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SEDIMENT TRANSPORT IN LOWER FRASER RIVER: SUMMARY OF RESULTS AND FIELD EXCURSION GUIDE

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Ray Kostaschuk and Bruno Tassone

Field guide for the
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Fraser River Project
The University of British Columbia
Department of Geography

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Preface

The studies reviewed in this field guide form part of an investigation of the processes governing channel stability and sedimentation in lower Fraser River. A major task is to develop a long term sediment budget for the reach to aid port management below Port Mann. Toward that end, this report gives a review of the available sediment transport observations on the river, which are amongst the more comprehensive available for any river. These have been reconsidered in light of current developments in the analysis of sediment transport measurements. As a result, some aspects of prior analyses have been substantially revised.

It should be realised, however, that the results presented here remain preliminary. They have not been approved by the Water Survey of Canada and should not be regarded as final or authoritative.

A series of reports has been issued to inform the client of progress in this project as follows:

Church, M. McLean, D., Mannerstrom, M. and Evans, D. 1984. Reference materials on sedimentation and morphology of the lower Fraser River. Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-SS-85-1.

McLean, D. and Mannerstrom, M. 1985. History of channel stability: lower Fraser River, Hope to Mission. Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-SS-85-2.

McLean, D. 1985. Lower Fraser River Survey, 1984: Agassiz-Rosedale Bridge to Mission. Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-SS-85-3.

McLean, D. and Church, M. 1986. A re-examination of sediment transport observations in the lower Fraser River. Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-SS-86-6.

Copies of these reports may be obtained, upon request, from:

Head, Sediment Survey Section, Water Survey of Canada
Water Resources Branch, Inland Waters Directorate
Environment Canada, Ottawa, Ontario, Canada, K1A 0E7

Préface

Les études passées en revue dans le cadre du présent manuel pratique s'inscrivent dans le cadre d'une enquête portant sur les processus régissant la stabilité des chenaux et la sédimentation dans le cours inférieur du fleuve Fraser. La mise au point d'un bilan des sédiments à long terme destiné à venir en aide aux autorités portuaires en aval de Port Mann constitue une tâche d'envirgure. A cette fin, ce rapport présente un examen des observations compilées au sujet du transport des sédiments pour le Fraser, qui sont parmi les plus complètes disponibles quel que soit le cours d'eau. Ces observations ont été examinées en fonction des progrès réalisés dans l'analyse des mesures du transport des sédiments. Par conséquent, certains aspects des analyses antérieures ont été révisés en profondeur.

Il faut cependant noter que les résultats présentés ci-après restent préliminaires et ne doivent pas être considérées comme définitives ou faisant autorité.

La série de rapports suivante vise à informer les clients des progrès réalisés dans le cadre de ce projet:

Church, M. McLean, D., Mannerstrom, M. and Evans, D. 1984. Reference materials on sedimentation and morphology of the lower Fraser River. Environnement Canada, Direction des ressources en eau, Section de l'étude des sédiments. Rapport IWD-HQ-WRB-SS-85-1.

McLean, D. and Mannerstrom, M. 1985. History of channel stability: lower Fraser River, Hope to Mission. Environnement Canada, Direction des ressources en eau, Section de l'étude des sédiments. Rapport IWD-HQ-WRB-SS-85-2.

McLean, D. 1985. Lower Fraser River Survey, 1984: Agassiz-Rosedale Bridge to Mission. Environnment Canada, Direction des ressources en eau, Section de l'étude des sédiment. Rapport IWD-HQ-WRB-SS-85-3.

McLean, D. and Church M. 1986. A re-examination of sediment transport observations in the lower Fraser River. Environnement Canada, Direction des ressources en eau, Section de l'étude des sédiments. Rapport IWD-HQ-WRB-SS-86-6.

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Table of Contents

Preface 1

List of tables 3

List of figures 4

1. Introduction 6

1.1. Drainage area 6
1.2. Channel morphology in the Lower Mainland 6
1.3. Hydrology 12
1.4. Sediment sources 12
1.5. History of sediment transport measurements 16

2. The Sediment budget of the lower Fraser River 18

2.1. Division of the load 18
2.2. Suspended load: measurement and analysis 18
2.3. Bedload: measurement and analysis 21
2.4. Separating the sand load 29
2.5. The sediment budget at the principal stations 38
2.6. Predicting annual sediment loads from flow volumes 41

3. Field excursion 46

3.1. Introduction 46
3.2. Agassiz gauge reach 47
3.3. Carey Point lookout 53
3.4. Mission gauge reach 59
3.5. Port Mann gauge reach 64
3.6. Estuarine reach: Main channel at Deas Island 69

4. References 84

APPENDIX: Field Stop Access Maps 87

List of tables

1. Lower Fraser River hydrometric station summary. 9

2. Discharge summary and channel characteristics of gauging sites (1966-1984). 14

3. Composition of bed material and annual sand load > 0.125 mm at Mission and Port Mann. 37

4. Agassiz total load summary: 1967-1982. 39

5. Mission total load summary: 1966-1982. 40

6. Comparison of predicted and measured annual total suspended load at Hope. 44

7. Summary of bank erosion rates along lower Fraser River: Laidlaw to Sumas. 58

8. Suspended bed material load at Port Mann and Mission (1966-1972). 65

List of figures

1. Fraser River drainage basin, highlighting the Interior Plateau. 7

2. Fraser River in the Lower Mainland, showing excursion stops. 8

3. Exceedance probability hydrographs at Hope. 13

4. Analysis of long term flow variations: Fraser River at Hope. 15

5. Downstream pattern of sediment yield in British Columbia, from WSC observations. 17

6. Classification of sediment transported in river channels. 17

7. Hysteresis of sediment transport in lower Fraser River: (a) annual flow and sediment hydrographs at Agassiz, 1972; (b) rating based on monthly data at Agassiz for several years. 22

8. Variation in bedload sample catches at Agassiz. 26

9. Variation in bedload sample catches at Mission. 26

10. Bedload rating curve at Agassiz, 1968-1976. 28

11. Bedload rating curve at Mission, 1968-1979. 29

12. Sand fraction and sand concentration rating curves: (a) Agassiz; (b) Mission. 32

13. Vertical distribution of suspended load at Mission. 33

14. Comparison of bed material and suspended sand load size distributions at (a) Mission and (b) Port Mann; and (c) comparison of sand load size distribution through the four principal stations. 35

15. Correlation of sand fraction > 0.125 mm with discharge. A. Agassiz; B. Mission. 36

16. Relation between suspended sediment load and flow volume: Agassiz and Mission. 42

17. Gauging cross-sections at Agassiz and Mission: example distributions of velocity and suspended sediment concentration. 48

18. Bed material size distribution at Agassiz and Mission, and in the Main Arm near Deas Island. 49

19. Hydraulic geometry in the gauge sections at Agassiz and Mission. 50

20. Variation of sediment load at Agassiz by season and by discharge. 52

21. Channel changes in the Herrling Island-Rosedale Bridge reach. 54

22. Channel changes in the Rosedale-Greyell Island reach. 55

23. Variation of sediment load at Mission by season and discharge. 60

24. Cumulative differences between suspended loads at Agassiz and Mission: 1968 and 1972. 63

25. Bed load transport at Port Mann and Mission, 1968. 67

26. Velocity-sediment transport correlations at Port Mann for suspended bed material load. 68

27. Fraser delta: large scale map. 70

28. Flow distribution in Fraser delta channels, based on 1954 freshet (Keane, 1957) and 1970 (WCHL, 1977). 71

29. Cross-section in Main Arm near the upstream end of Deas Island showing water velocity and suspended sediment concentration within the deepwater channel: measurements of June 22, 1978, 1210 to 1325 PDT (Beak, 1980). 73

30. Location of measurement sections in outer Main Arm of Fraser River (1985-86). 74

31. Water column over a tidal cycle at (a) Sand Heads and (b) Steveston (1986 measurements by R.A. Kostaschuk). 76

32. Along channel variation in water column state for high and low tides (1985 freshet measurements). 77

33. Variation in suspended sediment properties for rising and falling tides during 1985 freshet conditions. Sediment properties were derived from pumped 20 litre samples taken 2 m below the surface in stratified conditions: 2 m from the bed in unstratified conditions. 78

34. Flow and sediment transport during the 1986 freshet at (a) Sand Heads and (b) Steveston. 79

35. Sand waves in outer Main Arm: June 19-20, 1985: marked points indicate corresponding features on successive days. 81

1. INTRODUCTION

1.1. Drainage area

Fraser River drains 250 000 km^2 of southern British Columbia, comprising sections of the perhumid Coast Mountains, the subhumid Interior Plateau, and the western flanks of the Cariboo Mountains and part of the Rocky Mountains (figure 1). The main stem rises at Mount Robson in the Rocky Mountains, 1100 km from the sea. Since 1952, a major drainage diversion has been operated from the upper Nechako basin for hydroelectric power generation at Kemano, on the central British Columbia coast. Since then, the effective drainage area of the river has been 228 000 km^2 at the Mission gauge.

The river passes between the Coast Mountains and Cascade Mountains in the Fraser Canyon, between Lillooet and Yale, and then turns at the southern end of the Coast Mountains to flow west to the sea across the Lower Mainland, which includes the main alluvial reaches of the river (figure 2). A summary of gauging history at the 4 main gauges in the Lower Mainland is given in table 1. This history forms the basis for the discussion in this report.

1.2. Channel morphology in the Lower Mainland

From the place where the river emerges from its rock canyon at Yale, until it reaches Laidlaw the river flows in an irregular single channel and is nearly continuously confined by bedrock, slide debris or Pleistocene terraces. The Hope gauge is located within this reach.

The 50 km reach between Laidlaw and Vedder River displays a wandering or anastomosed channel pattern with frequent mid-channel islands that subdivide the river into several channels. The island stratigraphy is often very simple, consisting of gravel and sand overlain by 1 to 3 m of sand or silty sand floodplain deposits. The bed is composed primarily of gravel (typically with a median size of 25 to 30 mm) with 10 to 20%

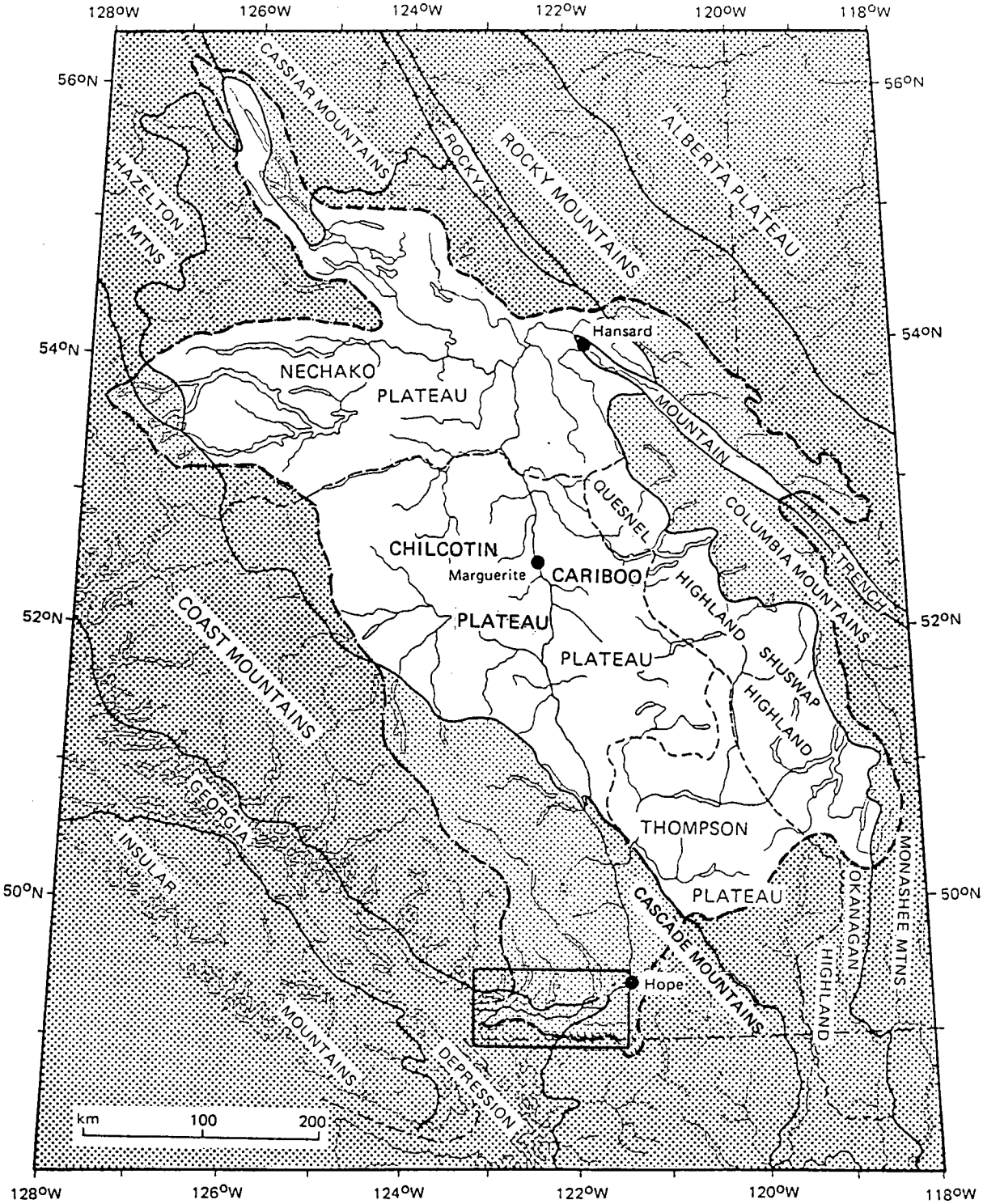
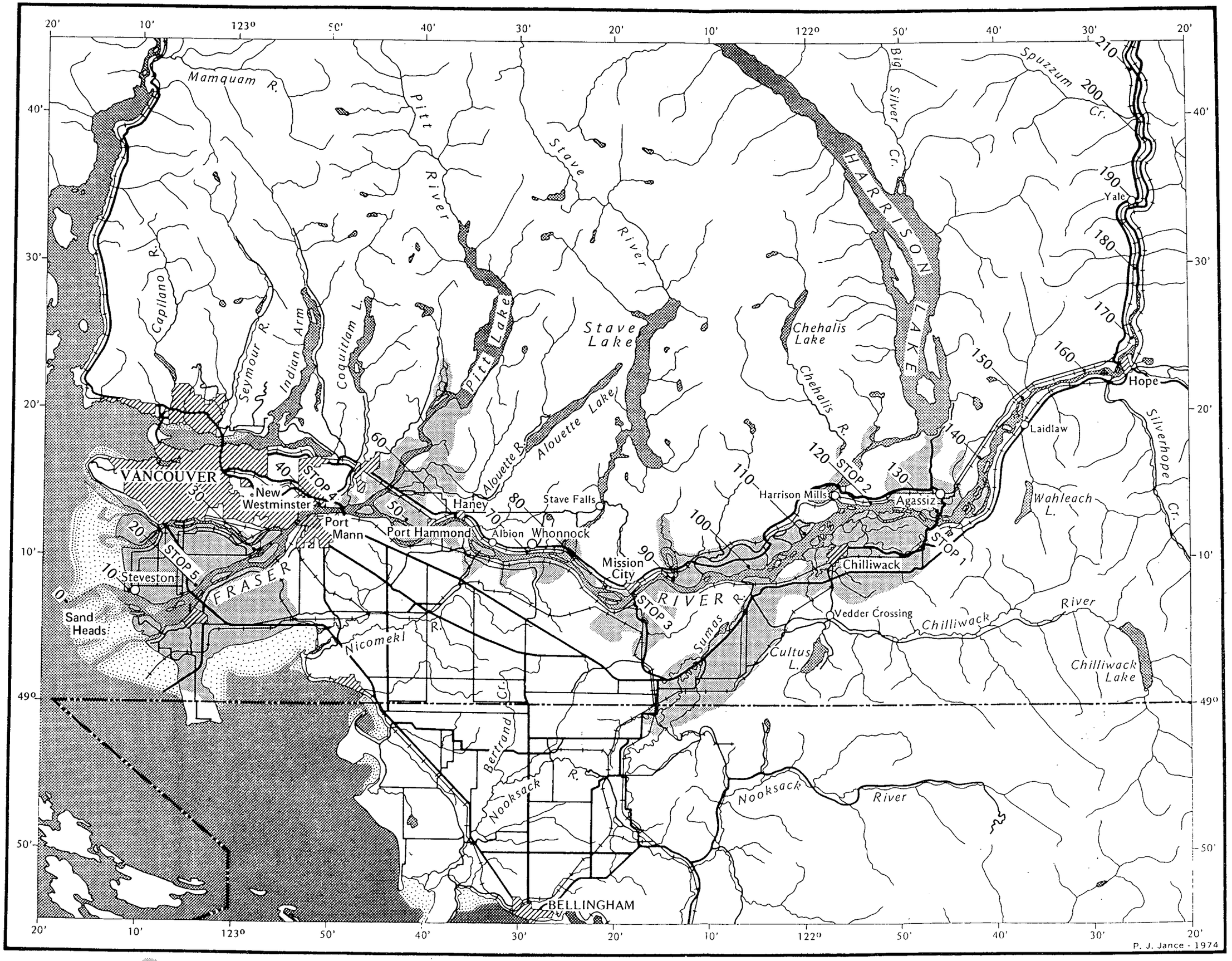


Figure 1. Fraser drainage basin, highlighting the Interior Plateaux which are the source region of most of the sediment load. The heavy dashed line is the boundary of the drainage basin. The study reach is outlined west of Hope.



Floodplain areas

Distances along Fraser River in Kilometres

10 0 Kilometres 20 30 40 50

5 0 Statute Miles 10 20 30

Fig 2

TABLE 1

LOWER FRASER RIVER HYDROMETRIC STATION SUMMARY

STATION	NAME	DRAINAGE AREA (km^2)	LOCATION	DISCHARGE	SUSPENDED LOAD: SEDIMENT YIELD	SUSPENDED LOAD: TYPE OF OBSERVATION	SUSPENDED LOAD: PARTICLE SIZE PI	SUSPENDED LOAD: PARTICLE SIZE DI	BED LOAD: PARTICLE SIZE	BED MATERIAL PARTICLE SIZE	REMARKS
08MF005	HOPE	217000	49 22 50 121 27 05	1912-49 MC 1950-86 RC	1965 1966-69 1970-79	MS MC MC	1965 1967-68 1970-78	1965 1966-69 1970-79			REG 52
08MF035	AGASSIZ	217870	49 12 16 121 46 35	1949-50 MS* 1951-55 RC* 1956-64 MC* 1965 RC* 1966 RS 1967-86 RC	1966 1967-69 1970-72 1973-79 1980-84	MS MC MC MC MC	1968 1970-72 1973-79 1981-84	1966 1967-69 1970-72 1973-78 1980-84	1970 1973-79 1980-84	1978-79	REG 52
08MH054	MISSION	228000	49 07 39 122 18 08	1876-1935 MS* 1936-64 RC* 1965-86 RC	1965 1966-71 1972-80 1981-86	MS MC MC MC	1965 1966-68 1972-79 1981-86	1965 1966-71 1972-80 1981-86	1973-80 1981-86	1965 1966-71 1972-80 1982	REG 52
08MH054	PORT MANN	232000	49 13 03 122 50 20	1956-71 RC*	1965 1966-72	MS MC	1968 1970-79 1981-84	1966 1967-78 1980-84	1973-78	1965-78	REG 52

NOTES:
M - manual sampling
C - continuous operation
S - seasonal operation
* - stage data only
REG - regulated flow
PI - point integrated samples
DI - depth integrated samples

sand. The reach has experienced frequent, irregular channel shifting with bank erosion volumes of roughly 750 000 m^3/year to 1 000 000 m^3/year over the last century (McLean and Mannerstrom, 1984). The Agassiz gauge is located within this reach.

Near km 90, above Mission, the channel pattern changes abruptly to a single thread, sand bed channel. Echo sounding profiles near Mission gauge indicate that dunes usually are found on the river bed when flows exceed about 4000 m^3s^{-1}. At discharges near 8300 m^3s^{-1} the dunes reach up to 2.5 m in height (average 1.5 m) and have an average spacing of 25 to 30 m. For some distance, the river flows in straight reaches between bends where it encounters erosion resistant, non-alluvial material. The bends contain alluvial islands. Farther downstream, the river becomes more sinuous.

At New Westminster the river flows into its modern delta and several channel divisions occur. Nonetheless, there is a clear major channel all the way to the sea at Sand Heads. The channel bed remains sandy and exhibits dune development in freshet. In the delta, the river channels are flanked by flats which carry the tidal prism. The river is seasonally tidal to Sumas 95 km above Sand Heads. A salt wedge is found in the main channel as far upstream as New Westminster in winter when the discharge is low and tidal range in large. In June, during the freshet, the salt wedge may be pushed out to Sand Heads.

The distal margin of the delta sustains a sequence of marshes, eel grass beds and sand tidal flats which collectively form a critically important wildlife habitat. Annual sediment yield from the river is significant in nourishing this zone, hence understanding sediment movement into this zone is a significant aspect of the overall problem of defining the sediment budget of the river.

Within the Lower Mainland, we observe the two major sedimentary transitions that occur in alluvial channels: the transition from gravel to sand bed near Sumas, followed by the transition from fluvial to

littoral-deltaic environment.

In our studies, channel shifting and bank erosion processes were studied in the reach upstream from Vedder River by comparing historical maps and airphotos. Channel shift maps were prepared by superimposing 1:15 840 or 1:31 680 legal township maps of 1876-1906 and airphoto maps from 1928 and 1943 onto 1:25 000 National Topographic maps of 1971. Additional photo maps were prepared to study specific channel areas using air photos from 1954, 1967, 1973, 1979 and 1982. Areas where erosion or deposition have occurred have been demarcated and measured to provide a basis for making bed material transport estimates from river morphology.

The overall channel pattern has remained remarkably stable over the last century. Most of the major island groups such as Peters Island, Herrling Island, Greyell Island and Yaalstrick Island (see NTS Maps 92H/4; 92G/1) were mapped in the original township surveys. Vegetation evidence suggests that some islands have existed for considerably longer than a century. A cottonwood on Yaalstrick Island was dated at 140 years. Large cedars found on Greyell Island and near Maria Slough suggest that these areas have remained stable for even longer periods.

However large areas of floodplain have been eroded since the turn of the century with major erosion occurring near Seabird Island, Maria Slough, Shefford Slough and upper Nicomen Island. Dyking for flood protection and riprap placement for bank protection have proceeded this century, with a major dyke-building program occurring after the 1948 flood (Fraser River Board, 1963). A major program of bank protection and dyke upgrading took place following the Federal-Provincial Flood Control Agreement of 1968. This work was substantially completed by 1975. By the end of this program approximately 45 km of riprap revetment was in place in the 50 km reach between Mission and Maria Slough, near Agassiz. As a result nearly half of the banklines along the floodplain have been protected with riprap.

1.3. Hydrology

Most of the Fraser drainage basin is alpine, or plateau country, with elevations near or above 1000 m. Hence, the annual winter accumulation of snow and its melt in spring forms the dominant hydrological event. The basin is too large for most individual storm events to have a notable effect on runoff. Figure 3 presents the variability of the daily flows that have been recorded at Hope. This plot illustrates the dominating effect of the annual snowmelt freshet, with the river very regularly rising in early April and peaking in the first weeks of June.

Table 2 summarises some key discharge values and hydraulic characteristics from the hydrometric stations at Hope, Agassiz and Mission. The drainage area increases by only 870 km^2 between Hope and Agassiz (roughly 0.4% of the area at Hope). However, between Agassiz and Mission the Harrison River and Chilliwack River contribute an additional 10 000 km^2 which corresponds to about 5% of the area at Hope. These tributary inflows typically increase the mean flow by about 18% and the freshet flows by 10 to 15%. Figure 4 shows that the long term pattern of runoff in the Fraser River has not remained stationary over the last century and that between 1957 and 1977 the runoff has been persistently higher than the long term average. In so large a basin, land use effects are unlikely to have seriously affected runoff, hence it is assumed that the changes reflect climate change.

1.4. Sediment sources.

Upland areas in the Fraser drainage basin are not prolific sediment sources today. Even in the high mountains, the main points of sediment production -- alpine glaciers, rockfall cliffs and avalanche slopes -- are poorly connected with the main river channel network. However, the region was intensely glaciated in the Pleistocene Epoch and thick valley fills of glacial deposits have been left in the preglacial valleys. The main rivers today have incised into these sediments, which continue to supply the main sediment load directly to the river banks. Consequently,

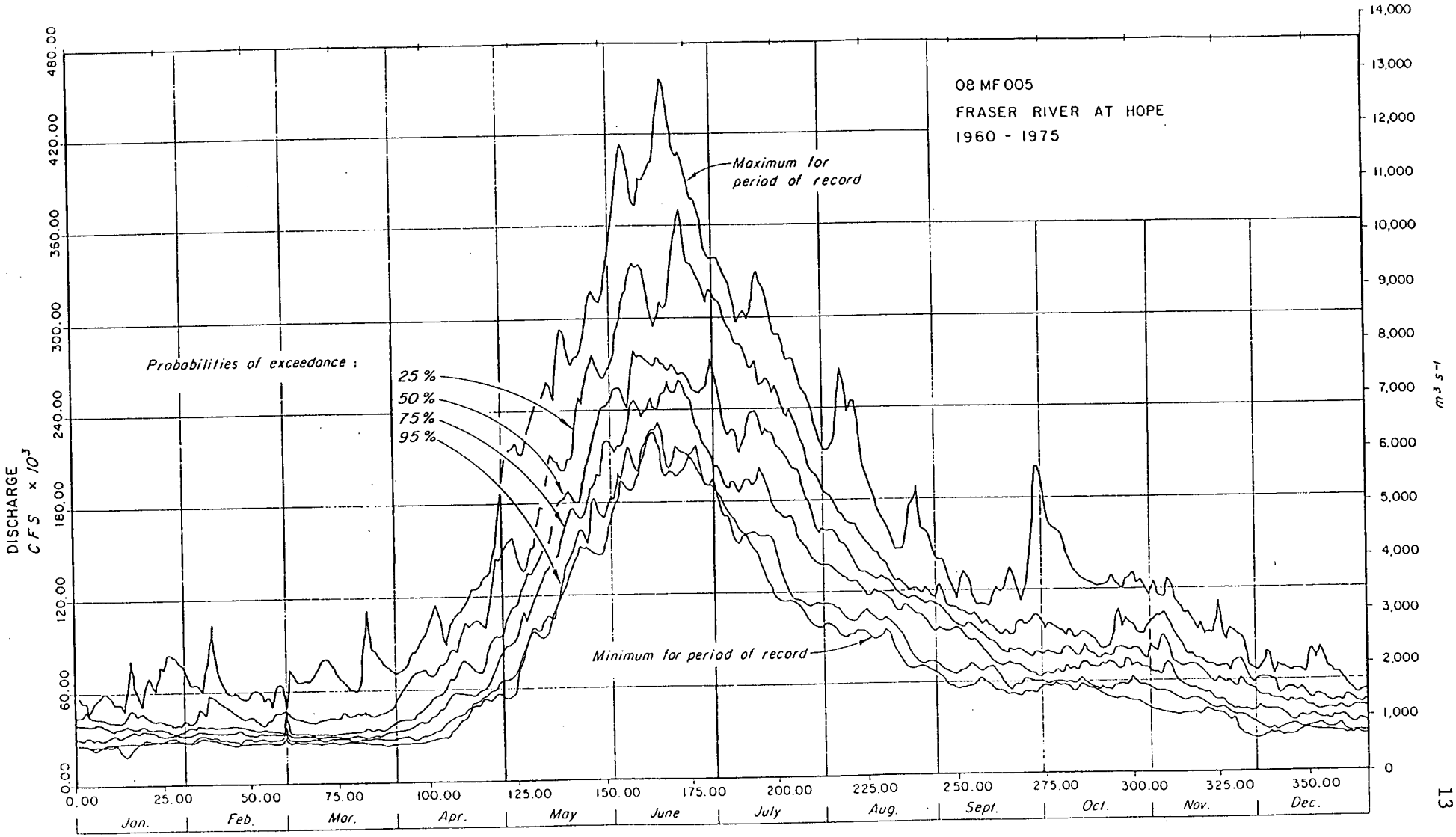


Figure 3. Exceedance probability hydrographs at Hope.

