CHANNEL STABILITY AND MANAGEMENT OF LOWER FRASER RIVER
FIELD EXCURSION GUIDE

Michael Church[1], David G. McLean[2],
Ray Kostaschuk[3], Steve Macfarlane[4],
Bruno Tassone[5], and Doug Walton[6]

1. Department of Geography, The University of British Columbia
2. Northwest Hydraulic Consultants, Ltd., North Vancouver
3. Department of Geography, The University of Guelph
4. Habitat Management Unit, Canada Department of Fisheries and Oceans, New Westminster
5. Water Resources Branch, Environment Canada, Pacific and Yukon Region, Vancouver
6. Waste Management Branch, British Columbia Ministry of Environment, Surrey

Water Survey of Canada, Water Resources Branch,
Inland Waters Directorate, Environment Canada
Vancouver, Canada

Fraser River Project
The University of British Columbia
Department of Geography

Part of this report summarizes a study of processes governing channel stability and sedimentation in the lower Fraser River, funded by Supply and Services Canada Contract No. 1 ST 83-00170 supervised by the Sediment Survey Section, Water Survey of Canada, Water Resources Branch, Environment Canada; and by the Natural Sciences and Engineering Research Council of Canada, Operating Grant A7950 (to M. Church).

Table of Contents

List of tables

List of figures

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, the western flanks of the Cariboo Mountains and part of the Rocky Mountains (figure 1). Thus the basin includes roughly one-quarter of the province, and nearly all of its landscapes. The main stem rises at Mount Robson in the Rocky Mountains, 1100 km from the sea. Since 1952, a drainage diversion has been operated from the upper Nechako basin for hydroelectric power generation at Kemano, on the central coast. Since then, the effective drainage area of the river has been 232 000 km^2 at Port Mann.

Between Lillooet and Yale, the river passes between the Coast Mountains and Cascade Mountains in the Fraser Canyon. It 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. Upstream, long-term gauges are located at Hansard (WSC Stn. 08KA004)and at Marguerite (WSC Stn. 08MC018).

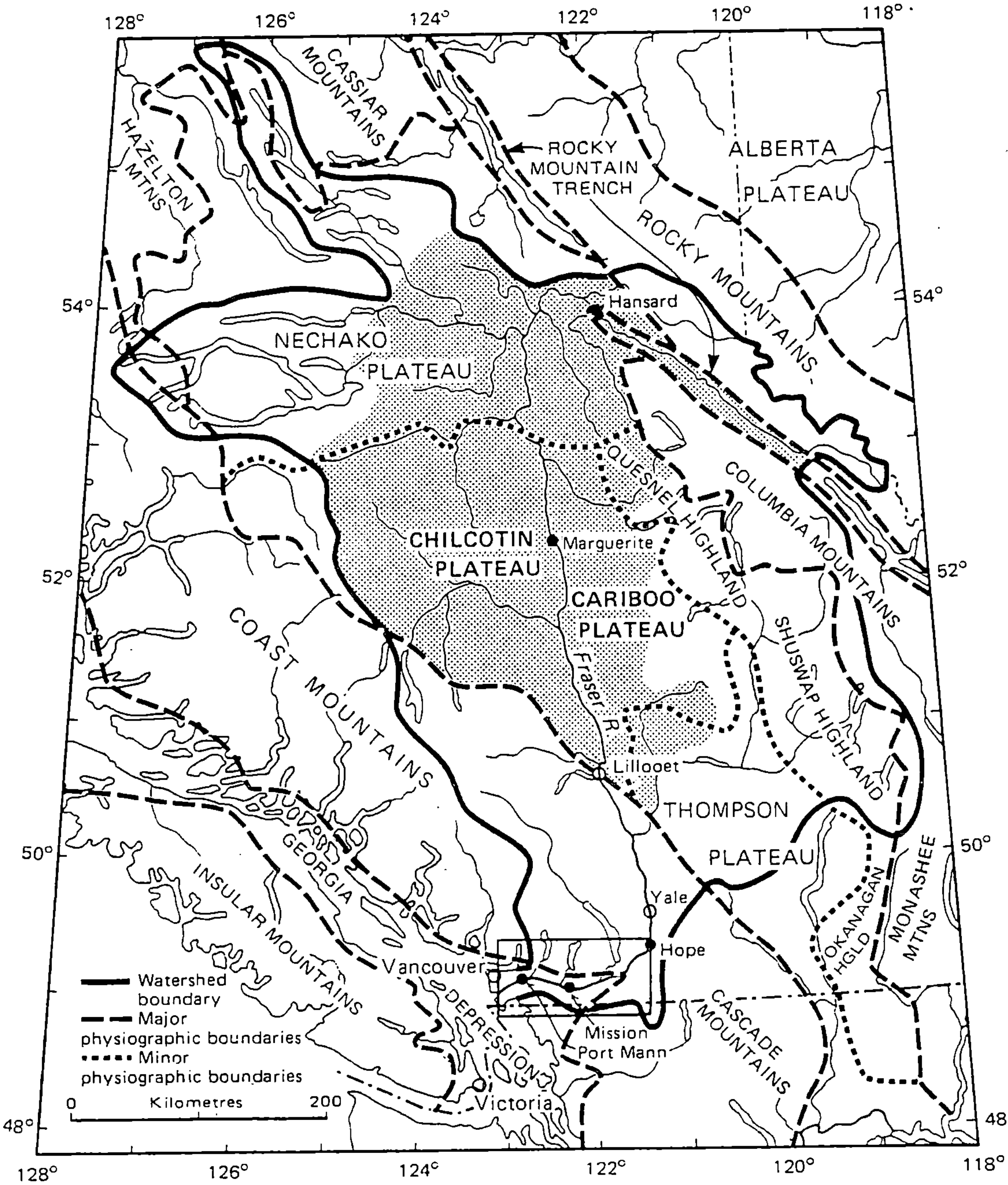
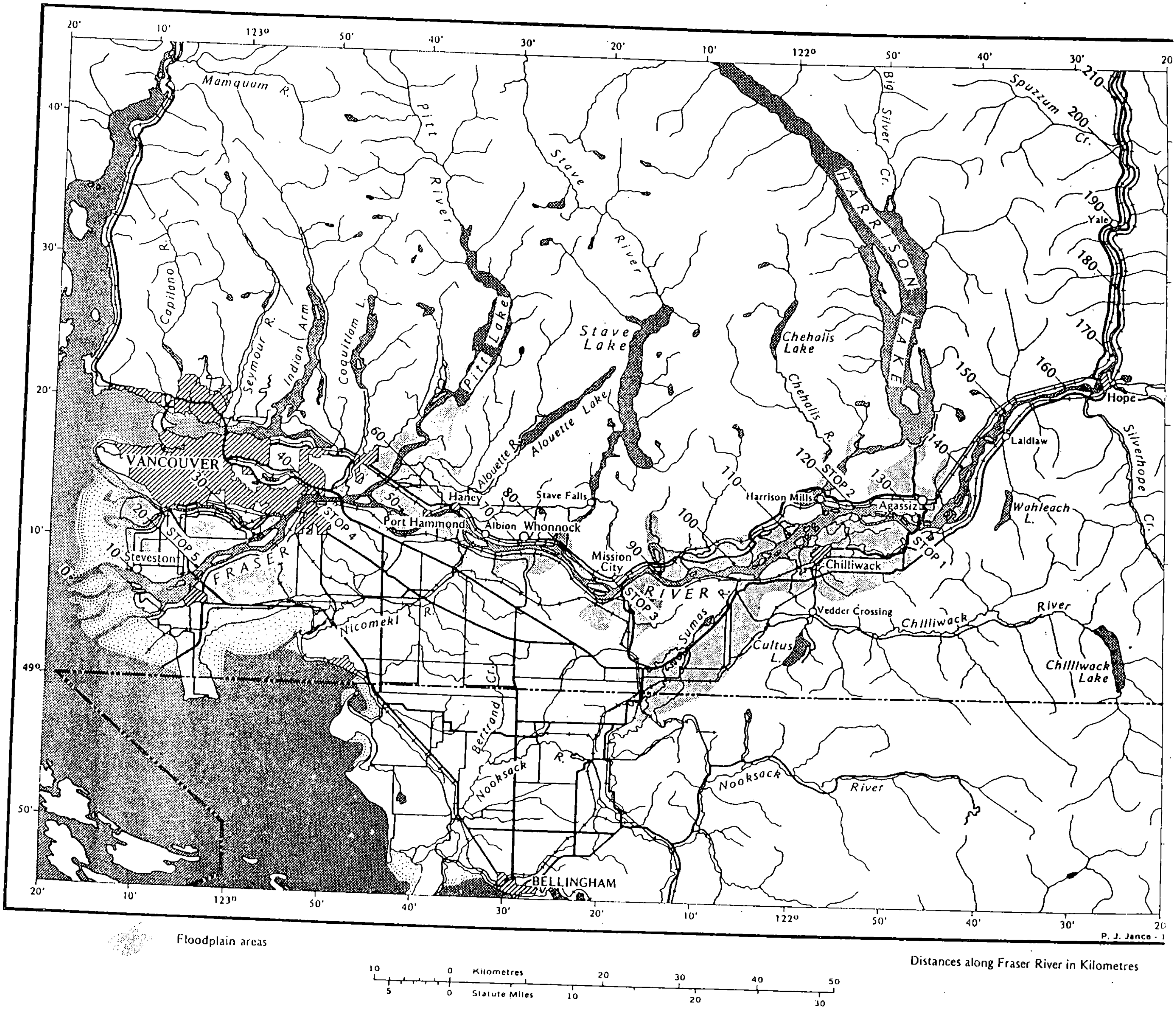


Figure 1. Fraser River drainage basin, emphasizing the area in the interior plateaux which is the source region of most of the sediment load of the lower river. The study reach lies within the box west of Hope.



Distances along Fraser River in Kilometres

Fi

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	1912-49 MC	1965	MS	1965	1965			REG 52
			121 27 05	1950-86 RC	1966-69	MC	1967-68	1966-69			
					1970-79	MC	1970-78	1970-79			
08MF035	AGASSIZ	217870	49 12 16	1949-50 MS*	1966	MS		1966			REG 52
			121 46 35	1951-55 RC*	1967-69	MC	1968	1967-69			
				1956-64 MC*	1970-72	MC	1970-72	1970-72	1970		
				1965 RC*	1973-79	MC	1973-79	1973-78	1973-79	1978-79	
				1966 RS	1980-86	MC	1981-86	1980-86	1980-86	1985	
				1967- RC							
08MH024	MISSION	228000	49 07 39	1876-1935 MS*	1965	MS	1965	1965		1965	REG 52
			122 18 08	1936-64 RC*	1966-71	MC	1966-68	1966-71		1966-71	
					1972-80	MC	1972-79	1972-80	1973-80	1972-80	
				1965- RC	1981-87	MC	1981-	1981-	1981-	1982,1985	
08MH054	PORT MANN	232000	49 13 03	1956-71 RC*	1965	MS	1967-68	1965			
			122 50 20		1966-72	MC	1970-78	1966-78	1973-78	1965-78	REG 52
								1984-85			
								1987			

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

1.2. Channel morphology in the Lower Mainland

From Yale, where it emerges from its rock canyon, until it reaches Laidlaw the river flows in an irregular single channel and is nearly continuously confined between terraces composed of Pleistocene deposits and landslide material. 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 consists 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% sand. The reach has experienced irregular channel shifting with bank erosion volumes of roughly 750 000 m^3yr^{-1} to 1 000 000 m^3yr^{-1} over the last century (McLean and Mannerstrom, 1984). The Agassiz gauge is located within this reach.

Near km 90, upstream from Mission, the channel pattern changes abruptly to a single thread, sand bed channel. Echo sounding profiles near Mission gauge indicate that dunes are found on the river bed when flows exceed about 4000 m^3s^{-1}. 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 one 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 effects of the tides in the Strait of Georgia propagate 100 km upstream to Sumas during low discharges (850 m^3s^{-1}) and as far as Mission during high discharges (9000 m^3s^{-1}) (Ages and Woolard 1976). A salt wedge is found in the main channel nearly to New Westminster in winter when the discharge is low and tidal range is large. In June, during the freshet, the salt wedge is pushed out to Sand Heads.

The distal margin of the delta supports 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.

1.3. Hydrology

Most of the Fraser drainage basin is alpine or plateau country, with elevations near or above 1000 m. Hence, melt in spring of the annual winter snow accumulation forms the dominant hydrological event. The basin is too large for most individual storm events to have a notable effect on runoff. Figure 3 illustrates the annual snowmelt freshet, with the river regularly rising in early April and peaking near the first of June. Some tributaries near the coast, such as Sumas and Coquitlam Rivers, experience peak flows in winter in response to rainfall, whilst in the eastern Fraser Valley, tributaries such as Chilliwack and Coquihalla Rivers exhibit both winter and summer peak flows.

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, Harrison and Chilliwack Rivers contribute an additional 10 000 km^2 (about 5% of the area at Hope). These tributaries typically increase the mean flow by about 18% and freshet flows by 10 to 15%. Figure 4 shows that the long term pattern of runoff has not remained stationary over the last century. Between 1957 and 1977 the runoff was persistently higher than the long term average. In so large a basin, land use effects are unlikely to have seriously affected runoff, so it is assumed that the changes reflect fluctuations of climate.

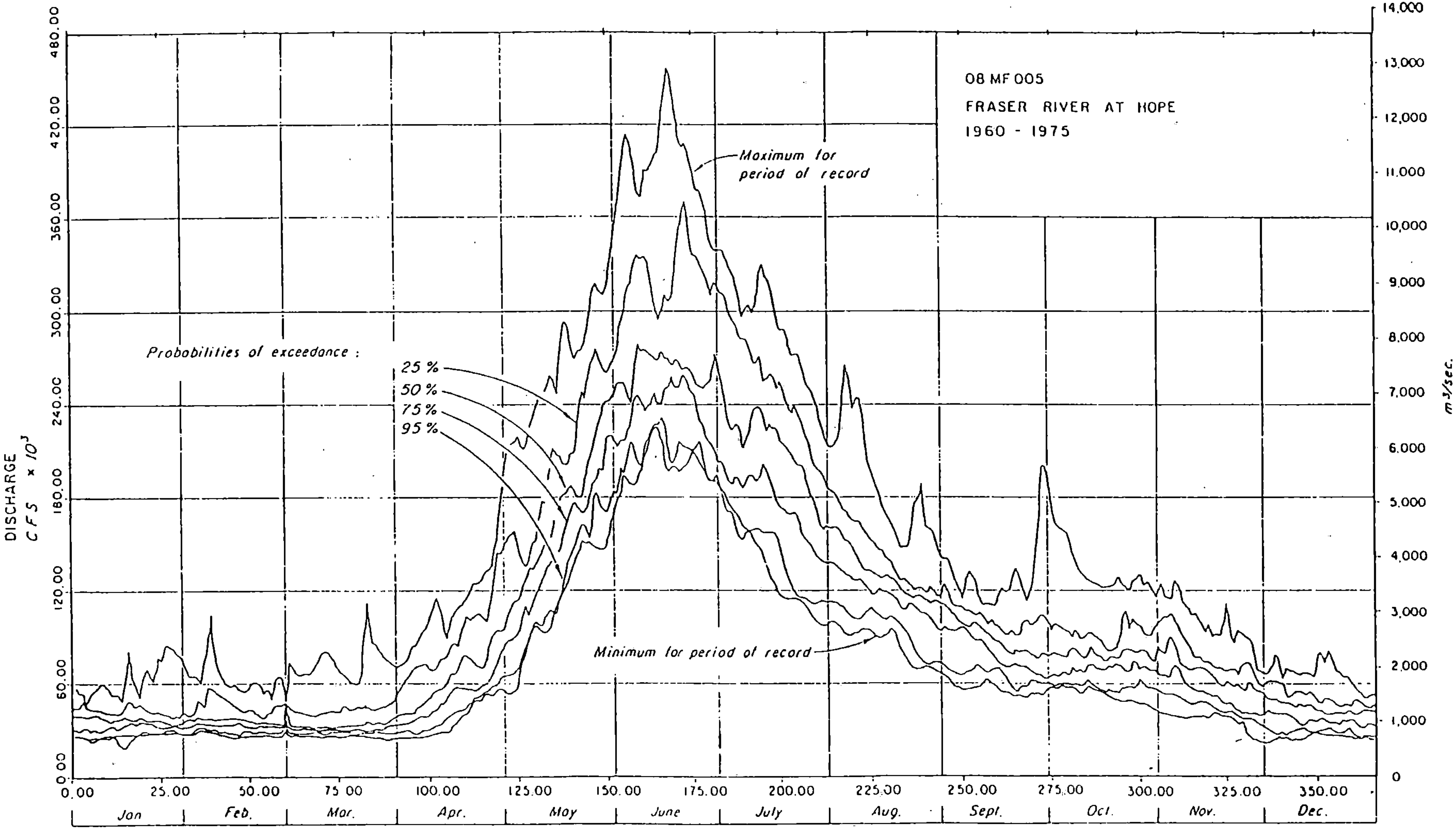


Figure 3. Exceedance probability hydrographs at Hope.

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	Subsurface mm
HOPE	08MF005	MDF	527[3]							
		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	08MF035	MDF	470[3]							
		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	082H024	MDF	648							
		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.

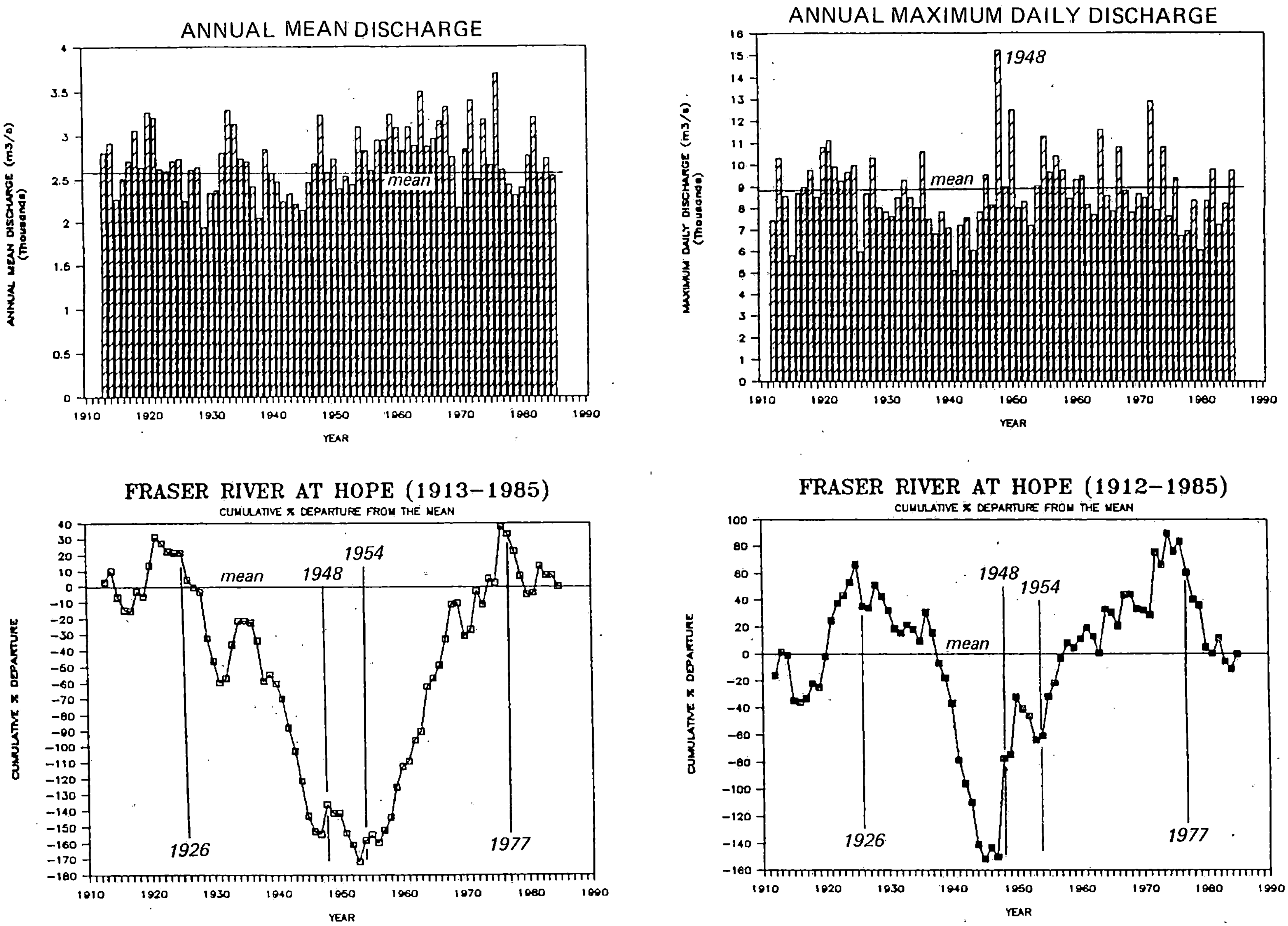


Figure 4. Analysis of long term flow variations: Fraser River at Hope (08MF005) for the period 1913-1985. Major points of change in the record are indicated by vertical lines in the cumulative departures plots.

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 major rivers today have incised into these sediments, which continue to supply the main sediment load directly from the river banks. Consequently, specific sediment yield increases downstream in the Fraser system until the drainage area is over 30 000 km^2 (figure 5). Large lakes on several major tributaries in the central part of the basin reinforce this trend. The area highlighted in figure 1 shows the main sediment source region, but the sources are largely restricted to the main channel banks.

In such a large and thinly populated basin, land use is unlikely to have affected overall sediment yield significantly. It is likely, then, 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 should follow a pattern similar to that for flows.

