Liard River Basin Spring Flood: Progress Report

B.J. Grey and D.A. Sherstone

DRAFT

DEPARTMENT OF INDIAN AFFAIRS AND NORTHERN DEVELOPMENT

Northern Program, Water Resources Program

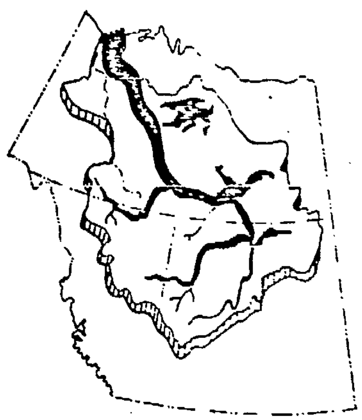
Headquarters

Liard River Basin

Spring Flood

Progress Report

B.J. Grey
D. A. Sherstone



Hull, Quebec

March, 1980

Prepared by
Snow & Ice Division, N.H.R.I.,
Inland Waters Directorate
Environmental Management Service
Environment Canada

A report under the 1978-81 Federal - Provincial
Study Agreement respecting the water and
related resources of the Mackenzie River Basin.

SYNOPSIS

Aerial reconnaissance and ground monitoring were used to determine the characteristics, pattern and timing of river ice break-up on the Liard River. Ice jams and their associated effects were studied, and channel morphometry was investigated at two ice jam-prone sites. A limited program to measure pre-break-up ice thickness was initiated. Ice thickness was variable across the channel, and decreased rapidly immediately before break-up. Discharge increase was the major factor in initiating and sustaining break-up. In 1979, ice jams were more frequent than in 1978 but of lower magnitude, and the locations were similar to those noted in 1978. Suspended sediment sampling was undertaken almost daily on the Fort Nelson and Muskwa Rivers at Fort Nelson, and occasionally on the Liard at Lower Crossing. Sediment loads were computed for these sites, and compared to data for the Liard River near the mouth, provided by Water Survey of Canada. The importance of the Fort Nelson/Muskwa Rivers as sediment sources to the Liard during break-up was confirmed, and a similar situation occurred during the mid-summer rainstorm period. However, in the period mid-May to mid-June, the upper Liard Basin, as represented by Liard at Lower Crossing, had higher suspended sediment discharge to the lower Liard than did the Fort Nelson system. The sediment role of the Liard Basin within the Mackenzie is also reviewed.

Snow and Ice Division,
National Hydrology Research Institute,
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OTTAWA, Ontario.
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March 10, 1980.

Mr. A.R. Waroway,
Hydrologist,
Water Resources Division,
Dept. of Indian Affairs and Northern Development,
Room 630, North Tower,
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OTTAWA, Ontario.
K1A 0H4

Dear Mr. Waroway:

Liard River Basin Spring Flood: 1979/80 Report

Enclosed are 30 copies of the aforementioned report, as per the letter of agreement between Water Resources Division, Dept. of Indian Affairs and Northern Development, and Snow and Ice Division, Environment Canada. This report has been prepared by Mr. B.J. Grey and Mr. D.A. Sherstone, and is an account of the progress made during the 1979 field reconnaissance and office studies pertaining to the hydrologic aspects of the Liard River Basin spring flood. I trust that the report meets with your approval.

Yours sincerely,

John C. Anderson

John C. Anderson

ACKNOWLEDGEMENTS

We wish to thank, first of all, the Mackenzie River Basin Committee, who through the Water Resources Division, Dept. of Indian Affairs and Northern Development, provided the financial support which allowed us to conduct this study. We also wish to acknowledge assistance from the following organizations and individuals: the Polar Continental Shelf Project, Dept. of Energy, Mines and Resources, Ottawa, for the supply of an air photo aircraft and air crew; Water Survey of Canada for the provision of preliminary stream discharge and suspended sediment data (M. Alford, K. Davies and W. Lutsiak), and for equipment storage at Whitehorse (M. Alford); Sediment Survey Section, I.W.D., Environment Canada, Ottawa, for the loan of sampling equipment (Y. Durette), and computational assistance (M. Cashman), and the provision of laboratory analysis (R. Myslick, Guelph); B.C. Hydro, Vancouver, for the provision of field research notes and miscellaneous sediment data; Mr. C. Bil (National Water Research Institute, Burlington, Ont.) for the loan of gauging equipment; the Climatological Applications Branch, A.E.S. (Downsview, Ont.), for the provision of meteorological data; J. Glynn (N.H.R.I., Ottawa) for assistance with computer analysis; J. Anderson (N.H.R.I., Ottawa) for assistance in the field, and discussion of the report; and finally, Max Perchanok, without whom much of the field work could not have been done.