TABLE 2

DISCHARGE SUMMARY AND CHANNEL CHARACTERISTICS AT GAUGING SITES (1966-1984)[1]

STATION	REF	FLOW	Q m^3/s	V m/s	d m	W m	S	BED MATERIAL Surface mm		BED MATERIAL Subsurface mm
HOPE		MDF	527[3]							
	08MF005	LTM	2830	1.5	7.9	240	.0006	D90	180	128
	mean	June	7030	2.8	9.7	258		D75	130	60
		MAF	8766	3.2	10.1	268		D50	100	30
		5yr	10200	3.5	11.1	270		D25	75	7
		10yr	11500	3.7	11.5	270		D10	40	1
	1972	flood[2]	12900	4.0	11.7	275				
AGASSIZ		MDF	470[3]							
	08MF035	LTM	2880	1.4	4.1	500	.00048	D80	80	80
	mean	June	7180	2.3	6.1	509		D75	56	50
		MAF	8760	2.6	6.6	512		D50	42	25
		5yr	10300	2.8	7.1	513		D25	30	8
		10yr	11600	3.0	7.5	515				
	1972	flood[2]	13100	3.2	7.9	516				
MISSION		MDF	648							
	082H024	LTM	3410	0.7	9.4	518	.00005	D90	8	
	mean	June	8140	1.3	12.0	530		D75	0.5	
		MAF	9790	1.5	12.6	540		D50	0.38	
		5yr	11500	1.6	13.2	550		D25	0.20	
		10yr	13000	1.7	13.7	552		D10	0.15	
	1972	flood[2]	14400	1.9	14.1	555				

NOTES: MDF = minimum daily flow
LTM = long term mean discharge
MAF = mean annual flood
Flow statistics for period 1966-1984

[1] Port Mann records remain unpublished because of unresolved effects of tides.
[2] Flood of record in period.
[3] Ice effects occur.

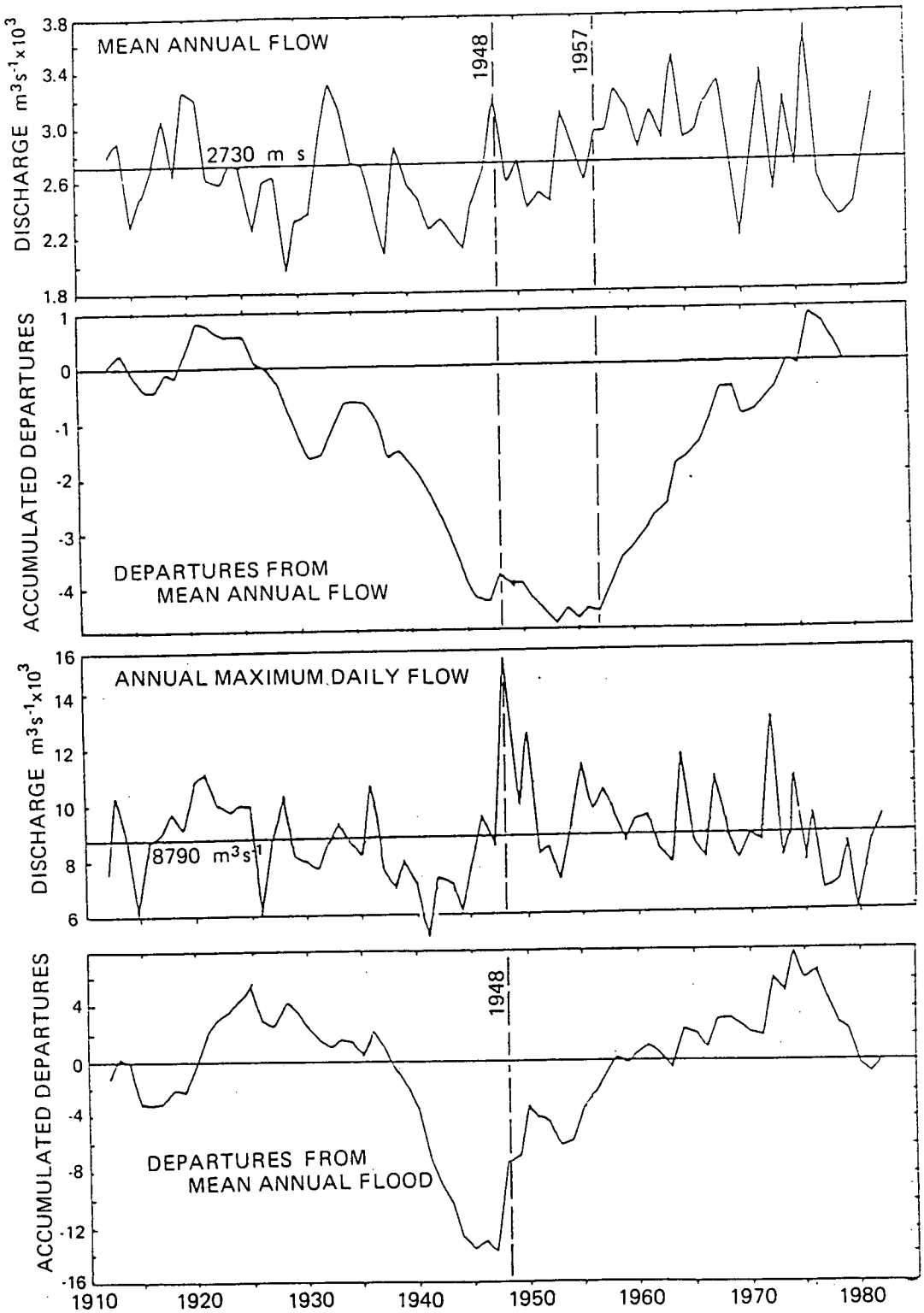


Figure 4. Analysis of long term flow variations: Fraser River at Hope (08MF005) for the period 1912-1982. Major points of change in the record are noted by dashed lines.

specific sediment yield increases downstream in the Fraser system until the drainage area is over 10 000 km^2 (figure 5). Large lakes on several major tributaries in the central part of the basin reinforce this trend, which contradicts the conventional wisdom about areal sediment yield. The area highlighted in figure 1 shows the main sediment source region, but the main sources are largely restricted farther to the main channel banks.

In such a large and thinly populated basin, land use is unlikely to have affected sediment yield significantly. Assuming, then, that the overall pattern of sediment supply has not changed much over the last century, it is likely that annual sediment yield reflects 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 follow a pattern similar to that for flows (figure 4).

1.5. History of sediment transport measurements.

The first sediment transport measurements on the Fraser River were collected by W.A. Johnston (1921) at New Westminster. A programme of measurements was carried out between 1950 and 1952 at Hope (Kidd, 1953). In 1965 the Water Survey of Canada began a comprehensive programme to measure the suspended load and bed load at several locations along the main stem and on some tributaries. Since this time bed load and suspended load have been measured periodically at Port Mann, Mission and Agassiz (Figure 2; Table 1). Only suspended load data have been collected at Hope. Some early results from these measurements were analysed by Tywoniuk (1972) and by Pretious (1972) and the most recent overview of the programme was prepared by Kellerhals (1984). However, for the most part, the data have heretofore received little systematic analysis.

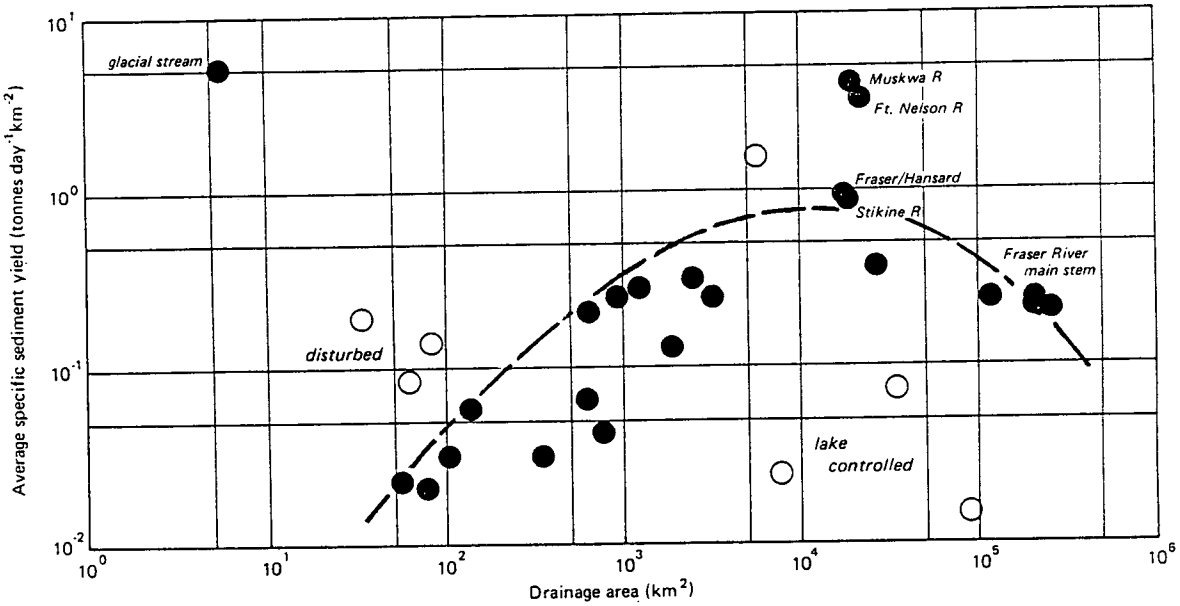


Figure 5. Downstream pattern of sediment yield in British Columbia from WSC observations.

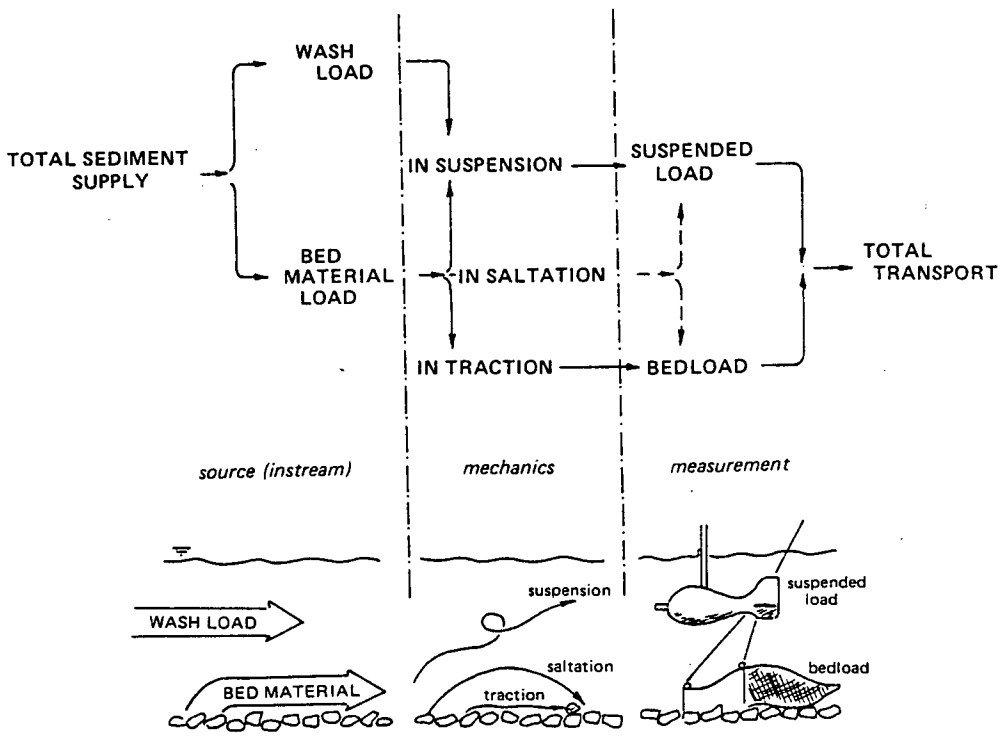


Figure 6. Classification of sediment transported in river channels.

2. THE SEDIMENT BUDGET OF THE LOWER FRASER RIVER

2.1. Division of the load.

To understand alluvial river channel processes, or for effective engineering management of the channel, it is necessary to consider the sediment load transported by the river in two categories. These are wash load, sediment which moves directly through the reach without deposition in the channel (though it may be deposited overbank in flood), and bed material load, material that is episodically moved and deposited in the channel, to form the bed and lower banks. It is the movement of this bed material that determines channel stability.

The methods available for measuring sediment transport do not conform with this division of the sediment load (figure 6). Sediment moving in suspension -- that is, with the sediment weight entirely supported in the water column -- is measured by taking a sample of water, whilst bedload -- sediment moving over the bed -- is sampled using a trap. The latter is a difficult measurement that is not often routinely attempted.

Whilst wash load moves essentially entirely in suspension in most rivers, the sand fraction of bed material may move in either mode. Hence, in order to establish the sediment budget in a manner that will be relevant for understanding river stability problems, it becomes necessary to divide the sand load moving in suspension into bed material and wash material.

2.2. Suspended Load Measurement and Analysis

The daily suspended loads reported at Hope, Agassiz and Mission are based on typically 150 to 220 depth-integrated concentration measurements each year at a single vertical. These samples (termed K samples) have been taken with sampling equipment permanently mounted on bridges. During the freshet period samples are collected virtually daily. Concentration values for days when measurements were not taken have been estimated by using a graphical interpolation procedure.

On 10 to 15 days each year depth-integrated measurements have been taken at five verticals to estimate the average concentration in the river. These complete measurements (termed R samples) were made from the highway bridge at Hope and from boats at the Agassiz and Mission gauging stations. By collecting both "K" samples and "R" samples the relation between the average concentration and the single vertical sample can be estimated. This ratio is termed the K-factor:

$$K = C_R/C_K$$

The K-factor is used to convert the measured single-vertical samples to estimated cross section averages. At Hope and Agassiz the K-factor appears to vary randomly over the year with an average of 0.88 and a range between 0.75 and 1.1. The K-factor at Mission appears to become systematically lower at higher discharges. It is believed that this variation is due to the location of the daily sampling station on the Mission bridge. During echo sounding surveys at high flows it was noticed that 2 to 3 m high dunes at the WSC gauging line disappeared as they approached the bridge. It is believed that the material comprising the bedforms was resuspended by the higher velocities and more turbulent conditions at the bridge causing the daily samples to have unusually high concentrations. K = 0.82 on average, with a range of 0.62 to 1.1.

Particle size analysis has been carried out on the multiple vertical, depth-integrated ("R") samples provided the amount of suspended sediment is sufficient for laboratory analysis. Typically this means that particle size analysis is not available for flows less than 2000 m^3s^{-1} at Hope or Agassiz and 3000 m^3s^{-1} at Mission.

Point integrated measurements have been carried out at Hope, Agassiz and Mission usually once or twice each year. The measurements are customarily carried out at five verticals in the cross section during the summer freshet. Velocity profile data is usually collected along with the point-integrated samples.

Total sediment transport is estimated by simple summation of daily results. In this project we have been concerned primarily with estimating the annual sediment load. For the purpose of assessing its precision, the annual load, G_s, can be expressed as:

$$G_s = K_1 \sum_{i=1}^{N_1} Q_i C_i + K_2 \sum_{i=1}^{N_2} Q_i C_i + K_3 \sum_{i=1}^{N_3} Q_i C_i \ldots K_j \sum_{i=1}^{K_j} Q_i C_i$$

where K_j is the K factor applied to time interval j
Q_i is the estimated daily discharge
C_i is the measured (or interpolated) daily concentration value determined at a single vertical

The precision of the annual load can be estimated by propagating the sampling errors in K_j, Q_i and C_i through this equation. These errors were determined as coefficients of variation and determined to be approximately as follows (see McLean and Church, 1986):

CV(C) = 0.10
CV(K) = 0.10
CV(Q) = 0.05

Given these values, the relative precision of any daily load would be approximately:

$$(0.1^2 + 0.1^2 + 0.05^2)^{0.5} = 0.15$$

The relative error in the annual load (CV(G)) was found to range between 0.04 and 0.06 at the three stations; i.e., the annual suspended load is measured to within about 5%. It was found that the precision of the annual load was governed mainly by the number of K-factor measurements that were made in the freshet season; that is, by the number of full R-measurements taken. The main assumption in the analysis is that the component errors are independent of each other.

The daily and monthly sediment loads display a very characteristic hysteresis over the year as illustrated in Figure 7. Sediment load is substantially higher on the rising limb than on the falling limb, indicating that the sediment supply becomes exhausted over the freshet season. This hysteresis has been described previously by Kidd (1953) and many others. The cause of it is exhaustion of the seasonally delivered sediment supply along upstream channel banks. In examining the daily sediment load graph it is apparent that three distinct periods can be identified:

- an early rising limb period when the sediment loads follow a well defined relation with discharge;
- a supply exhaustion period, which usually begins on the rising limb of the hydrograph. In this period the sediment concentration is virtually independent of discharge and rapidly declines with time whilst discharge continues to increase;
- a falling limb period when the flows are receding and a second well defined relation exists between sediment concentration and discharge.

This hysteresis greatly complicates the prediction of daily sediment load.

2.3. Bedload measurement and analysis

Between 1968 and 1976 110 measurements were collected at Agassiz, 62 of which were made during the freshet season (May-July) when virtually all of the bedload movement takes place. The measurements were collected with a half size VuV sampler (Novak, 1957) and a basket sampler at the higher flows (generally above 7500 $m^3 s^{-1}$). The VuV sampler has an opening width of 224 mm and a height of 115 mm. This pressure difference type sampler is designed so that the water and transported bed material enter the sampler with the same velocity as the undisturbed flow. The WSC basket sampler is based on early Swiss designs from the 1930s and has an opening width of 610 mm, a height of 255 mm and a basket mesh size of 6 mm. Due to the coarse mesh size the finer gravel and sand are not retained in the sampler.

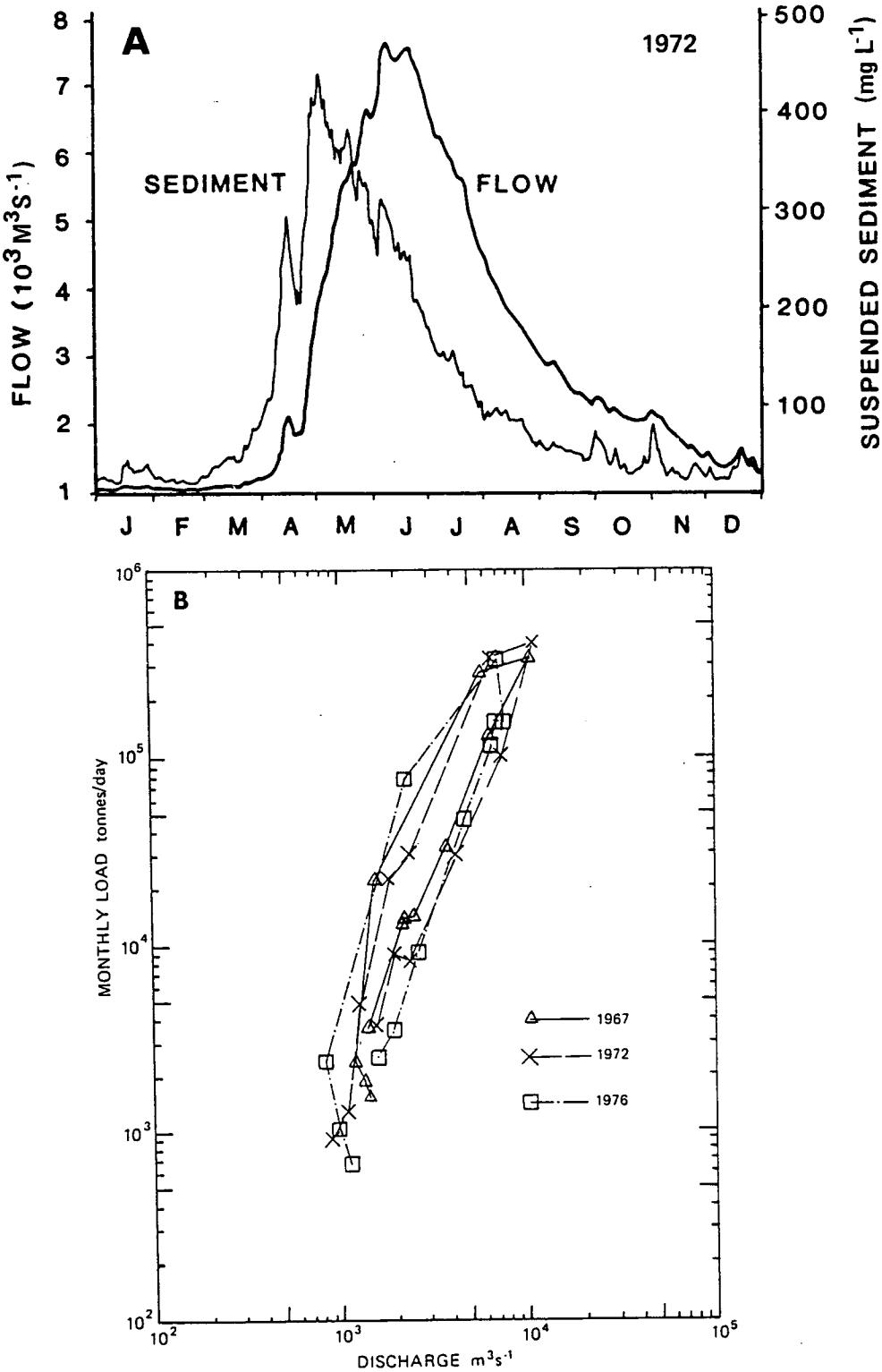


Figure 7. Hysteresis of sediment transport in lower Fraser River.
(a) annual flow and sediment hydrographs at Agassiz, 1972;
(b) rating based on monthly data at Agassiz for several years.

The Agassiz bedload measurements were collected at six or fewer verticals from a WSC boat on the gauging section line. Typically only two or three repetitive samples were collected at each vertical making a total of 12 to 18 samples in each measurement. The sampling times for both the VuV and basket measurements were usually two to three minutes and sample catches usually ranged from a few hundred grams up to 1 or 2 kg in the VuV sampler and up to 10 to 20 kg in the basket sampler.

The bedload measurements at Mission were made with a BTMA Arnhem sampler (Schaank, 1937; de Vries, 1973). This sampler is a pressure difference sampler with an intake opening 85 mm wide and 50 mm high. The Arnhem sampler was designed for measuring bedload in the Rhine River in the Netherlands where the material consists of coarse sand and fine gravel. The samples are collected at five verticals from a WSC boat on the gauging section line upstream of the Mission Railway bridge. Normally 3 to 5 replicate samples were collected at each vertical with individual sample catches ranging from a few grams to a few hundred grams. In some of the early years a complete measurement was often repeated two or three times in a day so that the daily load could be estimated from 50 to 75 samples. In later years the daily load must usually be estimated from about 15 samples.

The efficiencies of the basket and VuV samplers were estimated from recent laboratory calibrations performed at the Canada Centre for Inland Waters (Engel, 1982, 1983). These studies, as well as results from previous investigations (Gibbs, 1973), indicated that the efficiency of the basket sampler is about 33% for the hydraulic conditions at Agassiz. This factor must be further adjusted to account for the loss of sub-6 mm material through the mesh. The bed material samples near Agassiz indicated that about 15% of the sediment was finer than 6 mm. Therefore the overall correction factor adopted in this study was estimated as:

$$K = 1/0.33 \times 1/0.85 = 3.5 \text{ (or 28\% efficiency)}$$

For the hydraulic conditions at Agassiz and for sampling times of 2 to 3

minutes the efficiency of the half size VuV sampler was estimated to be about 33% (Engel, 1983), identical to that of the basket sampler. This estimated efficiency is surprisingly low compared to the results from previous laboratory studies.

The efficiency of the Arnhem sampler was determined from a series of model tests carried out in the 1930s at the ETH laboratories in Zurich (Meyer-Peter, 1937). The efficiency was found to decrease as the sampler filled with sediment, varying between 90% and 50%. In comparison, Water Survey of Canada carried out field calibrations of the sampler in 1968 at Mission and Port Mann by comparing estimates from the sampler with estimates of bed load movement based on dune tracking surveys (WSC, 1970). In most of these field tests the actual movement of the dunes between surveys was only 2 - 3 m, which is probably near the limit of the resolution of the surveys. Based on these field tests the catch efficiency of the Arnhem sampler was estimated to be only 0.23, indicating the measured loads need to be multiplied by a factor of 4.4 to provide correct estimates. This efficiency factor is about one third of the value normally quoted for the Arnhem sampler.

More recent dune surveys conducted in this project seem to support the low efficiency factor adopted by WSC. In addition, some flume experiments at UBC indicate that low catch efficiencies could occur as a result of clogging of the 0.30 mm mesh screen. In these tests, carried out with the flume recirculating natural Fraser River sands, the hydraulic efficiency was found to decrease from 1.3 when the sampler was first placed on the bed of the flume to only 0.2 after a few minutes of running. The problem arises from the use of the sampler to trap material substantially finer than the granule gravel for which it was designed. On the basis of this review, WSC's original correction factor of 4.4 was used for adjusting the measured loads. However, there is still considerable uncertainty associated with this factor and it would be very useful to conduct more definitive tests on the Arnhem sampler performance in sand.

Because of the sporadic nature of bedload movement and the physical difficulties involved in sampling, measurements of bed load are less reliable than measurements of suspended load. It is now well known that large temporal fluctuations occur in bedload passage even in steady flow.

Replicate measurements were made at Agassiz by WSC on June 11, 1985 with the half size VuV sampler at a discharge of approximately 7700 m^3s^{-1}. Twenty repeat samples were collected at two verticals and 14 samples were collected at the third vertical. Figure 8 illustrates the large fluctuations in sample catches that were observed and the frequency distribution of the transport rates. The most important feature of these results is that individual measurements could reach up to six times the overall mean transport rate. Furthermore, the distribution of transport rates was very non-symmetrical, with nearly 70% of the samples having loads less than average. The results support Einstein's (1937) estimate of the expected distribution of sample catches at low transport rate (cf. McLean and Tassone, 1987). These results should make it clear that the normal practice of estimating the mean bedload rate with only two or three samples could result in substantial errors.