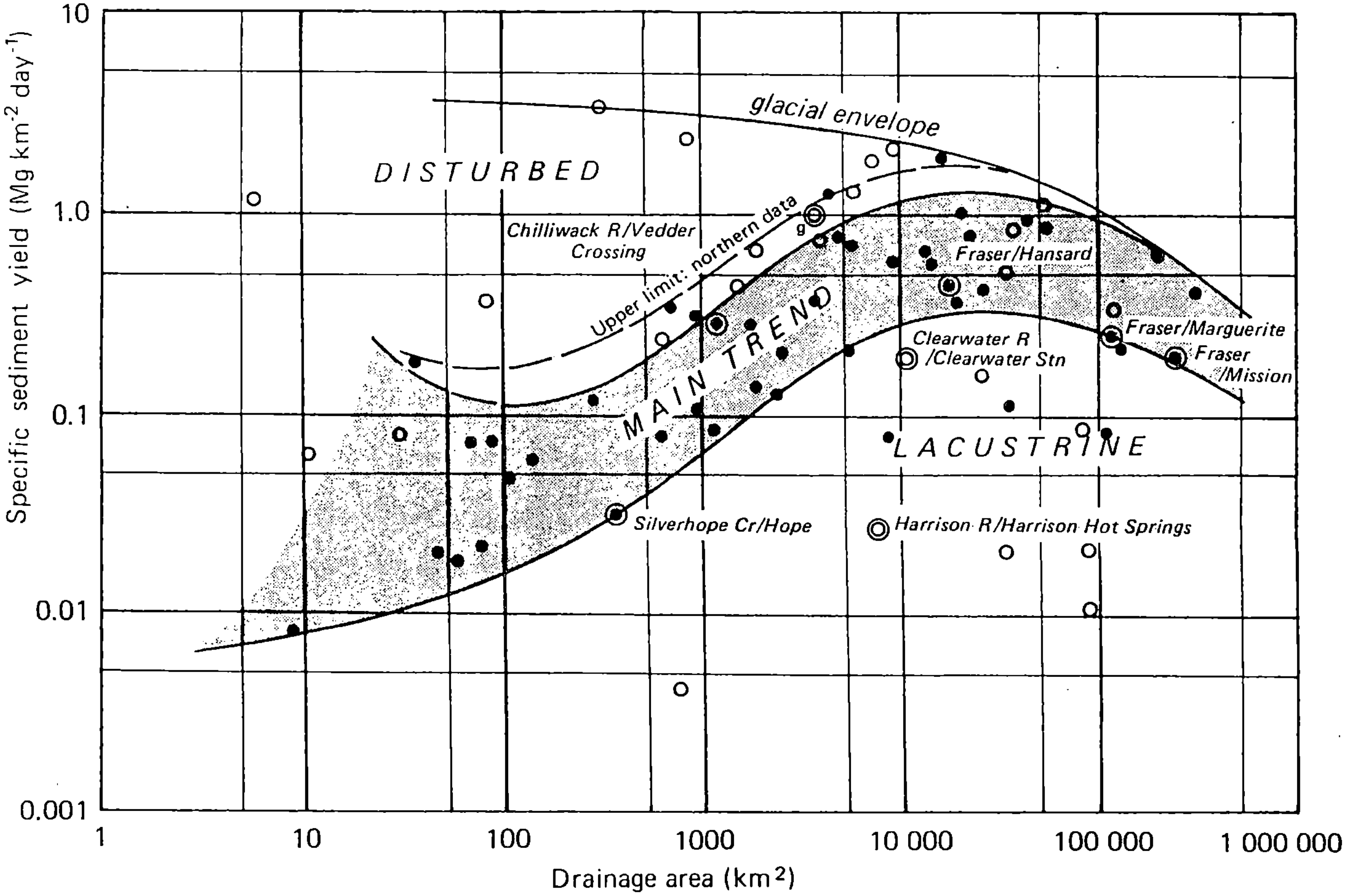


Figure 5. Downstream pattern of sediment yield in British Columbia rivers from WSC observations. Fraser basin stations specially marked: ◉

1.5. Water quality in Fraser River.

Land surface conditions and human activities throughout the basin influence Fraser River water quality. The river carries 12 million tonnes per year of silt and clay sized sediment, and many other water quality parameters -- notably metals -- vary directly with the fine sediment concentration. Since the sediment load varies seasonally with the flow, climate in the drainage basin and the resulting runoff and sediment yield patterns must be considered in order to explain water quality.

Sources of contaminants to Fraser River resulting from human activity include those industrial and municipal discharges authorized by permits administered by the British Columbia Ministry of Environment Waste Management Branch, stormwater, combined sewer overflows, chemical spills, and runoff from agricultural land. A federal-provincial water quality monitoring programme was initiated in 1985 to assess ambient water quality in British Columbia waters. Monitoring stations on Fraser River are located at Hansard, Marguerite and Hope. Records from these stations confirm the correlation of metal levels with fine clastic sediment concentration.

Although at least 60% of the province's population resides in the Greater Vancouver region, several centres upstream from Hope contribute industrial and municipal discharges. Attention has been focused on discharges from pulp mills located at Prince George, Quesnel and Kamloops. Emissions from these mills require treatment to meet emission requirements stipulated in their permits. Each permit requires a monitoring programme to ensure compliance. There are also stormwater and sewage treatment plant discharges from the upstream population centres. Studies on stormwater have shown the range and quantity of contaminants to be highly variable, with elevated levels of coliform bacteria, metals and organics often present (Swain, 1983; Lawson et al., 1985). Sewage treatment plants typically provide secondary or tertiary treatment. There are several mineral deposits in the basin and mining operations for copper, silver, molybdenum, gold, nickel, and other metals.

Within the Lower Mainland, the river can be divided into two reaches for water quality purposes. Between Hope and Kanaka Creek (river km 62, near Haney), the land use is largely agricultural and runoff is the major source of contaminants associated with farming. There are a few discharges (mainly cooling water) from food processing industries. Most food processers and slaughterhouses, however, spray irrigate or discharge to ground disposal systems or sanitary sewers. Separated sewage collection networks in Hope, Kent, Chilliwack, Abbotsford and Langley provide secondary treatment.

Water quality criteria have been established by the provincial Ministry of Environment for the province. These, along with other information, have been used to derive water quality objectives for the river and tributaries downstream from Hope. Water quality monitoring indicates that the objectives are generally met.

The Fraser River downstream from Kanaka Creek is the most heavily urbanized and industrialized major water body in British Columbia. At the same time, it is important for salmon migration and rearing. Considerations of water quality here are further complicated by tides and by the intrusion of the salt wedge. As a result, the estuary has undergone considerable study. Although a variety of discharges enter the river, the impact -- as measured by exceedances of water quality objectives and contaminant accumulation trends -- does not appear to be very great. This topic will be taken up at stops 4 and 5. Though arguably dilution is not "a solution to pollution", the diluting capacity of Fraser River provides a measure of protection. Efforts are currently underway to further reduce the load of contaminants in Fraser River.

1.6. Salmon utilization of the Lower Fraser River

Fraser River, with an average annual abundance of nearly 14 million Pacific salmon (Oncorhynchus), produces more salmon than any other river system in the world. In recent years, the Fraser has provided, on average, $260 million in economic value from the combined commercial, recreational and Indian food catch. It is home year round to salmon in either their adult or juvenile stages. In addition, the basin supports many other important fish species.

In a major review of Fraser River salmonines, Northcote and Larkin (1989) give reasons for the significance of this river. The geography of the basin is important. The river is navigable by salmon for 1200 km inland, providing access to diverse spawning and rearing habitats. Access to the large lakes in the upper and middle reaches of the system is of critical importance for the large Sockeye salmon population. The nival regime of the river provides a long summer freshet, attenuated in some sub-basins by the lakes, to facilitate migration by both adult and juvenile salmon. The lakes also attenuate turbidity by acting as sediment traps, so the overall moderate turbidity is thought to reduce predation on the fish without substantially hindering them. The estuary is important for rearing of several species. Rapid growth here may substantially increase subsequent survival at sea.

Water quality is very high and most waters have moderate nutrient status. This is the consequence of the nival source of large volumes of water, low rates of chemical weathering of rocks and soils, and sparse settlement. Many sub-basins drain volcanic and sedimentary rocks, the soils of which provide good buffering against acidification. However, some smaller sub-basins in the Coast Mountains and Shuswap Highlands are not well buffered.

Apart from the high diversity of fish species, populations are divided into genetically discrete stocks which utilize different portions of the basin at different, highly predictable times of year (cf figure 6). Thus, populations are highly adapted to take best advantage of the varied habitats of the basin and maximize their overall reproductive success.

Consequently, salmon are inseparably associated with this river. They have always been a staple food of the Indians, and they have supported a commercial fishery for a century and a half. The first salted salmon was exported from Fort Langley by the Hudson's Bay Company in 1830, and the first commercial cannery in British Columbia began operation on the river in 1870. By the early 1960s it was obvious that the fishery was overexploited and intensive management has since been applied with the goal of reestablishing optimum stocks. What constitutes optimum stocks today is closely tied to the extent and quality of habitat. Hence the salmon fishery depends critically upon the physial environment of the river and is affected by human activities along the river.

For purposes of discussing fish habitat, the river can be divided conveniently into three reaches: (i) Hope to Sumas, the gravel bed reach; (ii) Sumas to Kanaka Creek, the sand bed reach; and (iii) Kanaka Creek to the Outer Banks, the tidal reach. Chum and pink salmon spawn in the gravel reach upstream of Sumas. Details of the riverine habitat and its management are discussed at field stops in each of these reaches (Section 3).

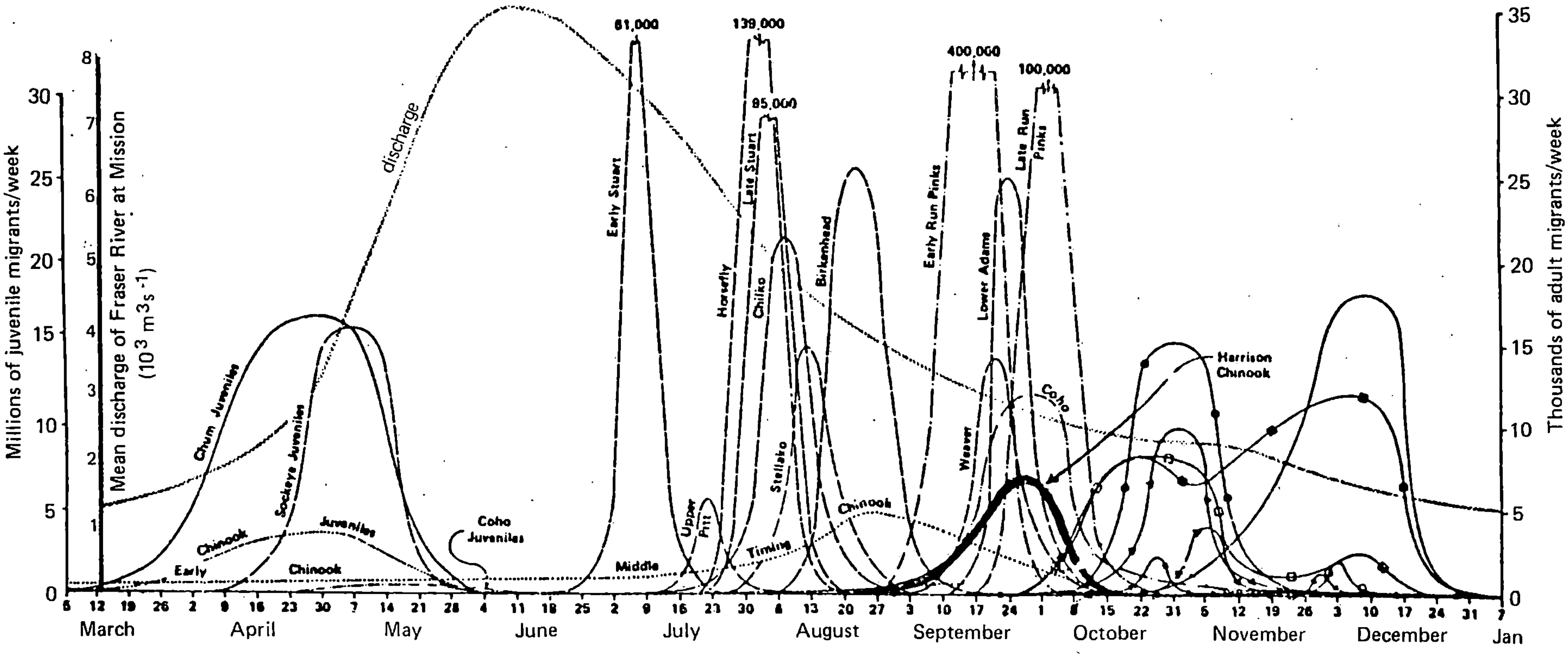


Figure 6. Approximate migration timing of salmon in the lower Fraser River, 1901-1981 cycle

2.THE SEDIMENT BUDGET OF THE LOWER FRASER RIVER

2.1. Division of the load.

To understand alluvial river channel processes, or for effective management of the channel, it is necessary to consider the sediment 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. The movement of bed material determines channel stability, whereas wash load is critically related to water quality.

The methods available for measuring sediment transport do not conform with this division of the sediment load (figure 7). 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, the sand fraction of bed material may move in either mode. Hence, in order to establish the sediment budget in a manner that is relevant for understanding river stability problems, the sand load moving in suspension must be divided into bed material and wash material.

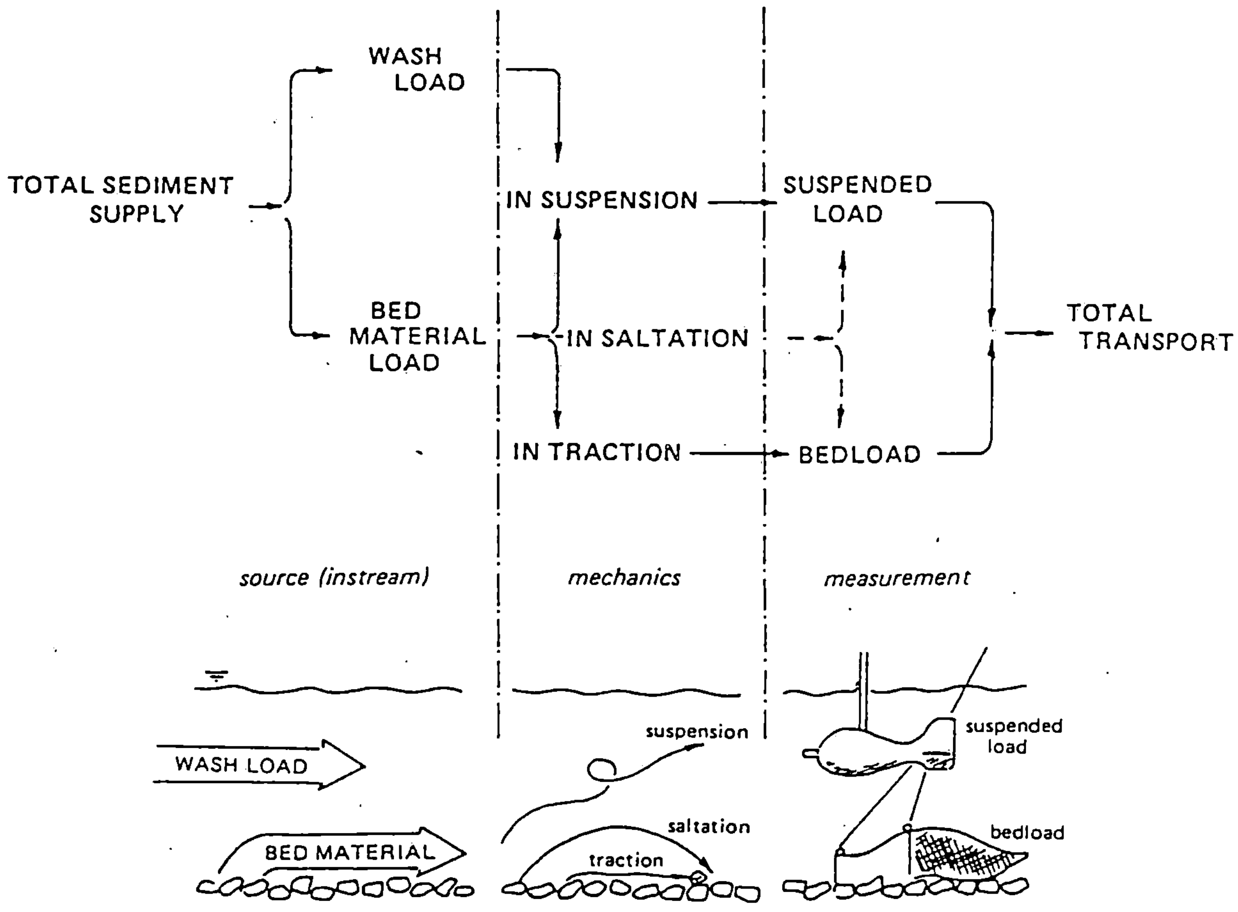


Figure 7. Classification of clastic sediment transported in rivers

2.2. Suspended Load Measurement and Analysis

The first sediment transport measurements on 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, under the direction of W. Stichling. 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 an overview of the programme was prepared by Kellerhals (1984). However, for the most part, the data have heretofore been subject to little systematic analysis.

The daily suspended loads reported at Hope, Agassiz and Mission are based on typically 150 to 220 depth-integrated concentration measurements at a single vertical each year, 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 are 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 suspended sediment concentration in the river. Using these samples, the ratio between the average concentration and the single vertical sample can be estimated. This ratio is used to convert the measured single-vertical samples to estimated cross section averages (see McLean and Church, 1986, for analysis of the concentration ratios).

Particle size analysis is carried out on the multiple vertical samples when the amount of suspended sediment is sufficient for laboratory analysis. Typically this means that particle size analysis is available for flows greater than 2000 m^3s^{-1} at Hope or Agassiz and 3000 m^3s^{-1} at Mission.

Total sediment transport is estimated by simple summation of daily results. The daily and monthly sediment loads display a characteristic seasonal hysteresis as illustrated in Figure 8. Sediment load is substantially higher on the rising limb than on the falling limb, indicating that the sediment supply becomes exhausted during the freshet. The 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. Hysteresis greatly complicates the prediction of daily sediment load.

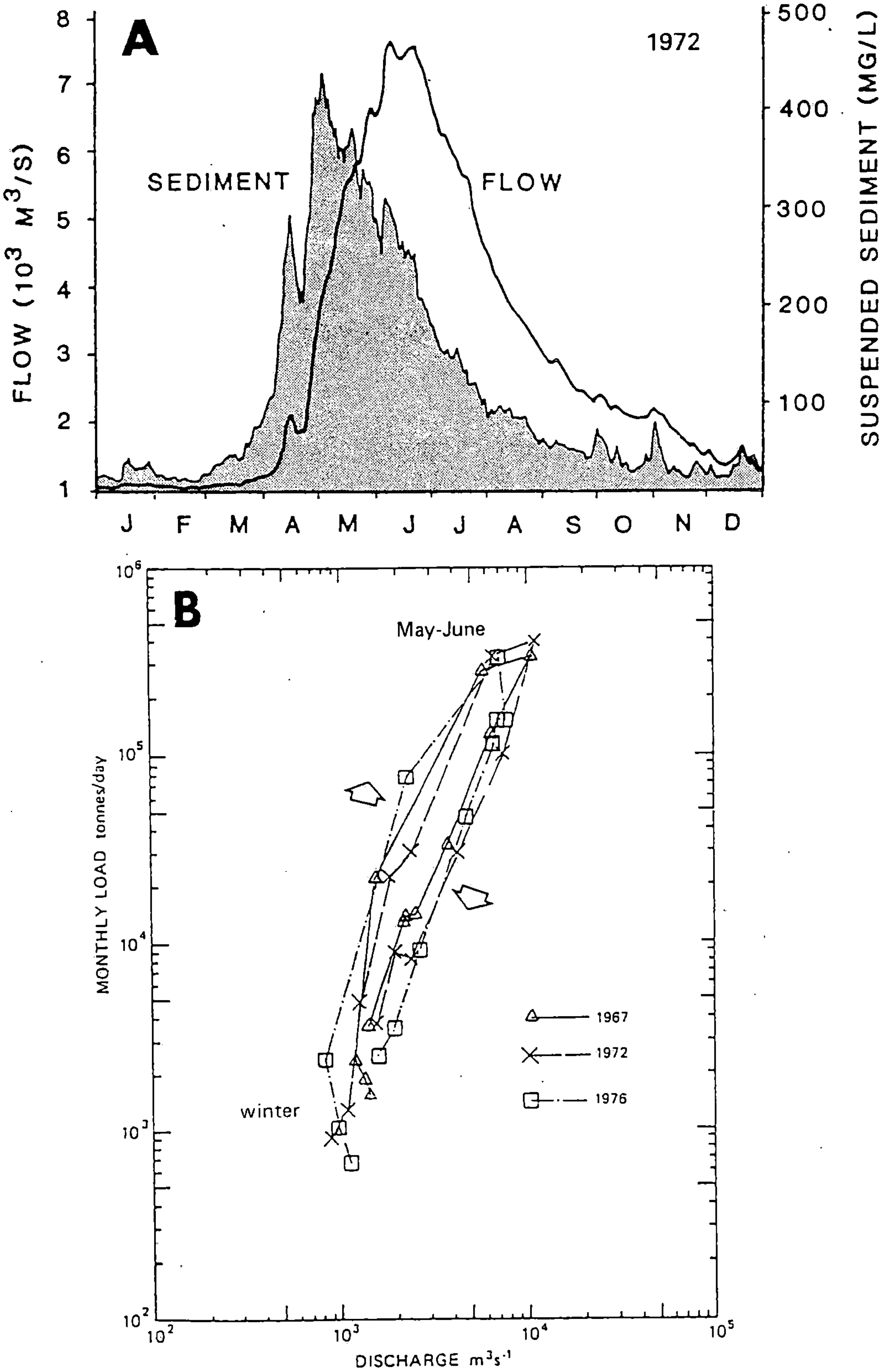


Figure 8. Hysteresis of sediment transport in lower Fraser River.
(a) annual flow and sediment hydrographs at Agassiz, 1972;
(b) rating based on monthly data at Agassiz for several years.

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, above about 7500 m^3s^{-1}, a basket sampler with a screen mesh size of 6 mm (Stichling, 1969). Due to the coarse mesh, finer gravel and sand are not retained in the sampler. The measurements were collected at six or fewer verticals from a boat on the gauging section line. Typically only two or three repeat 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.

Bedload measurements at Mission were made with a BTMA Arnhem sampler (de Vries, 1973), designed for measuring 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.

The efficiencies of the bedload samplers were estimated from laboratory calibrations. Corrections of sample weights to estimate the true bedload transport typically were in the range 3.0 (VuV sampler) to 4.4 (Arnhem sampler) (see McLean and Church, 1986, for a detailed discussion). A further problem that arises in assessing bedload transport rate is that, because of the sporadic nature of bedload movement, large temporal fluctuations occur in bedload passage even in steady flow. For example, from test measurements at Agassiz it was found that individual measurements could reach up to six times the overall mean transport rate, whereas nearly 70% of the samples indicated loads less than average. Accordingly, statistical methods have been used to assess the precision of the measurements (see McLean and Church, 1986; McLean and Tassone, 1987).

Because the measurements are rather sparse, actual load estimates were constructed from rating curves based on the measurements. Figure 9 shows that these are poorly defined. The estimated annual loads can be specified to within 40% with a two standard error confidence range, which is much lower than the precision of the annual suspended sediment load.

