurements (Figure 9a). This equation also provided a good estimate of threshold conditions for gravel transport.

The observed bed material loads at Mission displayed good correlation with hydraulic parameters, in particular, with the mean velocity V and with a velocity ratio V/w, wherein w is the particle fall velocity (Figure 12). Test computations were made to assess the feasibility of predicting the annual bed material transport rate by formula. This involved estimating the daily hydraulic geometry (mean velocity, channel width, and mean depth) from power law rating curves [*McLean and Church*, 1986], computing the corresponding daily loads for each discharge, and summing the results to produce annual predictions. The original Ackers-White equation [*Ackers and White*, 1973] and the *Toffaleti* [1969] equation both produced good overall estimates of the total annual bed material transport, with loads typically within 10% of the measured values (Figure 13). In contrast, the Engelund-Hansen equation [*Engelund and Hansen*, 1967] overestimated the average annual load by about 65%.

10. Conclusions

Sediment transport measurements along the lower Fraser River between 1966 and 1986 reveal that the annual total suspended loads at Hope, Agassiz, and Mission are virtually identical, averaging 17×10^6 t yr^{-1}. The corresponding sand load is about 5.2×10^6 t yr^{-1} (at Agassiz), which amounts to about 31% of the total load. In the gravel-bed portion of the river at Agassiz and Hope, the suspended sand load behaves as wash load. Significant gravel transport begins at Agassiz at a discharge of about 5000 m^3 s^{-1}. At lower flows, sediment caught in bed load samplers consists mainly of coarse sand and fine gravel. The annual bed load transport at Agassiz was estimated to be about 227×10^3 t yr^{-1}, about 1.3% of the total load.

In the sand-bed reach at Mission, sands finer than 0.177 mm make up more than 50% of the suspended sand load but are virtually absent from the bed material in the channel. Therefore a significant portion of the sand load at Mission can still be considered to be wash load. The total bed material load (bed load plus suspended sand coarser than 0.177 mm) was estimated to be 3.0×10^6 t yr^{-1}, or about 18% of the total sediment load. Nearly all of the bed material load is transported in intermittent suspension, about 5% being transported as bed load.

All of the gravel/cobble sediments transported at Agassiz are deposited in the reach upstream of Mission. Over the long-term, the suspended sand load at Hope and Agassiz is approximately equal to the load at Mission. However, over the course of individual freshet events some of the sand becomes temporarily stored and is subsequently removed by channel scour or bank erosion.

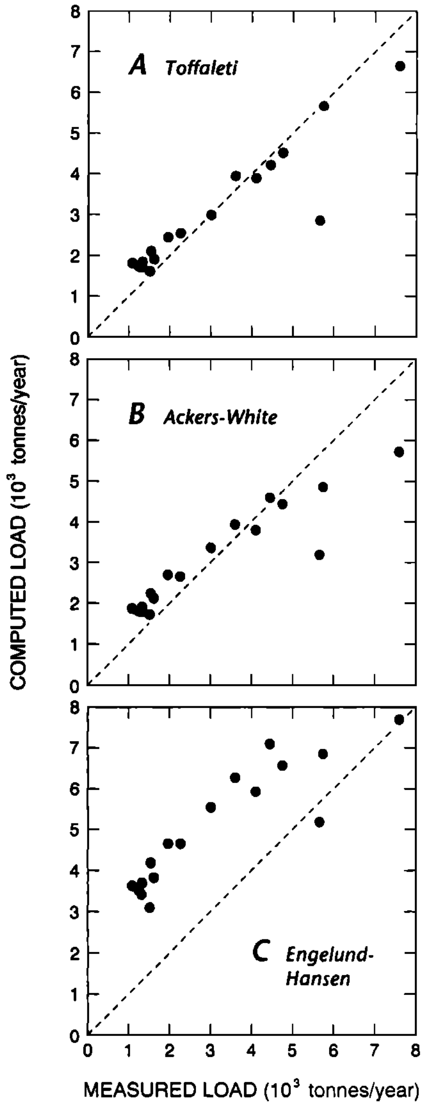

Figure 13. Comparison of measured annual bed material load at Mission with the load predicted by several computational formulae.

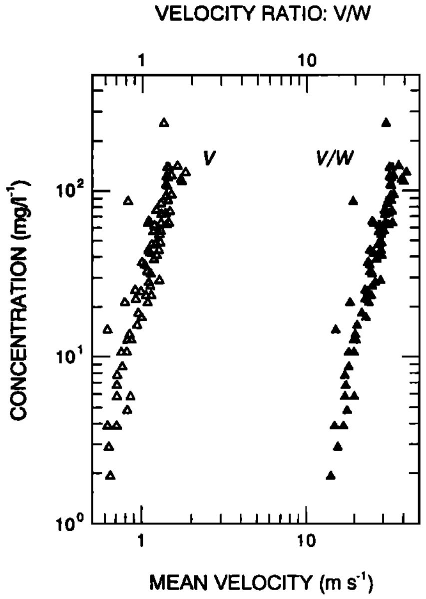

Figure 12. Correlation of bed material load with hydraulic parameters at Mission. V is mean water velocity; W is particle fall velocity.

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Canada deserve recognition for diligently conducting, over 20 years, one of the most comprehensive programs of sediment transport measurements on any major river. We thank Paul Jance for preparing the final figures, and we thank J. Major, R. H. Meade, and P. Whiting for helpful reviews.

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