Three sets of repeated bedload measurements have been collected at Mission in 1972 and 1974 under flow conditions that ranged from 10 800 m^3s^{-1} to 6570 m^3s^{-1}. On each occasion between 20 and 25 bedload samples were collected at a single vertical (Vertical 900) over a period of three to four hours. The variation in transport rates that was observed is summarised in Figure 9.

The actual distribution of transport rates in sand bed channels will be affected by the bed form characteristics that are present. The 1972 data showed that individual bed load measurements varied between 0.1 and 4 times the average rate estimated from all samples. The frequency distribution of transport rates roughly approximates the Hamamori distribution for the distribution of transport rates over a ripple or dune (deVries, 1973). Unfortunately, longitudinal profiles were not surveyed at the time of the bed load measurements in 1972 or 1974.

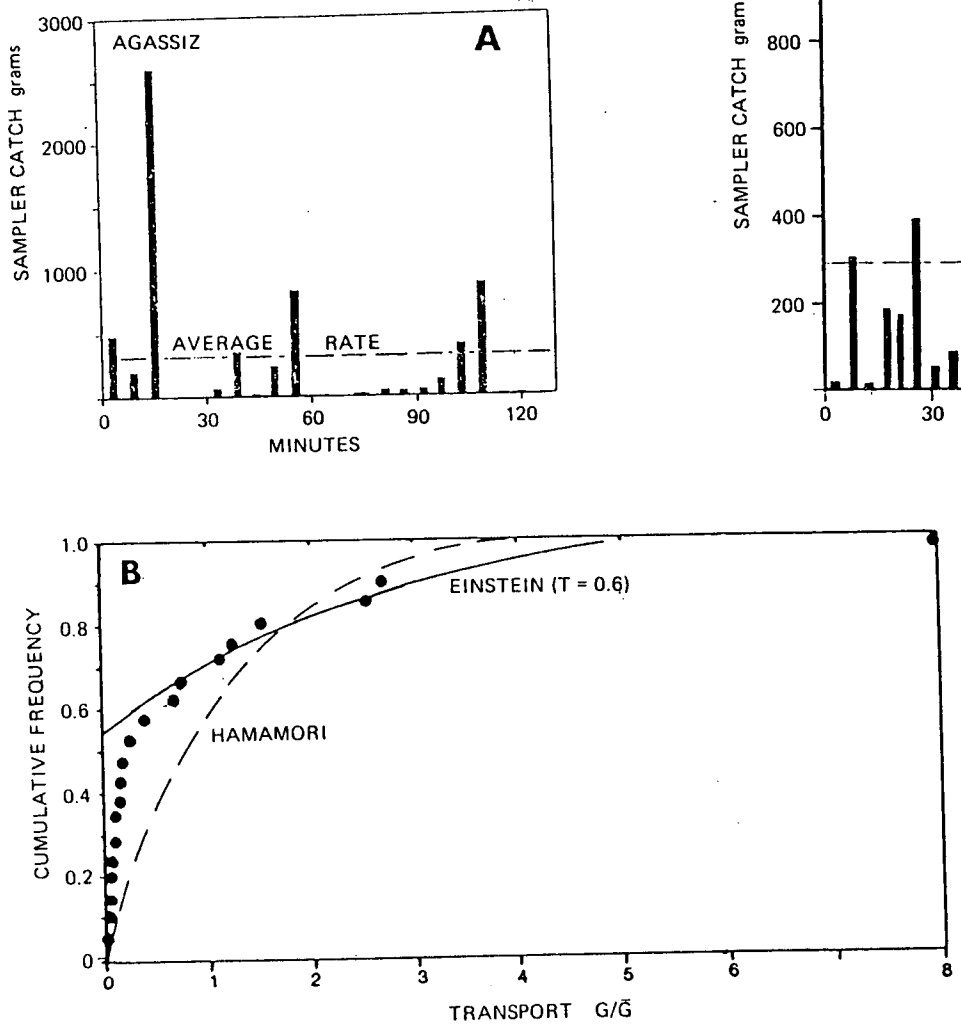


Figure 8. Variation in bedload sample catches at Agassiz.

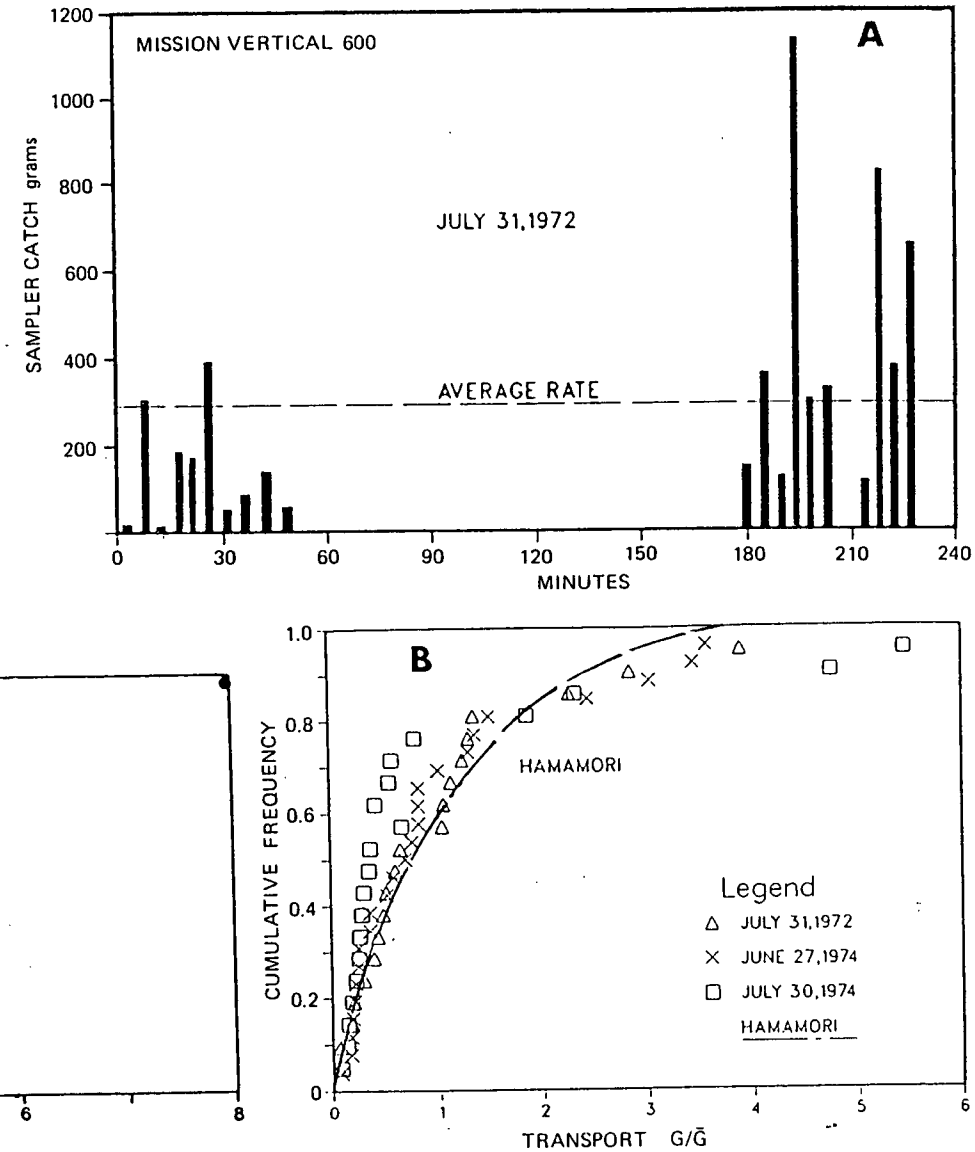


Figure 9. Variation in bedload sample catches at Mission.

Given the distribution of transport rates at a point, the reliability of estimating the true mean bedload rate from an n-sample average can be determined. In this study, the precision of the computed average bedload rates was estimated by using the Monte Carlo simulation technique in conjunction with the measured bedload probability distributions to generate a large number of n-sample averages. The precision of these synthesised measurements was then expressed as a coefficient of variation of the mean rate (McLean and Tassone, 1987; see deVries, 1973, on the method). For a three sample average the relative error (coefficient of variation of the mean) was 84% at Agassiz and 50% at Mission. At least 10 repeat samples would be required at Agassiz before the relative error was less than 50%. These values represent the expected error at a single vertical and not the error in total bedload transport rate at the cross section.

In order to estimate the error in the total bedload rate some information on the spatial variability of the bedload rates across the channel would be required (see Hubbell, 1987). A lower bound estimate for the precision of the total loads can be made by assuming that the actual mean bedload rate is uniform across the channel. For the normal sampling procedures on the Fraser River (5 verticals, 3 samples/vertical) the relative error (coefficient of variation of the mean) was found to be 40% at Agassiz and 26% at Mission. In examining the measured rates across the sections at Agassiz and Mission it was noted that the maximum rate at a vertical (estimated from 3 samples) seldom exceeded three times the mean rate at the cross section. For the case of a "bell shaped" exponential distribution and a maximum to mean ratio of three, the relative error increased to 58% at Agassiz and 34 % at Mission. These values could probably be considered upper bound estimates of the errors in the measured total bed load rates.

Because the measurements are rather sparse, actual load estimates were constructed from rating curves based on the measurements. Figures 10 and 11 show that there are only poorly defined relations between bedload transport rate and discharge. Substantial efforts to stratify

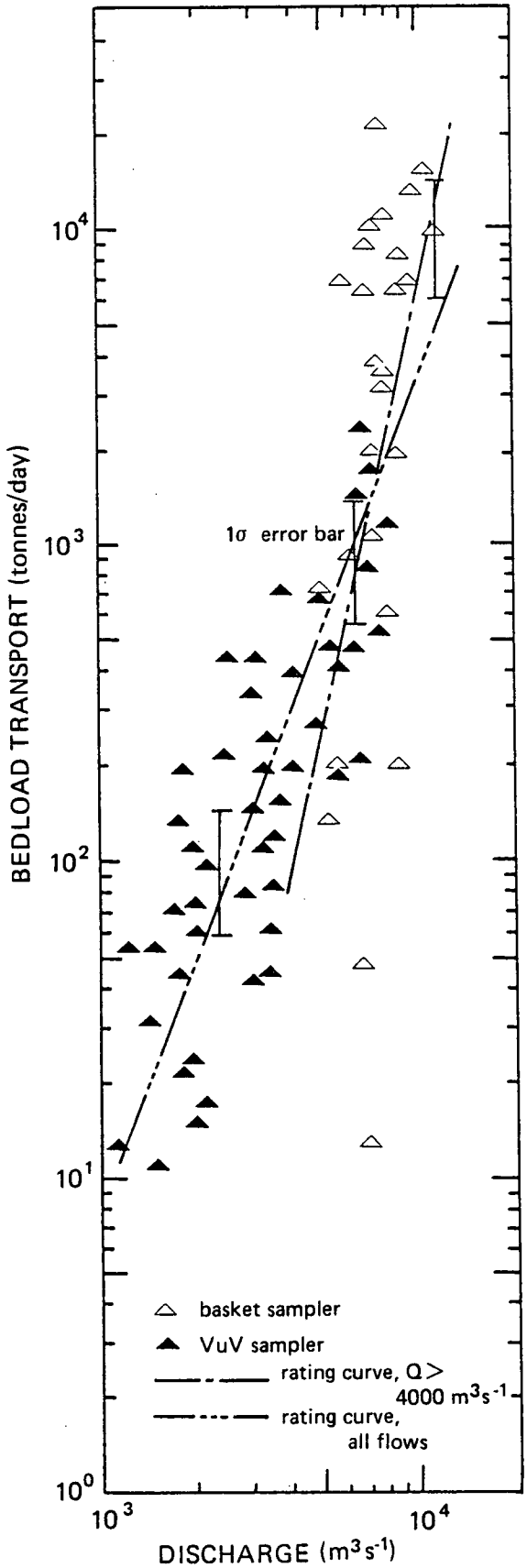


Figure 10. Bedload rating curve at Agassiz, 1968-1976.

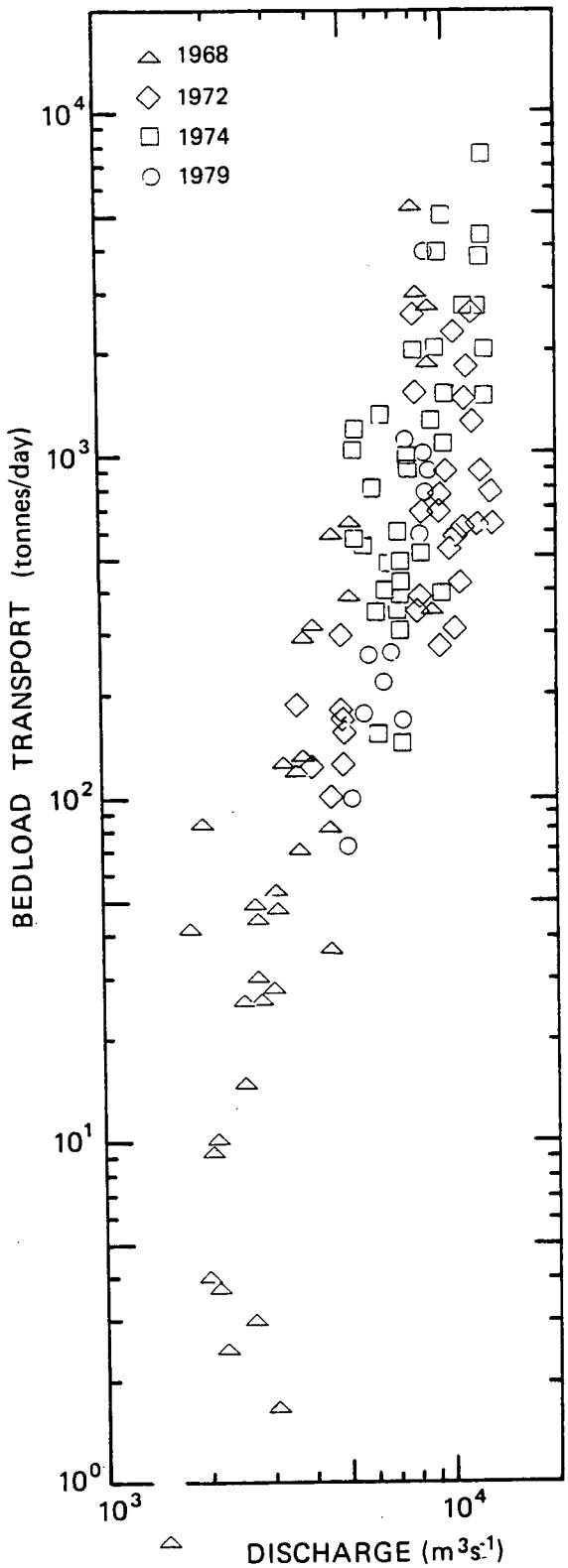


Figure 11. Bedload rating curve at Mission, 1968-1979.

the data (McLean and Church, 1986) produced no consistent improvement. For Agassiz, separate ratings were calculated for flows below and above 4000 m^3s^{-1}, which separates the predominantly sand transport range near threshold from the higher flow, gravel transport regime. This also produces estimates based mainly on VuV measurements at low flow, and on basket measurements at high flow. The one standard error confidence limits (coefficient of variation) on the rating curve line varied from +17.5% to -15% at a flow of 7500 m^3s^{-1} and from +30% to -23% at 14 000 m^3s^{-1}. The uncertainty in the annual load was estimated as follows:

1. the confidence interval (measured in per cent) of the rating curve estimate E_i was computed for flows ranging from 3000 m^3s^{-1} to 15 000 m^3s^{-1};
2. the fraction of the total annual load in each flow interval Q_i was computed to produce a weighting factor W_i;
3. the relative error in the annual load was then estimated as the sum of the weighted errors in each flow interval, $\sum W_iE_i$.

This calculation indicated that the estimated annual loads could be specified to within ±20% with a one standard error confidence interval or to within ±40% with a two standard error confidence interval. This compares well with the Monte Carlo estimates of daily precision.

2.4. Separating the sand load

There are two aspects of this problem, (i) isolating the sand component of the suspended load, and (ii) determining the proportion of the sand load that constitutes bed material.

The sand component of the suspended load can be estimated by analyzing the particle size data derived from the R samples (the K samples were examined and found not to be useful in this respect). Two approaches are then possible for providing predictive equations to estimate sand load (recalling that there are too few R samples to permit integration):

(a) conventional sediment rating curve techniques;

(b) development of a relation between the sand fraction (f) of the suspended load and discharge, thence computation of the daily sand load (g) as $g = fCQ$.

After considerable study (McLean and Church, 1986), it was decided that the sand fraction approach is best. The sand fraction shows the best correlation with discharge, and its total range is an order of magnitude smaller than that of sand concentration. Hence, it provides a consistent measure. Figure 12 illustrates the sand fraction and sand concentration correlations with discharge at Agassiz and at Mission.

The proportion of the sand load that constitutes bed material was estimated by comparing particle size distributions of the sand in suspension and the bed material. Bed material size distribution is based upon USBM54 samples grabs composited from 5 locations in the channel. Before these are compared with the suspended material, it must be recognized that the entire section is not sampled for suspended sediment: the samples do not extend below 0.25 m from the bed in order to prevent accidental scooping of bed material. Since sand concentrations increase very rapidly near the bottom (figure 13) substantial quantities of sediment could be transported in this unsampled zone. Therefore point integrated (PI) sediment samples were analyzed in order to estimate correction factors that should be applied to the DI measurements.

The analysis was carried out for 6 sets of PI and velocity profile measurements at Mission. Theoretical parameters describing the variation of velocity and sand concentration with depth were fit to the measurements in order to estimate the load transported in the unsampled zone near the bed. It was found that during freshet conditions only about 5 % of the 0.125 mm and 0.25 mm size fractions and 10% of the 0.500 mm size fraction is transported in the unsampled zone. These values were applied to the annual loads computed from the DI measurements to estimate the size distributions of the total suspended loads at Mission and at Port Mann.

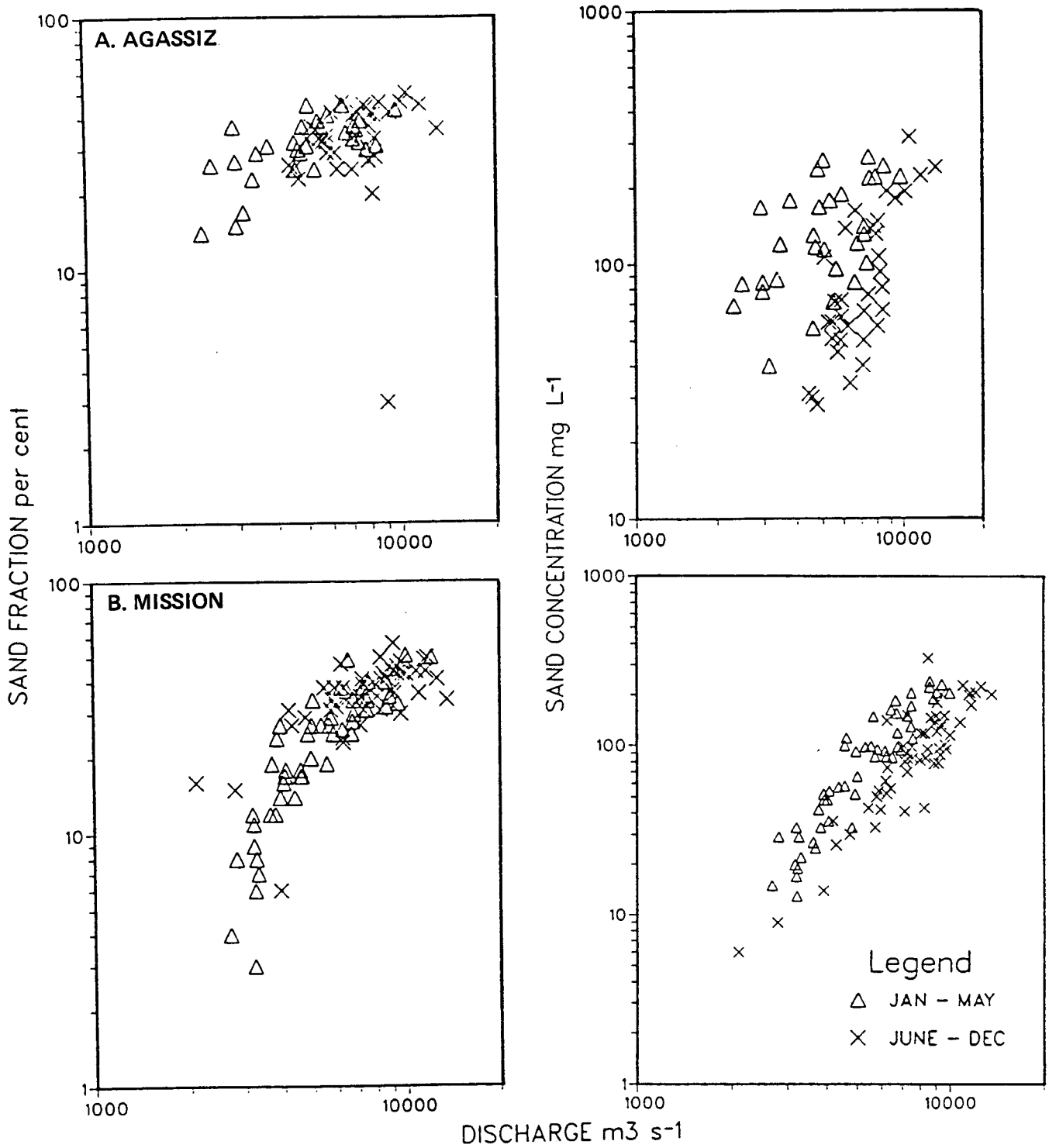


Figure 12. Sand fraction and sand concentration curves: (a) Agassiz; (b) Mission. Note the change in scale between abscissa and ordinate.

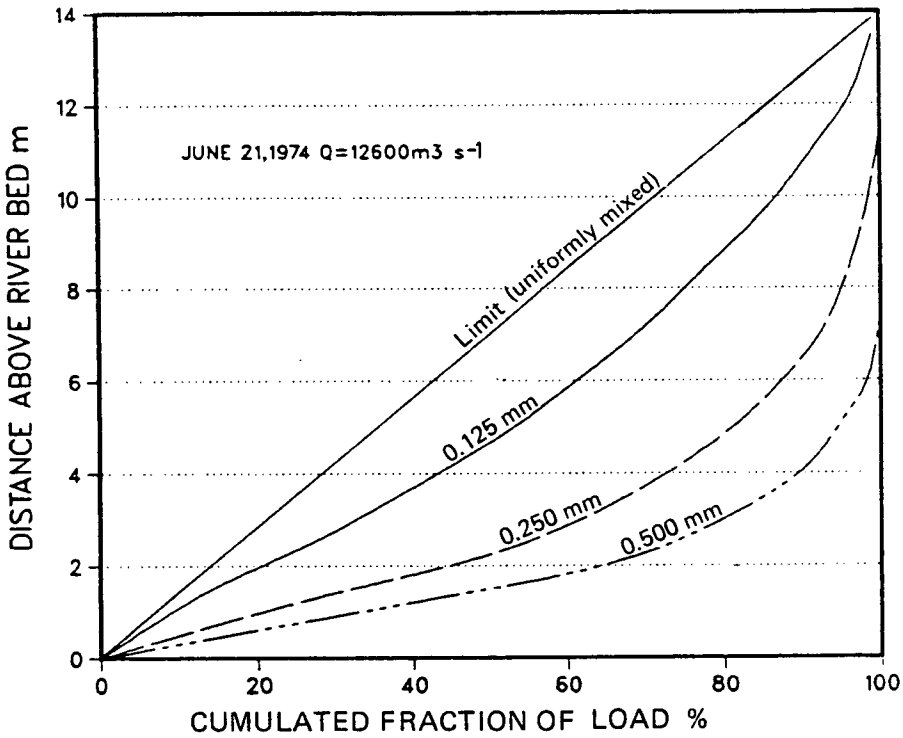


Figure 13. Vertical distribution of suspended load at Mission.

Figure 14 presents typical comparisons between bed material and suspended sand size distributions for Mission and Port Mann. There is little difference between the two stations, apart from a slight fining of the bed at Port Mann. It is apparent that the 0.063 to 0.125 mm fraction -- which accounts for nearly one-half the load -- is wash material. However the +0.125 mm fraction is substantially present in the bed. To a first approximation, then, one expects that material coarser than 0.125 mm constitutes bed material. The correlation between this fraction of the sand load and discharge (figure 15, compare figure 12b) indicates that this is a reasonable approximation, since fair correlation implies ready availability of material from the bed.

This judgement can be refined by examining the size distribution of the annual load in comparison with that of the bed material. This was done by dividing the available particle size data (from R samples) by month and estimating the fraction of the annual load transported in each month as a weighting factor for the weighted average fraction in each size class. For example

$$F_{125} = \sum_{i=1}^{12} f_{125i} g_i / \sum_i g_i$$

where f_{125i} is the size fraction in month i for 0.125 to 0.250 mm and

g_i is the total bed material load transported in month i.