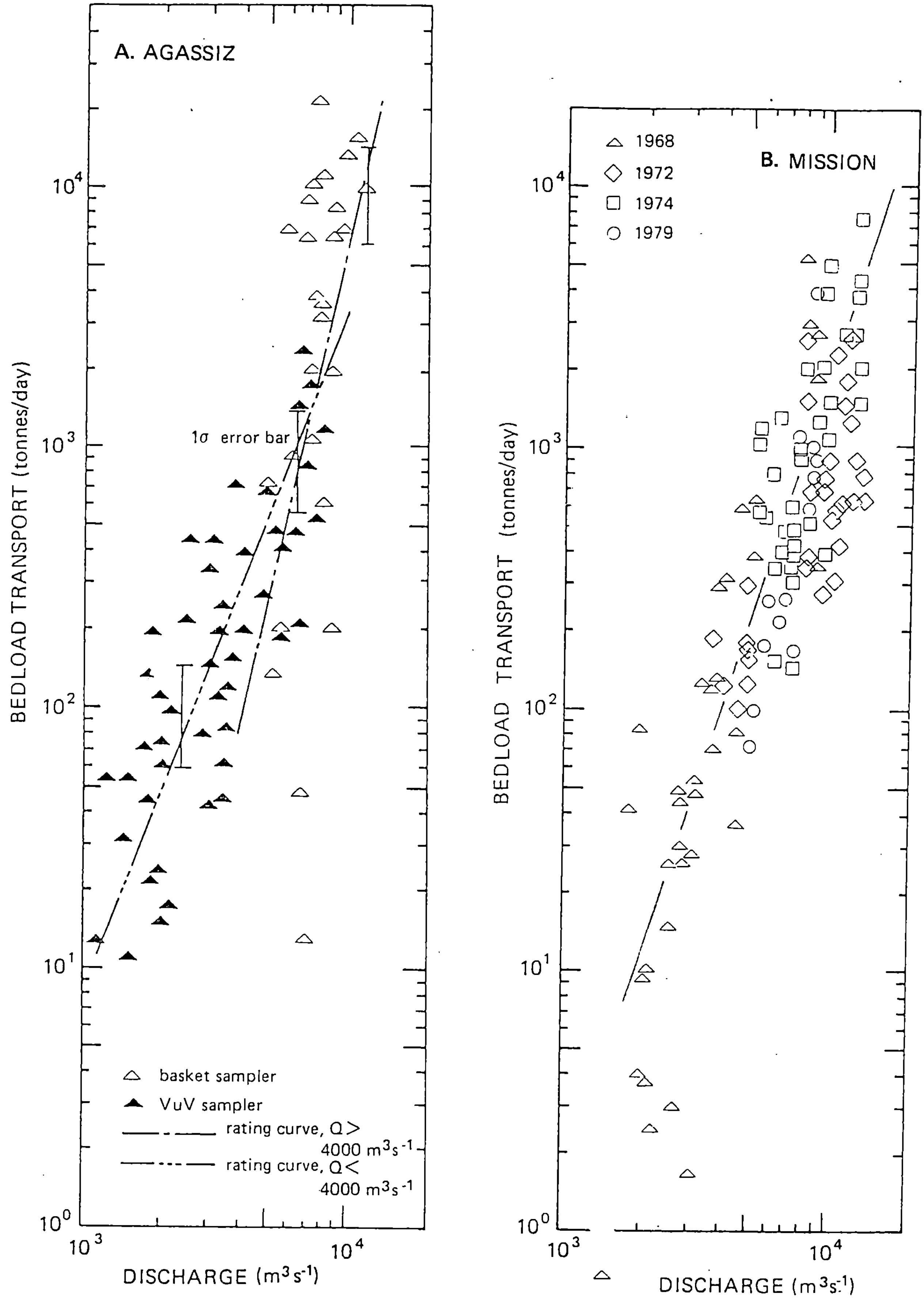


Figure 9. Bedload sediment transport rating curves: A. Agassiz(data of 1968-76), B. Mission (data of 1968-79)

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 proportion of the sand load that constitutes bed material was estimated by comparing particle size distributions of the sand in suspension and on the bed. A special study was made of the normally unsampled portion of the water column within 0.25 m of the bed, where relatively coarse sand might move in suspension (see McLean and Church, 1986). Bed material size distribution is based upon USBM54 sampler grabs.

Figure 10 presents typical comparisons between bed material and suspended sand size distributions for Mission and Port Mann. There is little difference between the two stations. 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 11) indicates that this is a reasonable approximation at Mission.

This judgement can be refined by examining the size distribution of the annual load in comparison with that of the bed materials (table 3). Whilst the +0.125 mm fraction constitutes

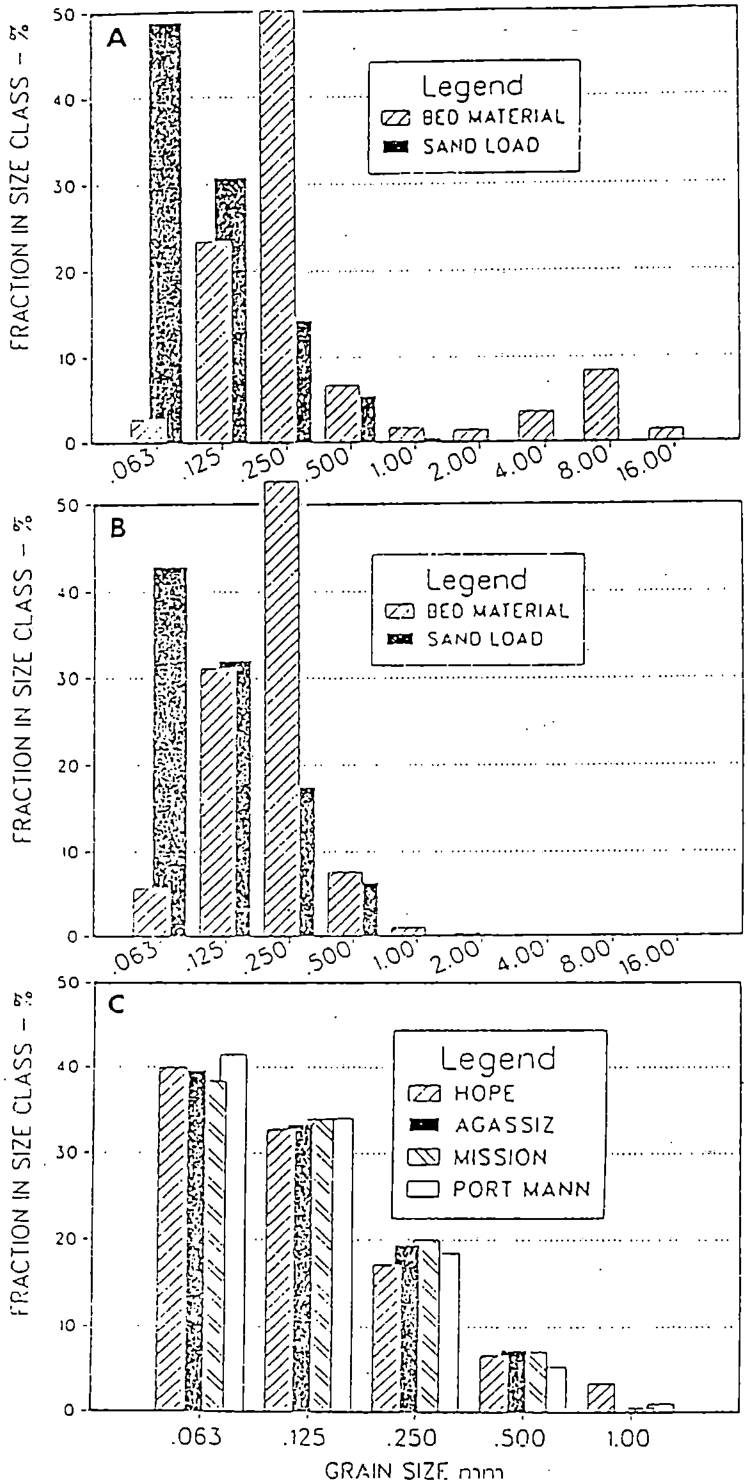


Figure 10. Comparison of bed material and suspended sand load size distributions at (a) Mission and (b) Port Mann; and (c) comparison of sand load size distributions through the four principal stations.

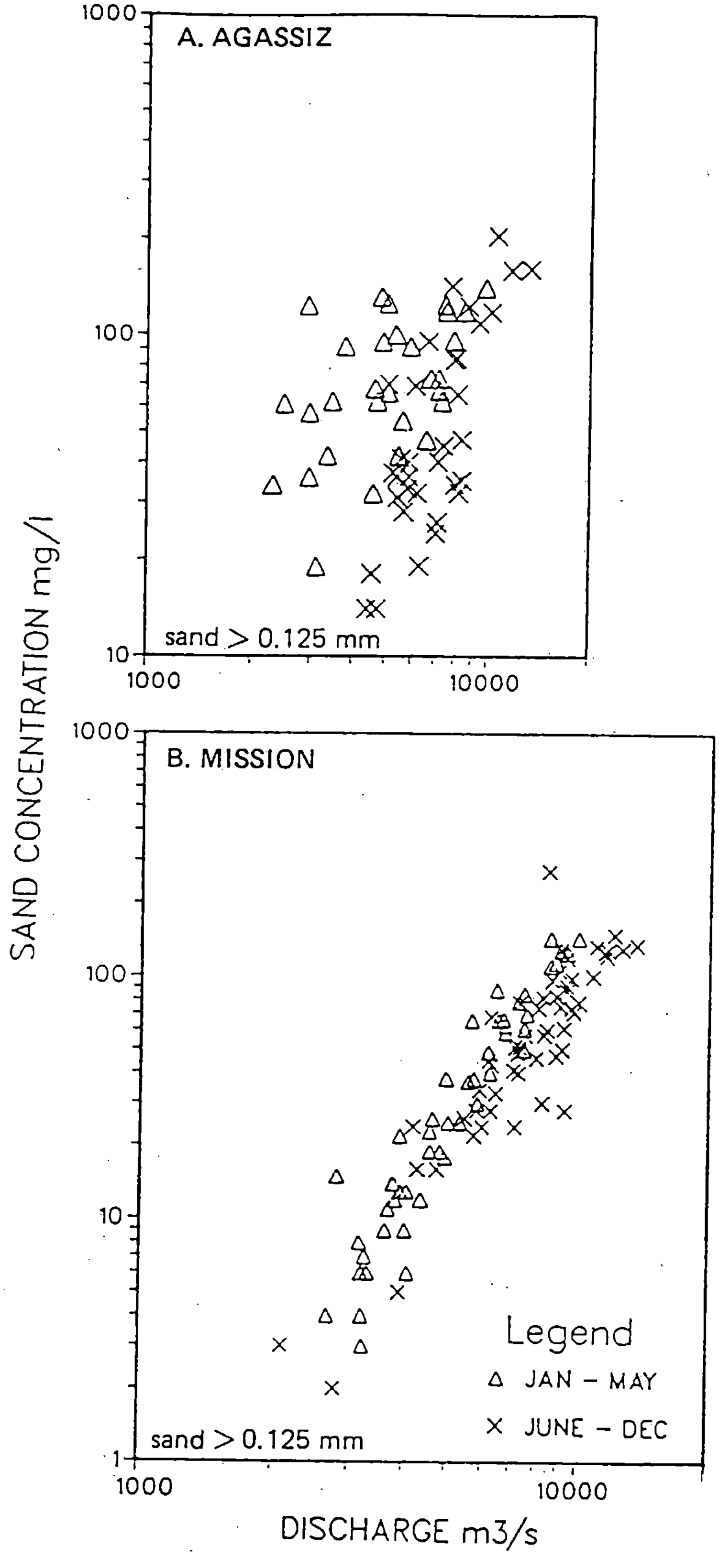


Figure 11. Correlation of sand fraction > 0.125 mm with discharge: (a) Agassiz; (b) Mission. Note the change in scale between abscissa and ordinate.

TABLE 3

COMPOSITION OF BED MATERIAL AND ANNUAL SAND LOAD > 0.125 mm

At Mission

SIZE FRACTION (mm)	SUSPENDED SAND > 0.125 mm	BED LOAD	BED MATERIAL
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.

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. The 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.

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 coarse bed material. Consequently, all fractions of the suspended sand load at Hope and Agassiz are considered to be "wash load". The poor correlation between flow and +0.125 mm sand concentration (figure 11a) confirms this conclusion.

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

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.

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. Silt and clay constitutes two-thirds of the load at Agassiz, 64% at Mission. The total is virtually the same 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 provide a good estimate of the total load of the river (though, not, of course, of the gravel transport).

3. FIELD EXCURSION

3.1. Introduction

Many of the details of the foregoing analysis were determined by the character of the river at each gauging point. 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, six 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. Issues related to the management of the river are introduced.

The locations of the stops are shown in figure 2. However, the scale of the map precludes display of details. Site maps showing road access are given in an Appendix (pp. 95ff). 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.

3.2. Agassiz gauge reach (river km 130; STOP 1)

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 uniformly across the channel (Figure 12). However, in recent years gravel bar accretion has occurred near the north side (right bank) of the channel. Aside from making measurements more difficult to collect this bar probably will induce greater variations across the section in channel velocities and sediment transport rates.

Figure 13 illustrates the size distribution of the bed material. Table 2 (page 9) summarizes hydraulic parameters of the gauge station, whilst figure 14 shows the sectional hydraulic geometry. Agassiz reach (slope = 5×10^{-4}) is an order of magnitude steeper than Mission reach (5×10^{-5}). Channel width is virtually the same, so that depth and velocity vary reciprocally between the two stations. The river at Agassiz exhibits velocities about twice as large as, and depths about one-half those at 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

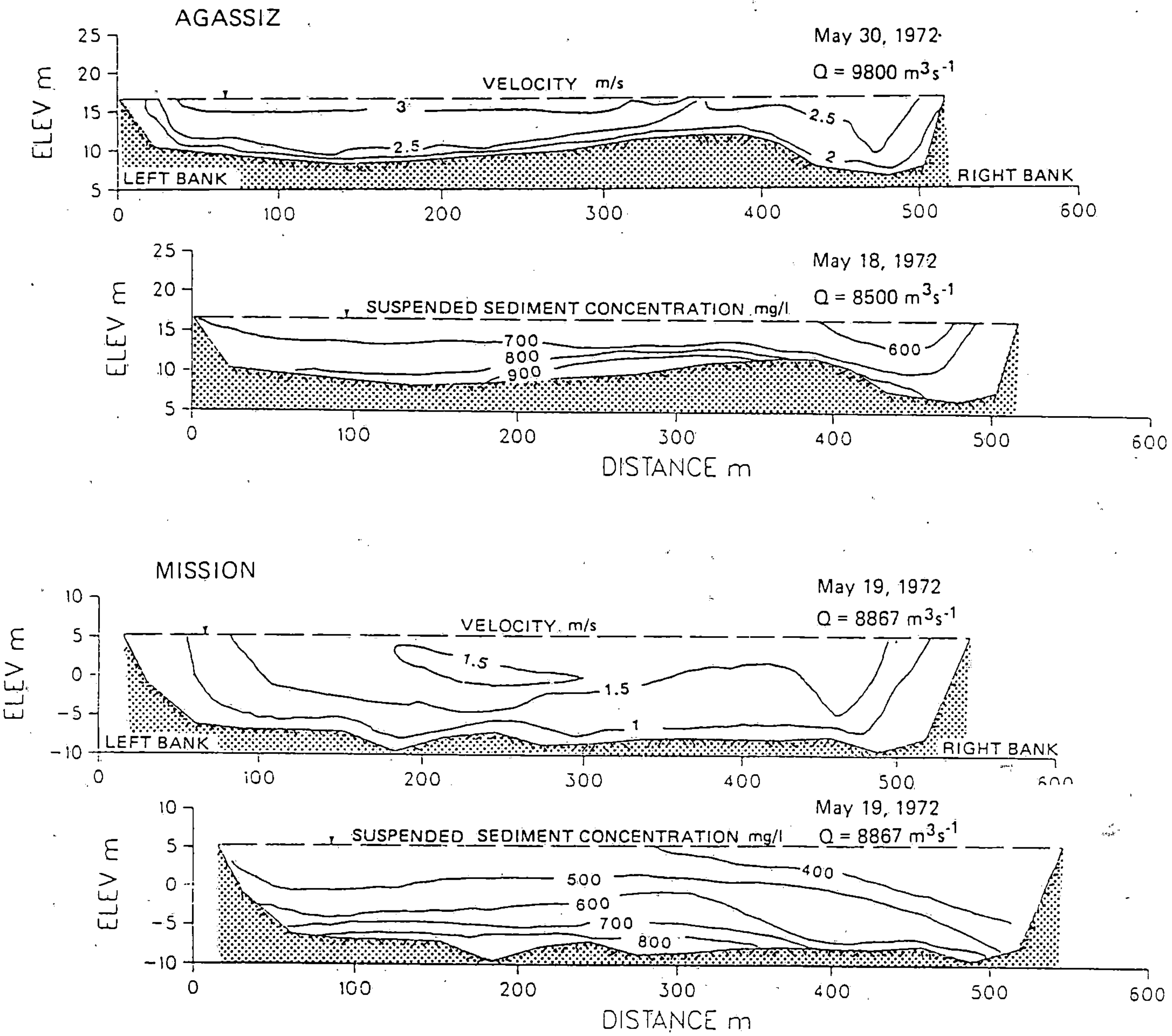


Figure 12. Gauging cross sections at Agassiz and Mission: example distributions of velocity and suspended sediment concentration.

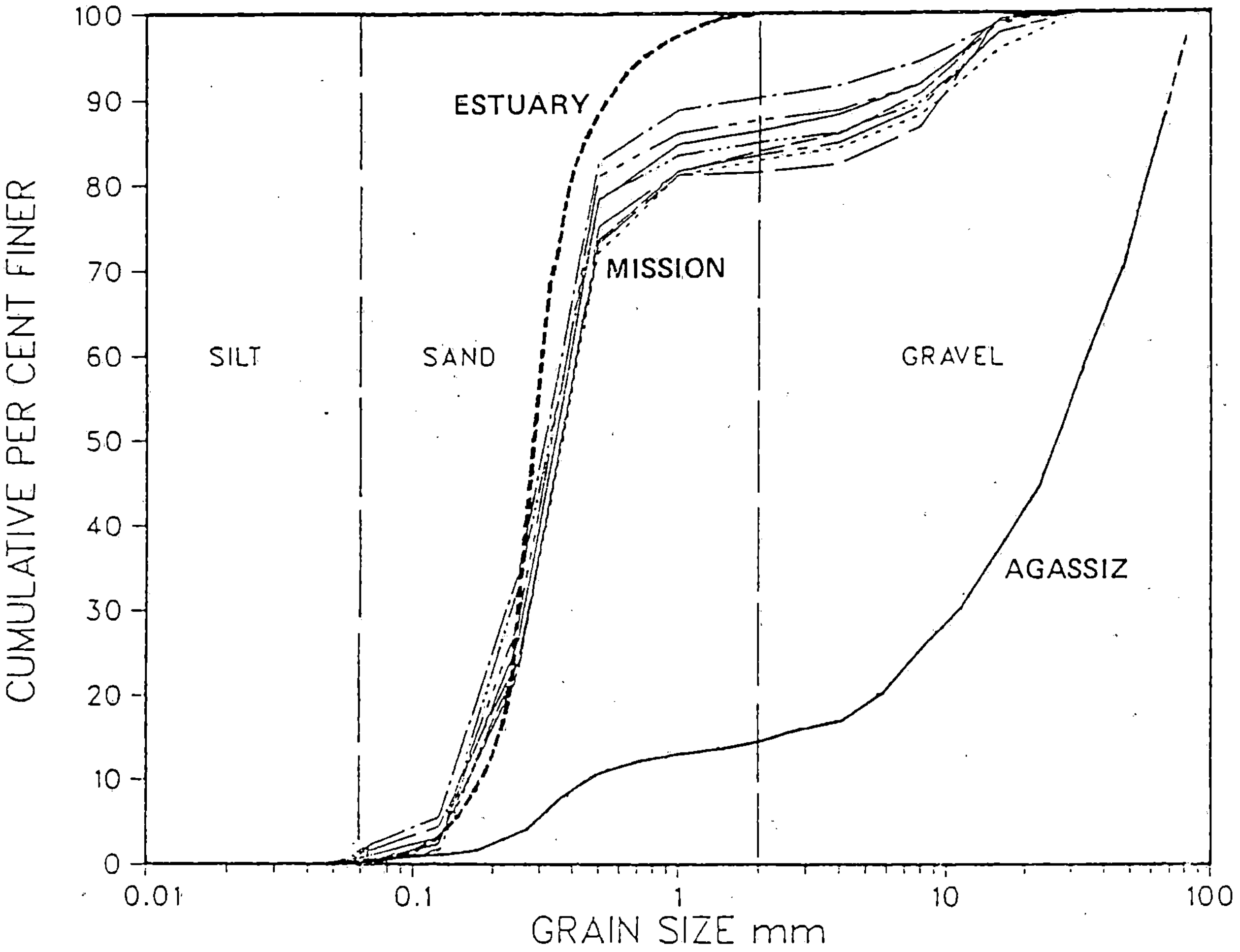


Figure 13. Bed material size distribution at Agassiz and Mission, and in the Main Arm near Deas Island. Mission samples obtained between 1966 and 1980 using a USBM54 sampler; Agassiz sample obtained from an exposed bar in 1984.

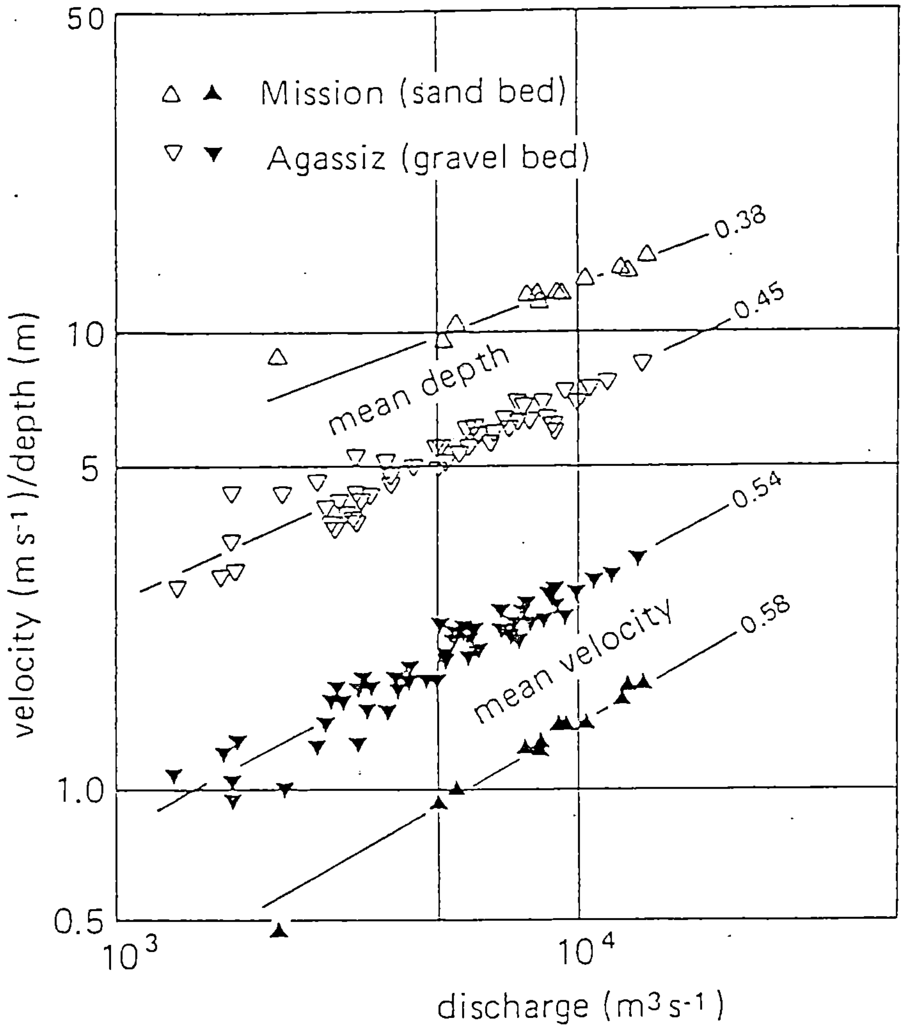


Figure 14. Hydraulic geometry in the gauge sections at Agassiz and Mission.

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 to 3.0 m of sand or silty sand. Areas covered with relatively young cottonwoods (10 to 30 years old), such as recently stabilized islands, generally have less than 1 m of silty and sandy 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. The variations in sand member thickness with the age of the surface indicate progress in vertical floodplain construction by overbank deposition of sand after the channel moves away from a site.