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CHAPTER I

INTRODUCTION

Covering approximately 280,000 km^2, the Liard River Basin (see Figure 1) is the second largest tributary area to the Mackenzie River, comprising 16% of that basin's total area. The Liard Basin encompasses portions of the southern Yukon, southwestern N.W.T., northern British Columbia, and northwestern Alberta, and displays a wide variety of topography, climate, vegetation, etcetera. (For background information on these and other aspects of the basin's physiography, see Mackenzie Basin Intergovernmental Liaison Committee, 1976).

Unlike the Athabasca and Peace Rivers (the third largest and the largest tributaries) whose flows are severely regulated by their passage through Lake Athabasca and Great Slave Lake en route to the Mackenzie River, the Liard River's discharge encounters no such storage delay from large lakes. Some of the consequences of this relatively unregulated flow for the Mackenzie River proper have been investigated in recent years. For example, it is now recognized that the Liard spring flood is the prime instigator of ice break-up on the Mackenzie River between Ft. Simpson and Ft. Good Hope, N.W.T. (MacKay and Mackay, 1973). Also, it has generally been assumed that the Liard River Basin, owing to its

MACKENZIE RIVER BASIN

FIGURE 1. LOCATION OF THE LIARD RIVER BASIN.

size and physical character, was the major contributor of suspended sediment to the Mackenzie River.

Nevertheless, knowledge of river ice processes and suspended sediment production and transport within the Liard River Basin itself was minimal. In 1978, the present study was initiated to investigate the hydrologic regime of the Liard River, with particular attention to the events of the spring flood period (Glaciology Division, 1978). This, the second report, presents the results of work conducted in 1979. It begins with a discussion of observations of the timing, magnitude and characteristics of river ice break-up on the Liard River and its major southern tributaries, the Ft. Nelson and Muskwa Rivers, and a reach of the Mackenzie River below Ft. Simpson, N.W.T. This is followed by an account of work undertaken to determine relative suspended sediment loadings and fluctuations in the Liard River Basin, focussing on the Muskwa and Ft. Nelson River contributions to the Liard. Some preliminary conclusions based upon the 1978 and 1979 studies are presented, and recommendations made for investigations to be undertaken during the third year of this project.

CHAPTER II

ICE BREAK-UP IN THE LIARD BASIN, 1979

D.A. Sherstone

A. Introduction

The progress report on break-up for 1979 concentrates on the major events during this period and the analysis of data gathered in 1978 and 1979. A description of the general processes and mechanics of ice break-up and spring flood will not be included in this report; readers desiring background information on this matter are referred to the Introduction of Chapter II of the 1978 "Liard Spring Flood-Progress Report" (Glaciology Division, 1978).

For 1979 the ice break-up component of the study involved five separate sub-studies. These were:

1. pre break-up ice thickness measurements;
2. aerial reconnaissance and monitoring of break-up;
3. selection of ice jam prone sites for detailed study in 1979 and 1980;
4. collection of channel geometry data during summer low flow periods for selected ice jam study sites; and,
5. latẽ summer examination of ice jam sites within the study basin, as determined from aerial monitoring/ photograhy, to aid in determination of factors responsible for jams.

As a background to the 1979 break-up the unspectacular nature of the spring flood must be noted. While air temperatures were normal, discharges throughout the early spring flood period were below those of 1978 (Table 1). As a result mechanical destruction of the ice cover did not occur at several locations; the ice cover simply melted out "in situ" over a period of several days. No major flooding from ice jams occurred. The frequency of ice jams increased but their severity was reduced compared to those observed in 1978. Ice thicknesses prior to and at break-up were also reduced.

Further, in the winter of 1978/79, precipitation was again below the 'normal', as was the snowpack prior to onset of the spring melt period (Table 2). As a result flow into the main channels in the basin was insufficient to produce a flood wave capable of mechanical destruction or lifting of the ice along the entire Fort Nelson - Liard system.