Table 3 shows the results. Whilst the +0.125 mm fraction constitutes nearly 60% of the +0.125 mm suspended load, it comprises only about 30% of the bed material. To bring the size distribution of the suspended load into conformity with the bed material distribution, it is necessary to consign between one-half and three-quarters of the 0.125 - 0.250 mm fraction to wash load. The adjustment cannot be made precise for the following reasons:

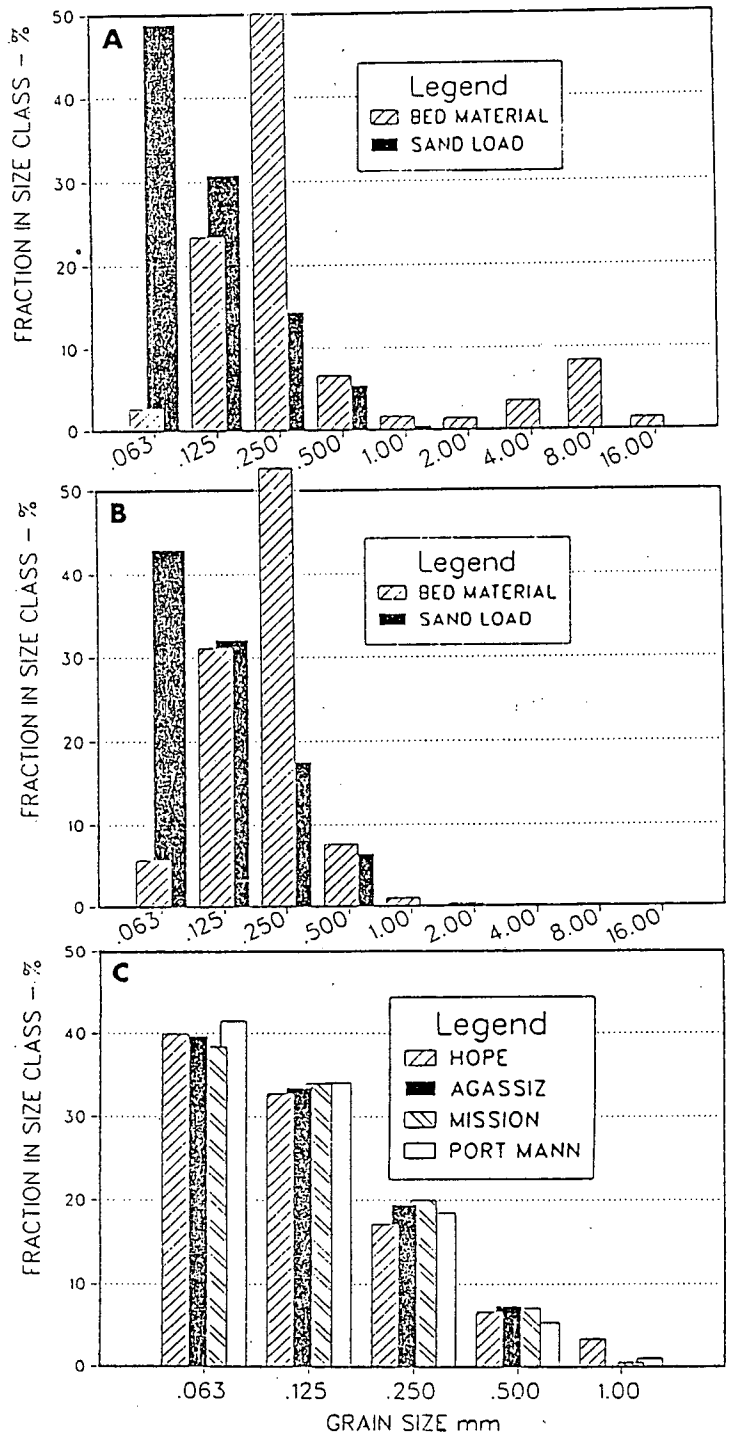


Figure 14. Comparison of bed material and suspended sand load size distributions at (a) Mission and (b) Port Mann; and (c) comparison of sand load size distributions through the four principal stations.

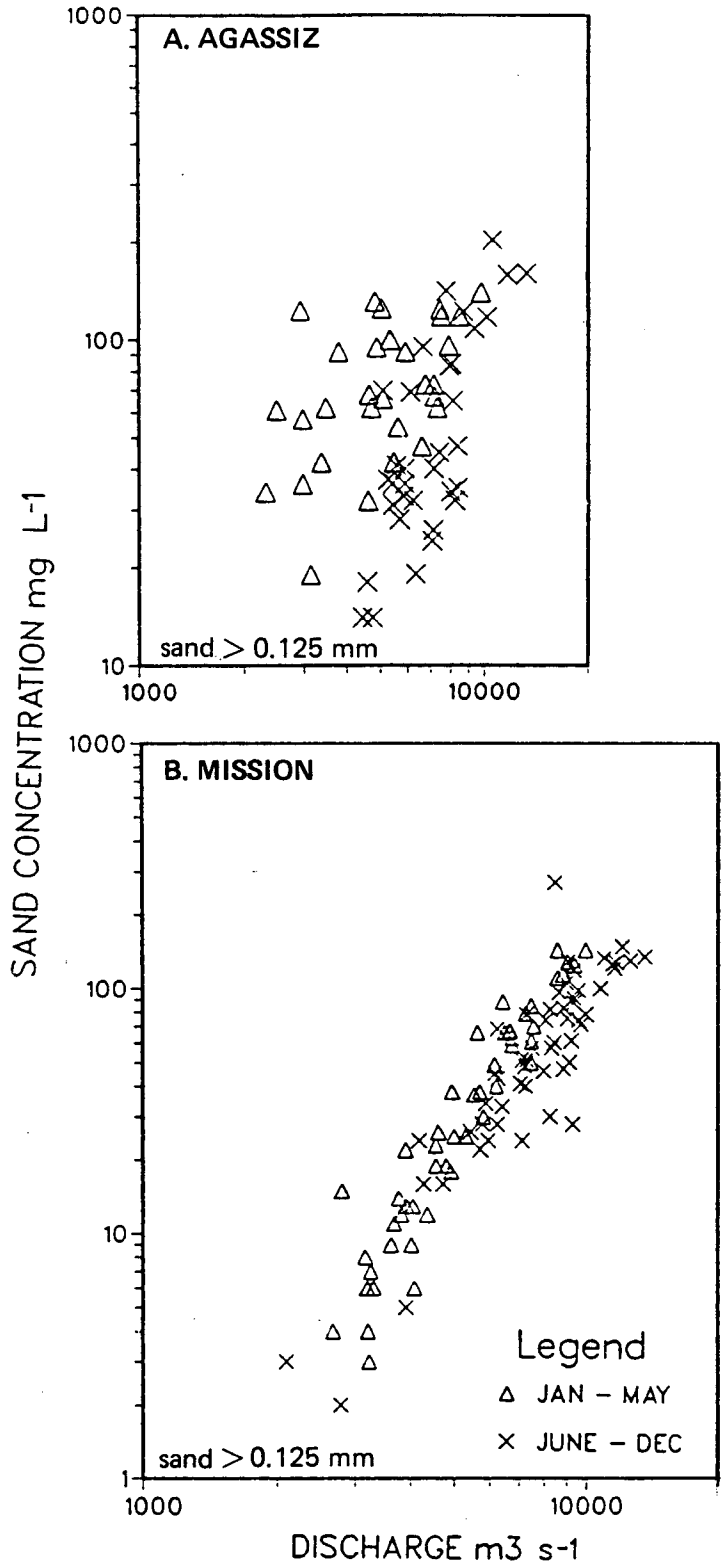


Figure 15. Correlation of sand fraction > 0.125 mm with discharge: (a) Agassiz; (b) Mission. Note the change in scale between abscissa and ordinate.

TABLE 3

COMPOSITION OF BED MATERIAL AND ANNUAL SAND LOAD > 0.125 mm

SIZE FRACTION (mm)	SUSPENDED SAND > 0.125 mm	BED LOAD	BED MATERIAL
At Mission			
0.125-0.250	58.3	29.5	27.7
0.250-0.500	30.0	61.5	59.5
0.500-1.000	11.7	7.8	8.0
1.000-2.000	0.0	0.8	1.9
> 2.000	0.0	0.4	2.9
At Port Mann			
0.125-0.250	58.3	23.3	33.0
0.250-0.500	31.3	67.2	55.7
0.500-1.000	10.4	8.3	8.0
1.000-2.000	0.0	0.7	1.1
> 2.000	0.0	0.5	2.2

NOTES:

- all percentages have been normalized for the fraction > 0.125 mm
- suspended sand fractions determined from a weighted average of monthly suspended size distribution measurements.

- the distinction between suspended and bed load is arbitrary and also affects the distribution of sizes;
- the fraction distribution calculation above would have to be iterated as the estimate of bed material load is changed;
- there is differential transport of the largest sizes anyway (which affects the fractions), as can be seen by inspecting the bedload fractions.
- there remains the effect of unmeasured sand load, which may not have been adjusted completely.

In the event, sediment transport has been divided so the 0.125 - 0.250 mm fraction accounts for 33% of the total bed material load, which is close to its representation in the bed. This adjustment is important since the fraction accounts for most of the +0.125 mm load, but further percentage point refinement would be well within all error margins of the underlying measurements.

In the gravel reach of the river, these issues do not arise. Material finer than 2 mm typically constitutes 10 to 15 percent of bed material, that proportion of wash material that easily may be trapped in the interstices of the bed material. All fractions of the suspended sand load at Hope and Agassiz are considered to be "wash load".

2.5. The sediment budget at the principal stations

On the basis of the analyses and conventions discussed above, the sediment budget was determined for Agassiz and Mission, the two stations for which there are comprehensive measurements extending over several years (tables 4 and 5). The tables are constructed somewhat differently in view of the different way in which the load is divided between the sand and gravel reaches.

Washload comprises a surprising 99% of the sediment transport at Agassiz, declining to 87% at Mission, the difference representing the sand that becomes bed material. The silt and clay constitutes two-thirds of the load at Agassiz, 64% at Mission. The total is virtually the same

TABLE 4

AGASSIZ TOTAL LOAD SUMMARY

(tonnes/yr)

YEAR	SUSPENDED LOAD (WASH LOAD)				BED LOAD (BED MATERIAL LOAD)			GRAND TOTAL
	CLAY[1]	SILT[1]	SAND	TOTAL	SAND[2]	GRAVEL[2]	TOTAL	
1967	4035000	12611000	8687000	25333000	47000	263000	310000	25643000
1968	3533000	11040000	6786000	21359000	33000	187000	220000	21579000
1969	2190000	6844000	3735000	12769000	16000	93000	109000	12878000
1970	2098000	6557000	3737000	12392000	13000	73000	86000	12478000
1971	2977000	9302000	5744000	18023000	25000	142000	167000	18190000
1972	4323000	13510000	10196000	18029000	56000	317000	373000	28402000
1973	2361000	7377000	4101000	13839000	16000	92000	108000	13947000
1974	3904000	12202000	8028000	24134000	44000	248000	292000	24426000
1975	1905000	5955000	3378000	11238000	19000	109000	128000	11366000
1976	4160000	13002000	8646000	25808000	45000	255000	300000	26108000
1977	2184000	6826000	3735000	12745000	13000	76000	89000	12834000
1978	1861000	5817000	2973000	10651000	11000	61000	72000	10723000
1979	2533000	7917000	4271000	14721000	13000	73000	86000	14807000
1980	1672000	5223000	2602000	9497000	10000	59000	69000	9566000
1981	2046000	6395000	3607000	12048000	16000	92000	108000	12156000
1982	3749000	11714000	7866000	23329000	40000	225000	265000	23594000
Average	2846000	8893000	5506000	17245000	26000	148000	174000	17419000
(% of grand total)	16.4	51.0	31.6	99.0	0.15	0.85	1.0	

[1] Divided according to particle size analyses of suspended sediment load.
[2] Divided according to particle size analyses of VuV bedload trap samples.

TABLE 5

MISSION TOTAL LOAD SUMMARY

(tonnes/yr)

YEAR	WASH LOAD (SUSPENDED)				BED MATERIAL LOAD			GRAND TOTAL
	CLAY	SILT	SAND[1]	TOTAL	SUSPENDED[2]	BED LOAD	TOTAL	
1966	2959000	10085000	4299000	17343000	2117000	300000	2417000	19716000
1967	2574000	12418000	7674000	22666000	3766000	540000	4306000	26972000
1968	2944000	10708000	5020000	18672000	2473000	390000	2863000	21535000
1969	2316000	7524000	2821000	12661000	1390000	240000	1630000	14291000
1970	1874000	6213000	2355000	10442000	1160000	150000	1310000	11752000
1971	2602000	9110000	4015000	15728000	1978000	300000	2278000	18006000
1972	2424000	14134000	9935000	26493000	4893000	660000	5553000	32046000
1973	2122000	6723000	2329000	11174000	1147000	180000	1327000	12501000
1974	2983000	12306000	6659000	21948000	3280000	450000	3730000	25678000
1975	1992000	6472000	2423000	10887000	1193000	240000	1433000	12320000
1976	3426000	12600000	6112000	22138000	3010000	450000	3460000	25598000
1977	2840000	8228000	2392000	13461000	1178000	150000	1328000	14789000
1978	2412000	6973000	2010000	11395000	990000	120000	1110000	12505000
1979	2820000	8434000	2591000	13845000	1276000	150000	1426000	15271000
1980	2045000	6218000	1825000	10088050	899000	150000	1049000	11137000
1981	2168000	6724000	2397000	11289000	1181000	180000	1361000	12650000
1982	3435000	12881000	6381000	22697000	3143000	360000	3503000	26200000
Average	2891000	8973000	4189000	16053000	2063000	300000	2363000	18416000
(% of grand total)	15.7	48.7	22.8	87.2	11.2	1.6	12.8	

67% of suspended sand load.
33% of suspended sand load.

at the two stations, there being only 1 per cent difference. The bed load transport at Mission -- only 300 000 tonnes -- falls within the error of measurement of the suspended load. Hence, the difference in the -2 mm load between the two stations, 1 million tonnes per annum, must derive either from errors in adjusting the sand load at Mission, from sediment contributed by Chilliwack River (Harrison River drains large lakes and contributes no sediment) or from real net erosion of sand between the two stations. The difference represents 17% of the sand load at Mission.

Since the bedload comprises such a minor portion of sediment transport, the total load may be estimated without reference to bedload measurements. This means, also, that the Hope measurements (Table 6) provide a good estimate of the total load of the river (though, not, of course, of the gravel transport).

2.6. Predicting Annual Sediment Loads from Flow Volumes

It would be useful to develop methods for estimating the annual suspended sand load and total load for years when sediment measurements are not available. One approach would be simply to extrapolate the daily total concentration or sand rating curves. An alternative approach is to develop rating curves based on much longer time scales and to predict the annual load directly using monthly flows or the annual flow volume as the independent variables. One of the main advantages of this approach is that by considering longer time scales some of the short term variability will become averaged out.

In fact very good correlations are exhibited between annual sediment loads and annual flow volumes at Hope, Agassiz and Mission, the latter two of which are illustrated in Figure 16. Measured annual suspended loads were compared against rating curves based on daily, monthly and annual discharges. For these tests the annual loads were estimated as follows:

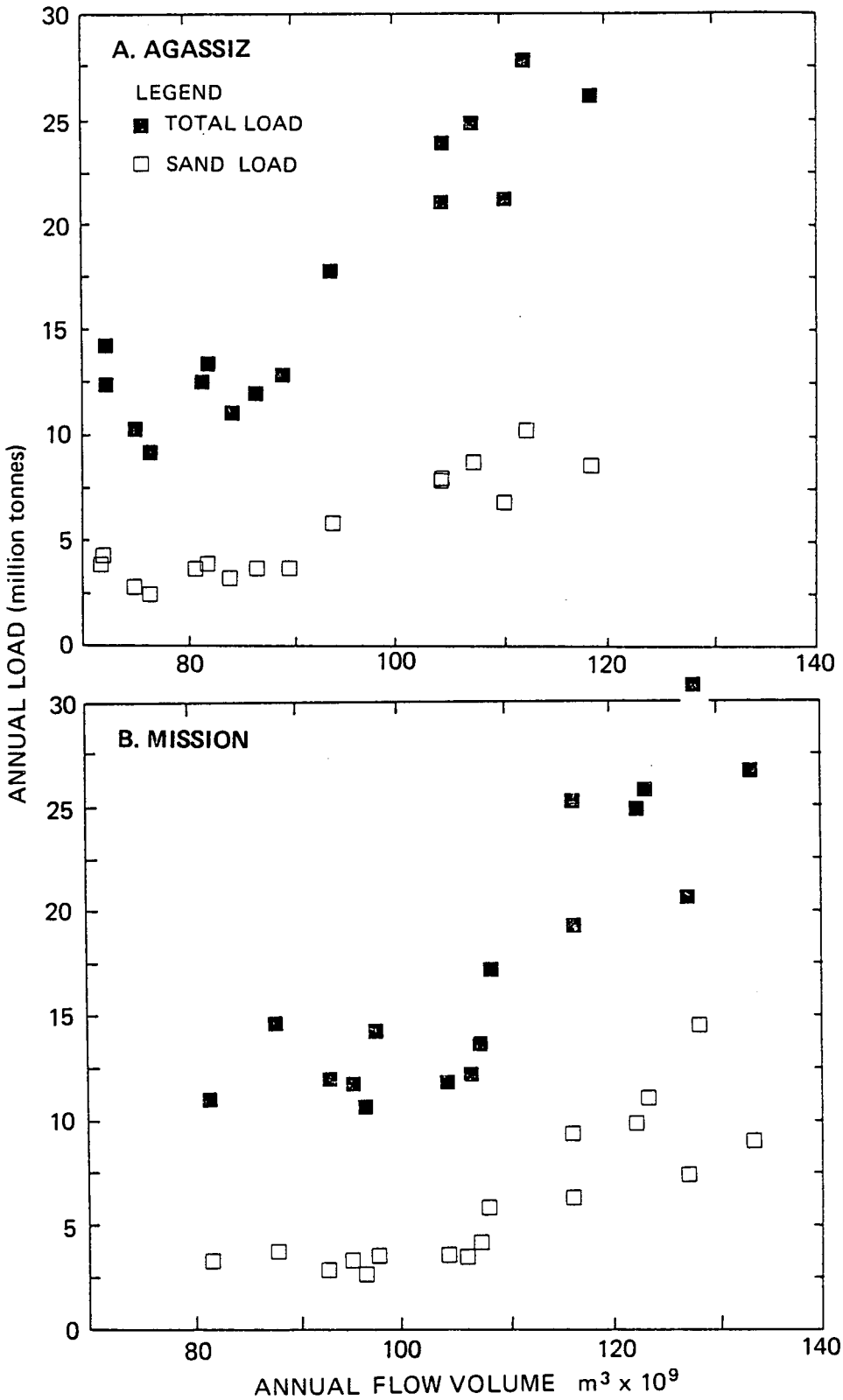


Figure 16. Relation between suspended sediment load and flow volume: (a) Agassiz and (b) Mission.

$G_a = C_d Q_i$ where daily concentration $C_d = AQ^b{}_i$
(daily rating curve)

$G_a = A_1 Q^{b_1}{}_{May} + A_2 Q^{b_2}{}_{June} + A_3 Q^{b_3}{}_{July} + \cdots$
(monthly rating curve)

$G_a = AQ^b{}_{annual}$ (annual rating curve)

The comparisons were made using the data at Hope so that load predictions could be made for the years 1950-1952 and compared with the estimates published by Kidd (1953) which were not used to develop the equations. This comparison provides an independent check on the longer term accuracy of the estimating equations.

Table 6 summarises the performance of the three rating curve regressions (columns 3 to 5). The daily concentration rating curve was based on 1338 measurements between 1966 and 1978. The best overall estimates of the annual loads were produced by the monthly rating curves (RMS error equalled 2 million tonnes/year or 11% of the mean annual load).

The only year in which the daily rating curves performed significantly better than the monthly or annual relations was in 1950. In this year the annual and monthly rating curves underestimated Kidd's estimate by about 20%. The 1950 flood was the second largest flood in the period of record between 1912 and 1984. However, both the annual flow volume and mean June discharge were unusually low. Therefore in years when the freshet is unusually "flashy" the daily rating curves might produce the best estimates. It appears, then, that the monthly or annual rating curves are reasonably stable in the long term, except when the freshet is of markedly unusual character. This stability is perhaps the most important characteristic of a correlation that is going to be used for temporal extrapolation.

Multiple regression relations were also developed to see whether the load estimates could be improved by including a number of different flow parameters. These relations were of the form:

TABLE 6

COMPARISON OF PREDICTED AND MEASURED ANNUAL TOTAL SUSPENDED LOADS AT HOPE

(all in loads in tonnes/yr)

YEAR	MEASURED LOAD	RATING CURVE PREDICTIONS DAILY RATING CURVE (polynomial)	MONTHLY RATING CURVE (powerlaw)	ANNUAL RATING CURVE (linear)	MULTIPLE REGRESSION RELATION (linear)
1950	20408000	20571000	16257000	16510000	24416000
1951	15252000	14271000	15324000	12170000	13310000
1952	15128000	16408000	16213000	14040000	14508000
1966	19746000	18918000	18751000	19310000	17068000
1967	23437000	24564000	22619000	22027000	22913000
1968	23626000	23432000	21666000	24216000	22057123
1969	13171000	16285000	16304000	16837000	15633000
1970	12003000	11419000	10545000	9335000	12132000
1971	16308000	18637000	19251000	17850000	16821000
1972	29061000	29646000	28683000	25027000	29473000
1973	16151000	14412000	13863000	13512000	13914000
1974	23230000	23763000	23318000	22189000	24890000
1975	12031000	16286000	13890000	15661000	13946000
1976	27637000	28300000	28146000	28676000	27618000
1977	12415000	14621000	14358000	14809000	12480000
1978	8993000	13123000	12018000	12701000	11338000
1979	15539000	13091000	13132000	11200000	13059000
RMS ERROR (ABS)		2380000	2040000	2920000	1680000
RMS ERROR (%)		13	11.2	16.1	9.3
BIAS (ABS)		900000	228000	-500000	0
BIAS (%)		5.6	1.3	-2.7	0

$$\text{Log } G = B_0 + B_1 \text{Log } Q_{annual} + B_2 \text{Log } Q_{June} + B_3 \text{Log } Q_{peak}$$

This type of relation improved the prediction of the 1950 load (Table 6: column 6); however the overall RMS error from all years was still about the same as that for the monthly regressions. This is because in most years the maximum daily, June mean and annual flow volumes are all highly inter-correlated.

Similar regression relations were developed for predicting the annual suspended sand load and total suspended load at Agassiz and Mission. At these stations the annual sand loads were predicted from the annual flow volume and mean June discharge (the peak discharge was found to not significantly improve the correlations). It was also found that the best predictions of the annual sand load and total load at Mission were made using flows measured at Hope rather than Mission, probably because the Harrison River can increase the flows in the Fraser River by 10 to 15% but contributes virtually no additional sediment and is not necessarily in phase with Fraser River flows.

The precision of the annual load estimates can be measured by the standard error of the regressions. The RMS error for the sand load at Mission is less than 10% of the mean annual load while the RMS error of the Mission suspended bed material load predictions is about 13.5% of the mean annual load.

These sediment load relations could be used for estimating the annual load below Mission from flow forecasts that are made in April and May before the peak of the freshet. Such predictions may eventually provide a basis for planning maintenance dredging requirements in the navigable portion of the river below New Westminster.

3. FIELD EXCURSION

3.1. Introduction

Many of the details of the foregoing analysis were determined by the character of the river at each of the principal gauging points. Furthermore, there are dramatic changes from reach to reach, encompassing transitions from cobble-gravel to sand bed, and from non-tidal to tidal regime.

In this section, five field sites are described -- including the Agassiz, Mission and Port Mann gauge sites -- which provide a view of the changing character of the river. The discussion for each stop describes the geometry of the channel and the sediments, and gives details of observing programmes and analyses pertinent to each reach.

The locations of the stops along the river are shown in figure 2, which emphasizes the relative position of each stop along the river. However, the scale of the map precludes display of any details. Site maps showing road access are given in an Appendix (pp. 87 ff). National Topographic Series maps 92G/1, G/2, G3 and 92H/4 illustrate the entire river from Agassiz to the sea at 1:50 000.

The excursion may be taken in either direction. The guide is organized in downstream order, which facilitates discussion of the changing character of the river. (Road access at stops 2 and 3 is easier and safer if they are approached in upstream progression.) The excursion may also be made on the river. However, it should be realized that the round trip covers 220 km and that the river currents may exceed 3 m s^{-1} (10 km hr^{-1} or 5.5 knots) and that the river is heavily navigated from Port Mann downstream. Upstream from Mission, the boater must know how to "read" bar positions in order to navigate the gravel-bed channel.

3.2. Agassiz gauge reach (river km 130, refer to STOP 1 on Figure 2)

The Agassiz gauging station is located in a relatively straight reach of the river 300 m downstream from the Agassiz-Rosedale bridge. Over most of the period of observations the Agassiz site has been close to ideal for measurements with the velocity and suspended load being distributed very uniformly across the channel (Figure 17). However, in recent years, gravel bar accretion near the north side (right bank) of the channel has caused the river to become divided at lower flows. Aside from making future measurements more difficult to collect this bar probably will induce greater variations across the section in channel velocities and sediment transport rates.

Figure 18 illustrates the size distribution of the bed material. Table 2 summarizes hydraulic parameters of the gauge station, whilst figure 19 shows the sectional hydraulic geometry. In a straightforward comparison of the principal gauge sections, Agassiz (slope = 5×10^{-4}) is an order of magnitude steeper than Mission (5×10^{-5})); channel width is virtually the same, so that depth and velocity vary reciprocally between the two stations. Agassiz exhibits velocities about twice as large as, and depth about one-half those of Mission.

The alluvial stratigraphy in the Agassiz reach -- sand over channel gravel -- is common in the mountain valleys of the Cordillera, and indeed in gravel rivers with low bedload transport rates everywhere.

Bankfull stage varies considerably along the river and is strongly related to the island and floodplain stratigraphy, and to the age and species of vegetation present. Along banks populated with very old cottonwoods (up to 150 years) or maple and cedar, bankfull stage is 1.0 m to 2.0 m above the 1.5 year flood level. In these areas the banks are capped by 2.0 - 3.0 m of sandy or silty sand sediments. Areas covered with relatively young cottonwood (10-30 years old), such as recently stabilized islands, generally have less than 1 m of silty and sandy

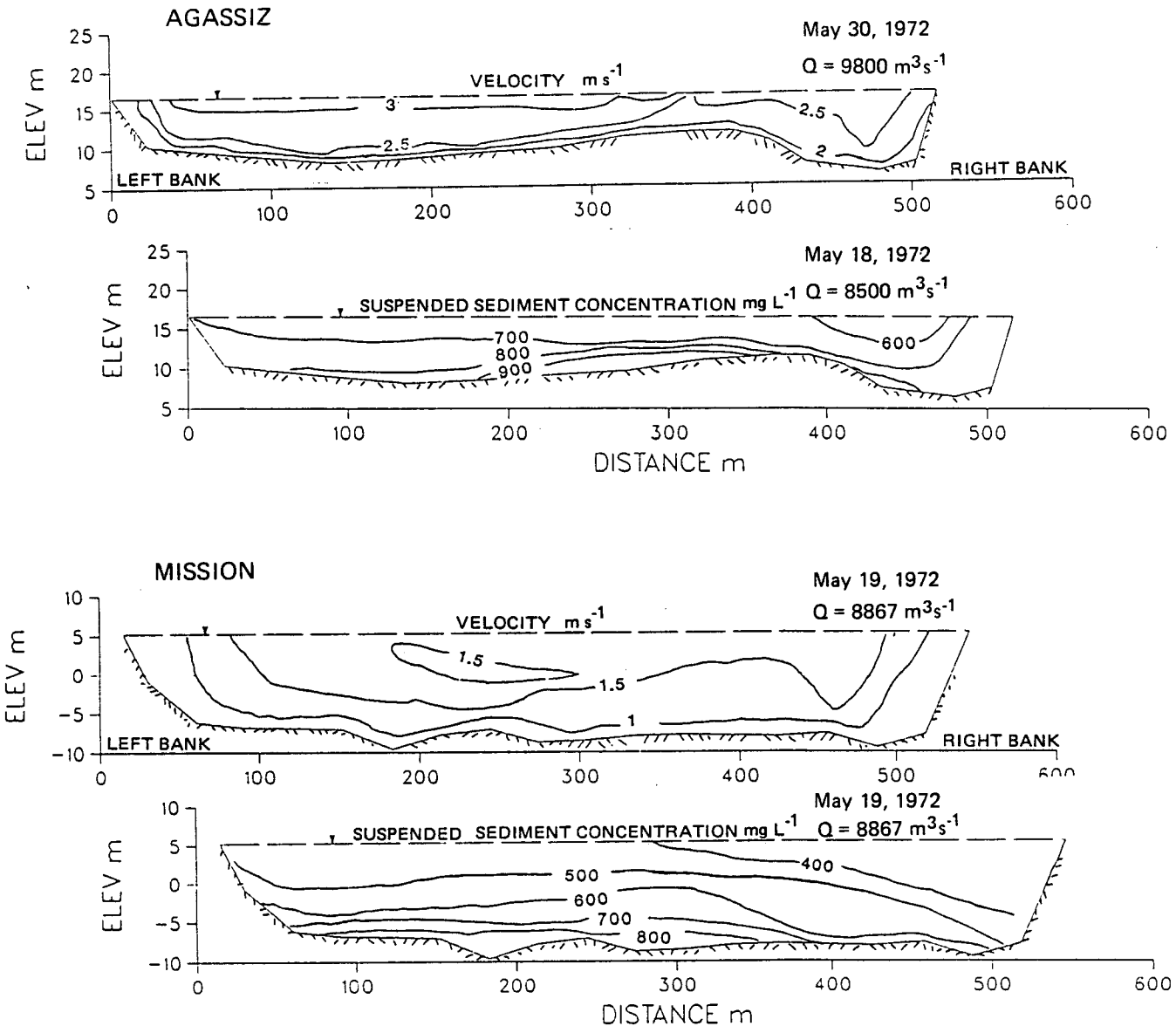


Figure 17. Gauging cross sections at Agassiz and Mission: example distributions of velocity and suspended sediment concentration.