The sediment load is given in Table 4 (page 32), and the seasonal variations in sediment loads are illustrated in Figure 15a (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 15b. This analysis shows that the flows contributing the largest fraction of the sediment load are between 7500 and 8000 m^3s^{-1} at Agassiz (or Hope). These discharges correspond to about the 1.5 year flood at each of the

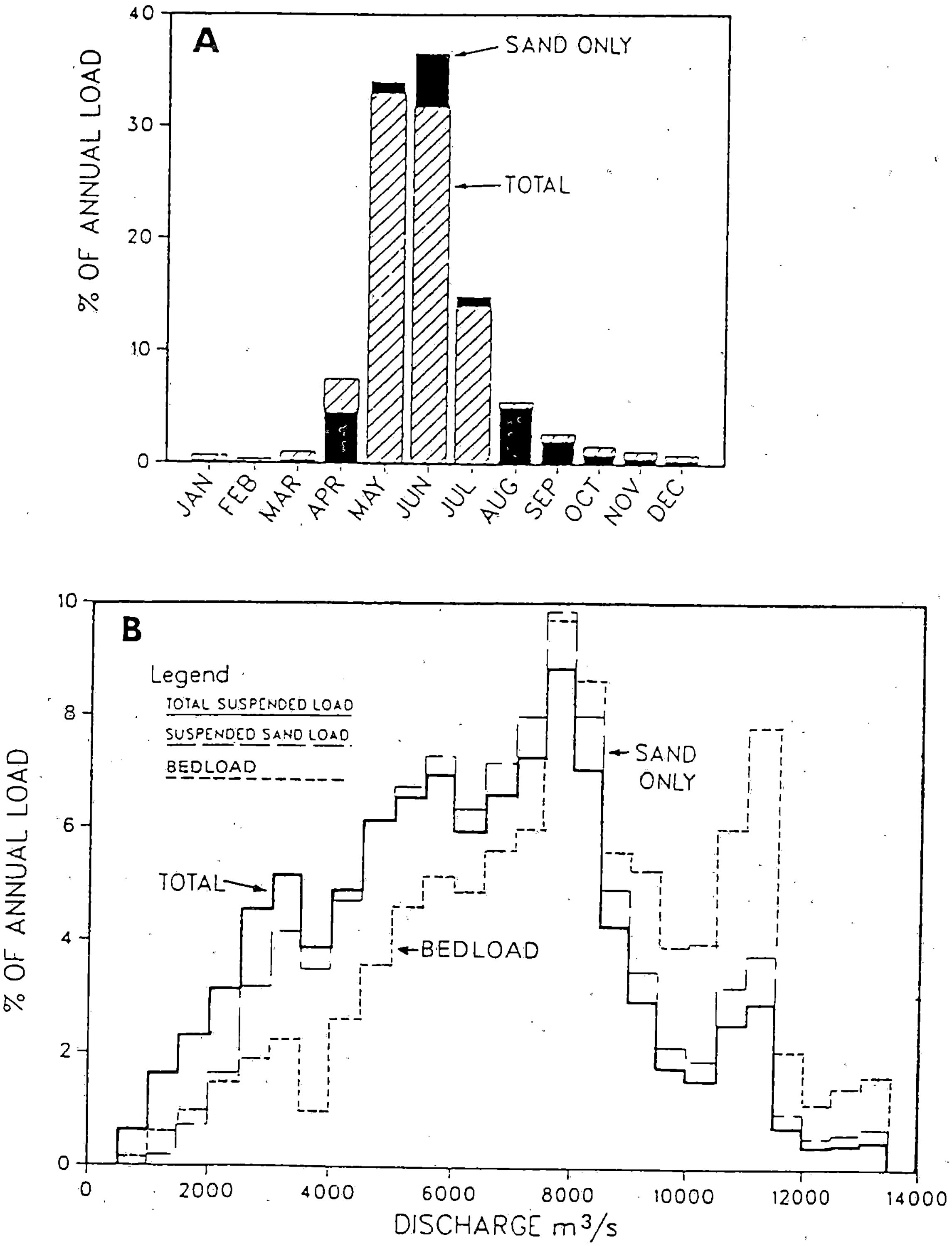


Figure 15. Variation of sediment load at Agassiz (a) by season, and (b) by discharge: mean of 1966-1982 results.

sites. By comparison discharges above 10 000 m^3s^{-1} (5 year return period at Agassiz or Hope) account 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 cumulative quantity of sediment transported is relatively small. This result is in accordance with findings on many other streams (Wolman and Miller, 1960). It seems to be typical for large rivers, but not for small ones.

Analysis of the hydraulic measurements at the gauge site shows that the shear stress on the bed at the "dominant" flow -- 8000 m^3s^{-1} -- is only about 50% higher than the critical shear stress required to mobilise the bed surface (Parker et al., 1982). This indicates that the greatest proportion of bedload transport takes place when 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 changes in the transport rate. Therefore, the bedload transport rates will not exhibit a very systematic relation with local hydraulic conditions (see figure 9a, page 26). 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; STOP 2)

This site, 10 km downstream from the Agassiz gauge and opposite Carey Point, serves to illustrate some features of the pattern of channel shifting in the "wandering" gravel-bed reach between Laidlaw and Vedder River. Erosion and deposition are linked along the channel. Events at this site can be related to events for many kilometres upstream. Bank erosion and channel shifting were studied by preparing channel shift maps from superimposed historical maps and airphotos (McLean and Mannerstrom, 1984).

The overall channel pattern has remained remarkably stable over the last century. Most of the major island groups were mapped in the original township surveys and the vegetation suggests that some islands have existed for much longer than a century. However, extensive areas of floodplain have been eroded this century, particularly 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 major construction occurring after the 1948 flood (Fraser River Board, 1963). Another major program of bank protection and dyke upgrading took place following the Federal-Provincial Flood Control Agreement of 1968. By the end of this program in 1975 about 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 banks along the floodplain have been protected with riprap.

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 Rosedale Reach (in view). Major deposition zones include lower Herrling Island, Vedder River confluence and lower Nicomen Island. Much of the channel instability along the river has been associated with local changes in flow alignment that developed as a result of earlier channel changes farther upstream. An important result of this observation is to establish the rate at which channel instabilities propagate along the river. For example in the Rosedale Reach the following sequence has occurred:

1. 1943-1971: Powerline Island eroded as the channel shifted to the north side in response to island and bar construction at lower Herrling Island (figure 16);
2. ca. 1954: Material mainly from Powerline Island was deposited in a prominent left bank bar that became attached to Ferry Island and deflected the river toward a large, formerly stable island near Hopyard Hill (figure 16);
3. 1954-1961: 'Hopyard Island' eroded 1 km, material deposited ca. 2 km downstream (figure 17);
4. 1961-1971: Sediment from Hopyard Island deposited 1.5 km downstream causing the main channel to shift southward toward Greyell Island (figure 17);
5. 1971-1979: Material eroded during the 1971 shift was deposited in the new channel about 1.5 km downstream, forcing the main

channel into a new alignment against the bluff to the north, thence directly across the channel zone to attack Carey Point. The disturbance (starting with the growth of the bar at Ferry Island) travelled 5 km downstream in about 25 years.

Eroded areas were planimetered from 1:25 000 channel shift maps prepared for the 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, derived from channel surveys of 1952 and 1964 and from field surveys during 1984. This allowed estimates to be made of the volumes of gravel and sand that have been transferred from the islands and floodplain to the active channel over the last century (Table 6).

The bank erosion rate was about 25% higher in the period 1928-1943 compared to 1943-1971. Yet 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 were governed by processes that developed over many years and not during any single flood event. Therefore the appropriate time scale for considering channel instability processes on Fraser River is measured in years or decades. Extreme floods, such as those of

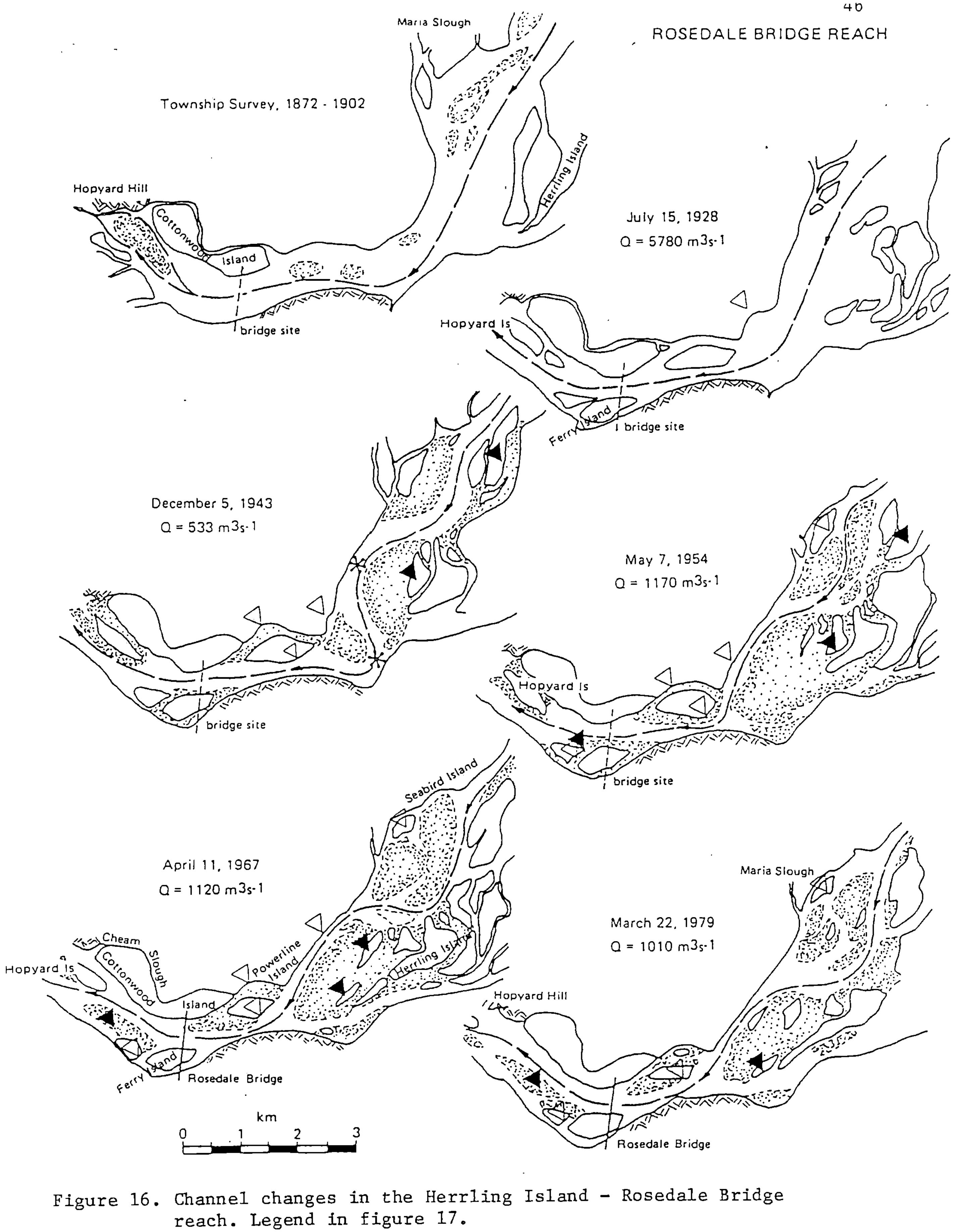


Figure 16. Channel changes in the Herrling Island - Rosedale Bridge reach. Legend in figure 17.

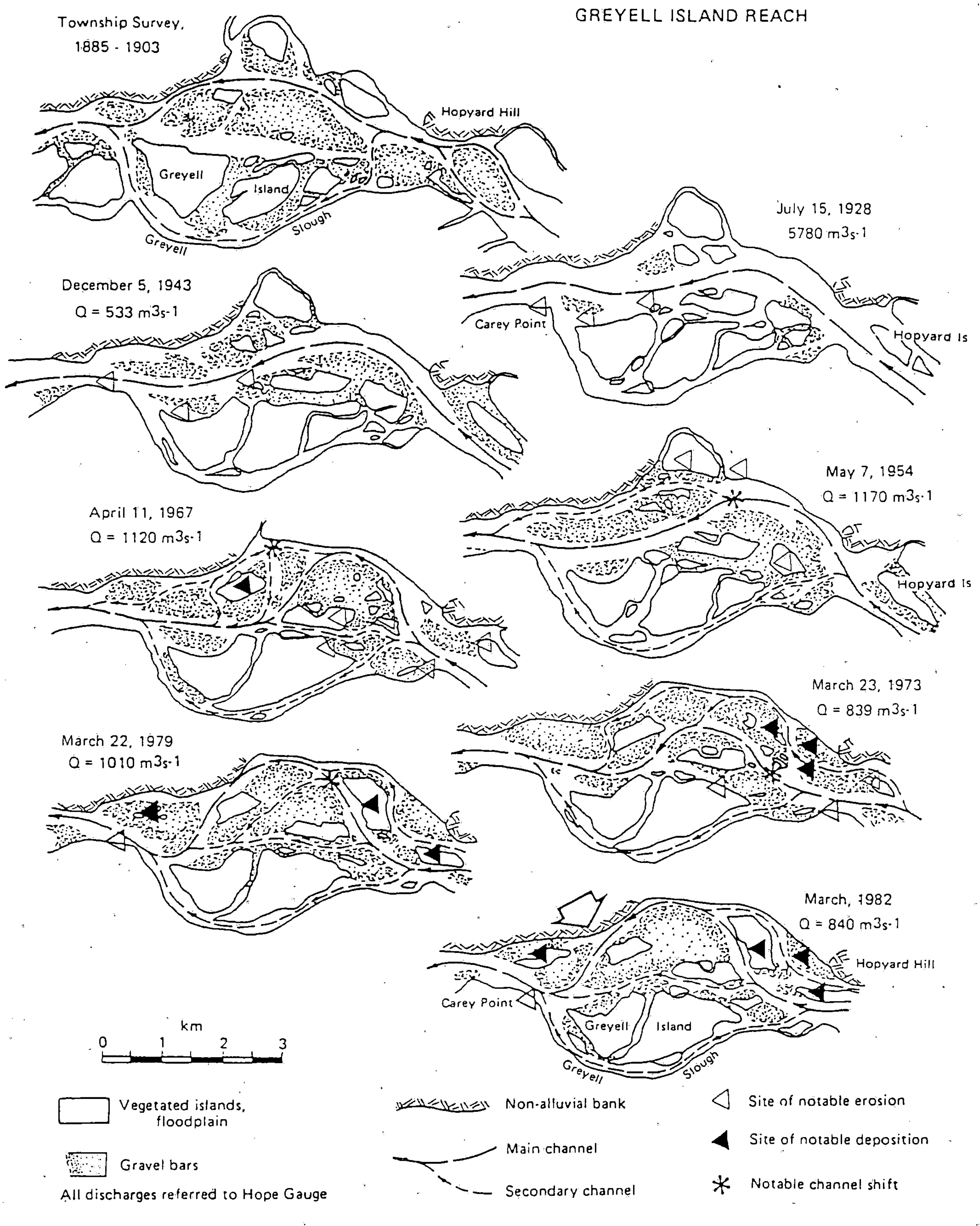


Figure 17. Channel changes in the Rosedale-Greyell Island reach.

TABLE 6

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.

1948 and 1972, completed or accelerated channel changes that were already underway. An example is the change in flow alignment near Herrling Island and consequent erosion at Powerline Island between 1943 and 1954, which encompassed the 1948 flood.

The eroded volumes form the basis for estimates of bed material transport in the river which can be compared with the measured transport rates. Between 1943 and 1971 the average erosion volume in the reach between Rosedale Bridge and Carey Point (9 km) was $255x10^3$ m^3 yr^{-1} or 28.4 m^3m^{-1} length of channel. Major, active sediment deposition zones along the river are spaced 2.8 km apart in this reach. This spacing must approximate the annual transport distance. Using this figure, we obtain an estimate for bed material transport of $0.8x10^5m^3yr^{-1}$. Measurements during the period 1967-1984 yield an average bedload transport of $1.0x10^5$ m^3yr^{-1} (with bulk density assumed to be 1.6 tonnes m^{-3}).

Table 7 gives a comparison of several methods for estimating bedload or bed material transport, supposed to be equivalent in this gravel-bed reach. Considering the disparate periods of measurement, the similarity of the figures is remarkable: the difference lie well within the precision of the figures. Amongst a range of bedload transport formulae tested (Mannerstrom and McLean, 1985), more than an order of magnitude variation was found in the predictions. The best results, quoted in table 7, were yielded by those formulae consistently reported to be most reliable.

TABLE 7

COMPARISON OF BED MATERIAL (BEDLOAD) TRANSPORT NEAR AGASSIZ, ESTIMATED BY VARIOUS METHODS

METHOD	PERIOD	TRANSPORT RATE (10^5 m^3yr^{-1})
WSC measurements[1]	1967-84	1.0
Sediment budget[2]	1952-84	1.2
Morphologic change[3]	1943-71	0.8
Formulae:		
Meyer-Peter and Müller[4]		0.7
Einstein		1.0
Ackers and White[4]		1.0

1. Interpreted using rating equations derived from data displayed in figure 9(a)
2. Based on complete surveys of the channel zone in 1952 and 1984
3. As reported in this paper
4. Threshold for transport adjusted to agree with WSC sample observations

Details of the comparisons presented here are given by McLean (1990)

On the basis of the comparisons given here, estimates of gravel transport were extended along the entire reach between Rosedale Bridge and Mission for the period 1952-84 using the sediment budget approach. Results are displayed in figure 18. Transport declines abruptly in two reaches -- one between Rosedale and Carey Point, the other near Sumas Mountain -- which are the major reaches of recent sedimentation and channel instability.

The gravel-bed reach, characterized by extensive side channels and numerous tributary inputs, is heavily utilized by salmon. Chum (Oncorhynchus keta) and pink (O. gorbuscha) salmon spawn in the river between Hope and Sumas wherever suitable gravels and flow exist. Locations vary from year to year. The annual escapement of the two species is approximately 475 000 and 1.8 million respectively. Of special interest is the fact that pink salmon spawn in Fraser River only in odd years. An indication of the primary importance of this reach for the Fraser pink salmon run is gained from table 8. Rearing of juvenile salmon -- particularly chinook (O. tshawytscha) -- also occurs here.

The reach has been subjected to considerable industrial pressures, by far the greatest impact deriving from gravel borrowing operations. Gravel is removed as a source of material for local developments such as highway and railway upgrading, and as a commercial venture particularly in the Minto Landing area. Figure 19 compares gravel removal in recent years with the estimated annual transport at the Agassiz gauge. Gravel removal

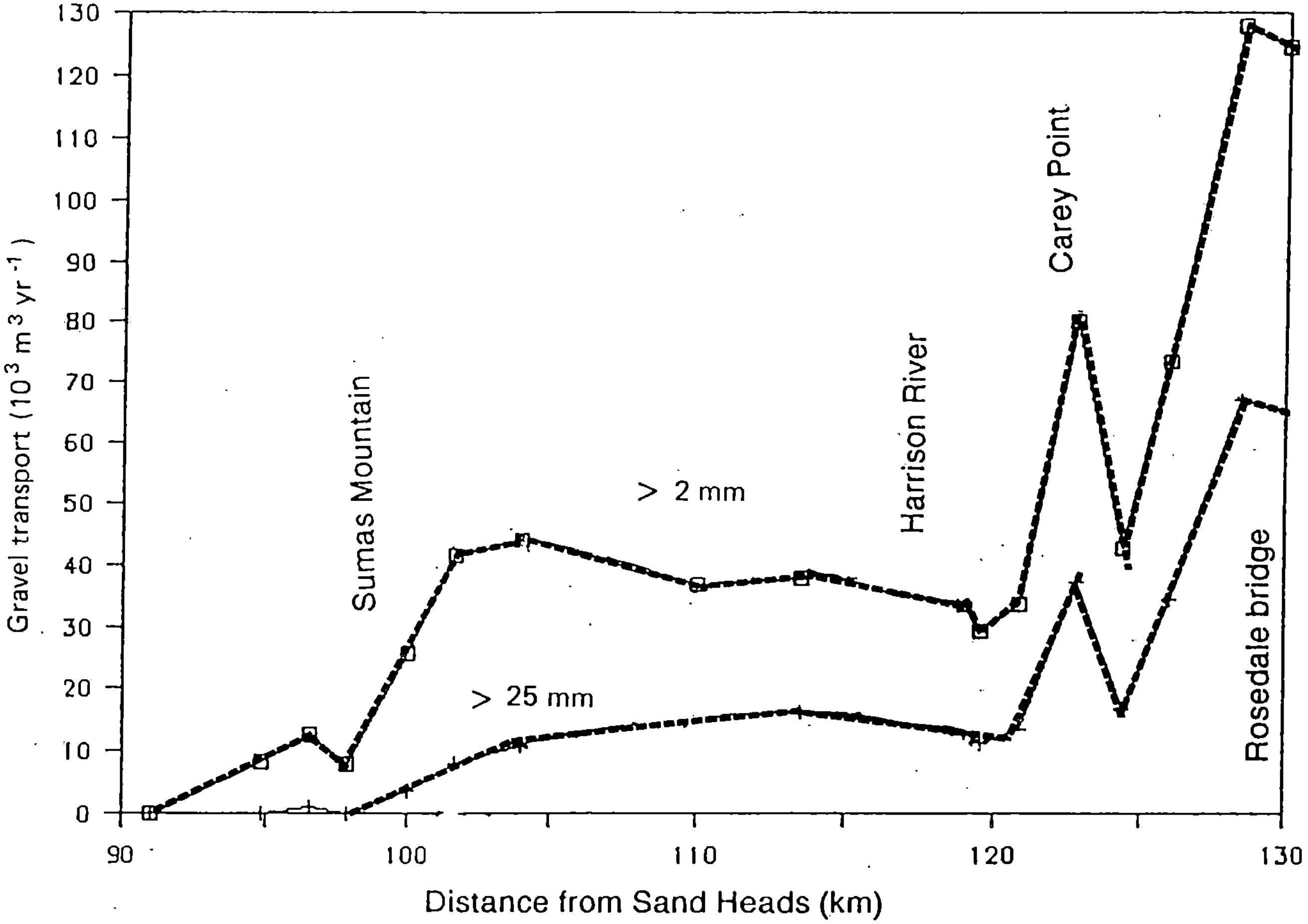


Figure 18. Average gravel transport between Rosedale bridge and Mission over the period 1952 to 1984

TABLE 8

PER CENT DISTRIBUTION OF PINK SALMON SPAWNERS AMONG MAJOR SPAWNING AREAS SINCE 1971

SPAWNING RIVER	1971	1973	1975	1977	1979	1981	1983	1985
LOWER FRASER MAINSTEM	50.6	43.8	23.0	31.6	42.9	50.3	71.5	81.4
HARRISON	5.9	12.0	13.5	5.6	7.7	7.1	3.2	6.9
CHILLIWACK-VEDDER	9.5	12.9	7.1	2.2	3.7	1.6	2.3	1.7
SETON/ ANDERSON	18.8	14.2	20.5	18.2	20.1	14.0	10.8	4.2
THOMPSON	14.1	16.2	35.1	41.0	25.1	26.0	11.1	3.0
OTHER TRIBUTARIES	1.1	0.8	0.7	1.4	0.5	1.1	1.1	2.8
TOTAL FRASER RUN	1,836,176	1,750,527	1,367,263	2,387,811	3,551,417	4,488,336	4,631,621	6,560,616