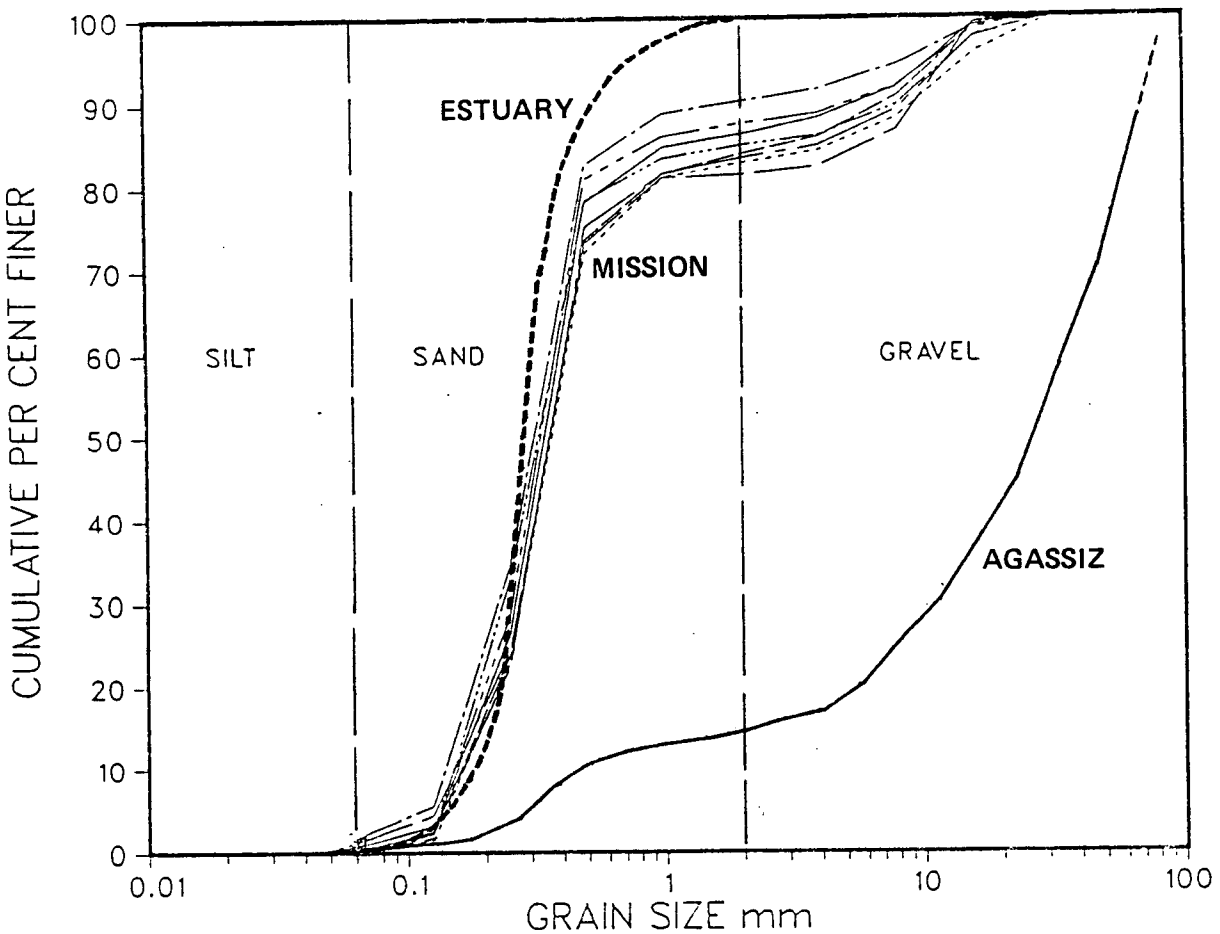


Figure 18. Bed material size distribution at Agassiz and Mission, and in the Main Arm near Deas Island. Mission samples obtained between 1966 and 1980 using a USBM54 sampler; Agassiz sample obtained from an exposed bar in 1984.

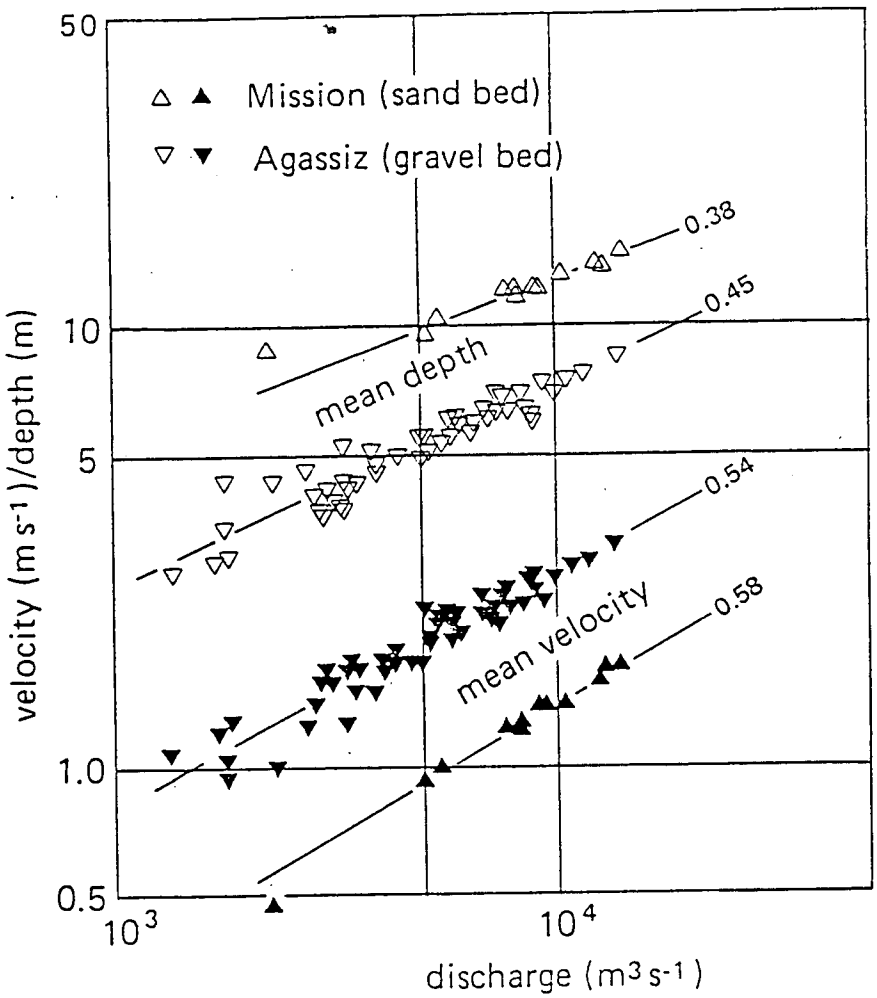


Figure 19. Hydraulic geometry in the gauge sections at Agassiz and Mission.

sediments overlying the basal gravels. In these areas bankfull stage is only 0.1 m to 0.5 m above the 1.5 year flood stage. Therefore it is not reasonable to specify a single estimate of bankfull discharge along the Fraser River. The variations in sand member thickness with the age of the surface indicate the progress in vertical floodplain construction by overbank deposition of sand after the channel moves away from a site.

The seasonal variations in sediment loads are illustrated in Figure 20a (virtually identical results were found for the measurements at Hope). Approximately two thirds of the annual load is transported in May and June while the period between October and March accounts for less than 6% of the total. The sand component is relatively more concentrated during freshet than is the total load (most of which is finer than sand).

The fractions of the annual load transported by various discharges at Agassiz are shown in Figure 20b. This analysis shows that the flows contributing the largest fraction of the sediment load are between 7500 - 8000 m^3s^{-1} at Agassiz (or Hope). These discharges correspond to about the 1.5 year flood at each of the sites. By comparison discharges above 10 000 m^3s^{-1} (5 year return period at Agassiz or Hope) accounted for only about 12% of the long term sediment load, although they account for 24% of the bedload. It is apparent that over the long term the relatively frequently occuring, moderate freshet flows account for the greatest proportion of the river's annual sediment load while the very high flows occur so infrequently that the actual quantity of sediment contributed is relatively small. This result is in accordance with findings on many other streams (Wolman and Miller, 1960).

It is notable that the distribution of bedload transport is not greatly dissimilar to that of suspended sediment transport. Based on the hydraulic measurements at the gauge site, the shear stress at the "dominant" flow -- 8000 m^3s^{-1} -- was found to be only about 50% higher than the critical shear stress required for mobilising the surface armour (Parker _et al._, 1982). This illustrates that the greatest proportion of

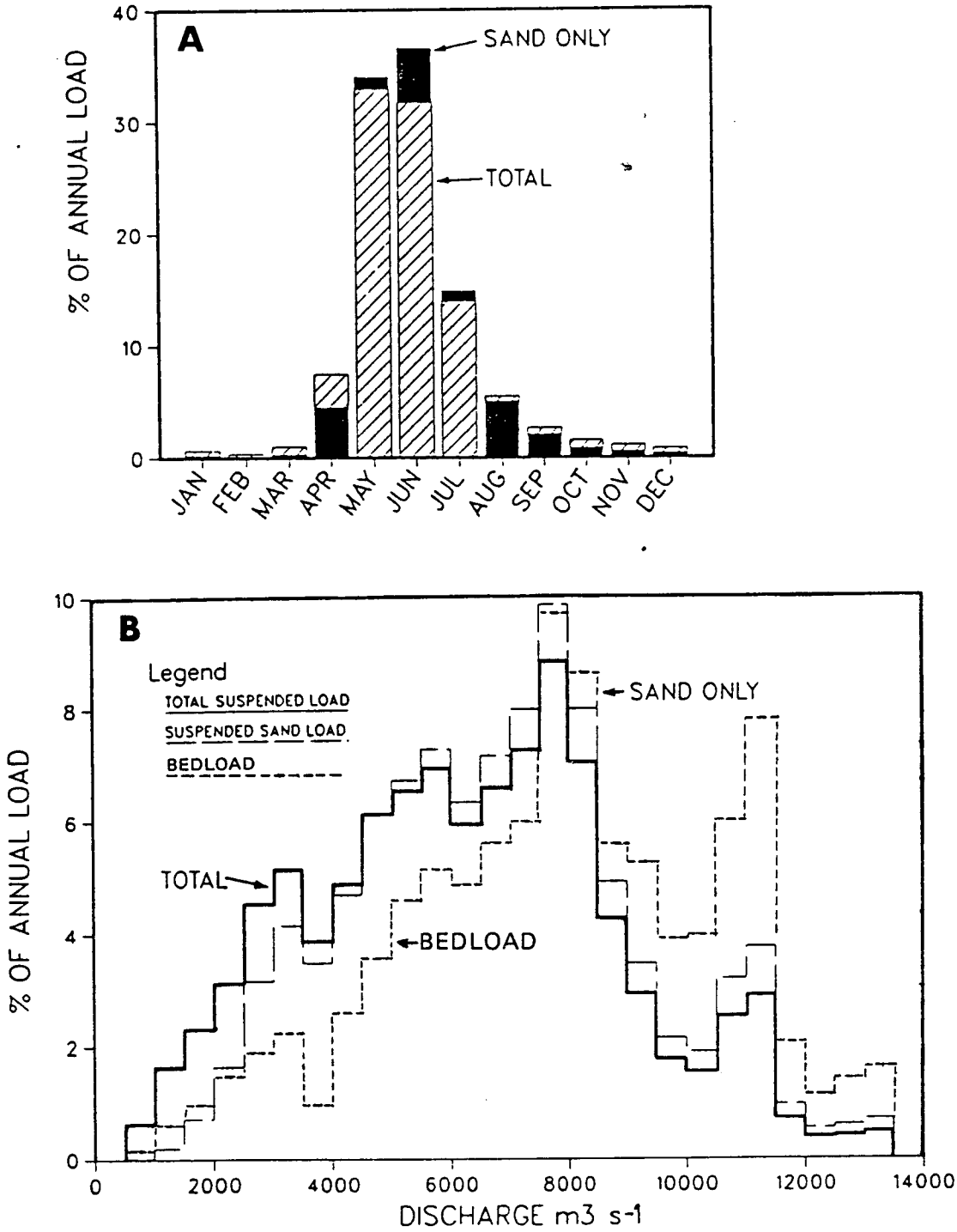


Figure 20. Variation of sediment load at Agassiz by season and by discharge: mean of 1966-1982 results. Each displayed component of the load is independently distributed according to its own annual total.

the transport take place when the bedload movement is weakly established. At conditions near threshold, minor changes in the state of the bed, (such as the surface size distribution or extent of imbrication) can induce very large relative changes in the transport rates. Therefore, for most of the annual load, the bedload transport rates will not show a very systematic relation with local hydraulic conditions. This makes it very difficult to predict the transport rates from theoretical formulae (Mannerstrom and McLean, 1985).

3.3. Carey Point Lookout (river km 120, see STOP 2, Figure 2)

This site, 10 km downstream from the Agassiz gauge and opposite Greyell Island and Carey Point, serves to illustrate some features of the pattern of channel shifting in the "wandering" gravel-bed reach of the river near Rosedale. Erosion and deposition are linked along the channel and, because the river is so large, this is obvious. Events at this site can be linked to events for many kilometres upstream. Channel instability was greatest in the first half of the century in the Cheam (upstream), Chilliwack and Sumas (downstream) Reaches, but greater in the latter half in the Rosedale Reach. Major deposition zones include lower Herrling Island, Vedder River confluence and lower Nicomen Island.

Upstream from the Agassiz gauge reach (Rosedale Bridge), extensive bank erosion took place between the turn of the century and 1943 along the north side of the river between Maria Slough and Cheam Slough (figure 21). This period of erosion was accompanied by island construction along Lower Herrling Island. Bar deposition in the widened channel promoted the development of a very sinuous main channel which caused further erosion near the south bank. Between 1943 and 1954 this alignment had straightened out and the main channel had shifted to the north side of the river. This new alignment and additional erosion along the north bank initiated rapid erosion after 1954 at Powerline Island just upstream of the Agassiz-Rosedale bridge. It is material from this source that now threatens the alignment and suitability of the channel for gauging at Agassiz.

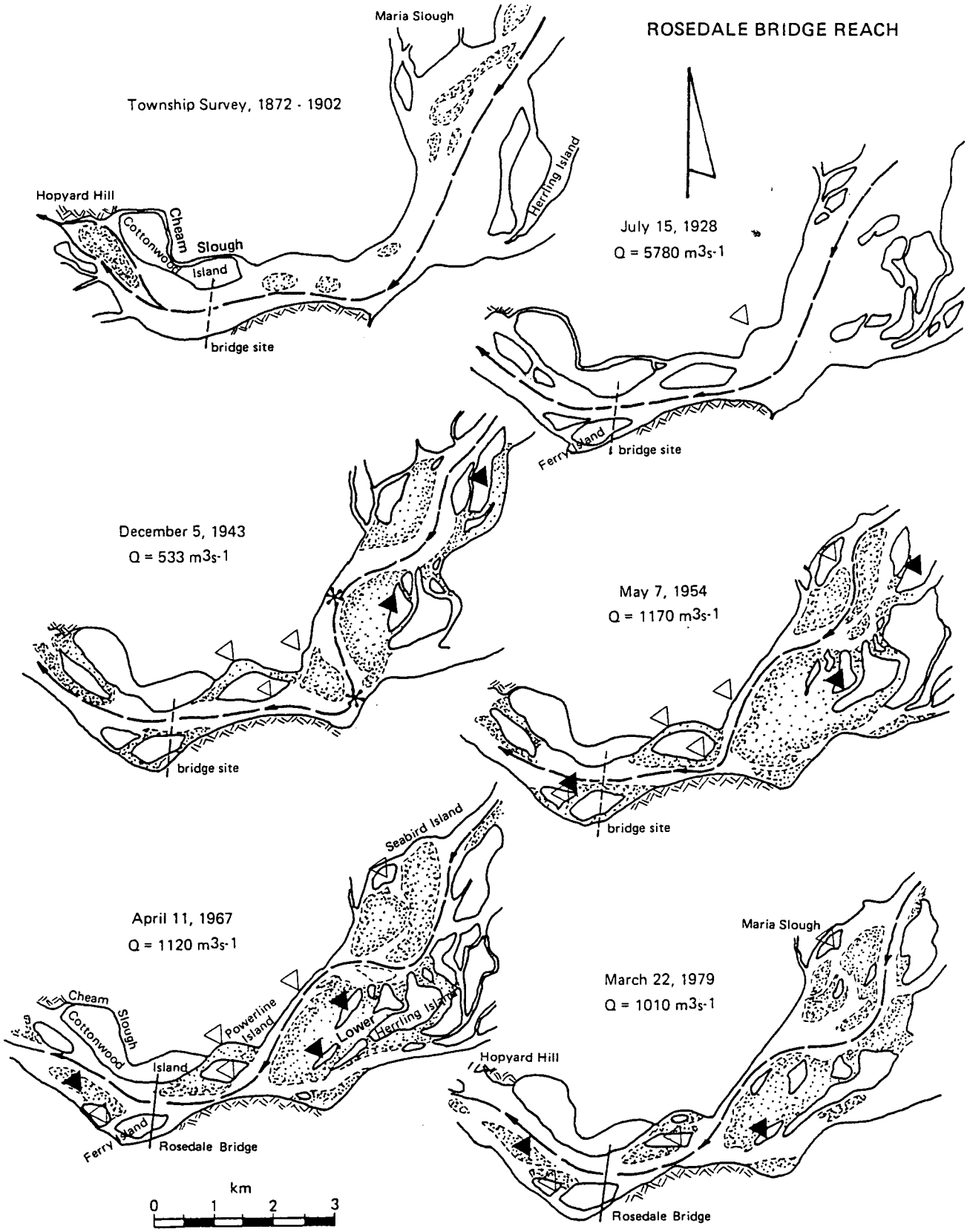


Figure 21. Channel changes in the Herrling Island-Rosedale Bridge reach. Legend on figure 22.

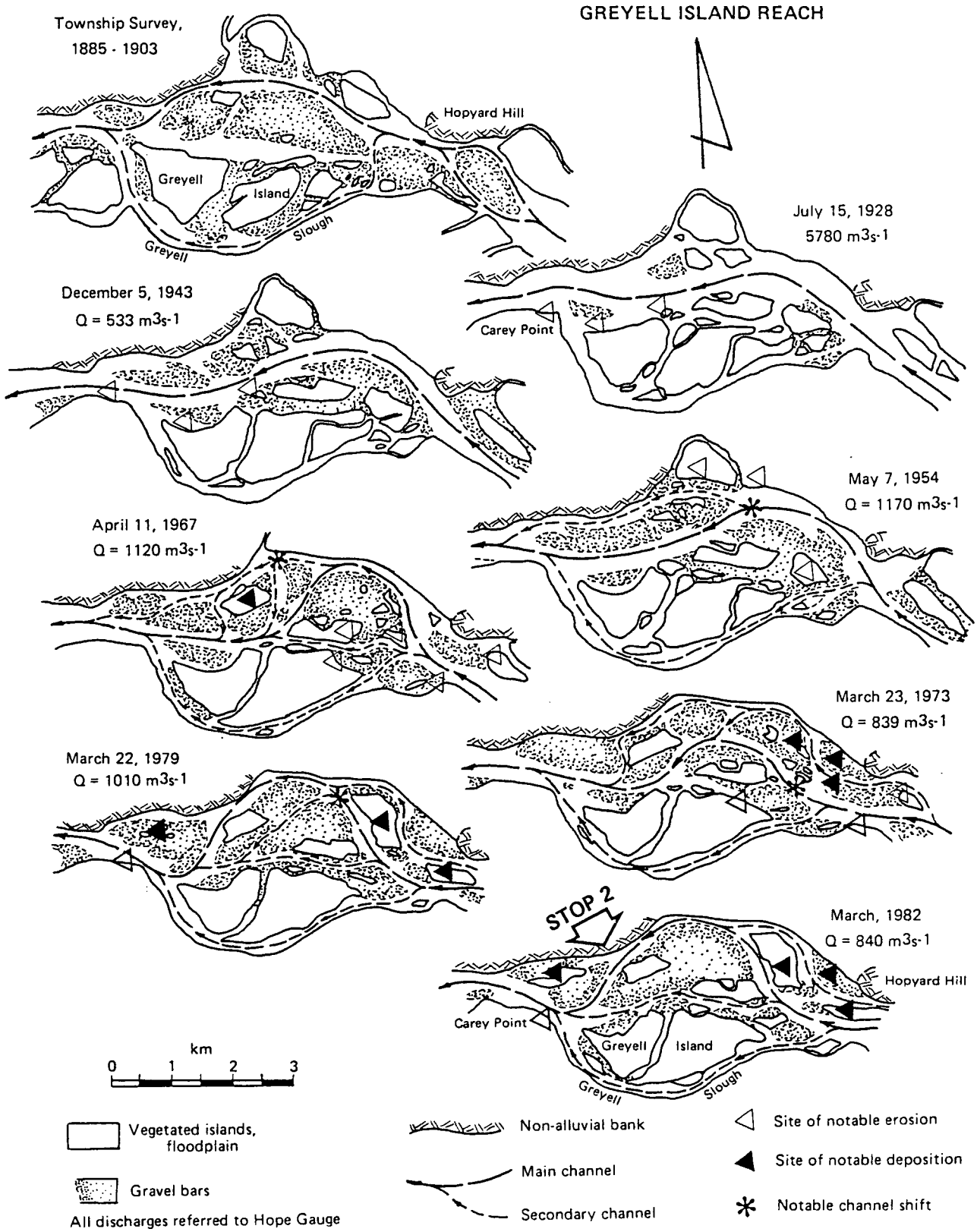


Figure 22. Channel changes in the Rosedale-Greyell Island reach.

Eroded material from the Cheam Reach (probably mainly from Powerline Island) was deposited in a prominent lateral bar that became attached to Ferry Island (figure 21) about 1954. This bar grew rapidly throughout the 1960s and gradually forced the main channel towards the north side of the river. As a result flow was directed towards a large stable island near Hopyard Hill. This island was rapidly eroded between 1961 and 1979 which eventually led to major channel changes further downstream.

Sediment eroded from Hopyard Hill Island was deposited immediately downstream in the main channel (figure 22). By 1971 this deposited material forced the channel southwards towards the head of Greyell Island and by 1973 the main channel had completed a major southward shift. Sediment eroded during this shift appears to have been redeposited 1.5 km downstream which plugged the channel and forced a second shift between 1973 and 1979 back toward the north side of the river. This latest change in alignment has forced the river to attack Carey Point which has experienced rapid bank erosion in recent years.

Much of the channel instability along the river has been related to relatively localized changes in flow alignment that developed as a result of earlier channel changes farther upstream. An important practical result would be to establish the time required for channel instabilities to propagate along the river. For example if we consider the Rosedale Reach the following sequence developed:

1. 1943-1971: Powerline Island eroded;
2. 1954: Ferry Island bar starts to grow and deflects river towards Hopyard Island;
3. 1954-1961: Hopyard Island eroded 1 km;
4. 1961-1971: Sediment from Hopyard Island deposited 1.5 km downstream causing main channel shift toward Greyell Island;
5. 1971-1979: Material eroded during 1971 shift, which has brought the river to the north side, then across the channel zone from the lookout bluff to attack Carey Point.

The disturbance (starting with the growth of the bar at Ferry Island) travelled 5 km downstream in about 25 years. During this period the lateral bar at Ferry Island grew about 2.0 km in length, illustrating that the channel disturbance can obviously travel much faster than the sediment. The channel shifts have had "knock-on" consequences farther downstream.

The bank erosion rate was about 25% higher in the period 1928-1943 compared to 1943-1971. Between 1928 and 1943 the largest flood had a return period of only 5 years, while in the period 1943-1971 four floods had return periods exceeding 10 years, including the flood of 1948 which had a return period of greater than 100 years. This decrease in erosion rate over time may reflect to some extent the effect of bank protection works that have been constructed since the 1940s. However, comparison of the channel shift maps shows that most of the channel changes along the river were governed by processes that developed over a number of years or decades and not during any single flood event. Therefore the appropriate time scales for considering channel instability processes on the Fraser River also are measured in years or decades. Extreme floods, such as in 1948 and 1972, were able to complete or "speed up" channel changes that were already underway. Large floods were also able to alter the flow alignment within the channel zone which later on initiated new patterns of channel instability. The change in flow alignment near Herrling Island between 1943 and 1954, and subsequent erosion at Powerline Island is an example of this type of process.

Bank erosion areas were planimetered from the 1:25 000 channel shift map sheets for the anastomosed-braided reach between Laidlaw and Sumas. Approximate volumes of material eroded were calculated by multiplying the erosion areas by the estimated bank heights at each site. These bank heights were derived from channel surveys of 1952 and 1964 and from field surveys during 1984. For the purpose of computing erosion volumes it was assumed that the banks were composed of gravel and sand overlain by 2 m of sand and silt. This allowed estimates to be made of the volume of gravel and sand sediments that have been transferred from the islands and

TABLE 7

SUMMARY OF BANK EROSION RATES ALONG LOWER FRASER RIVER: LAIDLAW TO SUMAS

REACH	LENGTH (km)	EROSION AREA (ha)	SEDIMENT VOLUME x 10^6 (m^3)	ANNUAL EROSION VOLUME (m^3/year) x 10^3
		Period 1890 (approx) - 1928		
Sumas	10.5	88	-	-
Chilliwack	17.5	410	10.1	265
Rosedale	12.2	162	5.36	141
Cheam	21.0	423	16.7	440
Total		1083	32.16	847
		Period 1928-1943		
Sumas	10.5	10	-	-
Chilliwack	17.5	173	4.47	298
Rosedale	12.2	372	1.94	129
Cheam	21.0	170	7.67	511
Total		725	14.08	938
		Period 1943-1971		
Sumas	10.5	21	-	-
Chilliwack	17.5	177	3.68	131
Rosedale	12.2	153	6.25	223
Cheam	21.0	264	11.15	398
Total		615	21.08	752

NOTE: Annual Erosion volumes do not include fine sandy and silty floodplain deposits.

floodplain to the active channel over the last century (Table 7). These volumes will form the basis of a comparison with measured sediment transport rates.