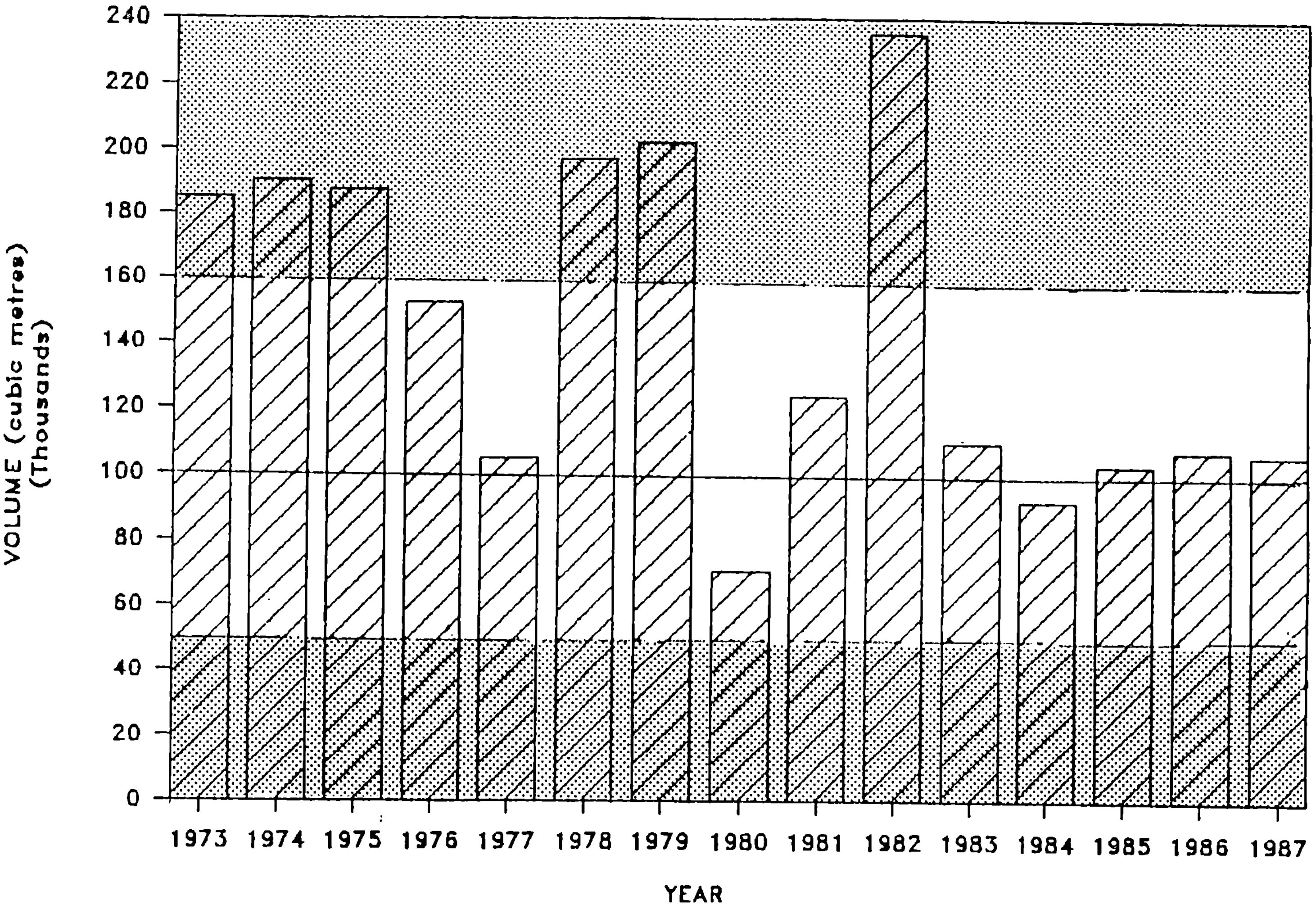


Figure 19. Annual variation in the volume of gravel mined between Hope and Sumas, for the period 1973-1987. The superimposed line is the mean annual bedload (gravel) transport at Agassiz, with the limits of precision of this estimate indicated by the upper and lower dashed lines. Borrow totals from Kellerhals et al. (1987).

appears to exceed gravel recruitment. There is concern that continued removal equal to or greater than annual recruitment would result in long term degradation of spawning habitat for salmon. The Canada Department of Fisheries and Oceans has imposed a moratorium on large scale gravel removal, with the exception of the operations with long term tenure at Minto Landing, until further information is available about the effect of gravel removal on fish, fish habitat, and river morphology.

In 1988, in conjunction with the British Columbia Ministry of Transportation and Highways, DFO commissioned a pilot study near Agassiz to determine areas where gravel removal could occur with the least impact to river stability and to fish habitat. Gravel deposits and bars were classified into four types, A to D, with A being areas of rapid accumulation of gravel and D being areas that are more stable (i.e., with less accumulation). The D areas are considered to be most sensitive to gravel removal as the impact is apt to be long term, or possibly permanent. Further studies were undertaken in 1989 in the Minto Landing area, funded by the British Columbia Ministry of Energy, Mines and Petroleum Resources, the Aggregate Producers of British Columbia, and the District of Chilliwack. The final phases of the study, to cover the balance of the Hope-Sumas reach, are planned to be undertaken in 1990-91.

3.4. Mission gauge reach (river km 82; STOP 3)

The gauging section at Mission 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 12, page 37). At lower flows the Mission site is tidally influenced, which causes diurnal variations in discharge and stage. However, during freshet conditions tidal influences are minor.

The natural channel here has a sand bed (figure 13, page 38) and banks, but heavy riprap immobolizes the banks (at about the natural width). Figure 14 (page 39) gives the hydraulic geometry of the section. The sediment load at this station is reported in Table 5 (page 33). Figure 20 shows that the annual distribution of the load is very similar to that at Agassiz (Figure 15, page 41).

The data of tables 4 and 5 yield a sediment balance for the Agassiz-Mission reach. Approximately 150 000 tonnes yr^{-1} of gravel (material coarser than 2 mm) was transported past Agassiz between 1967 and 1982, whereas gravel transport past Mission (2000 tonnes yr^{-1}) is negligible. Therefore approximately 2.7 million tonnes of gravel was deposited in the Agassiz-Mission reach between 1967 and 1984 (the period of measurements), and roughly 5 million tonnes was deposited between 1952 and 1984 (the period between major channel surveys).

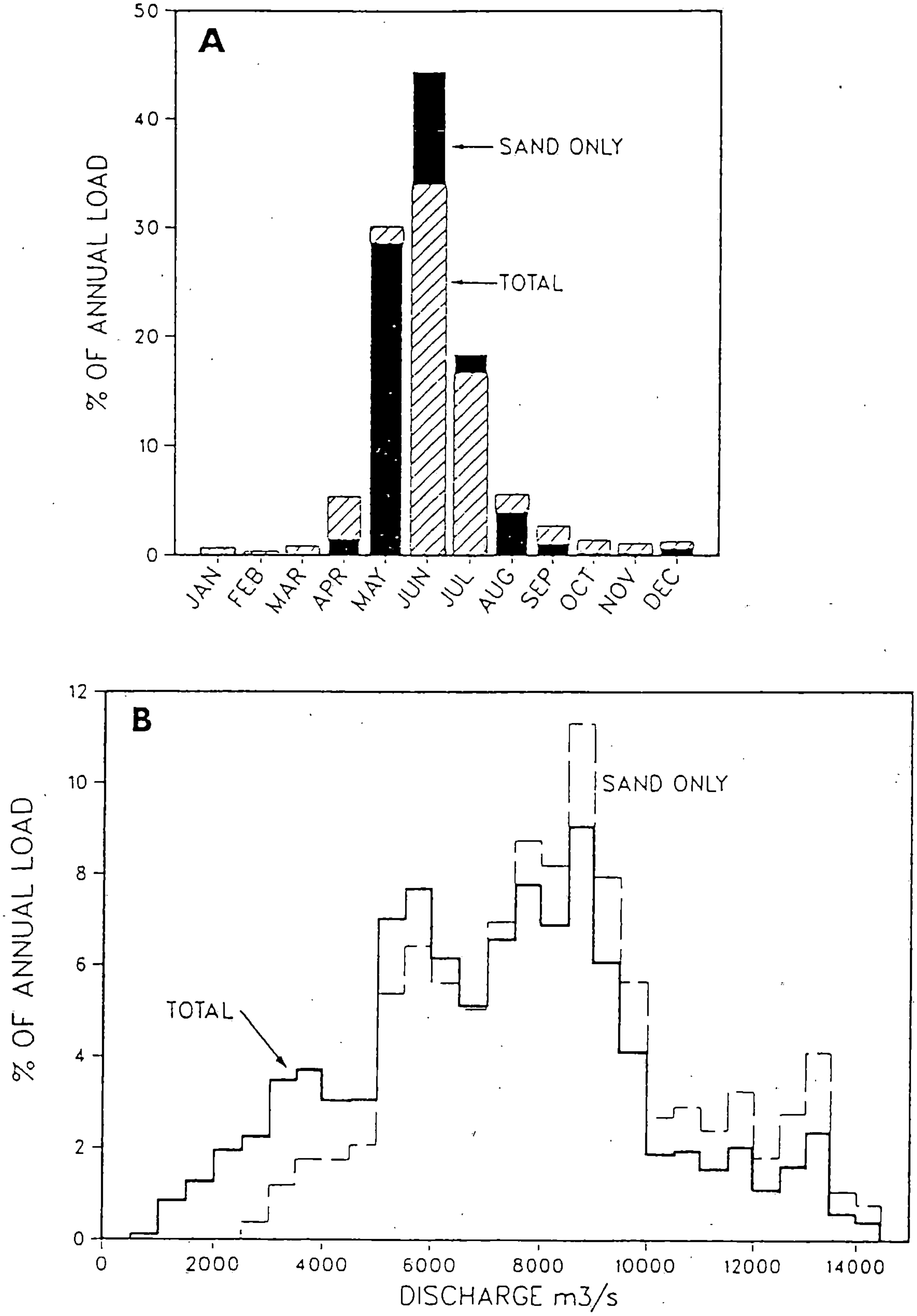


Figure 20. Variation of sediment load at Mission by season and by discharge: mean of 1966-1982 results.

The estimated annual sand loads at Mission exceeded the Agassiz loads by 1 million tonnes yr^{-1} on average between 1967 and 1982. This long term difference is 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. Based on the published sediment records from Chilliwack River at Vedder Crossing it is apparent that the sediment inflows from tributaries between Mission and Agassiz are negligible in comparison with the larger observed increases in annual load at Mission. Apparently, large quantities of predominantly sand sized sediment can be derived from the Agassiz - Mission reach in some years.

The average monthly sand load is characteristically lower in May at Mission than at Agassiz. Conversely, in June it is considerably higher at Mission. 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. Figure 21 illustrates the variation of the cumulative differences during 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 within the year. The change from sediment accumulation to sediment depletion coincides with the onset of supply exhaustion at Agassiz. This pattern of sediment

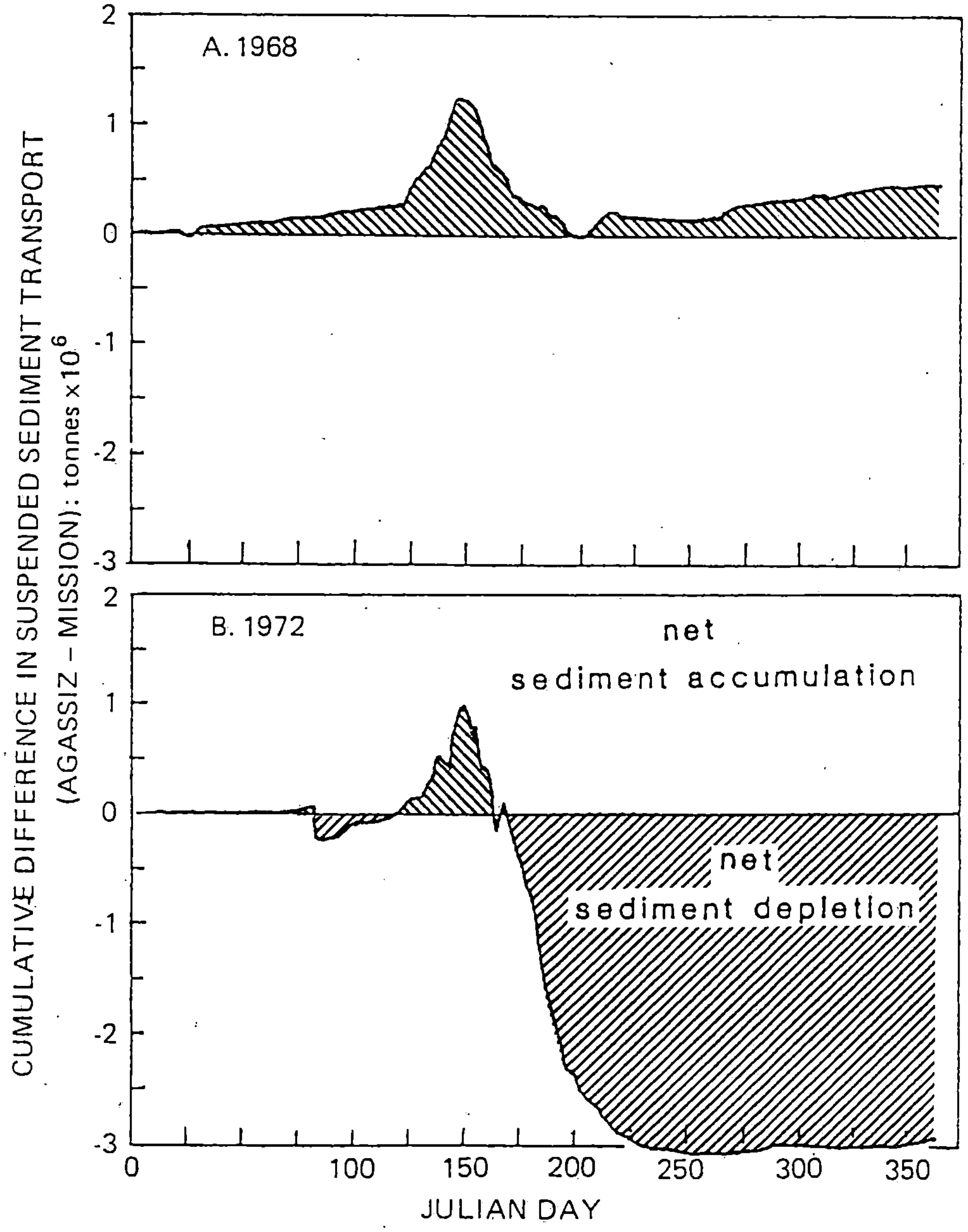


Figure 21. Cumulative differences between suspended loads at Agassiz and Mission: 1968 and 1972.

accumulation on the rising limb of the flood has occurred in virtually every year. In most years a period of sediment depletion takes place on the falling limb so that the net change in sediment storage within the reach at the end of the freshet is virtually zero.

In 1972 substantial net sediment depletion occurred. Figure 21 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. The individual annual accumulations fall within annual compilation error, but the episodic loss exceeds it.

From a fisheries perspective, this reach of the river is used primarily by salmon as a migratory corridor. Rearing occurs near the river margins and in the lower reaches of some tributaries. However residency generally is short-term as juveniles -- particularly chinook -- migrate passively to the estuary. DFO operates a counting facility annually at Mission to determine the number and timing of downstream migrants. It is estimated that over 1 billion juveniles migrate down the river in even years and that 0.5 billion migrate out during odd years.

The major impacts facing fish and fish habitat in this reach are associated with suction dredging, and with flood and erosion control works such as dyke construction and maintenance. Monitoring studies by DFO and the original International Pacific Salmon Fisheries Commission have provided the information necessary to minimize the impact of dredging on juvenile fish. For example, chum salmon tend to disperse evenly across the river during downstream migration. They also tend to reside in the upper 5 metres of the water column. This allows DFO to specify in non-pink years that during the chum downstream migration dredging can occur only in water that is at least 5 metres deep and that the cutter-head can be operated only within 1.5 metres of the bottom. Pink salmon, on the other hand, tend to disperse evenly throughout the cross-section. For this reason there is no recourse but to place a closure on channel dredging during the major part of the downstream migration. This generally lasts for about 30 days during the period April 15 to May 15 in even years. The closure commences when the Mission fry count exceeds 4 million per day and continues until it drops to 5 million per day. In additon to these timing criteria, DFO has also directed dredging operations which employ surge valves to screen all intakes to prevent entrainment of salmon juveniles.

3.5. Port Mann gauge reach (km 40; STOP 4)

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, tides ranging to 1.3 m during high flows and to 2.3 m at low flows. However, salt water does not penetrate to this point. Although measurements were conducted for many years at this station (table 1, page 4), only part of the record is published because of difficulties in estimating the tidal effects between measurements. These are further complicated by the transient storage of water in Pitt Lake and Pitt River. Recently, a continuous acoustic flow monitoring device has been installed at New Westminster. When tests are completed, it will be capable of providing a direct, continuous flow record.

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 and interpretation of sediment data as well. As a result, most studies have relied on data at Mission for estimating sediment delivery into the estuary.

Figure 10 (page 28) shows 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 might 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 9 provides a comparison of the estimated suspended bed material load at Mission and at Port Mann on the same computational basis. The load at Port Mann ostensibly is 16 percent larger, on average, over these years, although in some years there is near equality. In view of the uncertainties attendant upon the computation of flow at Port Mann, it cannot be concluded that the difference is real.

Bed load data are available for Port Mann in 1968. These are compared in figure 22 with Mission data from the same year. Within the scatter of the observations there are no obviously distinct trends, 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 differences in total bed material transport that are comparable with the likely resolution of the comparison lead to acceptance of Mission data as the measure of sediment yield to the estuary.

Table 9

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).

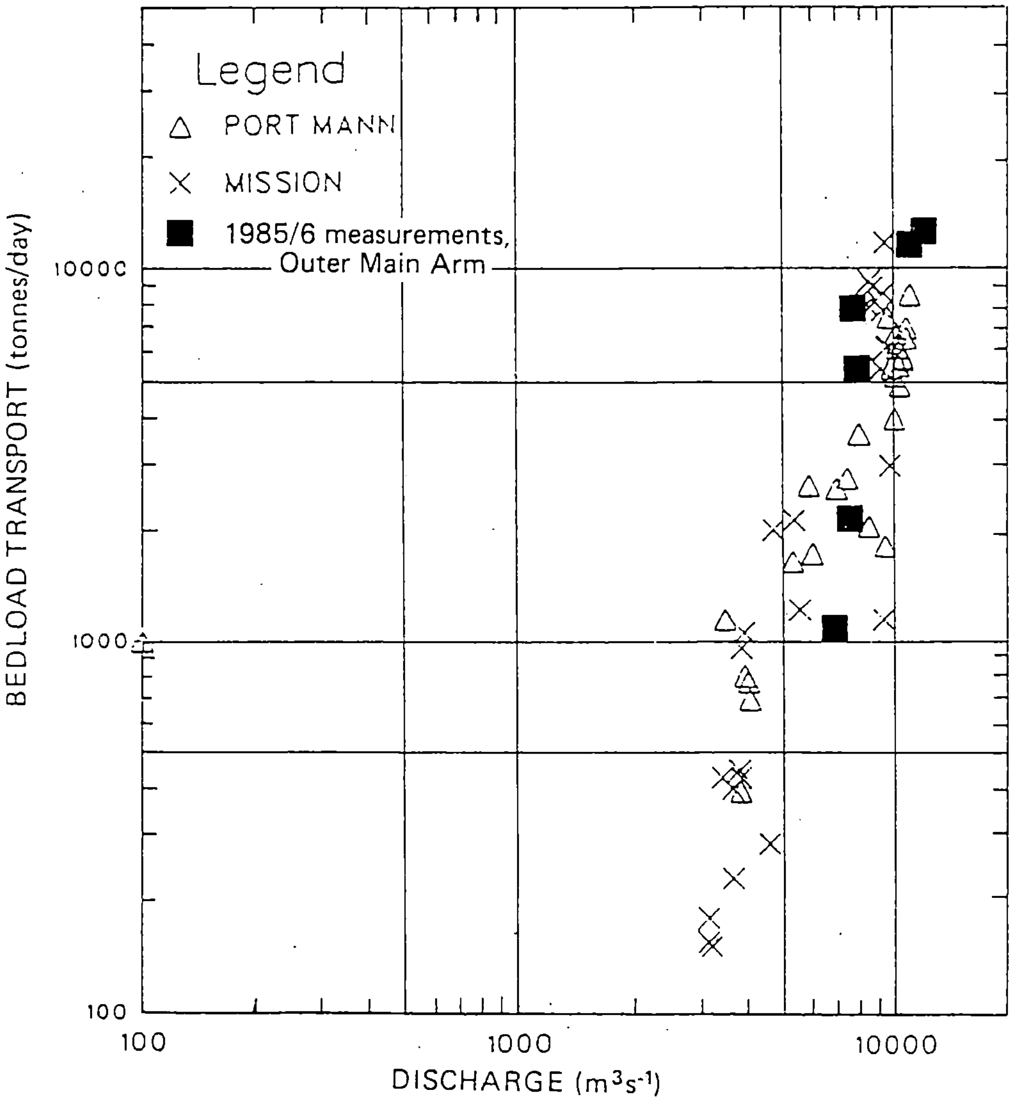


Figure 22. Bed load transport at Port Mann and Mission, 1968.

There are 11 industrial effluent dischargers to the main stem of Fraser River downstream of Kanaka Creek, with a further 27 dischargers to the Main Arm, and 11 to the North Arm. The combined maximum industrial discharge is 252 000 m^3day^{-1} (compare 600 000 m^3day^{-1} for the Annacis sewage treatment plant alone). Eleven of the industrial discharges consist of cooling water only. On the basis that 5000 m^3day^{-1} constitutes a "significant flow", there are only 13 dischargers of note. These include metal finishing, cement manufacturing, chemical manufacturing and forest products operations. Environmental audits have been conducted on the majority of them (Supervisory Coordinating Committee, 1987).

Storm runoff is a major source of contaminants entering the Fraser. From urban areas runoff increases levels of fecal coliforms, suspended particulates, chemical oxygen demand, nitrogen and metals (aluminum, iron, copper, lead, zinc). Runoff from forest industry antisapstain operations also impact the river (Krahn et al., 1987). Concern has also been expressed concerning the levels of chlorophenols in yard runoff. Regulations have forced the industry to adopt replacement chemicals of which 2-(thiocyanomethylthio)benzothiazole (TCMTB) probably is dominant. Stormwater impact probably is greatest in the North Arm, where the number of outfalls is greatest and the flow is relatively small.

Older parts of Vancouver and New Westminster use a combined sewer system. During rain when flows exceed the capacity of the sewers untreated effluent can discharge into the Main Stem at New

Westminster and into the North Arm by South Vancouver. Both cities have programmes to separate their sewer systems which will, in the long term, reduce the number of overflows.

Of 1913 chemical spills reported to the provincial Ministry of Environment between March, 1989 and March, 1990, half occurred in the Lower Mainland. Not all of these incidents were associated with the river. The importance of such discharges if they do reach the river is the potential of "shock load" which may result in fish kills. Significant incidents during 1989 included the discharge of approximately 11 m^3 (3000 gal) of TCMTB to the Fraser River at Fraser-Surrey Dock, an unknown amount of the wood preservative copper chromium arsenate at Gunderson Slough, 10 to 11 m^3 (2500 - 3000 gal) of diesel fuel (about 60% of which was recovered) to the ground and thence into the Brunette River. Historically, approximately 50% of the spills involve petroleum products, 10% involve PCBs, and the rest may involve virtually any chemical.