As a preliminary comparison, we note that between 1943 and 1971 the average erosion volume in the reach between Sumas and Wahleach (50.7 km) was 752 x 10^3 m^3y^{-1} (Table 7), or 14.8 m^3 per metre length of channel. The average channel width in the reach is 1270 m at the 2-yr flood level. If we assume that the transport distance is $2\pi W$ -- that is, from "riffle" to "riffle", with mean riffle scale assigned to the river -- we obtain an estimate of 1.2 x 10^5 m^3yr^{-1} for bed material transport. Measurements during the period 1967-1982 yield an average bedload transport of 1.1 x 10^5 m^3yr^{-1} (with bulk density assumed to be 1.6 tonnes m^{-3}). The similarily of these figures is remarkable: the difference is well within the precision of either figure.

3.4. Mission gauge reach (river km 82, see STOP 3, Figure 2)

At Mission the gauging section is located in a straight reach of the river 340 m upstream of the Canadian Pacific railway bridge. This section is very uniform and should be close to ideal for conducting sediment transport observations (figure 17). One complicating factor is that at lower flows the Mission site becomes tidally influenced, which causes diurnal variations in discharge and stage. However, during freshet conditions tidal influences are believed to be minor.

The natural channel here has sand bed (figure 18) and banks, but heavy bank protection effectively immobolizes the banks (at about the natural width). Figure 19 gives the hydraulic geometry of the section. The sediment load at this station is reported in Table 5. Figure 23 shows that the annual distribution of the load is very similar to that at Agassiz (Figure 20).

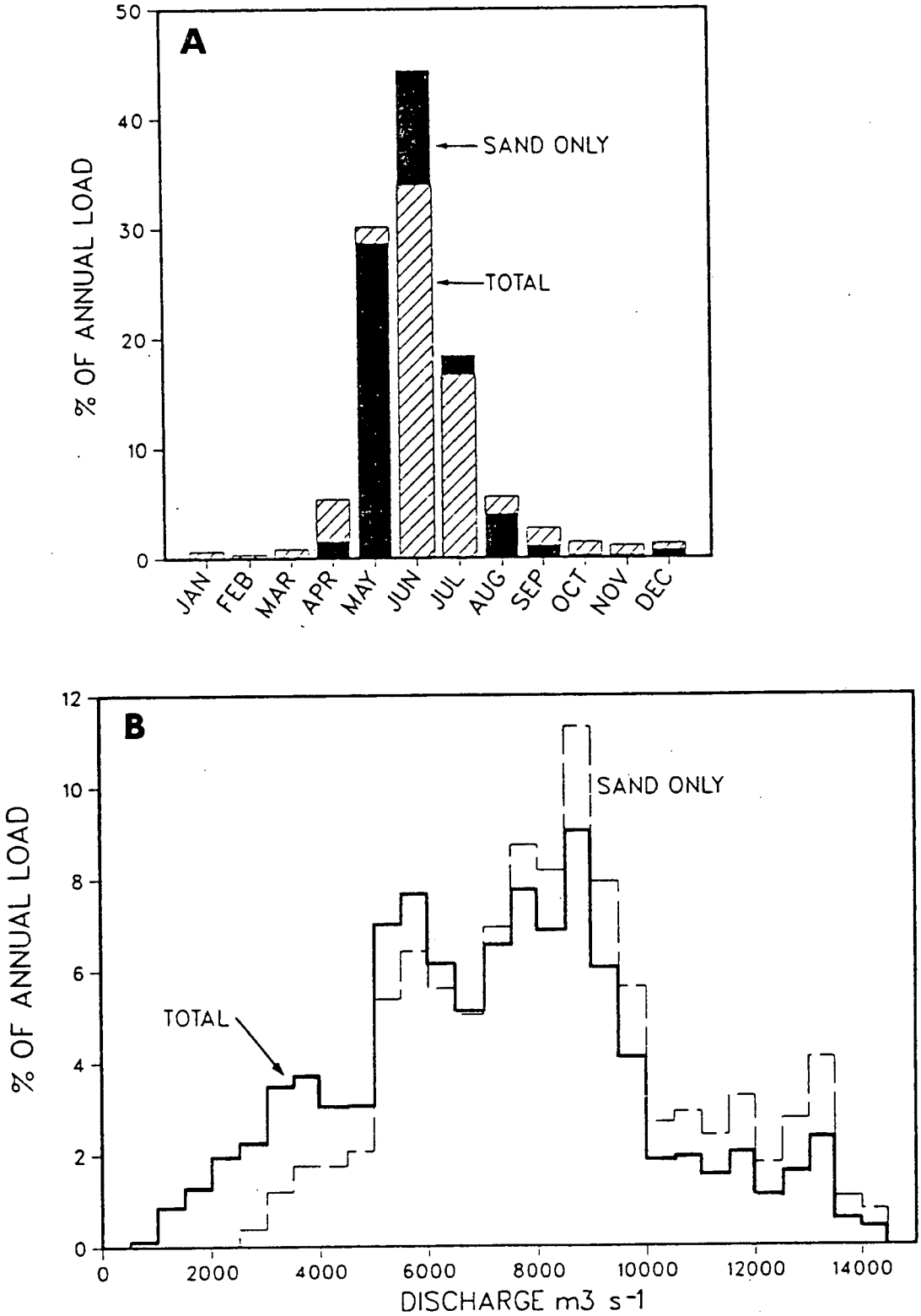


Figure 23. Variation of sediment load at Mission by season and by discharge: mean of 1966-1982 results.

The data of tables 4 and 5 lead to a sediment balance for the Agassiz-Mission reach. Approximately 150 000 tonnes/year of gravel material (coarser than 2 mm) was transported past Agassiz between 1967 and 1982, whereas gravel transport past Mission (2000 tonnes/year) is negligible. Therefore approximately 2.4 million tonnes of gravel was deposited in the Agassiz-Mission reach between 1967 and 1982 and roughly 5 million tonnes has been deposited since 1950.

The estimated annual sand loads at Mission exceeded the Agassiz loads by 1 million tonnes/year on average between 1967 and 1982. This long term difference is statistically significant in comparison with measurement precision. In years characterised by unusually large freshets (such as 1967, 1972, 1974 and 1982), the annual sand load at Mission exceeded the load at Agassiz and Hope by as much as 20 to 40%. These differences are substantially larger than the expected measurement errors. For example, in 1972 the sand load at Mission exceeded the load at Agassiz and Hope by over 5 million tonnes. Apparently in some years large quantities of predominantly sand sized sediment can be derived from the Agassiz - Mission reach. Based on the published sediment records from the Chilliwack River at Vedder Crossing it is apparent that the sediment inflows from tributaries between Mission and Agassiz are negligible in comparison to some of the observed increases in annual load at Mission. The source of this sediment is still under investigation.

Comparison of average monthly load summaries (Figures 20 and 23) indicate that the sand load at Mission in May is characteristically lower than at Agassiz. Conversely, the sand load in June is considerably higher at Mission than at Agassiz. This indicates that substantial quantities of sand are being stored in the Agassiz-Mission reach on the rising limb of the freshet and then are deflated from the reach on the falling limb. These storage changes were examined further by computing the cumulative difference between the total suspended load at Agassiz and Mission at daily intervals over the year.

Figure 24 illustrates the variation of the cumulative differences over the 1968 and 1972 freshets. The 1968 data show that even when the annual loads at Agassiz and Mission are virtually identical, systematic variations in transport rates may take place between stations. On the rising limb of the flood in May the incoming load at Agassiz consistently exceeded the load at Mission while after June 1st the loads at Agassiz were consistently lower than at Mission.

The change from sediment accumulation to sediment depletion coincided with the onset of supply exhaustion at Agassiz. This pattern of sediment accumulation on the rising limb of the flood occurred in virtually every year. In most years a period of sediment depletion took place on the falling limb so that the net change in sediment storage within the reach at the end of the freshet was virtually zero.

In 1972 substantial net sediment depletion occurred. This plot shows that the sediment depletion took place on the falling limb of the freshet after a period of initial sediment accumulation.

Examination of similar plots over the full record makes clear that modest net accumulation occurs in the Agassiz-Mission reach in most years, and is then removed in exceptional floods (1967, 1972, 1974). The individual annual accumulations fell within annual compilation error, but the episodic loss exceeds it. The storage area and exchange mechanisms for this material remain to be determined.

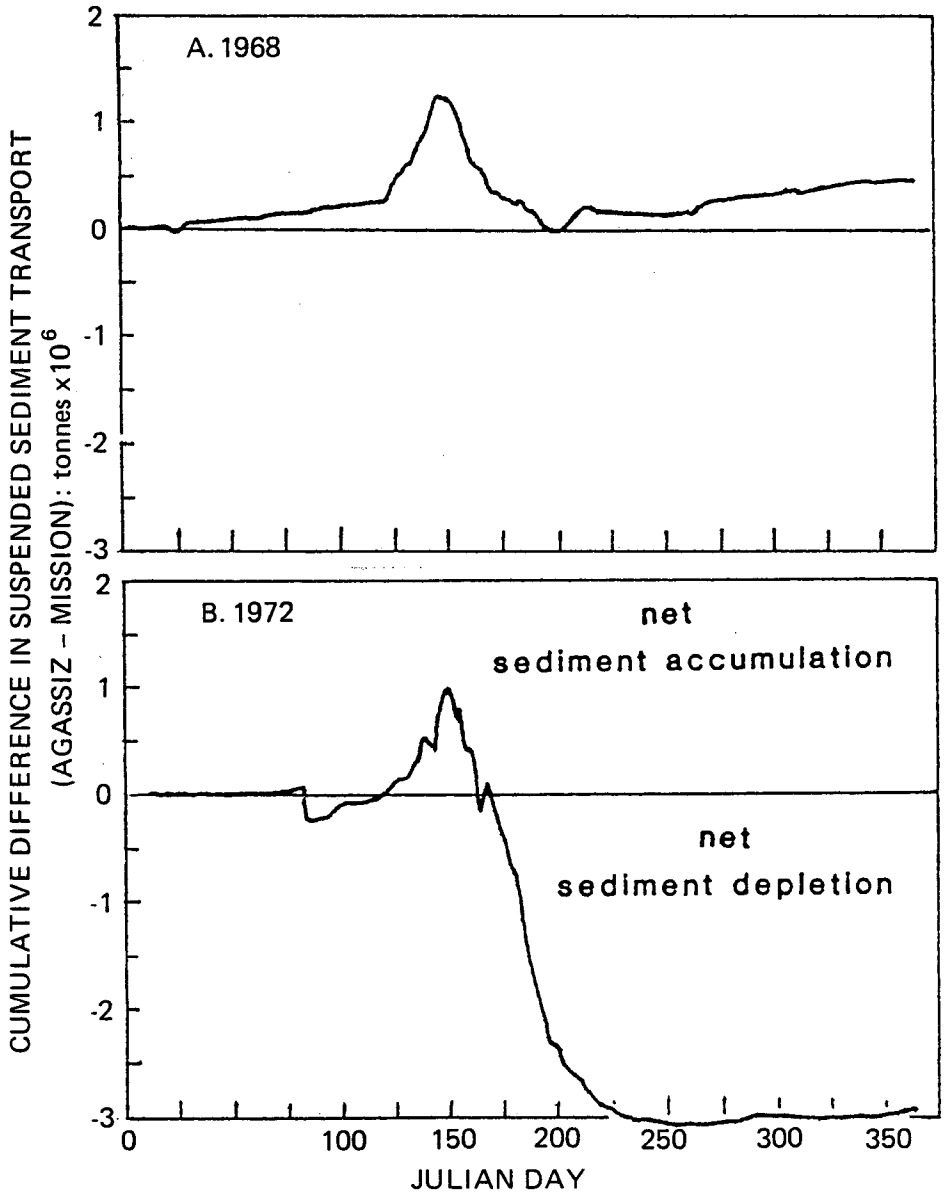


Figure 24. Cumulative differences between suspended loads at Agassiz and Mission: 1968 and 1972.

3.5. Port Mann gauge reach (km 40, see STOP 4, Figure 2)

The station at Port Mann is located about 1500 m downstream from Port Mann bridge, near the narrowest point in Queens Reach. The channel is 580 m wide here and the cross section is regular. The average depth at half-tide is about 12 m, but the centre of the channel is at about -17.0 m elevation. The river is tidal year round, though salt water does not penetrate to this point. Although measurements were conducted for many years at this station (table 1), only part of the record is published because of difficulties in estimating the tidal effects between measurements.

Ideally, sediment loads delivered into the heavily navigated estuary should be based on measurements at Port Mann. However, the tidal effects greatly complicate the collection of reliable sediment and hydrometric data. (Furthermore, a recent re-assessment of the published 1968 discharge data at Port Mann using a one dimensional flow model suggested that the daily flows were systematically underestimated by about 10% during the freshet period (Morasse, 1985). As a result of these kinds of problems most previous studies on the Lower Fraser River have relied on the data at Mission for estimating sediment loads into the estuary. In this study annual loads were calculated for the common period of record (1966-1972) at Mission and Port Mann to provide a basis for concluding whether major differences occur between the two stations.

Figure 14 illustrated that there is very little change in the size distribution of the sand load along the river, apart from apparent slight fining toward Port Mann. Within the approximation permitted by the measurements, we may assert that significant sorting or selective sedimentation of the sand load does not occur upstream of Port Mann, and this suggests that Mission data may provide a reasonable approximation of sediment transfer past Port Mann, certainly for wash load.

For the period 1966-1972 Port Mann records permit calculation of the suspended load. Table 8 provides a comparison of the suspended bed

Table 8

Suspended bed material load at Port Mann and at Mission
(tonnes/yr)

YEAR	PORT MANN LOAD (1)	MISSION LOAD (2)	DISCREPANCY (1)/(2)
1966	2 360 000	2 117 000	1.11
1967	4 895 000	3 766 000	1.30
1968	3 053 000	2 473 000	1.23
1969	1 916 000	1 390 000	1.38
1970	1 149 000	1 160 000	0.99
1971	2 410 000	1 978 000	1.22
1972	4 846 000	4 893 000	0.99
Average	2 947 000	2 540 000	1.16

Calculated on the same basis as Mission suspended bed material load (Table 6); i.e., 0.40 of the 125-250μ fraction is considered to be bed material.

The discharges upon which the figures are based have been adjusted upward by 10% from published figures following Morasse (1985).

material load at Mission and at Port Mann for this period on the same computational basis. The load at Port Mann ostensibly is 16 percent larger, on average, over these years. In view of the uncertainties attendant upon the computation of flow at Port Mann, it cannot be concluded that this difference is real. In some years there is near equality.

Bed load data are available for Port Mann in 1968. These are compared in figure 25 with Mission data from the same year, obtained by the same means. Within the appreciable scatter of the data there is no obvious distinction of the observations, so it is concluded that the same bedload rating curve may be applied at both stations. Again, bedload is quantitatively of little importance in comparison with suspended bed material.

The consistency of bedload and material characteristics, and the appearance of a difference in total bed material transport that is comparable with the likely resolution of the comparison lead to provisional acceptance of Mission data as a useful measure of sediment yield to the estuary. Nonetheless, it should be possible to improve the comparison. The main factor to consider still is the flow record at Port Mann.

One means to overcome the difficulty of rating the Port Mann section for flow may be to examine the correlation between velocity and bed sediment transport. Figure 26 illustrates two such correlations. The best prediction of sediment concentration is the ratio (v/w) of mean flow velocity to sediment fall velocity. The latter parameter -- based upon the median size of the bed material -- accounts for sediment size and for variations in kinematic viscosity induced by changes in water temperature. For this correlation, $R^2 = 0.884$ and SEE = 0.367 logarithmic units. The standard error provides a range of 26 mg l^{-1} to 140 mg l^{-1} at a nominal value of 60 mg l^{-1}; i.e., 43% to 230% of the nominal value. The large range reflects the extremely sensitive relation. The results are consistent with findings by Colby (1964).

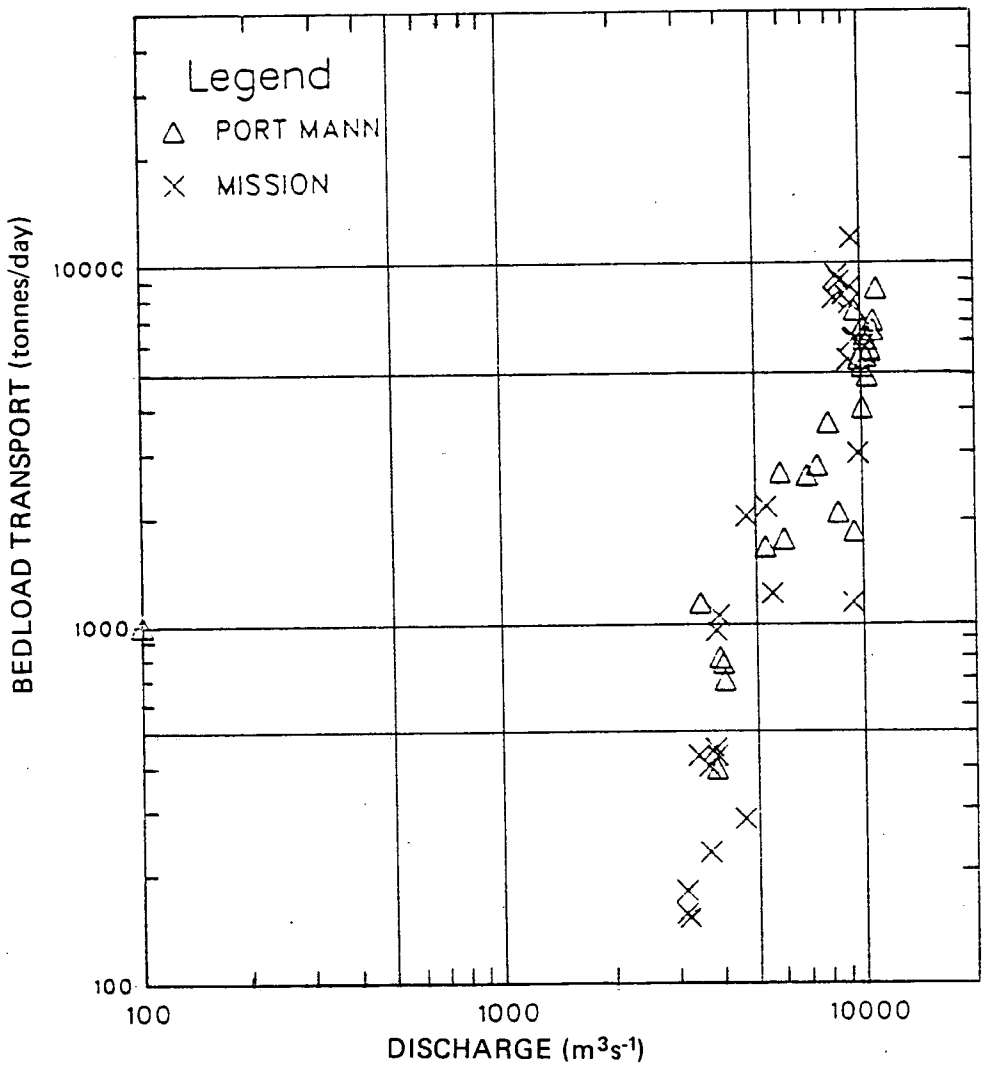


Figure 25. Bed load transport at Port Mann and Mission, 1968.

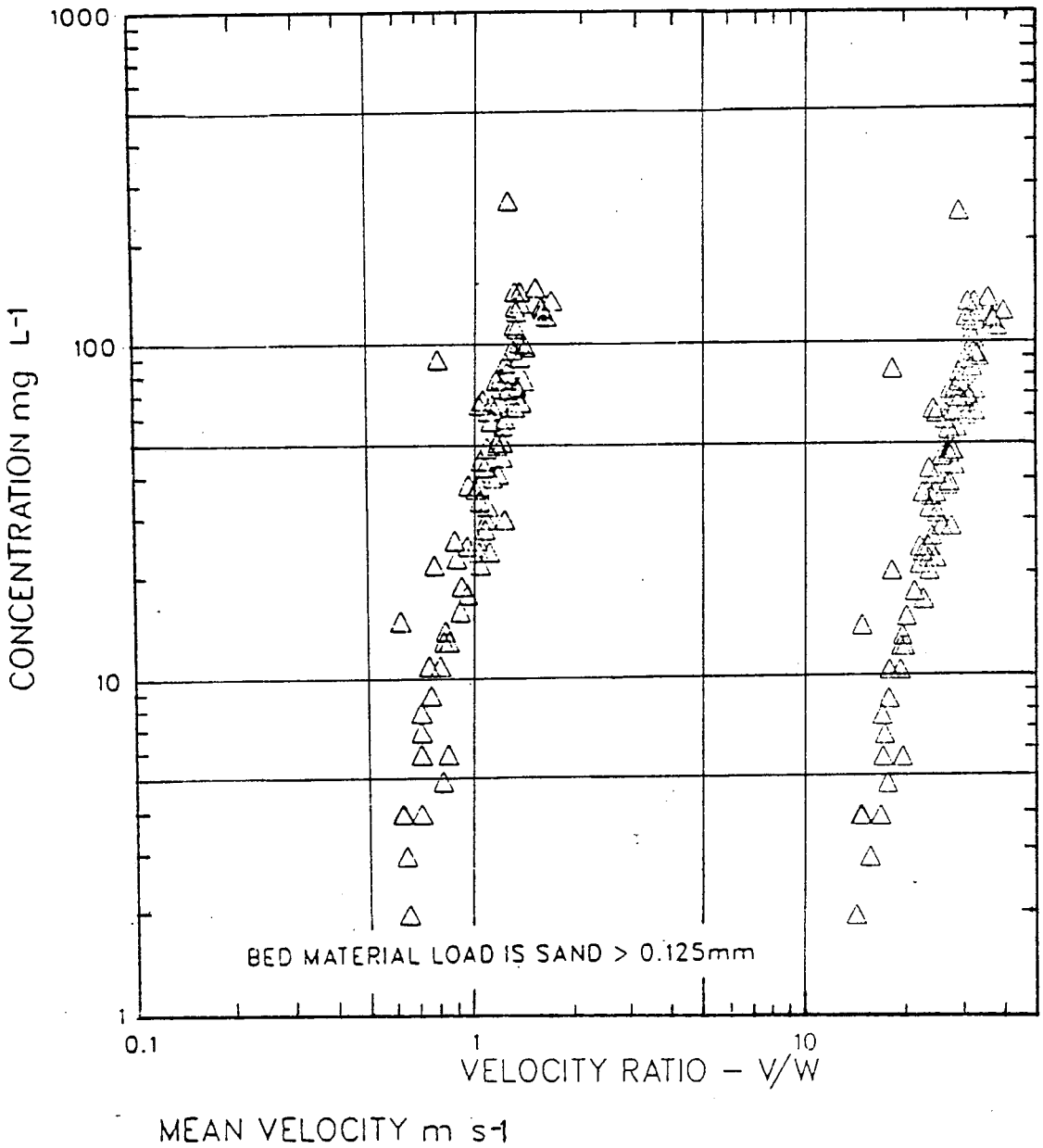


Figure 26. Velocity-sediment transport correlations at Port Mann for suspended bed material load.

3.6. Estuarine reach: main channel at Deas Island (km 20, see Figure 2)

At river km 35, 7 km below Port Mann, the river enters its modern delta and divides into three channels just downstream from New Westminster and Surrey docks. Ultimately there are four distributaries; North Arm, Middle Arm, Main Arm and Canoe Pass (figure 27). The distribution of flow into the various channels is shown schematically for two dates in figure 28. The changes over the 16-year period are attributed to a combination of dredging and construction of river control works. The division varies seasonally and still is not well known. It is supposed that sediment transport is more strongly concentrated in the main channel than is the flow, but there are no measurements to confirm that.

The effects of the mixed semi-diurnal tides in the Strait of Georgia propagate upstream as far as Chilliwack during low discharges (850 $m^3 s^{-1}$) and as far as Mission during high discharges (9000 $m^3 s^{-1}$) (Ages and Wollard 1976). The tide at Sand Heads ranges to 3.4 m at high discharges and to 4.0 m at low discharges. At New Westminster the tide effect ranges to 1.3 m at high dischages and to 2.3 m low discharges. At low discharge (late winter) the salinity wedge may intrude 30 km upstream, while at high discharges the intrusion is less than 5 km upstream from Sand Heads.

During the development of the delta, the main channel has successively been in the vicinity of Boundary Bay, Point Grey and Steveston (figure 27). Meander scrolls on the delta indicate that within the past millenium the Main Arm has been up to 3.2 km north or south of its current location (Blunden 1973). The present course of the river is controlled by a number of in-channel river training structures and flood protection dykes in low lying reaches.