Loads of suspended solids, total phosphorus, copper and zinc in Fraser River as it enters the Vancouver area are much greater than the combined loads from all sources (including non-point sources) within the region. This is a function of the great discharge volume of the river. The review of the British Columbia Ministry of Environment water quality objectives monitoring results for 1988 (Water Management Branch, 1989) for Fraser River downstream from Kanaka Creek show that the objectives were met.

3.6. Estuarine reach: Main Arm at Deas Island (km 20; STOP 5)

At river km 35, 7 km below Port Mann, the river enters its modern delta and divides into three channels just downstream from the New Westminster and Surrey docks. Ultimately there are four distributaries; North Arm, Middle Arm, Main Arm and Canoe Pass (figure 2, page 3). The distribution of flow into the various channels is shown schematically for two dates in figure 23. The division varies seasonally and is not well known. It is supposed that sediment transport is more strongly concentrated in the Main Arm than is the flow, but there are no measurements to confirm that.

The mixed semi-diurnal tide at Sand Heads ranges to 3.4 m at high discharges and to 4.0 m at low discharges. Here, the tide ranges to about 2 m at high discharges and to about 3 m at low discharges. At low discharge (late winter) the salt wedge may intrude 30 km upstream, past Annacis Island, while at high discharges the intrusion is less than 10 km.

During the development of the delta, the river channels naturally shifted position, and the lowest lying parts of the delta surface flooded annually. Today, the course of the river is controlled by a number of in-channel river training structures, and there are continuous flood protection dykes. These have modified the pattern of deltaic sedimentation throughout this century.

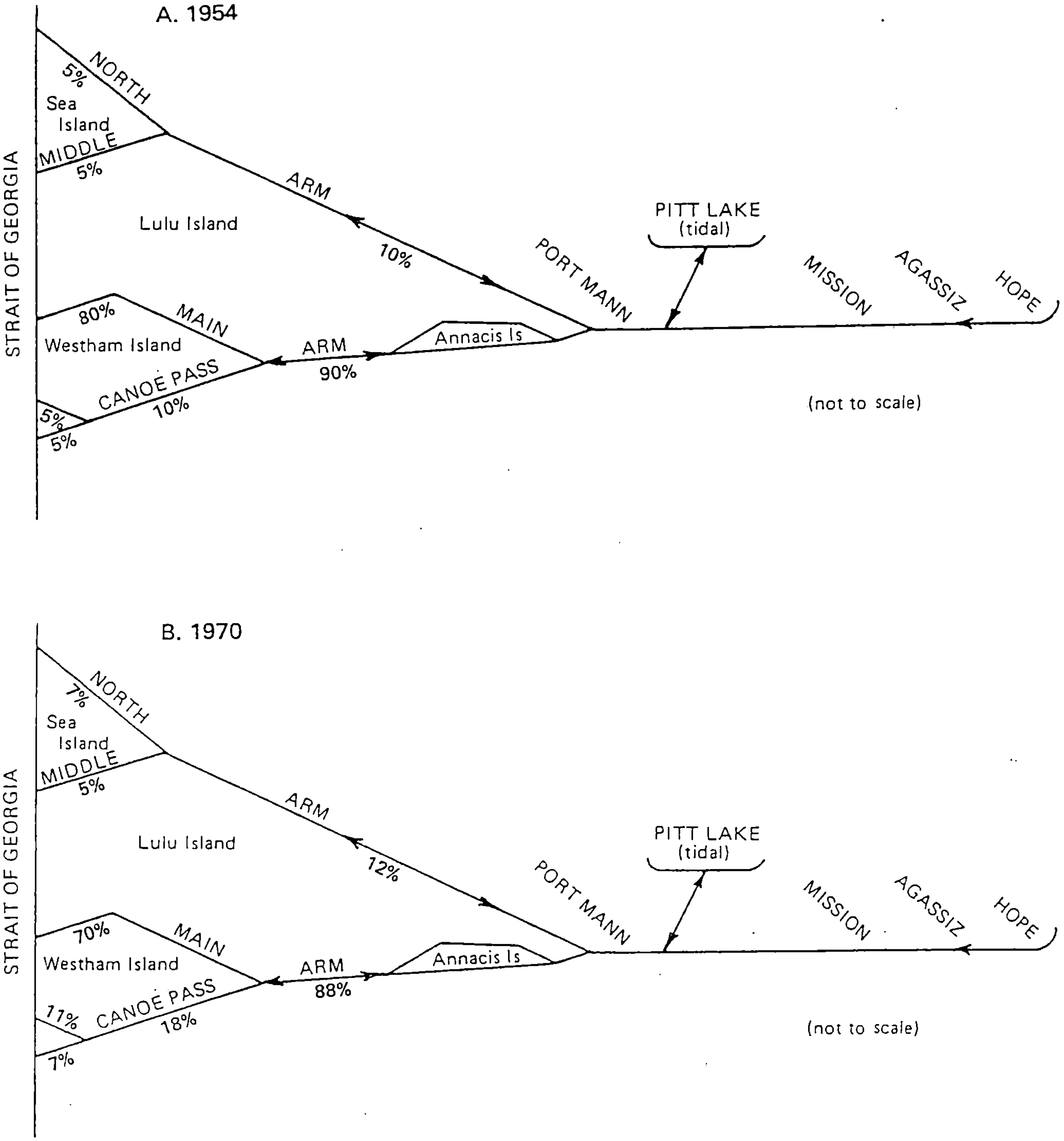


Figure 23. Flow distribution in Fraser delta channels, based on 1954 freshet (Keane, 1957) and 1970 (WCHL, 1977).

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. The main flow is restricted to a 400 m channel and the balance of the section consists of wide, shallow "berms" which carry the tidal prism. Figure 13 (page 38) 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 24). Figure 25 displays velocity and suspended sediment concentrations in freshet at a section several hundred metres upstream from Deas Island Tunnel.

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 programme of sediment transport measurements in the estuary channels. We take up the question of sediment transport assessment again at the next stop.

Three major sewage treatment plants provide primary treatment for a mix of domestic and industrial effluents in the Greater Vancouver region, and discharge into the estuary. The Annacis and Lulu plants discharge into the Main Arm, whilst the Iona plant discharges to deep water off Sturgeon Bank. The collection systems for the Annacis and Lulu plants are separated, although there is

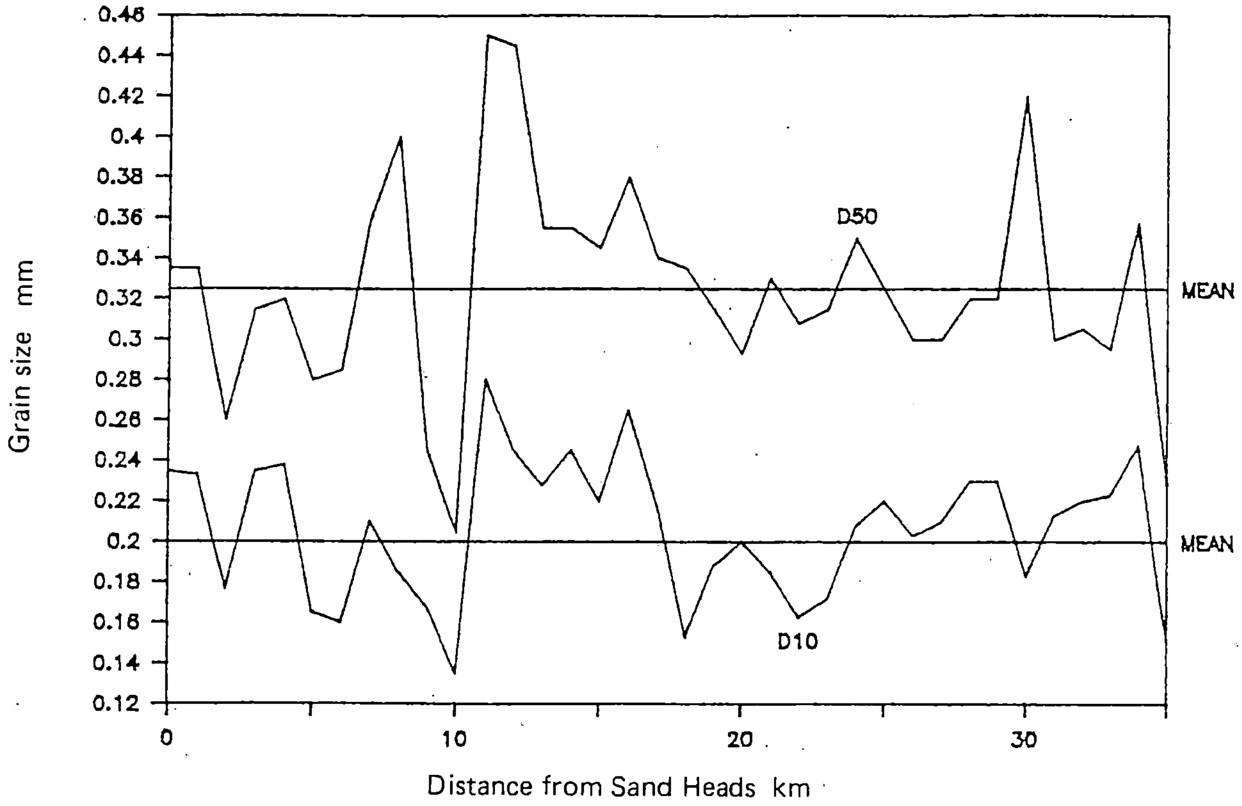


Figure 24. Bed material in the Main Arm of Fraser River (survey of February, 1988, by Canada Department of Public Works). The very fine material at km 10 and 35 indicates sites where the river has scoured into deltaic silts and till respectively.

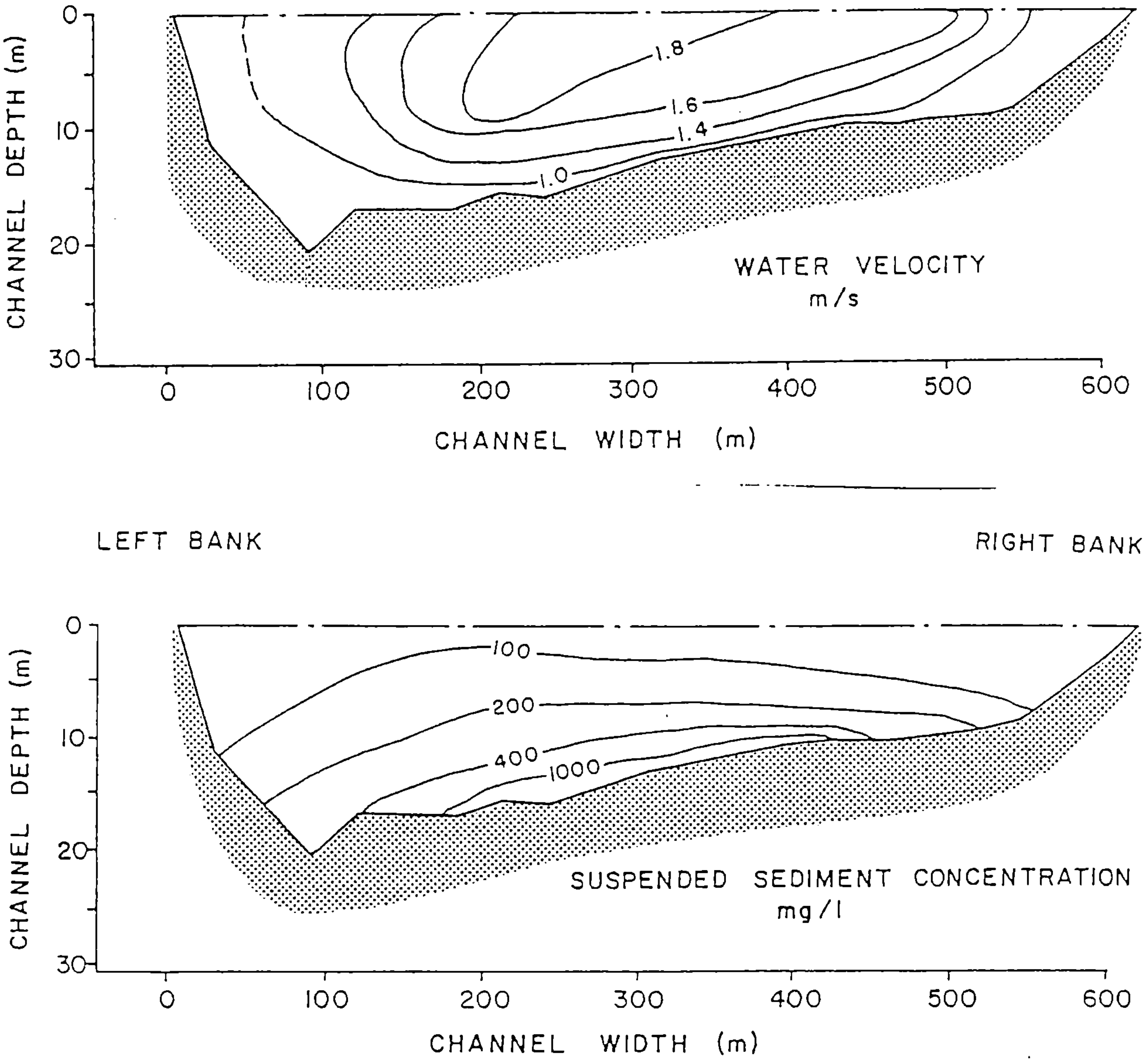


Figure 25. Cross-section in Main Arm near the upstream end of Deas Island showing water velocity and suspended sediment concentration within the deepwater channel: measurements of June 22, 1978, 1210 to 1325 PDT (Beak, 1980).

significant infiltration of storm water, especially at Annacis. These two plants also provide effluent chlorination and dechlorination during the summer months. The estimated combined contaminant loadings from the Annacis and Lulu treatment plants generally exceed the estimated loadings from urban runoff and combined sewer overflows (GVRD, 1989), and are much greater than those from direct industrial discharges. Some exceptions exist, such as cadmium and lead, of which the calculated loadings from stormwater equal or exceed those from the two treatment plants. The Iona collection system is combined, hence stormwater enters the plant as well as effluent. Monitoring programmes examining the treatment plant effluent show elevated levels of several nutrient and metal parameters. Exceedances of objectives have been noted for fecal coliforms at three locations, typically downstream from the sewage treatment plants.

In 1987 and 1988 major studies were undertaken by the provincial Ministry of Environment with the Fraser River Harbour Commission to determine metal and organic contaminant concentrations in sediment, benthos and fish in the estuary. PCBs were detected in only one of 75 sediment samples, while chlorophenols were found in two samples from the Main Stem, four samples from the North Arm, and one sample from the Main Arm (Swain and Walton, 1988). Values of other characteristics were generally lowest in the Main Stem and highest in the Main Arm (except zinc, which was highest in the North Arm, possibly due to the comparatively greater stormwater input).

Benthic organisms were collected at two sites in each reach. The same organisms were not found at all sites. Analyses were possible only for chlorophenols. The highest levels were found in oligochaetes and lampreys in the Main Stem, in pelecypods in the Main Arm, and in polychaetes in the North Arm. In the North Arm, high values were found in other organisms as well. The data indicated a significant level of contamination, which is not surprising considering the number of wood preservation facilities located along the North Arm.

Fish collected from the three reaches were analysed for metals, PCBs, chlorophenols, PAHs, phthalate esters and organochlorine pesticides. Overall, concentration differences amongst species appear to be random (Swain and Walton, 1989). Fish collected from Barnston Island (Main Stem), upstream from many of the contaminant sources in the area, appear to be no less contaminated than fish from the lower reaches. Furthermore, Fraser River fish generally carry metal burdens similar to or lower than those of fish from uncontaminated lakes in British Columbia. Arsenic load is higher in all species in the river, and some metals are higher in some species.

As possible, 1988 results were compared with results from earlier studies in 1980 (Singleton, 1983) and 1972-73 (Northcote et al., 1975). Higher concentrations of metals generally were found in liver, as opposed to muscle, tissue, as in the earlier surveys (chromium and mercury were exceptions). Of five metals that could be compared across the three surveys, similar or declining values were found for copper, mercury and zinc, whilst iron and manganese exhibited no trends. Chlorophenol and PCB concentrations in muscle tissue did not exceed water quality objectives in any sample, and appear to have been reduced considerably since 1980. It appears that chlorophenols may be accumulating in livers (where, however, analytical detection limits are higher). No trends were detected in phthalate esters and PAHs, although it appears that the latter accumulate in liver tissue. The most commonly measured organochlorine pesticides were α- and γ-chlordane, dieldrin, DDT, DDD, and DDE. Only DDE was detected sufficiently frequently for comparison: concentrations appear to be lower in fish muscle tissue in 1988 than they were in 1972-73.

The estuary is critical to the maintenance of fish stocks in Fraser River, yet it is estimated that over 70% of the original estuary habitat has been lost as the result of land development, filling, and dyking. All salmon species utilize the estuary although residency varies from a relatively short time (2 weeks for pink salmon) to several months (chinook and coho). Rearing salmon are found year-round in the estuary, particularly in marshes and side-channel/slough areas. Examples of the latter include Deas and Tilbury Sloughs. From March to the end of August, fish use is high and the fish can be found virtually anywhere. In even years during the April 15 to May 15 period, over 1 billion juvenile salmon occupy the estuary, of which about one-half are pinks.

Water quality in the sloughs and side-channels is consequently of concern. Tilbury Slough, for example, is prone to low dissolved oxygen and contamination due to frequent discharges into the head of the open slough through a drainage pump which collects water draining from agricultural land and industrial developments. Generally, the North Arm is the worst area since flow is relatively low compared with the number of effluent discharges.

Development activity continues to pose the greatest threat to the physical environment. The Fraser Estuary Management Programme (FREMP) has been established as a process for coordinating the review of proposed projects by regulatory and management agencies. The Environmental Review Committee (ERC) is an associated committee to assess the environmental impacts of proposed projects. This provides a single coordinated response to environmental issues raised by a proposal.

In order to ensure that further loss of habitat or productive capacity in the estuary does not occur, DFO has undertaken to classify shoreline habitats along Fraser River according to sensitivity and productivity. The first effort was directed at the North Arm. The three category classification (high productivity; moderate productivity; low productivity) established baseline data for development of the North Fraser Harbour Environmental Management Plan. This plan, endorsed by the North Fraser Harbour Commission facilitates an active approach to port development and environmental management. It also led to the first agreement on a Habitat Compensation Bank; that is, compensatory habitat is being developed now by the Harbour Commission in anticipation that future development will result in habitat losses that may not be practically compensated at the site. The project is being expanded to the entire FREMP management area below Kanaka Creek.

Another major concern is the impact of encroachments into the river on the migration of certain fish stocks. The issue of cumulative impact of various projects has only recently been identified. For example, the Alex Fraser Bridge, despite its great span, still required piers within the channel. To protect them from navigation hazards, large sand islands were constructed about the piers, reducing channel width by 28%. There was concern that this might create a velocity barrier to upstream migrants, particularly for the early Stuart sockeye which migrate through the lower Fraser during freshet when velocities are high (early July). To mitigate any effect, rock groynes were installed along the riverside faces of the islands to create low velocity zones which the fish could use for resting. Velocity monitoring is underway to determine the effectiveness of the groynes. Should they prove not effective, the Ministry of Highways has agreed to construct a bypass channel at the south sand island.

3.7. Outer Main Arm and delta front near Steveston (km 10; STOP 6)

From this point, the river flows through a 10 km reach of tide flats to reach deep water at Sand Heads. A major management problem in this reach is the maintenance of the navigation channel, since the channel tends to shoal as it approaches base level and drops the remaining portion of its bed material load. The lack of a routine program of sediment transport measurements in this reach has proven a substantial handicap for effective planning of channel dredging, and for assessment of the long-term effects of dredging. The difficulty to obtain measurements derives, of course, from the fully tidal nature of the river. A programme of eight, 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, remains the most comprehensive measurement exercise conducted to date. Measurements were made on several profiles of velocity, water temperature, salinity and suspended sediment concentration through tidal cycles at Sand Heads and at Steveston. Some results from that program are discussed here, and a provisional estimate is made of the sand budget.

The study reach is bound on its right bank by Steveston Jetty and its left bank is partially confined by Albion Dyke. 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 10 m draft or better (with respect to low water) and the measurements have been made within that channel.

The limited incursion of the salt wedge at the peak of the freshet (the water column remains fresh at Steveston) is notable. Figure 26, based on the 1986 measurements, 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, upward diffusion of eddies from the bed is strongly suppressed. The most significant results are that on rising to high tide (salt water incursion), the percent sand in the water column becomes very small and there is substantial deposition on the bed. On the falling tide, resuspension of sand occurs as the salt wedge retreats downstream, promoted especially by intense turbulence at the salt wedge tip (Ward, 1976; Kostaschuk and Luternauer, 1989). However, persistent shoaling occurs in the reach so not all of the deposited material evidently is resuspended. This phenomenon of sand deposition beneath the salt wedge is common in estuaries.

Figure 27 summarizes the observations of flow and sediment transport at the two measurement stations during the 1986 season. From the observations shown in figures 26 and 27 the following conclusions may be made concerning sediment transport in the outer Main Arm (cf. Kostaschuk et al., 1989a):

- there is a direct relation between seasonal discharge and sediment transport, as is expected by sediment transport from

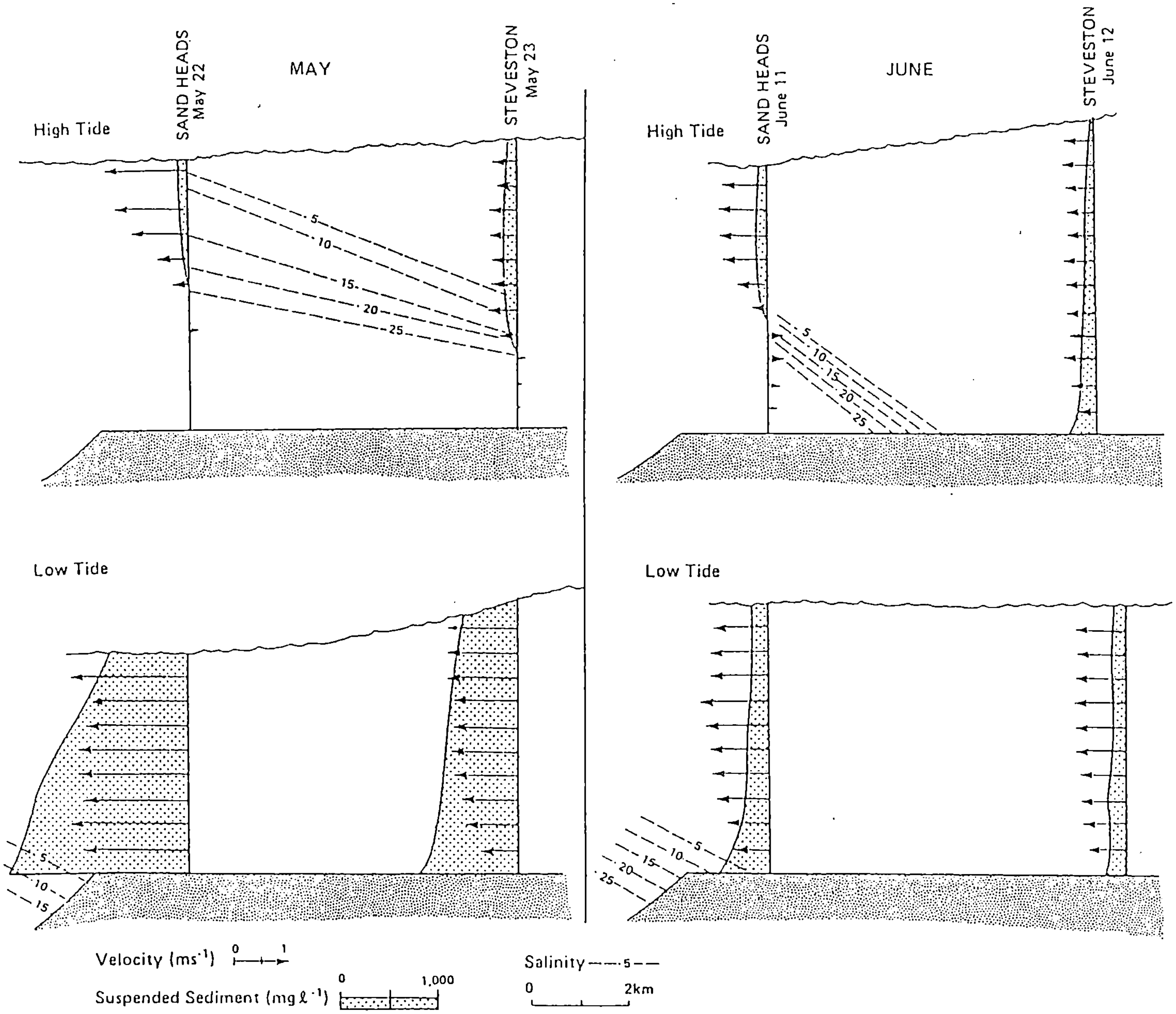


Figure 26. Along channel variation in water column state for high and low tides (1985 freshet measurements).

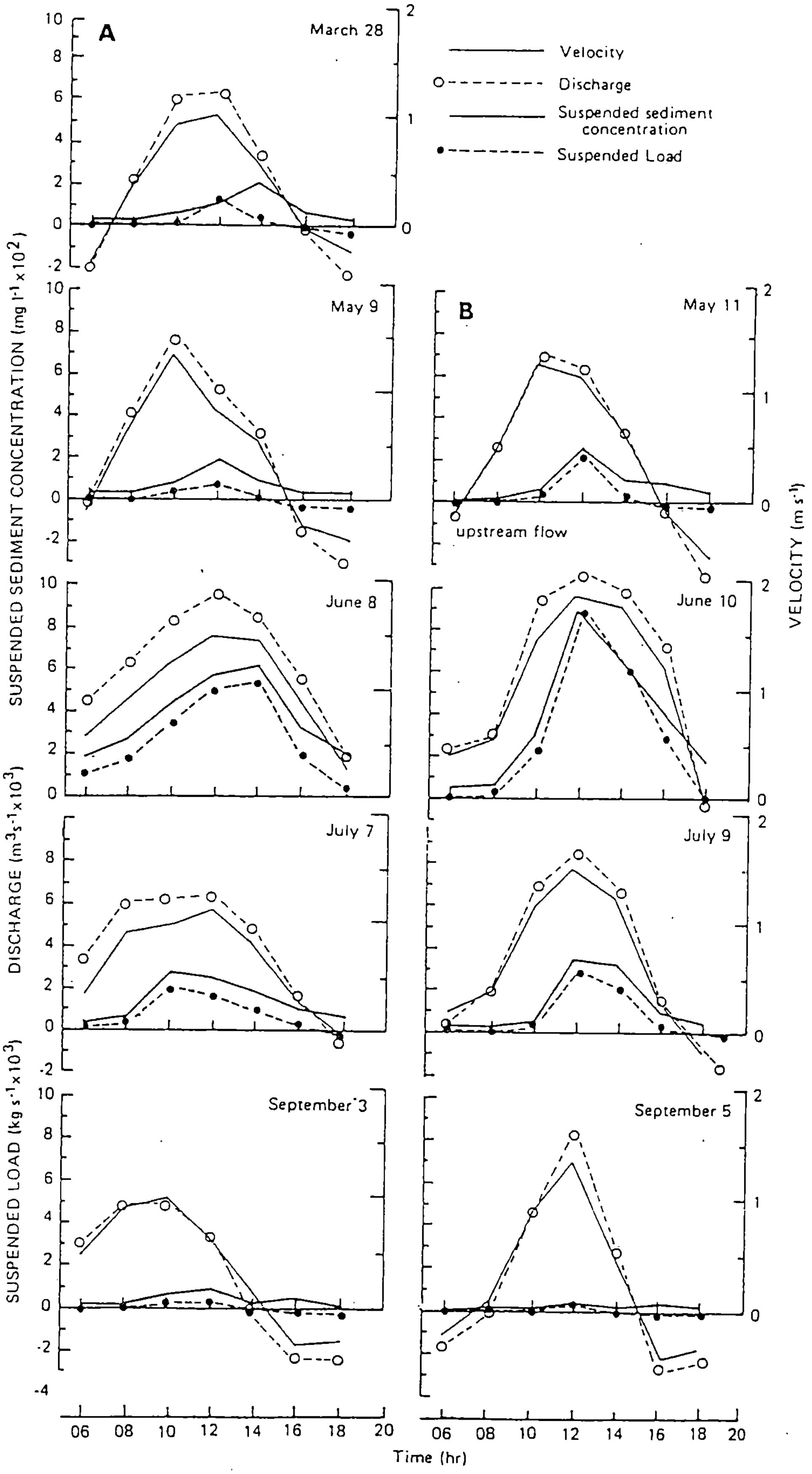


Figure 27. Flow and sediment transport during the 1986 freshet at (a) Steveston and (b) Sand Heads.

upstream, and the relation reveals the known hysteresis controlled by fine sediment supply;

- sediment transport varies directly with tidal range;
- sediment transport and suspended sediment texture vary inversely with tidal stage within the daily cyles.

Milliman (1980) made similar observations and also noted that silt and clay concentrations remain relatively constant over the tidal cycle, 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 was studied in 1986 at Sand Heads and Steveston and provides the basis for a first estimate of bedload transport (Kostaschuk et al., 1989b). Average bedform amplitudes were in the range 0.5 - 2.0 m (figure 28), although individual amplitudes as great as 4 m have been observed at Steveston. Wavelengths typically are in the range 10 - 60 m, extending to over 100 m. Wave celerities vary from 0 (in neap tides) to order 10 m day^{-1}, rising as high as 50 m day^{-1}. (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 Pretious and Blench, 1951). Bedform development appears to be restricted to flows above 4000 m^{3}s^{-1} (as at Mission), and so they evolve during the period of about 60 to 75 days that mark the peak of the annual flood. The sand wave development typically lags the flow.

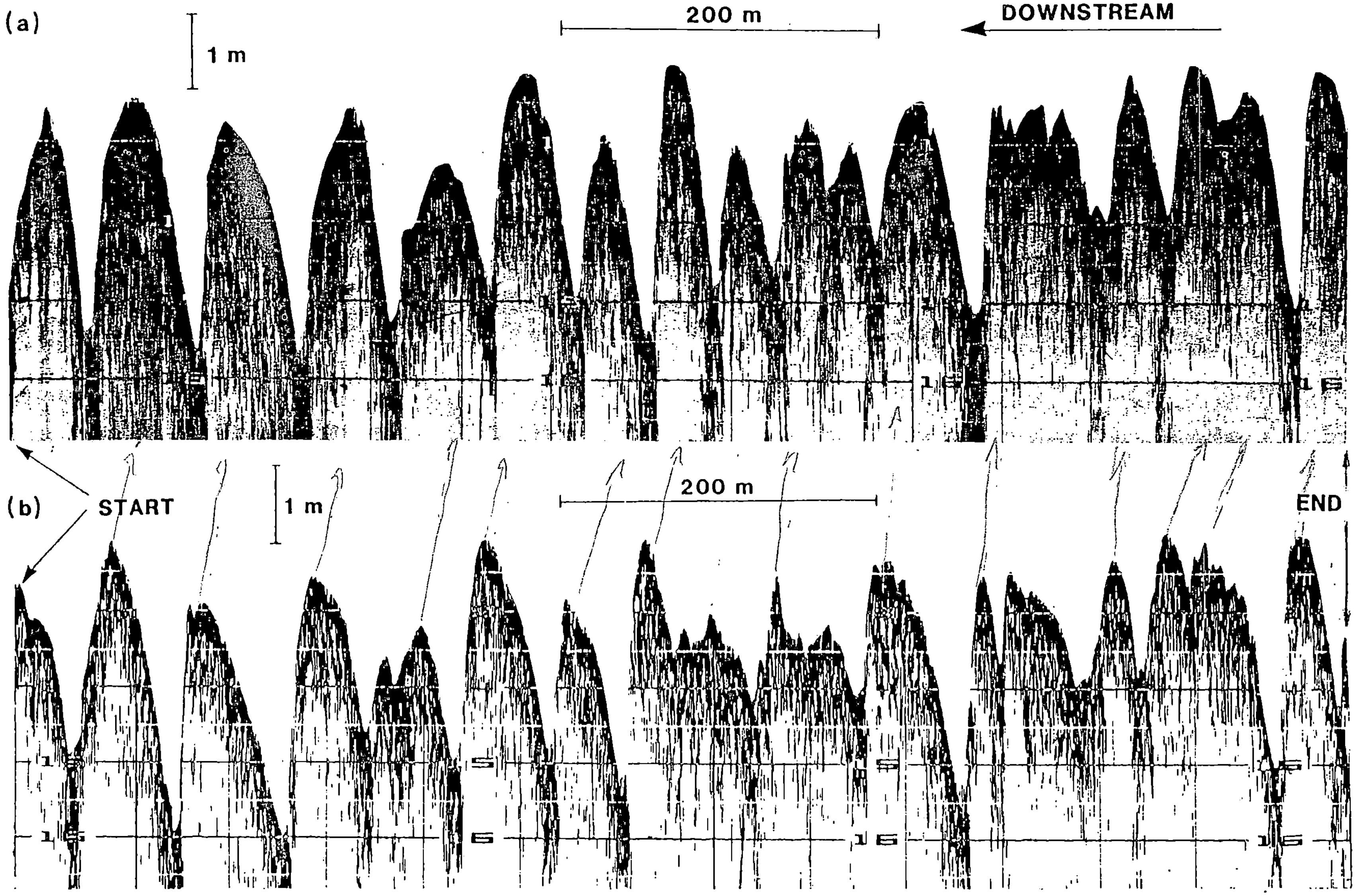


Figure 28. Replicate echo sounding records along the Sand Heads survey line, illustrating bedform migration. Average migration rate was 14.8 m day^{-1}. Some evolution of individual bedforms is evident. (a) Line began at 0831 and ended at 0839 on June 25. (b) Line began at 0837 and ended at 0845 on June 26, 1986.

These data form the basis for estimates of sand transport associated with the bedforms varying from 1000 to 10 000 tonnes day^{-1} (see Kostaschuk et al., 1989b, for details). The estimated transport rates compare well with estimates for Mission and Port Mann (see figure 22, page 65), and are well correlated with the flow at Port Mann. By using the known sand transport at Mission as a "template", the relatively sparse measurements were applied to make a first estimate of the seasonal sand transport in the estuary (figure 29). Our estimate was 0.35×10^6 tonnes. However, this result incorporates a correction factor for lee-side flow separation over sand waves (Engel and Lau, 1981). Subsequent current meter studies have failed to confirm the separation. Ignoring this factor would yield a revised estimate of 0.50×10^6 tonnes for the 1986 freshet. At Mission, the total transport of +0.125 mm sand (bed material) in 1986 was 3.8×10^6 tonnes.

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

$$I - D + \Delta S = 0$$

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

For a 10-year period, 1975-84, for which all of the left-hand terms are available, an estimated sediment budget for bed material in the estuary is given in table 10. These figures indicate net degradation (deepening and widening) of the delta channels during

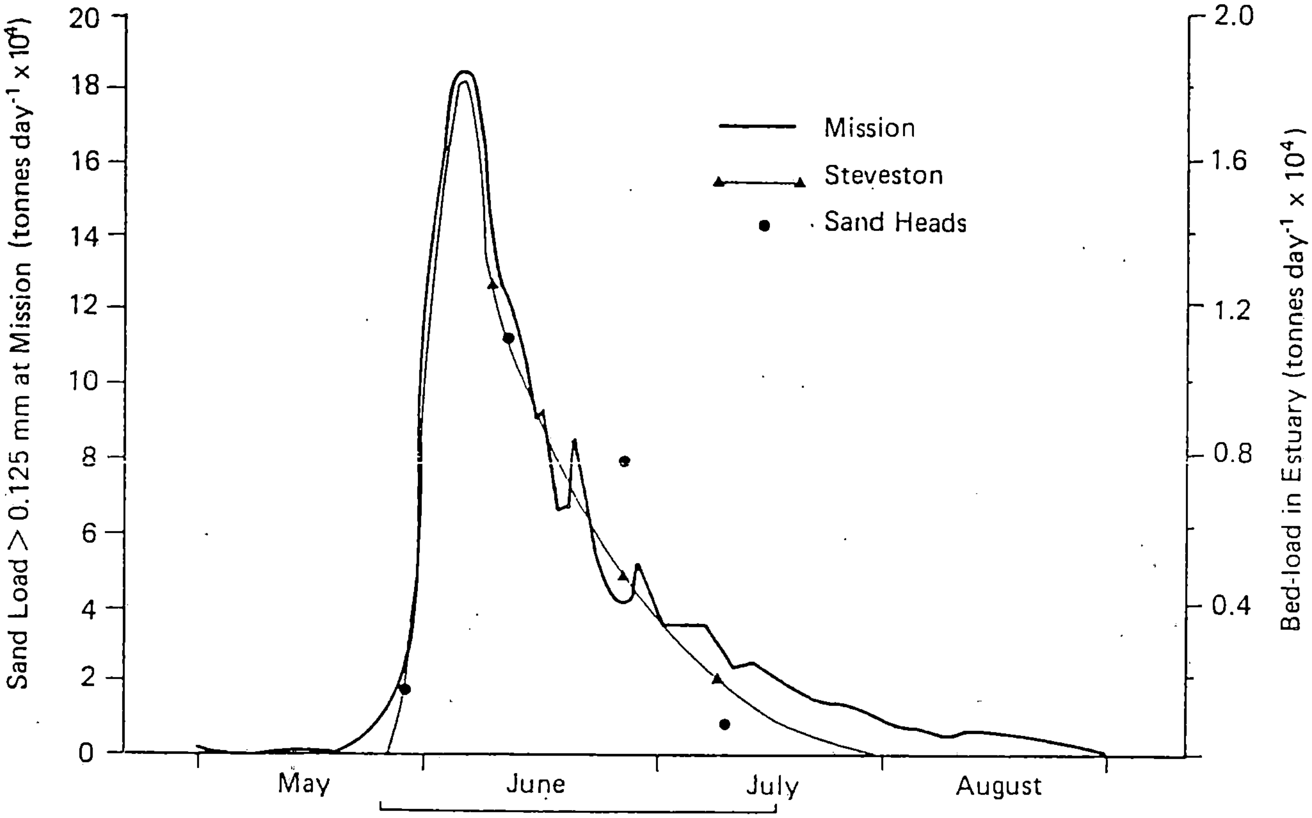


Figure 29. Observations of bedload transport associated with sand wave migration in the Main Arm (1986) superimposed on the bed material (+0.125 mm) sand load at Mission for the 1986 freshet. The Steveston line represents an interpolated hydrograph for bedload in the outer Main Arm guided by the Mission data and Steveston observations. The line under the diagram represents the period when Port Mann flows exceeded 6380 m^3s^{-1}, which corresponds with the indicated duration of bed wave movement.

the period, essentially all of which occurs along the Main Arm and Main Stem.

The estimated outgoing bed material load at Sand Heads is about twice the bedload transport estimated in 1986, a year with a relatively high freshet. The difference may represent bed material transport not associated with the sand waves, or it may represent errors in one or another of the volume estimates, or it may reflect the particular results of dredging in 1985-86. The sediment balance indicates that, in the long term, dredging activities are reducing delivery of +0.180 mm sand to the delta front by about 1.5×10^6 tonnes yr^{-1} -- about 60% of the natural load.

It is interesting to speculate what the effect might be of this change in coarser sand delivery to the delta front. Luternauer and Murray (1973) found that this material is deposited on the tide flats near the distributary mouths. It is apparent that foreshore structures have influenced its spatial distribution for many years. In general, the delta front slope is directly related to sediment size on a delta front: coarser grained deltas stand at steeper foreslope angles. A recent analysis of precisely navigated hydrographic sounding lines (Stewart and Tassone, 1989) shows that -- as measured at the -90 m contour -- the delta front is advancing, as would be expected. However, the -10 m contour exhibits variable behaviour in recent years, with frequent cases of retreat of order 10 m. These results can be interpreted to imply that the delta front is evolving toward a flatter upper foreslope.

TABLE 10

ESTIMATED AVERAGE ANNUAL BED MATERIAL (+0.18 mm) BALANCE BELOW PORT MANN, 1975-1984

TERM	MAGNITUDE (10^6 tonnes yr^{-1})
I Inflow of bed material (estimated at Mission; long term average)	2.4
D Main Arm dredging:	
Navigation maintenance	2.6
Borrow	1.6
ΔS Change in channel storage	-2.7(net loss)
Ø Outflow at Sand Heads (residual)	0.9

This could be a consequence of the change in size distribution of sediments reaching Sand Heads.

It is interesting to leave the last words on sedimentation 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 using 1929 and 1959 detailed charts -- essentially identical with Stewart and Tassone's figure of 8.6 m yr^{-1}. 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 $23x10^6$ tonnes of sediment input per year. The result differs from the observed yield at Mission by only 20%.

Another topic about which there is not yet sufficient understanding is water quality in the outer estuary. Physical and chemical characteristics of the water are not easily measured because of dilution, tidal action, natural variability, and other factors. Some areas of specific degradation are known, however. A zone of severe degradation occurred over a limited area at Sturgeon

Bank due to the Iona Sewage Treatment Plant outfall where impacts were documented on sediments and biota. Relocation of the outfall to deep water should substantially improve water quality in the area. Bacterial contamination in Boundary Bay has resulted in closures to commercial bivalve harvesting for many years. Much of the problem at this location can be attributed to tributary creeks and the Serpentine River, all of which carry major agricultural drainage.

There remains a clear need to continue to undertake monitoring programmes in the estuary for sediments, water quality, and biota. Onshore, the continuing development of riparian land poses major problems for aquatic habitat maintenance. Most important of all, perhaps, is a need to initiate studies of how these various factors interact, to improve our understanding of the complexities of the estuary.

4. REFERENCES

Ages, A. and Woolard, A. 1976. The tides in the Fraser River estuary. Environment Canada, Institute of Ocean Sciences, Sidney, British Columbia. Report 76-5. 100 pp.

Beak Consultants Ltd. 1980. Proposed improvements to the Fraser River Shipping Channel, unpublished report to Public Works Canada, Vancouver, B.C.: 330 pp.

Colby, B.R. 1964. Discharge of sands and mean-velocity relationships in sand-bed streams. United States Geological Survey Professional Paper 462-A: 47 pp.

de Vries, M. 1973. On measuring discharge and sediment transport in rivers. Internation Association for Hydraulic Research, Seminar on Hydraulics of Alluvial Streams, New Delhi, p. 1-9.

Engel, P. and Lau, Y. L. 1981. Bed-load discharge coefficient. American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division 107: 1445-1454.

Fraser River Board. 1963. Final report on flood control and hydro-electric power in the Fraser River basin. Victoria, B.C., Queen's Printer, 106 pp.

Johnston, W.A. 1921. Sedimentation of the Fraser River Delta. Geological Survey of Canada Memoir 125, 46 pp.

Keane, J.C.B. 1957. Report on the hydrometric surveys and discharge computations for the Fraser River estuary for May, June and August, 1954. Dominion-Provincial Fraser River Branch, Victoria, British Columbia. Technical Monograph. Open File Report.

Kellerhals, R. 1984. Review of sediment survey program, Lower Fraser River British Columbia. Consulting report to Sediment Survey Section, Water Survey of Canada, 36 pp.

Kellerhals, R., Miles, M.J. and Zallen, M. 1987. Effects of gravel mining on the Salmonid resources of the lower Fraser River. Kellerhals Engineering Services, Ltd. Report to Canada Dept. Fisheries and Oceans. Various pagination.

Kidd, G.J. 1953. Fraser River suspended sediment survey: interim report for the period 1949-1952. Department of Lands and Forests, Water Rights Branch, Water Resources Division, Province of British Columbia, 35 pp.

Kostaschuk, R. A. and Luternauer, J. L. 1989. The role of the salt-wedge in sediment resuspension and deposition: Fraser River estuary, Canada. Journal of Coastal Research 5: 93-101.

Kostaschuk, R. A., Luternauer, J. L. and Church, M. A. 1989a. Suspended sediment hysteresis in a salt-wedge estuary: Fraser River, Canada. Marine Geology 87: 273-285.

Kostaschuk, R. A., Church, M. A. and Luternauer, J. L. 1989b. Bedforms, bed material, and bedload transport in a salt-wedge estuary: Fraser River, British Columbia. Canadian Journal of Earth Sciences 26: 1440-1452.

Krahn, P., Shrimpton, J. and Glue, R., 1987. Assessment of stormwater related chlorophenol releases from wood protection facilities in British Columbia. Environment Canada 87-14.

Lawson, E., Mitchell, G., and Walton, D. 1985. Stormwater monitoring in an industrial catchment basin located in Burnaby, British Columbia. British Columbia Ministry of Environment. Unpublished report.

Luternauer, J.L. and Murray, J.W., 1973. Sedimentation on the western delta-front of the Fraser River, British Columbia. Canadian Journal of Earth Sciences 10: 1642-1663.

Mannerstrom, M. and McLean, D.G. 1985. Estimating bed-load in the Lower Fraser River. Canadian Society for Civil Engineering, 7th Hydrotechnical Conference, Saskatoon, vol. 1B, pp. 97-116.

Mathews, W.H. and Shepard, F.P. 1962. Sedimentation of Fraser River Delta, British Columbia. American Association of Petroleum Geologists Bulletin 46: 1416-1443.

McLean, D.G. 1990. Channel instability and sediment transport on lower Fraser River Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-SS-90-xx. In press.

McLean, D.G 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-86-62 56 pp and tables, figures.

McLean, D.G. and Mannerstrom, M. 1984. History of channel instability: Lower Fraser River, Hope to Mission. Environment Canada, Water Resources Branch, Sediment Survey Section. Report IWD-HQ-WRB-55-85-2: 18 pp + tables, figures.

McLean, D.G. and Tassone, B. 1985. discussion of: Bed-load sampling and analysis by David Hubbel. In Thorne, C.R., Hey, R.D., and Bathurst, J.C., editors. Sediment Transport in Gravel-bed Rivers, Chichester, Wiley. In press.

Meyer-Peter, E. 1937. discussion of: Appareil pour le jaugeage du debit solide entraine sur le fond du cours d'eau by J. Smetana. International Association of Hydraulics Structure Research, Berlin, pp. 113-116.

Milliman, J.D. 1980. Sedimentation in the Fraser River and its estuary, southwestern British Columbia. Estuarine and Coastal Marine Science, 10, pp. 609-633.