In the vicinity of Deas Island the river forms a long slightly curved reach. The channel here is about 1250 m wide and flow depth is about 10 m at low water (tides up to 3 m occur). The main flow is restricted to a 400 m channel and the balance of the section consists of wide, shallow

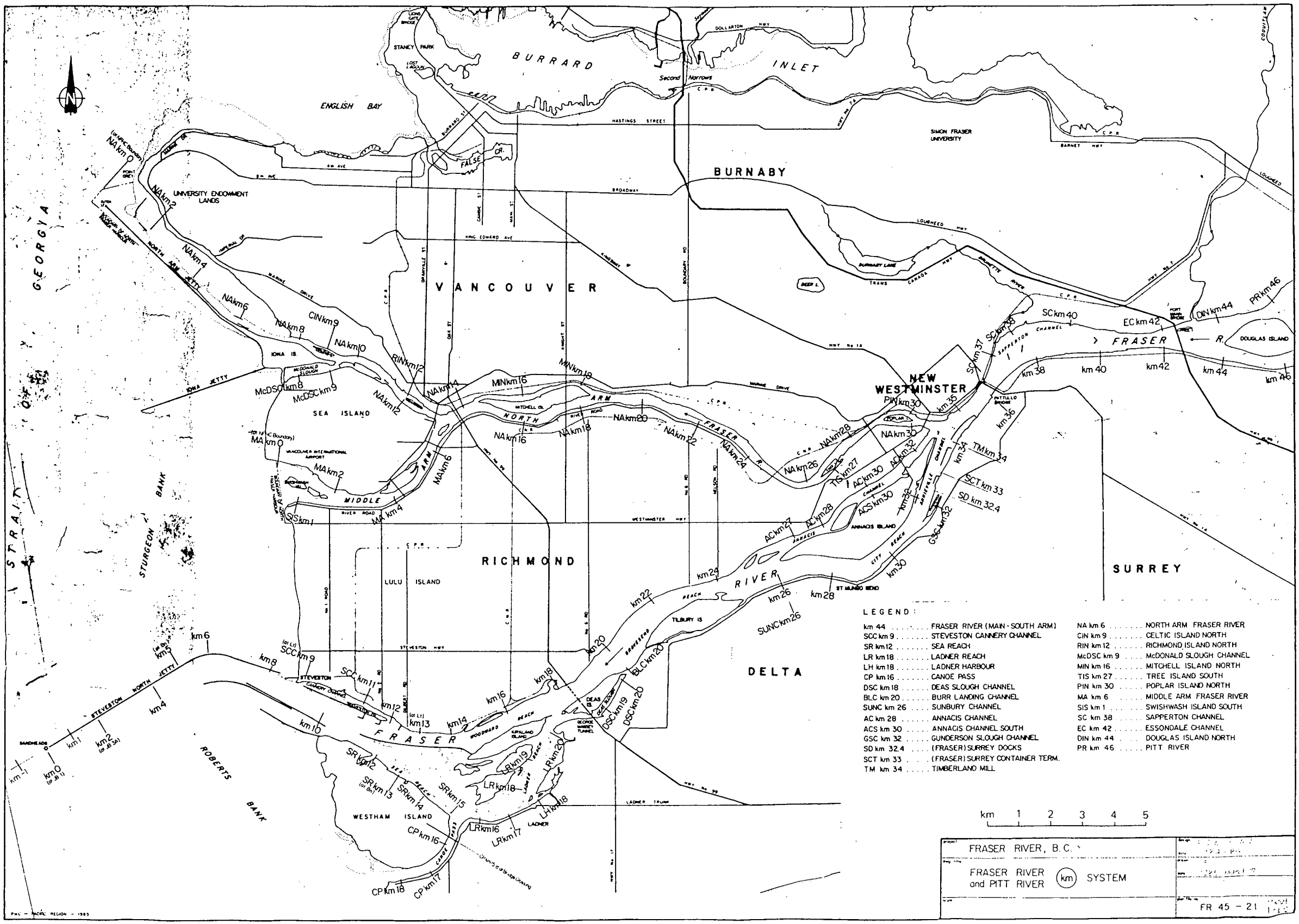
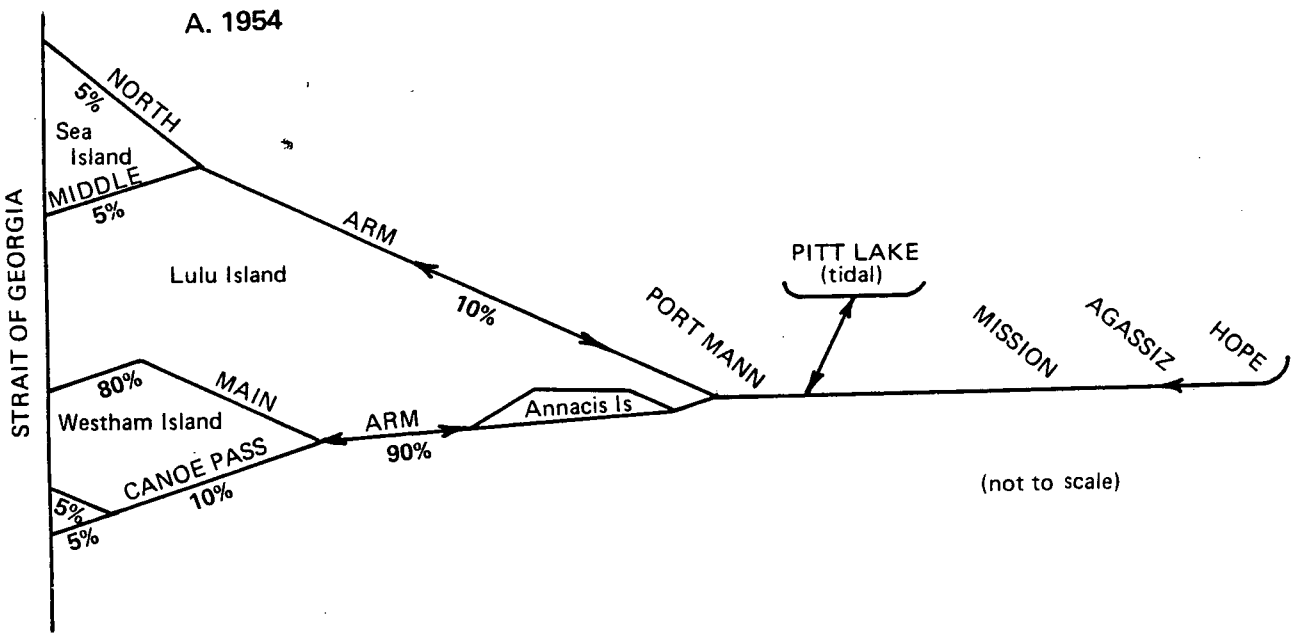


Figure 27. Fraser delta: large scale map.



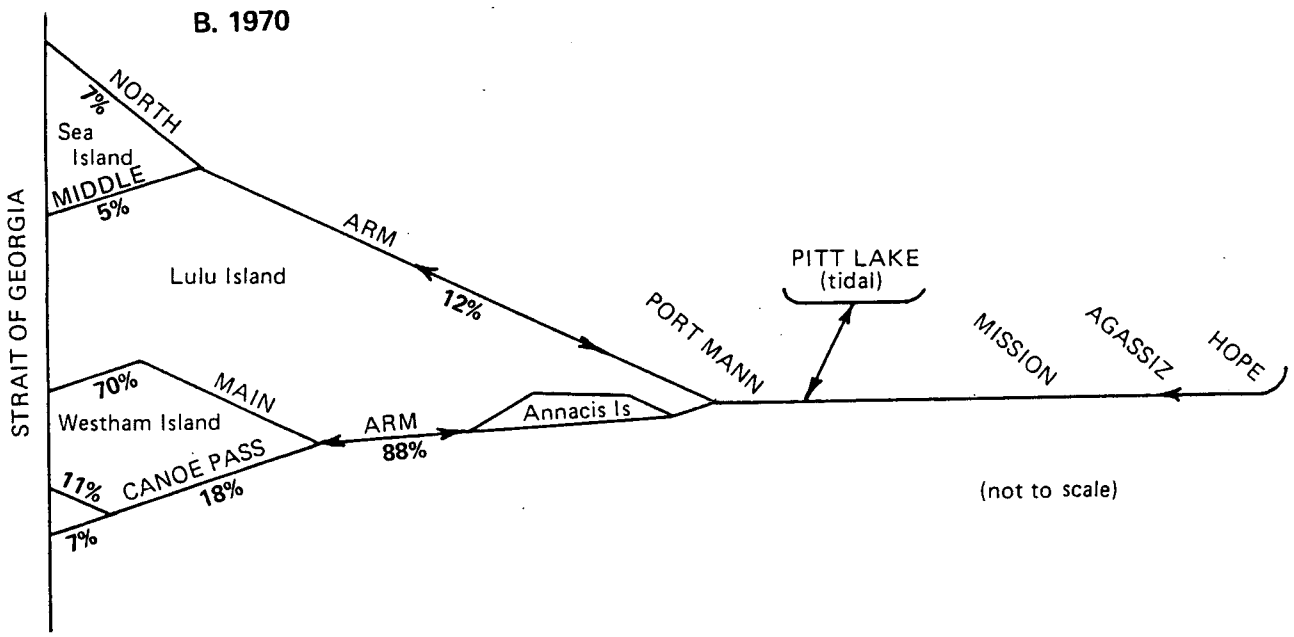


Figure 28. Flow distribution in Fraser delta channels, based on 1954 freshet (Keane, 1957) and 1970 (WCHL, 1977).

"berms" which carry the tidal prism. Along much of the estuarine course of the river, the channel is artificially restricted behind pilings in an attempt to maintain a strong, deep flow capable of moving sediment to the sea. This presumably has modified the pattern of deltaic sedimentation.

Figure 18 shows the size distribution of bed material in this reach. Approximately 90% of the bed material is composed of sand between 0.125 and 0.50 mm in diameter. There is relatively little change in size distribution downstream from Mission, and none below Port Mann. Figure 29 displays velocity and suspended sediment concentrations in freshet at a section several hundred metres upstream from the Deas Island Tunnel. Although the channel is deeper near the left bank, velocities and concentrations both are fairly uniform in the section.

There are no continuous measurements of sediment transport in the estuary. Measurement of sediment transport in this fully tidal reach requires that profiles of velocity and sediment concentration be obtained simultaneously and more or less continuously. Several programmes of synoptic observations have been carried out but there is as yet no systematic assessment of sediment transport in the estuary channels. A programme of 8 week-long cruises between April 22 and June 20, 1985, and between March 28 and September 5, 1986, to characterize sediment transport in the outer Main Arm during the freshet, is the most comprehensive exercise conducted to date. Measurements consisted of observations on several profiles for velocity, water temperature, salinity and suspended sediment concentration through tidal cycles at Sand Heads and at Steveston (figure 30). Measurements were made on successive days at each station. Some results from that programme are reported here.

The study reach is bound on its right bank by Steveston Jetty and on its left bank is partially confined by Albion Dyke. However, there is a substantial spill of water over the dyke at high flow, which remains unassessed. A 250 m wide navigation channel is maintained by dredging to 9 m draft or better (with respect to low water) and the measurements have

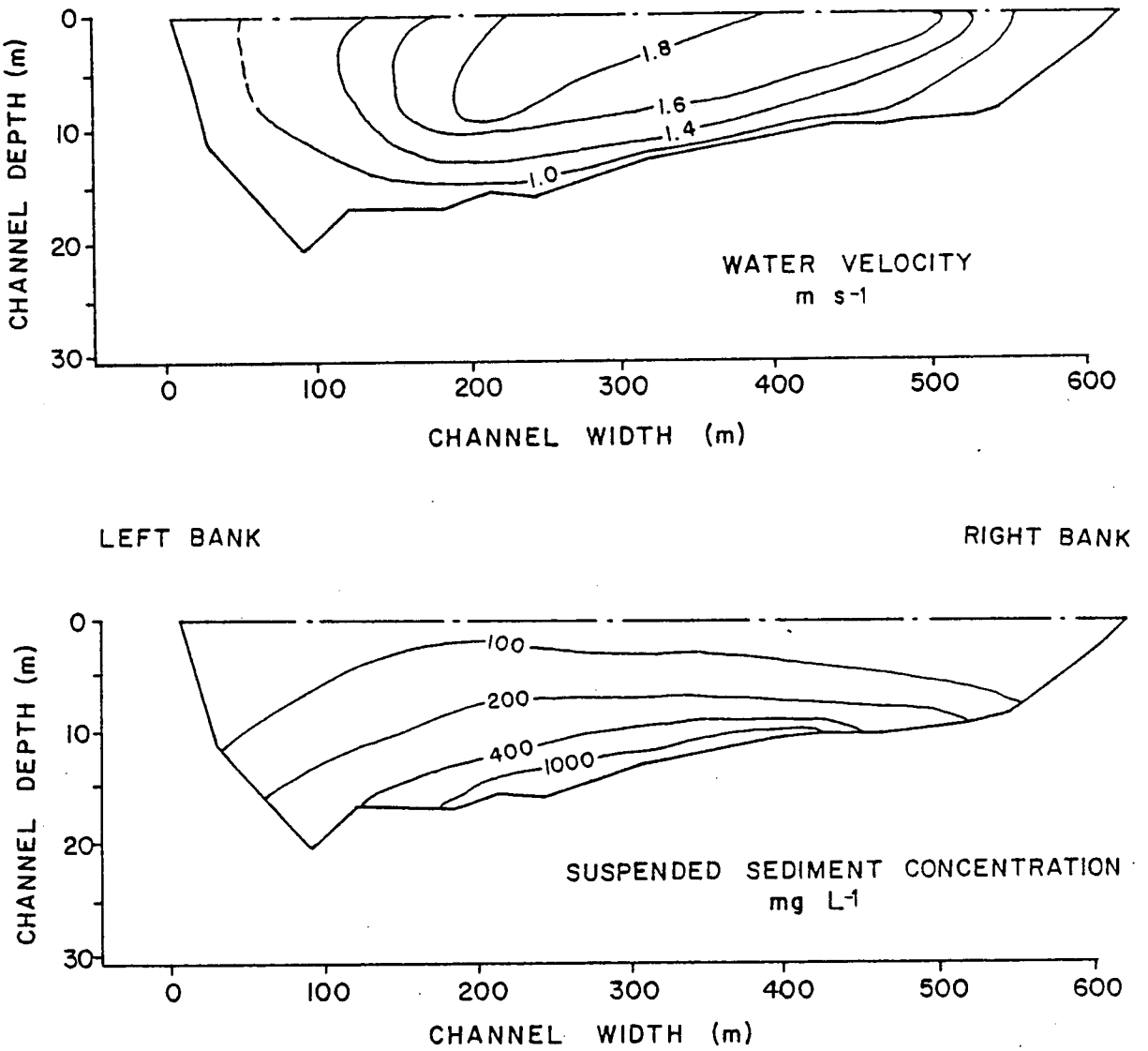


Figure 29. Cross-section in Main Arm near the upstream end of Deas Island showing water velocity and suspended sediment concentration within the deepwater channel: measurements of June 22, 1978, 1210 to 1325 PDT (Beak, 1980).

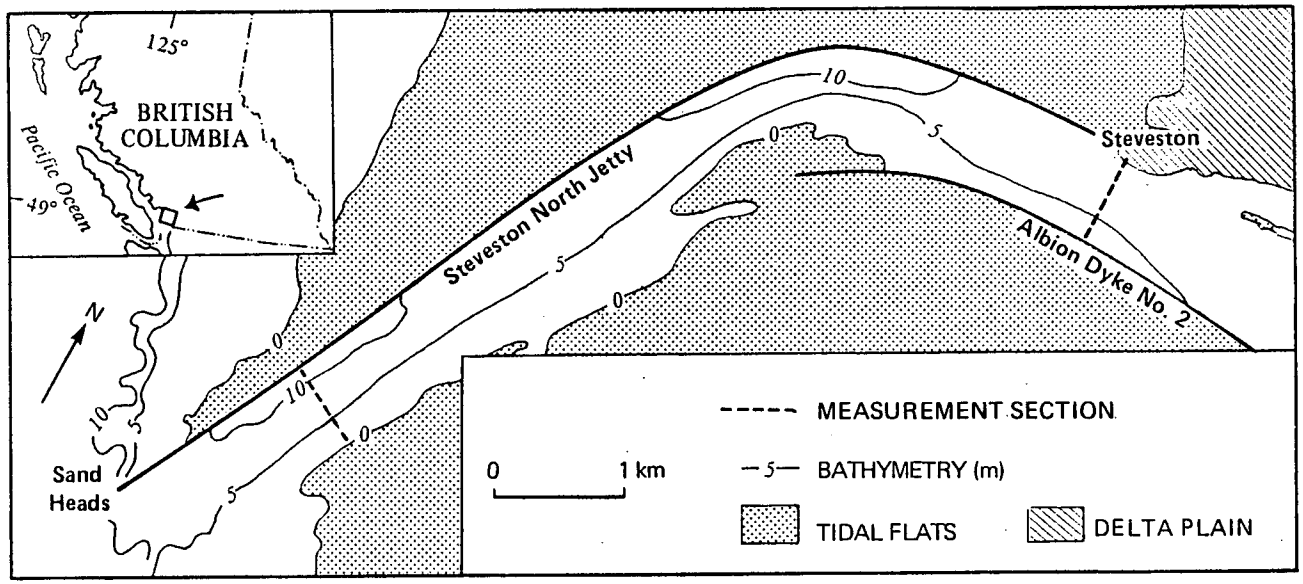


Figure 30. Location of measurement sections in outer Main Arm of Fraser River (1985-86).

been made within that channel. In Steveston Bend, depths reach 20 m locally. Bed material has a mean size in the range 0.25 to 0.35 mm everywhere in the reach, except that cohesive clayey silt is exposed in Steveston Bend with a veneer of coarser sand.

Figure 31 illustrates section averaged salinity and velocity profiles of each section on the measurement dates. The measurements are centered on low tide (the time of greatest discharge) and the measurement periods were selected for relatively high tidal range. The limited incursion of the salt wedge at the peak of the freshet (the water column remained fresh at Steveston) is notable. Figure 32 illustrates the summary effect along the channel of the change in water column state. At high tide and moderate flow, the incursion of the salt wedge raises the freshwater flow from the bed. Since the channel is partly confined, flow velocity must then increase substantially in the upper part of the water column. Yet in this stratified flow situation, upward diffusion of turbulent eddies from the bed is strongly suppressed. The effect on suspended sediment properties is noted in Figure 33. The most significant features revealed in this figure are that on rising to high tide (salt water incursion), the percent sand in the water column becomes very small. There is then substantial deposition on the bed, not all of which evidently is recovered on the subsequent tide since persistent shoaling in the reach must be balanced by dredging. Sand deposition at the foot of the salt wedge is a common phenomenon in estuaries.

Figure 34 summarizes flow and sediment transport at the two measurement stations during the 1986 season. From the observations summarized in figures 31-34 the following conclusions may be made concerning sediment transport in the outer main channel:

- there is a direct relation between seasonal discharge and sediment transport, as is expected by sediment transport from upstream, and the relation reveals the known hysteresis controlled by fine sediment supply;
- sediment transport varies directly with tidal range over the daily cyles;

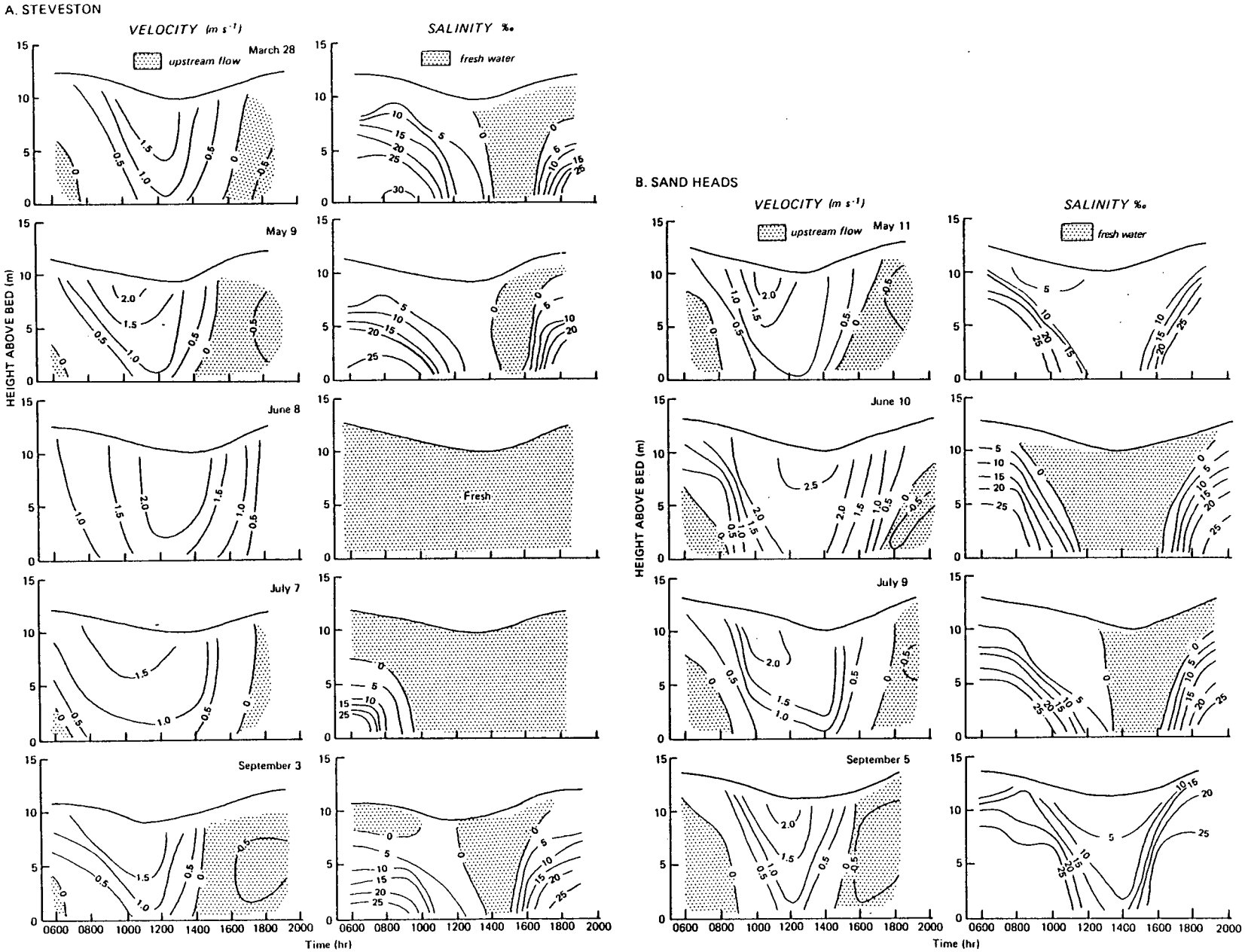


Figure 31. Water column over a tidal cycle at (a) Steveston and (b) Sand Heads (1986 measurements by R.A. Kostaschuk).

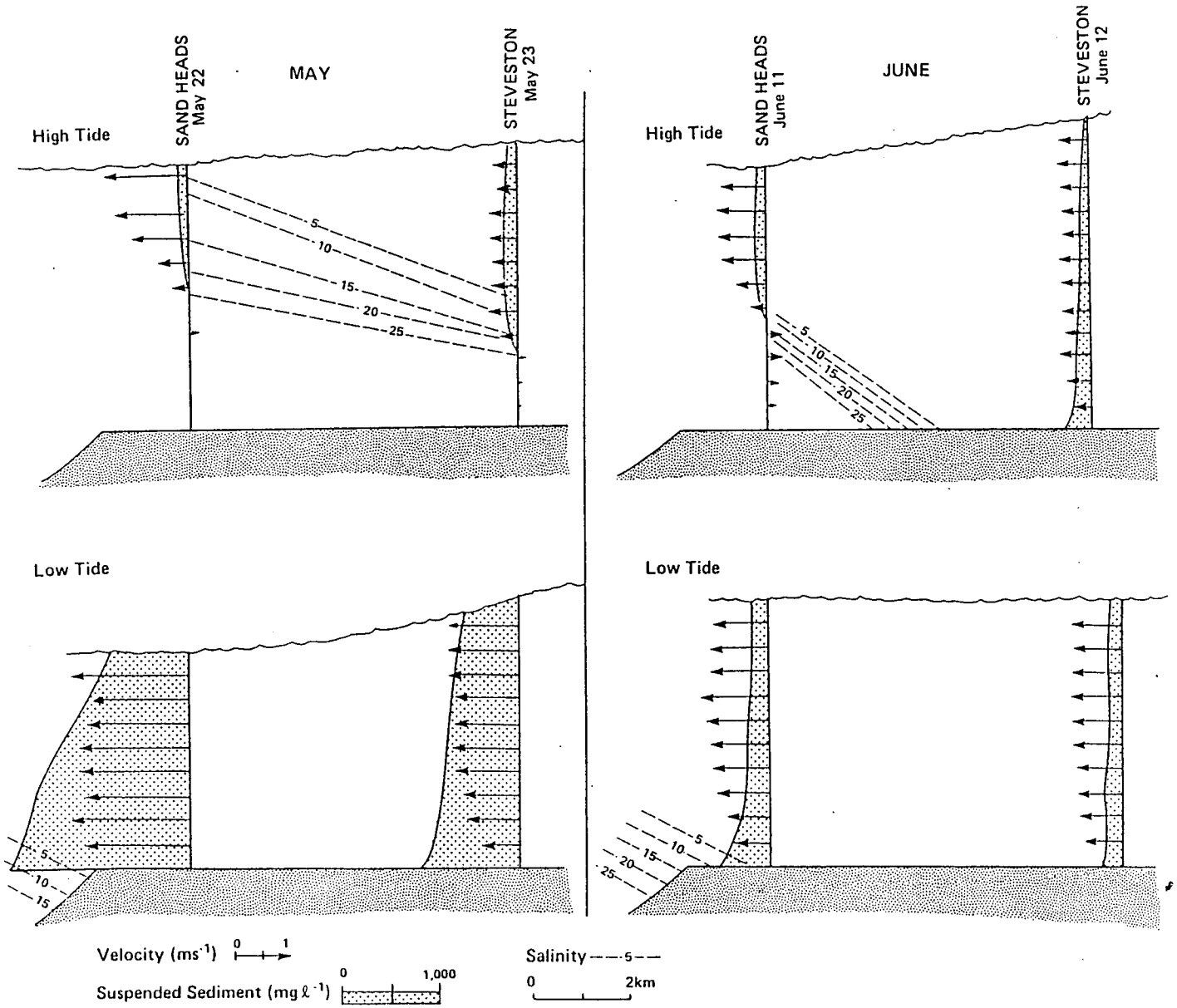


Figure 32. Along channel variation in water column state for high and low tides (1985 freshet measurements).

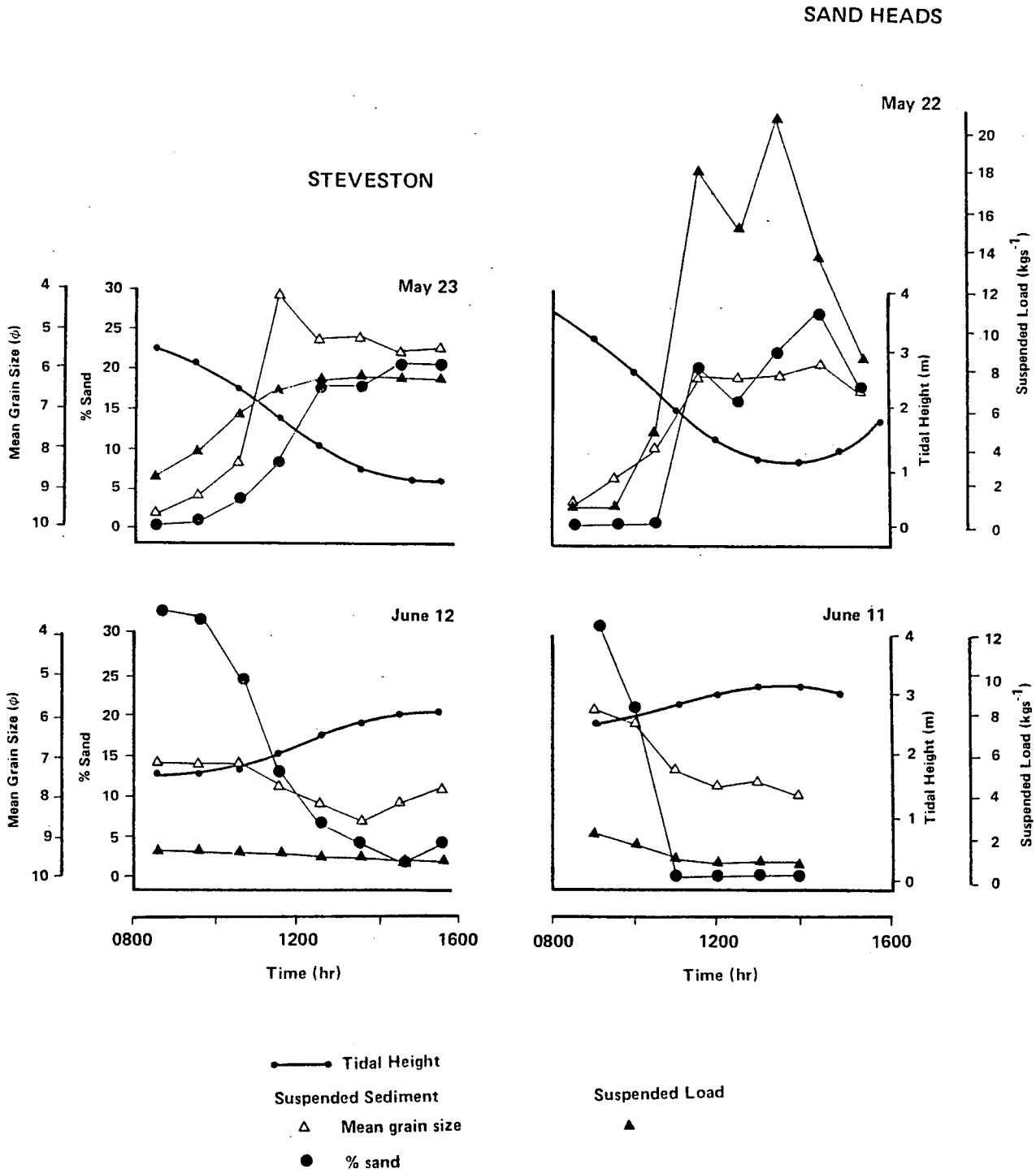


Figure 33. Variation in suspended sediment properties for rising and falling tides during 1985 freshet conditions. Sediment properties were derived from pumped 20 litre samples taken 2 m below the surface in stratified conditions: 2 m from the bed in unstratified conditions.

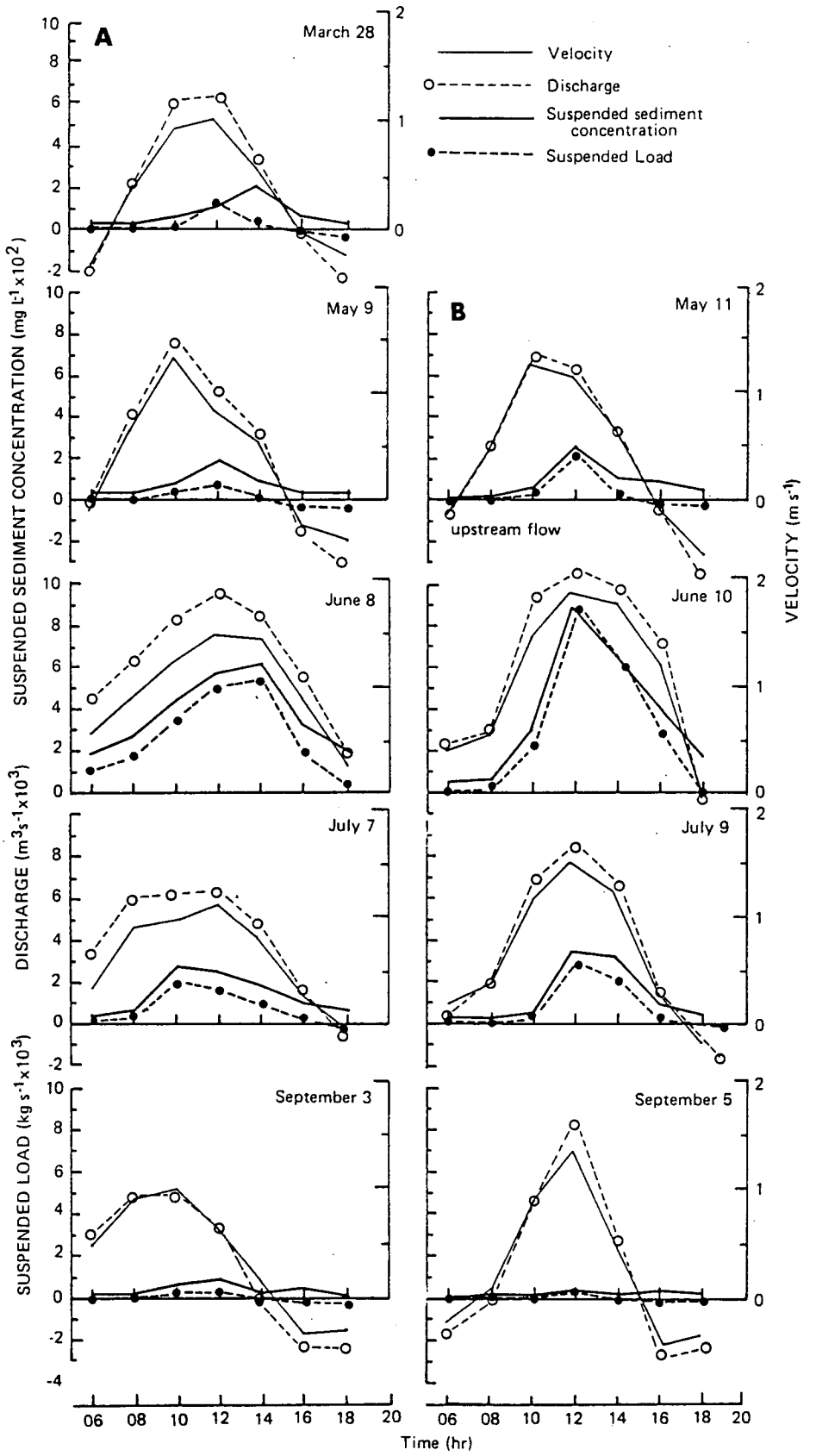


Figure 34. Flow and sediment transport during the 1986 freshet at (a) Steveston and (b) Sand Heads.

- sediment transport and suspended sediment texture vary inversely with tidal stage in the short term.

Milliman (1980) made similar observations and also noted that silt and clay concentrations remained relatively constant over the tidal cycles, further implicating the behaviour of the sand as the chief variable quantity.

During high flow, sand waves form on the bed and migrate slowly downstream. Sandwave celerity in the channel was studied briefly in 1985 and provides the basis for a first estimate of bedload transport. Over two tidal cycles at about 7000 m^3s^{-1} mean flow, the 32 m long x 1.4 m amplitude features (figure 35) migrated 30 m downstream, indicating a bedload of 0.008 $m^3s^{-1}m^{-1}$. Sidescan sonar indicates that the features occupy about 80 m width on the channel bed. On the assumptions that the bedforms attenuate linearly toward the channel side and that bulk density is about 1.6 tonnes m^{-3}, the transport rate would be about 0.5 tonnes s^{-1}, or 40 x 10^3 tonnes day^{-1}. The celerity was measured during an extreme tide and probably is near the maximum rate. (However, in 1950 a wave of height 4.5 m and length 150 m was observed in the vicinity of Deas Island, migrating downstream at a rate of 75 m/day: see Pretions and Blench, 1957). Bedform development appears to be restricted to flows above about 4000 m^3s^{-1} (as at Mission), and so evolve during the period of about 60 to 75 days that mark the peak of the annual flood. On this time scale, it appears that tidal bedload transport could be on the order of one million tonnes a^{-1}. This is substantially more than is estimated for upstream stations. The exceedingly shaky basis for the comparison is obvious. On the other hand, the interference of the salt wedge with sand suspension in this reach is demonstrated, so it is quite reasonable to expect an increase in transport along the bed here. In comparison, 1.14 x 10^6m^3 or (on the same density assumption) 0.71 x 10^6 tonnes of sand were dredged from this reach in 1985 to maintain the navigation channel.

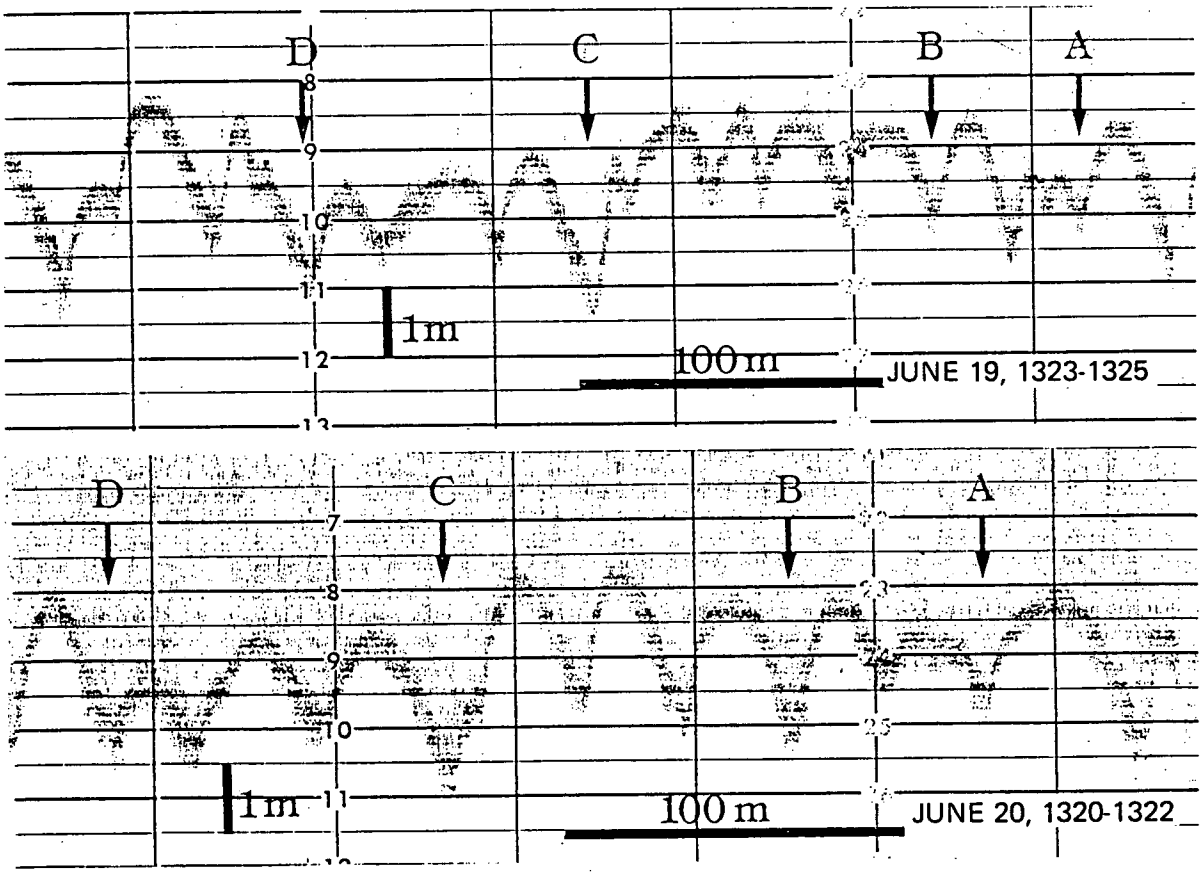


Figure 35. Sand waves in outer Main Arm: June 19-20, 1985: marked points indicate corresponding features on successive days.

The sand budget of the estuarine reach may be described by:

$$I - D + \Delta S = \emptyset$$

where I = incoming sand load
D = mass of dredged material
ΔS = change in channel storage
$\emptyset$ = outgoing sand load

There have been difficulties in determining a reasonable balance. The station with long term sediment loads is at Mission which is 50 km upstream from New Westminster, although there appears to be a reasonable correlation between Mission and Port Mann transport. The sand fraction of the load must also be determined and, as we have described, that is at present largely a matter of interpolation. Dredging records are available from Public Works Canada, however, an unknown quantity of dredgate is dumped into deep self-scouring sections of the river. The change in storage can be determined from Public Works sounding charts (cf. Kostaschuk and Luternauer, 1987). The sand load transported into the Strait of Georgia has not been systematically monitored, whence the importance of observations like those described above.

In this circumstance, it is interesting to leave the last words to some of the pioneer investigators who have attempted to compare Fraser River sediment yield with the volume of sediments deposited offshore. Johnston (1921) arrived at an estimate of 26 ft yr^{-1} (7.9 m yr^{-1}) for the rate of advance of the delta on the basis of a comparison of soundings from 1859 and 1919 whence he deduced that the delta must be about 8000 years old, on the assumption of a constant, linear growth rate. Mathews and Shepard (1962) arrived at 28 ft yr^{-1} (8.5 m yr^{-1}) off the main channel on the basis of 1929 and 1959 detailed charts. Although they noted some errors in Johnston's assumptions, these were largely offsetting, and they concurred with his estimate of the age (Radiocarbon evidence has proved Johnston, remarkably, correct.) They went on to estimate that the apparent growth rate would require about 23 x 10^6

tonnes of sediment input per year. The result is larger than the observed yield at Mission by some 20%, but of the appropriate magnitude. Finally, Lutermauer and Murray (1973), following a much more detailed comparison of hydrographic survey lines over a 3-freshet period came to essentially similar conclusions.

The wash load of the river is widely distributed into the Strait, so its size would be hard to determine with any precision from sedimentary evidence. However, we know its size upstream rather well and we know that nearly all of it reaches the sea (there is some loss to sloughs, channel sides, and tidal flats). The size of the morphologically important sand load remains uncertain. However, it is deposited in a relatively restricted area off the mouth of Main Arm and to the south, as demonstrated in grab samples and cores. Hence, it may very well prove possible to estimate the sand accumulation for fixed periods. Along with other methods, this possibility for measurement ought to be pursued.

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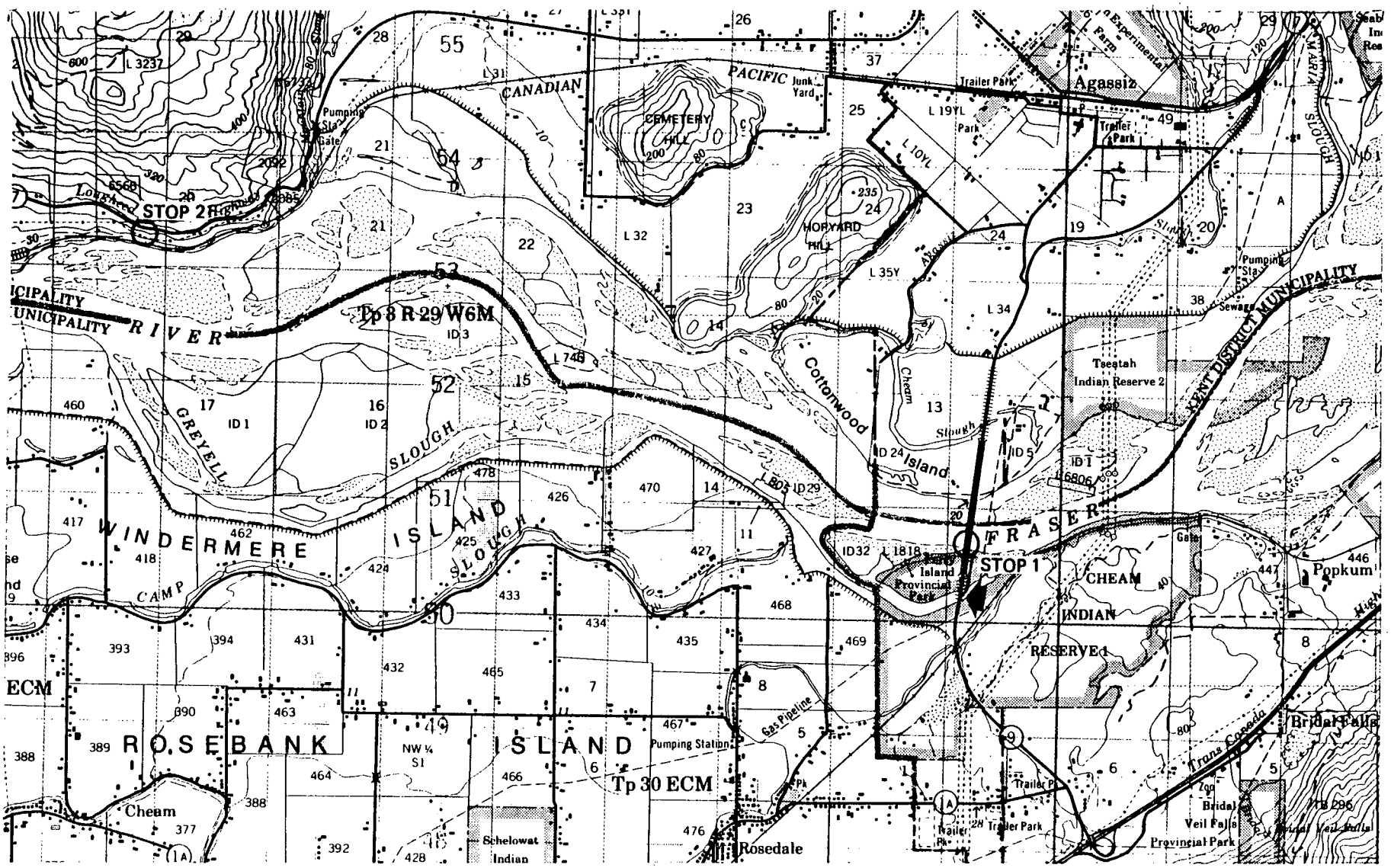
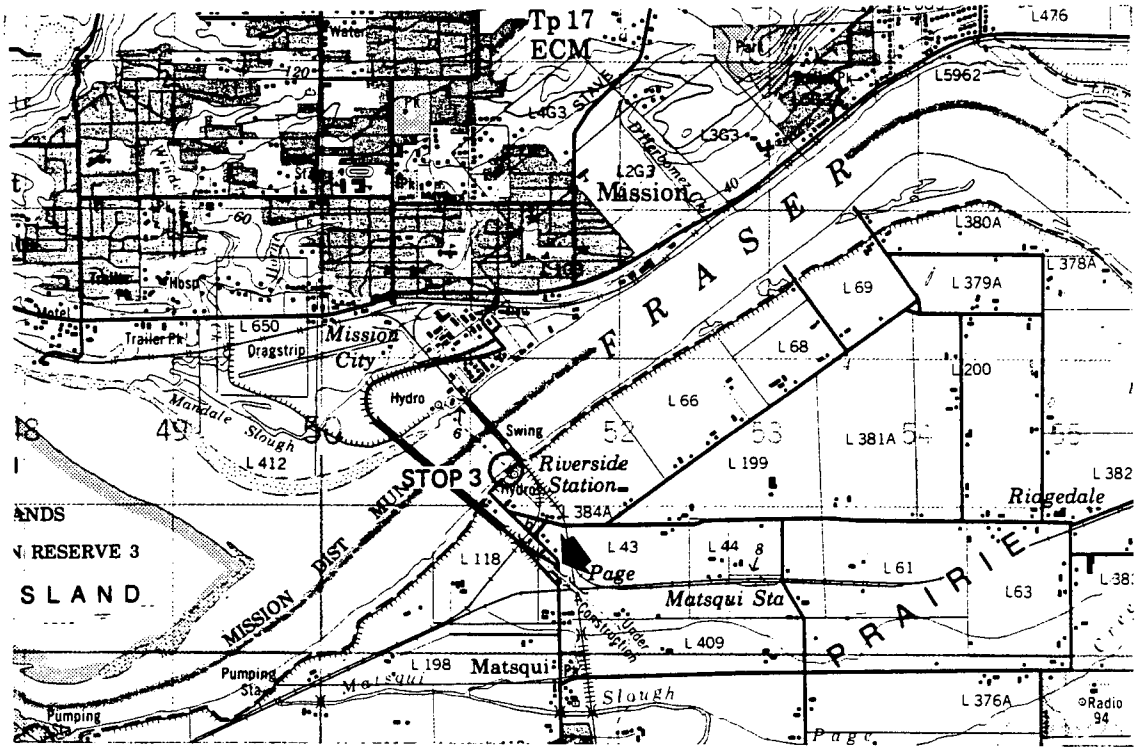
APPENDIX

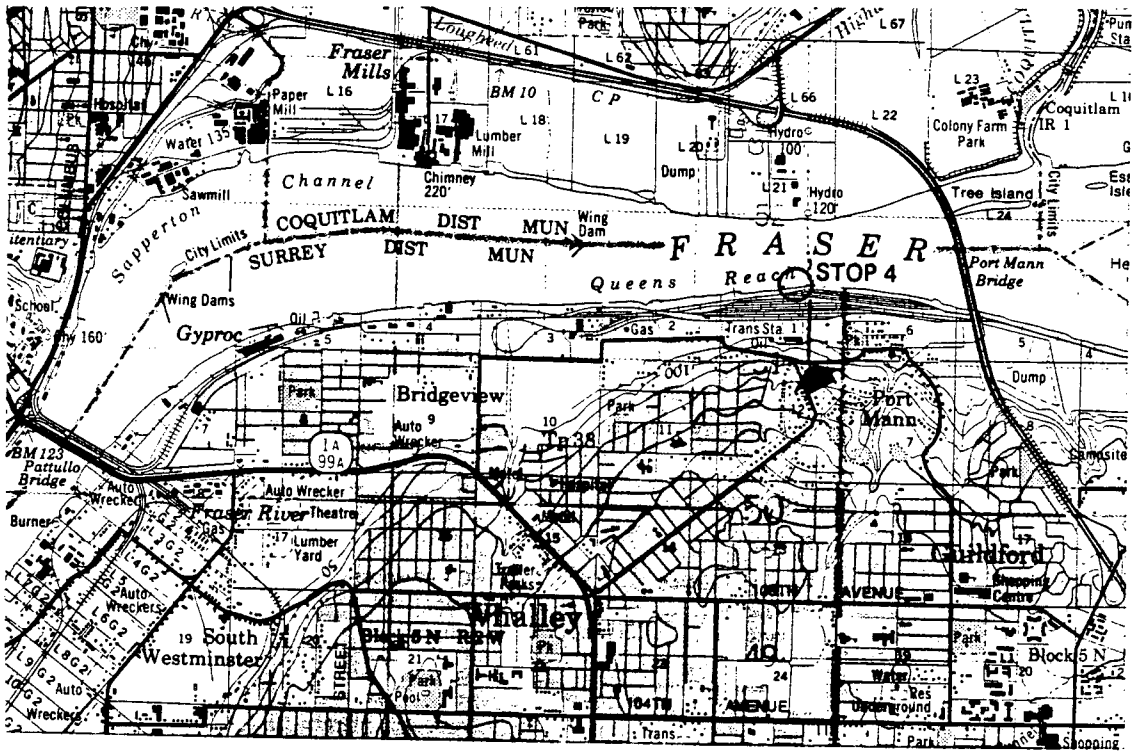
FIELD ACCESS MAPS



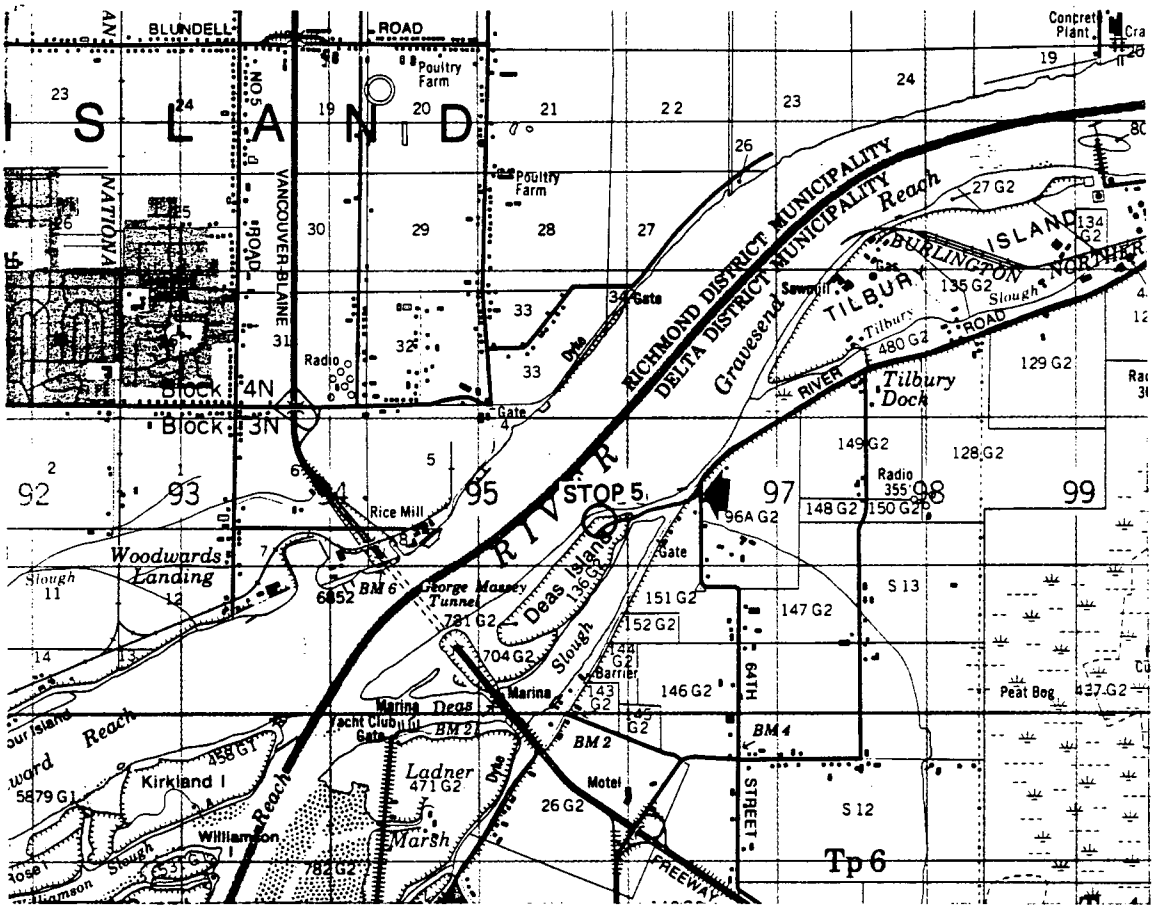
STOPS 1 and 2. Access to Stop 1, by the Rosedale Bridge in Ferry Island Provincial Park, is by a right turn of Highway 9 when travelling north, immediately before the bridge. When travelling south, the turn is nearly 180^0. Stop 2 is a roadside picnic stop and lookout on Highway 7. Vision is very restricted for the left turn off the highway when travelling west.



STOP 3. Access is from the Matsqui village main road, by a right exit from Highway 11 when travelling north. Take the first off-ramp after the bridge when travelling south. The lookout is at a parking place on the dike immediately before the railway.



STOP 4. From Highway 1A/99A descend Roebuck Avenue or Grosvenor and McBride Avenues to 116 Avenue. Access to the site is across the CN Railway yard, which is not a public right-of-way. An alternate viewpoint is at a public launching ramp on the north side of the river.



STOP 5. Enter Deas Island Regional Park from River Road. Park at the first picnic area and walk to the river bank.