Morasse, B. 1985. Fraser River model study: generation of the 1968 hydrometric data of the lower Fraser River using the 1-D hydrodynamic model. Environment Canada, Inland Waters Directorate, Water Planning and Management Branch: 167 pp.

Northcote, T., Johnston, N. and Tsumura, K. 1975. Trace metal concentrations in lower Fraser River fishes. The University of British Columbia, Westwater Research Centre, Technical Report 7.

Northcote, T.G., and Larkin, P.A. 1989. The Fraser River: a major salmonine production system. In Dodge, D.P., editor, Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Science 106: 172-204.

Novak, P. 1957. Bed-load meters - development of a new type and determination of their efficiency with the aid of scale models. International Association for Hydraulic Research, 7th Congress, Lisbon. Proceedings, vol. 1: 11 pp.

Parker, G., Klingeman, P. and McLean, D.G. 1982. Bedload and size distribution in paved gravel-bed streams. Journal of the Hydraulics Division, American Society of Civil Engineers, Hy4, pp. 544-571.

Pretious, E. 1972. Downstream sedimentation effects of dams on Fraser River, B.C. Department of Civil Engineering Water Resources Series No. 6, University of British Columbia, 91 pp.

Pretious, E.S. and Blench T. 1951. Final report on special observations of bed movement in Lower Fraser River at Ladner Reach during 1950 freshet. Canada National Research Council. Fraser River Model Project, 12 pp.

Singleton, H. 1983. Trace metals and selected organic contaminants in Fraser River fish. British Columbia Ministry of Environment, Technical Paper 2.

Stewart, I. and Tassone, B. 1989. The Fraser River delta: a review of historic sounding charts. Environment Canada, Inland Waters Directorate, Pacific and Yukon Region, Vancouver: 39pp.

Stichling, W. 1969. Instrumentation and techniques in sediment surveying. 7th Canadian Hydrology Symposium: Instrumentation. Proceedings. National Research Council of Canada, Associate Committee on Geodesy and Geophysics, Subcommittee on Hydrology. vol. 1: 81-139.

Supervisory Coordinating Committee, 1987. Summary report of the 1986 effluent monitoring program. Fraser River estuary monitoring. Fraser Port and the British Columbia Ministry of Environment.

Swain, L. 1983. Stormwater monitoring of a residential catchment area. British Columbia Ministry of Environment. Unpublished report.

Swain, L. and Walton, D. 1988. Report on the 1987 benthos and sediment monitoring program. Fraser River estuary monitoring. Fraser Port and the British Columbia Ministry of Environment.

Swain, L. and Walton, D. 1989. Report on the fish monitoring program. Fraser River estuary monitoring. Fraser Port and the British Columbia Ministry of Environment.

Tywoniuk, N. 1972. Sediment budget of the Lower Fraser River. Thirteenth Coastal Engineering Conference, American Society for Civil Engineers, vol. 2, pp. 1105-1122.

Water Management Branch, 1989. The attainment of ambient water quality objectives in 1988. British Columbia Ministry of Environment. Report.

Water Survey of Canada. 1970. Hydrometric and sediment survey, Lower Fraser River. Progress Report 1965-1968. Sediment Survey Section. Water Resources Branch, Ottawa: 133 pp.

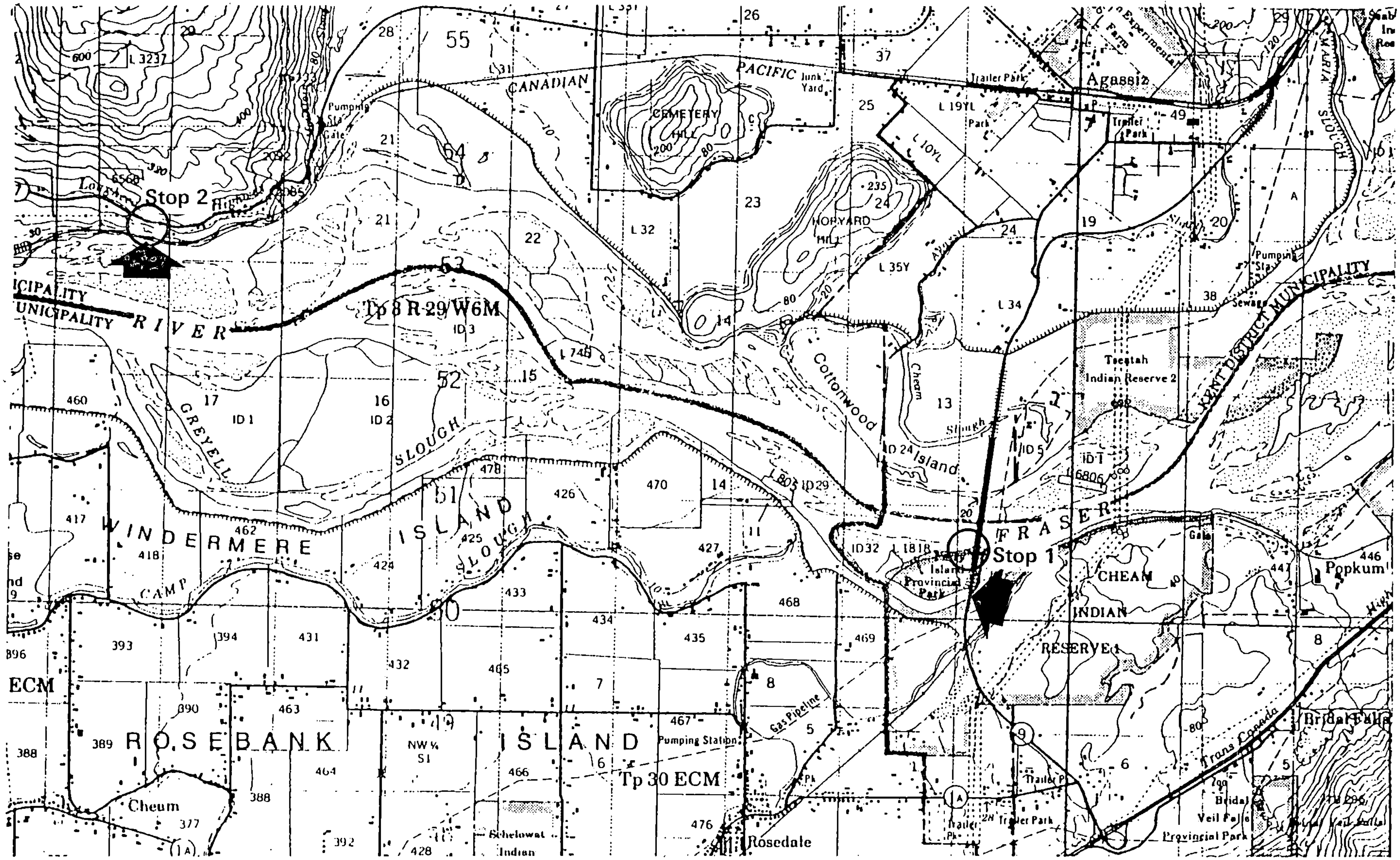
Western Canada Hydraulic Laboratories Ltd. 1977. Feasibility study, development of a forty-foot draft navigation channel New Westminster to Sandheads. Unpublished report to Public Works Canada: 107 pp.

Ward, P. R. B. 1976. Seasonal salinity changes in the Fraser River estuary. Canadian Journal of Civil Engineering 3: 342-348.

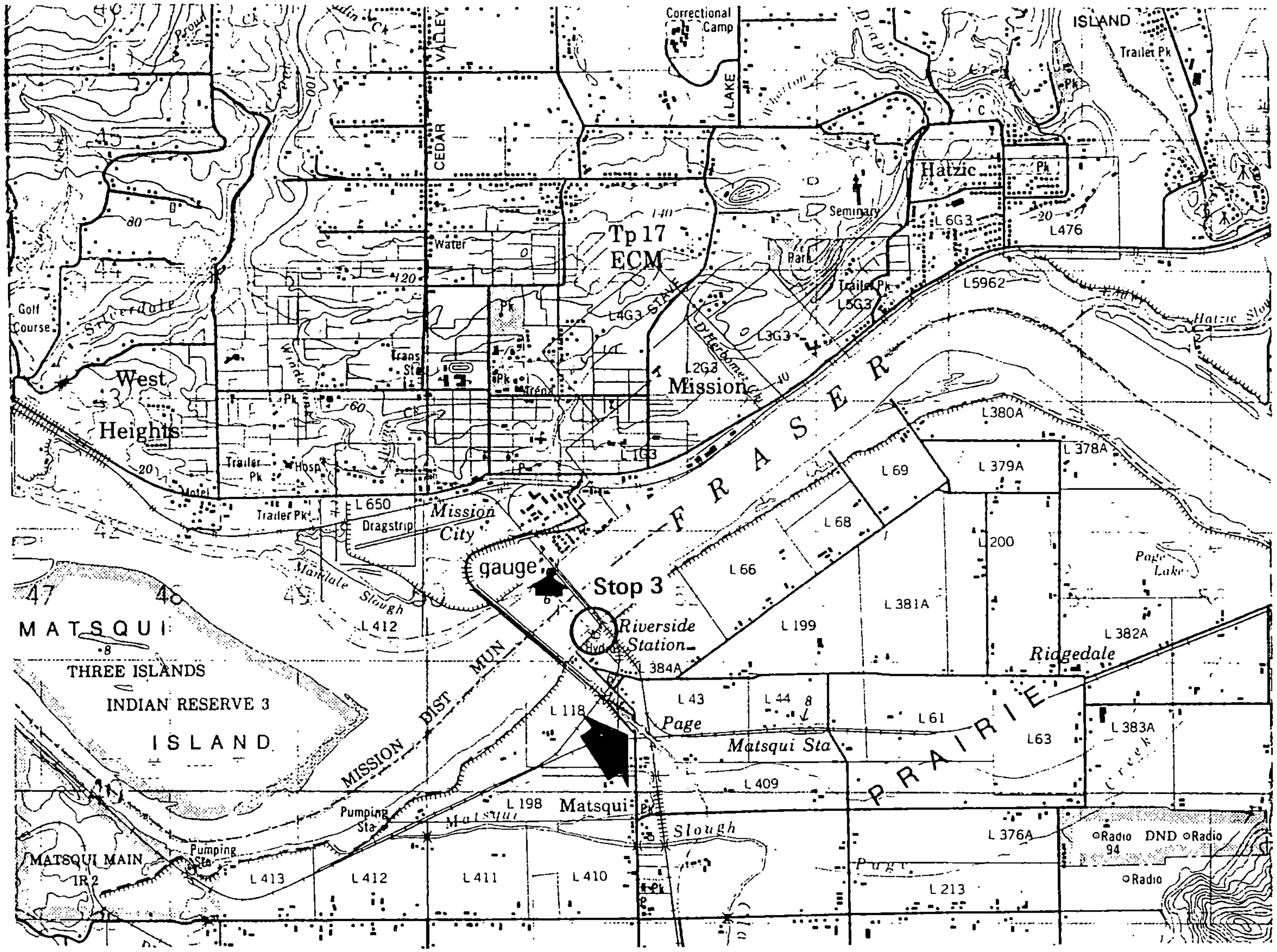
Wolman, M.G. and Miller, J.P. 1960. Magnitude and frequency of forces in geomorphic processes. Journal of Geology, vol. 68: 54-74.

APPENDIX

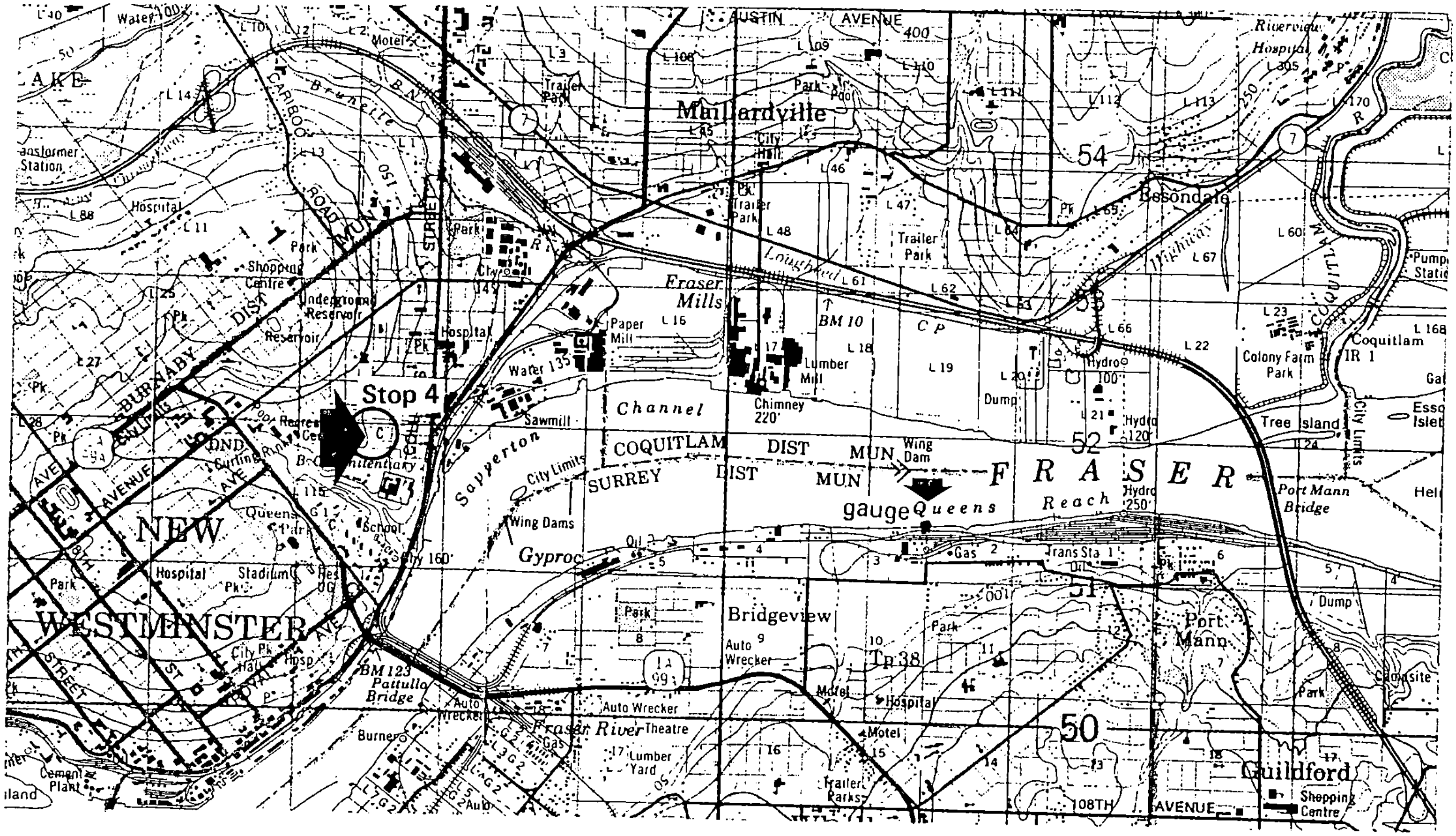
FIELD ACCESS MAPS



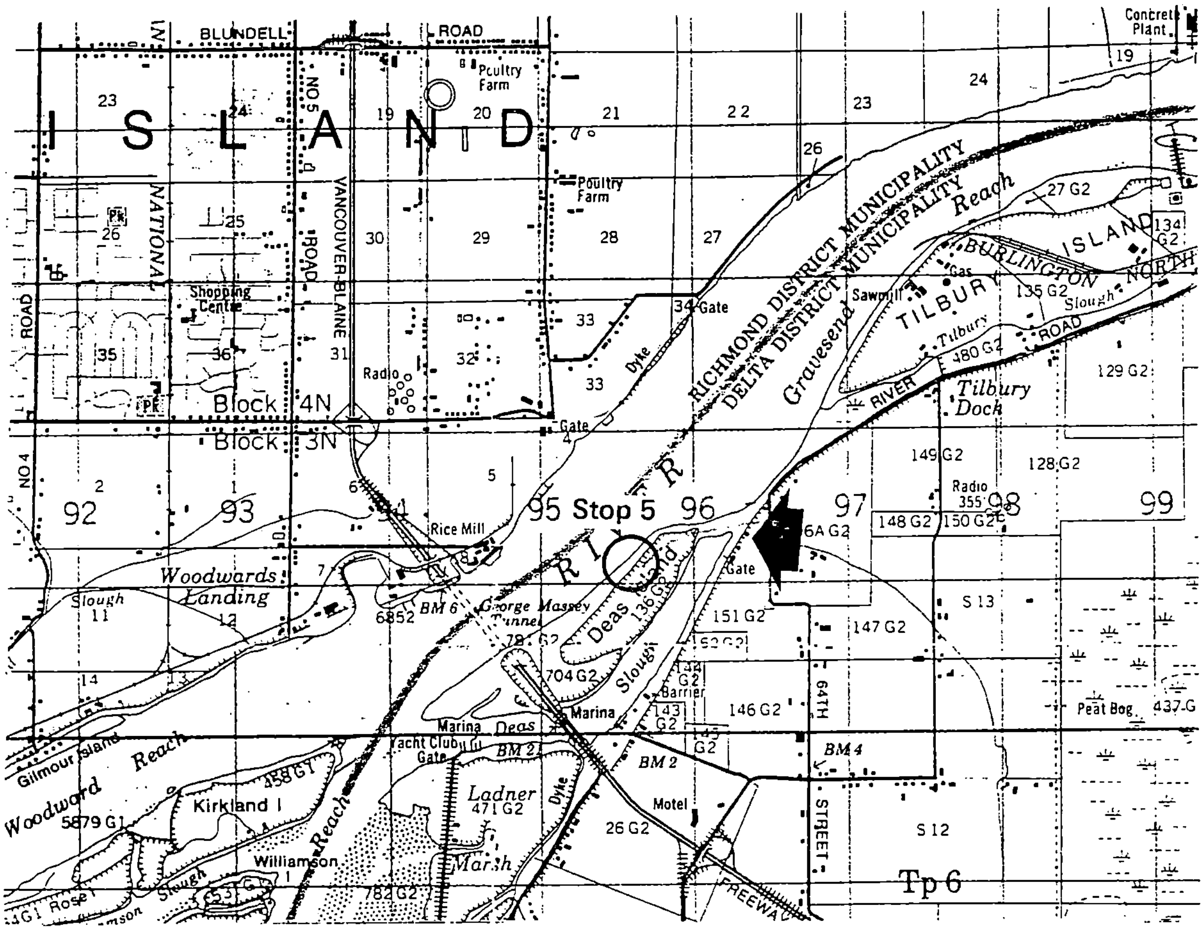
STOPS 1 and 2. Access to Stop 1, by the Rosedale Bridge in Ferry Island Provincial Park, is by a right turn of Highway 9 when travelling north, immediately before the bridge. When travelling south, the turn is nearly 180°. Stop 2 is a roadside picnic stop and lookout on Highway 7. Vision is very restricted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



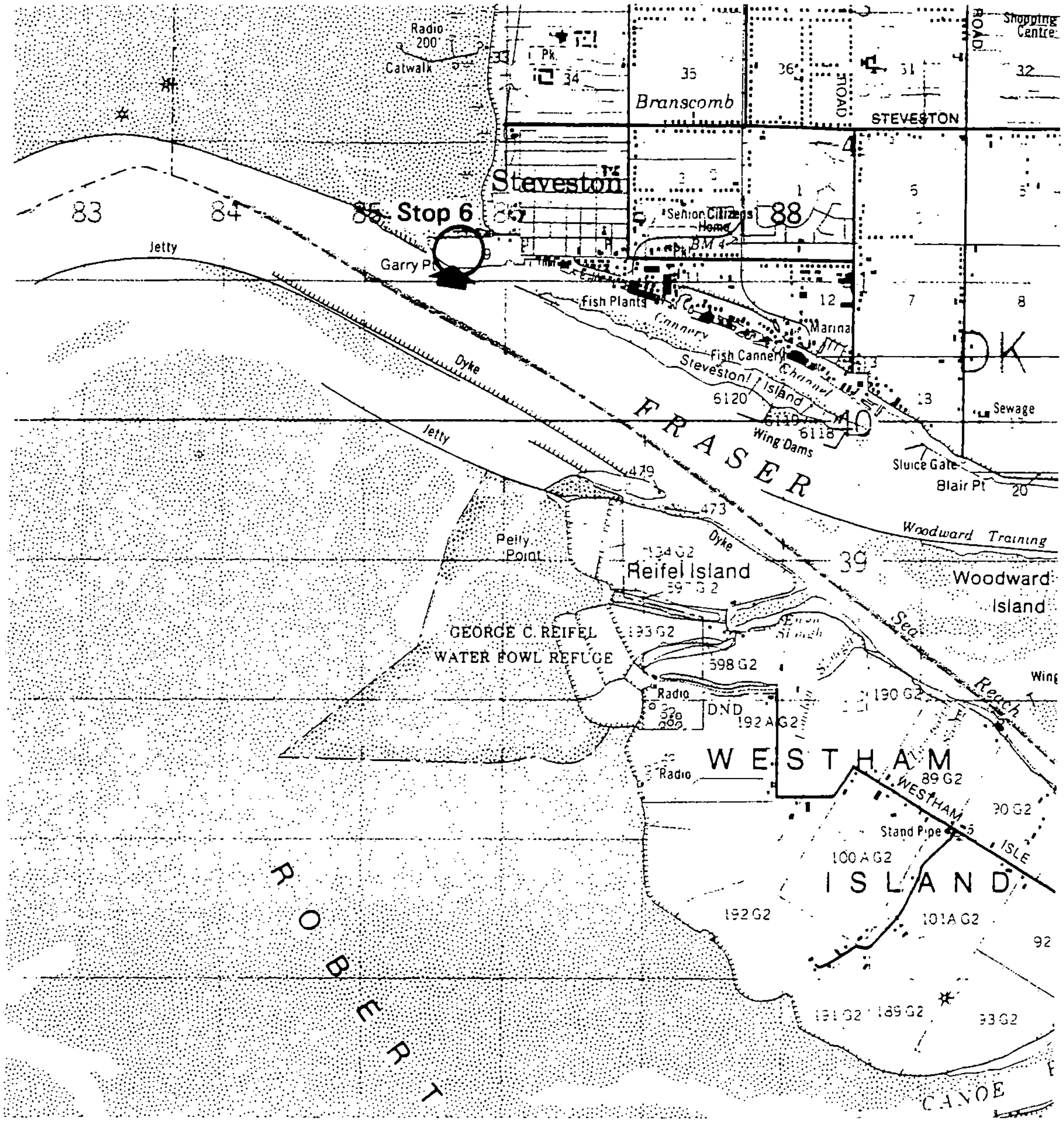
STOP 3. Access is from the Matsqui village main road, by a right exit from Highway 11 when travelling north. Take the first off-ramp after the bridge when travelling south. The lookout is at a parking place on the dike immediately before the railway.



STOP 4. Take the Brunette south exit from Highway 1; right onto Braid Street (first intersection - traffic light). Cross Columbia Street and bear left onto 8th Avenue; turn left into Richmond Street. View the river from Richmond at the New Westminster Cemetary. Approaching from Pattullo Bridge or Highway 1A (McBride Blvd.), turn east at 6th Avenue (traffic light), then right at Cumberland and left at Richmond.



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



STOP 6. Proceed through central Steveston to the park at Garry Point.

Channel stability and
management of Lower Fraser
River: field excursion guide.

Channel stability and management of Lower Fraser River: field excursion guide.

DATE	ISSUED TO

DATE	ISSUED TO