In 1979 the wide disparity of temperatures between Fort Nelson, B.C. and Fort Simpson, N.W.T. which existed in 1978, did not occur. Cooler temperatures persisted in the upper Mackenzie River - Great Slave Lake region but did not enter the Liard basin. Warmer temperatures prevailed throughout the study region.

Thus, from this year's program of break-up studies it would appear that Liard River discharge was less than sufficient to ensure destruction and flushing of the ice cover, even given favorable climatic conditions.

TABLE 1

MEAN DAILY DISCHARGES: APRIL 20 TO MAY 20: 1978 and 1979

(IN M^3/SEC)

DATE	MUSKWA RIVER AT FT. NELSON STA. 10CD001 1978	MUSKWA RIVER AT FT. NELSON STA. 10CD001 1979 *(1)	LIARD RIVER AT FT. LIARD STA. 10ED001 1978	LIARD RIVER AT FT. LIARD STA. 10ED001 1979 *(1)	LIARD RIVER NEAR THE MOUTH STA. 10ED002 1978	LIARD RIVER NEAR THE MOUTH STA. 10ED002 1979 *(1)
20	49	47	340	368	363	429
21	53	51	346	371	363	430
22	60	54	351	377	363	431
23	73	62	363	391	363	432
24	90	69	382	394	365	435
25	113	78	402	399	374	439
26	133	98	425	402	382	440
27	334	122	453	410	397	445
28	371	170	538	422	425	448
29	397	221	708	453	481	449
30	346	218	1303	453	623	455
1	303	204	2266	453	1048	461
2	270	195	2744	481	1756	470
3	220	190	2974	510	2266	480
4	179	158	2733	552	3398	495
5	151	135	2342	552	3115	510
6	129	124	2263	651	2889	535
7	118	103	2181	680	2662	555
8	112	95	2385	793	2492	590
9	112	95	2198	963	2322	625
10	112	100	2133	1133	2379	700
11	98	106	2005	1699	2436	900
12	97	116	1999	2266	2492	1150
13	106	120	1937	2549	2634	1450
14	118	112	1997	2690	2549	1850
15	156	99	2062	2832	2492	2400
16	156	98	2124	2974	2407	3000
17	169	101	2189	3087	2342	3980
18	208	105	2251	3087	2362	4060
19	208	105	2297	3200	2526	4340
20	185	101	2489	3370	2733	4840
TOTALS IN m^3/sec-day	5226	3652	51180	38962	53802	38224

*(1) Preliminary data only: supplied by Water Survey of Canada District Office

All other data from Water Survey of Canada published reports

TABLE 2

SNOW SURVEY DATA : FORT NELSON B.C., 1978 and 1979

1978		1979	
DATE	MEAN SNOW DEPTH(cm.)	DATE	MEAN SNOW DEPTH(cm.)
March 15	64.4	March 15	58.0
April 1	54.5	April 1	48.9
April 15	37.9	April 15	38.7
May 1	No Snow	May 1	No Snow

B. Pre-Break-Up Ice Thickness Measurements

In order to obtain an insight into ice thickness and eventually ice strength prior to initial movement, measurement of ice depths at three locations was proposed. In fact weak ice and a rapid increase in daytime temperatures resulted in only two sites being sampled, on April 24; MRAB and FNHRB.(1) The results of this restricted survey are nevertheless of interest in that they illustrate the extreme variability of the ice cover prior to initial movement. In 1979 the ice underwent weakening prior to disturbance, due to heat input from solar radiation and conduction from water moving in the channel. Further, increasing discharge caused erosion of the underside of the ice. The early disappearance of snow cover during warm weather in mid-April permitted solar radiation to accelerate weakening of the exposed ice cover. Much of the snow cover on the ice had disappeared by April 22, which suggests accelerated decay beyond those values recorded by Russian observers under similar conditions (Polyakova, 1966).

The ice began to break-up at both MRAB and FNHRB sites on April 27. If, as previous researchers have indicated, ice achieves maximum strength near the end of the winter, then internal weakening of the ice cover prior to the onset of mechanical break-up is significant

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(1) Symbols represent ice jam and sediment sampling site identifiers. For locations see Figures 2 & 3. For a description of the sites see Chapters II and III of the 1978 "Liard Spring Flood-Progress Report".

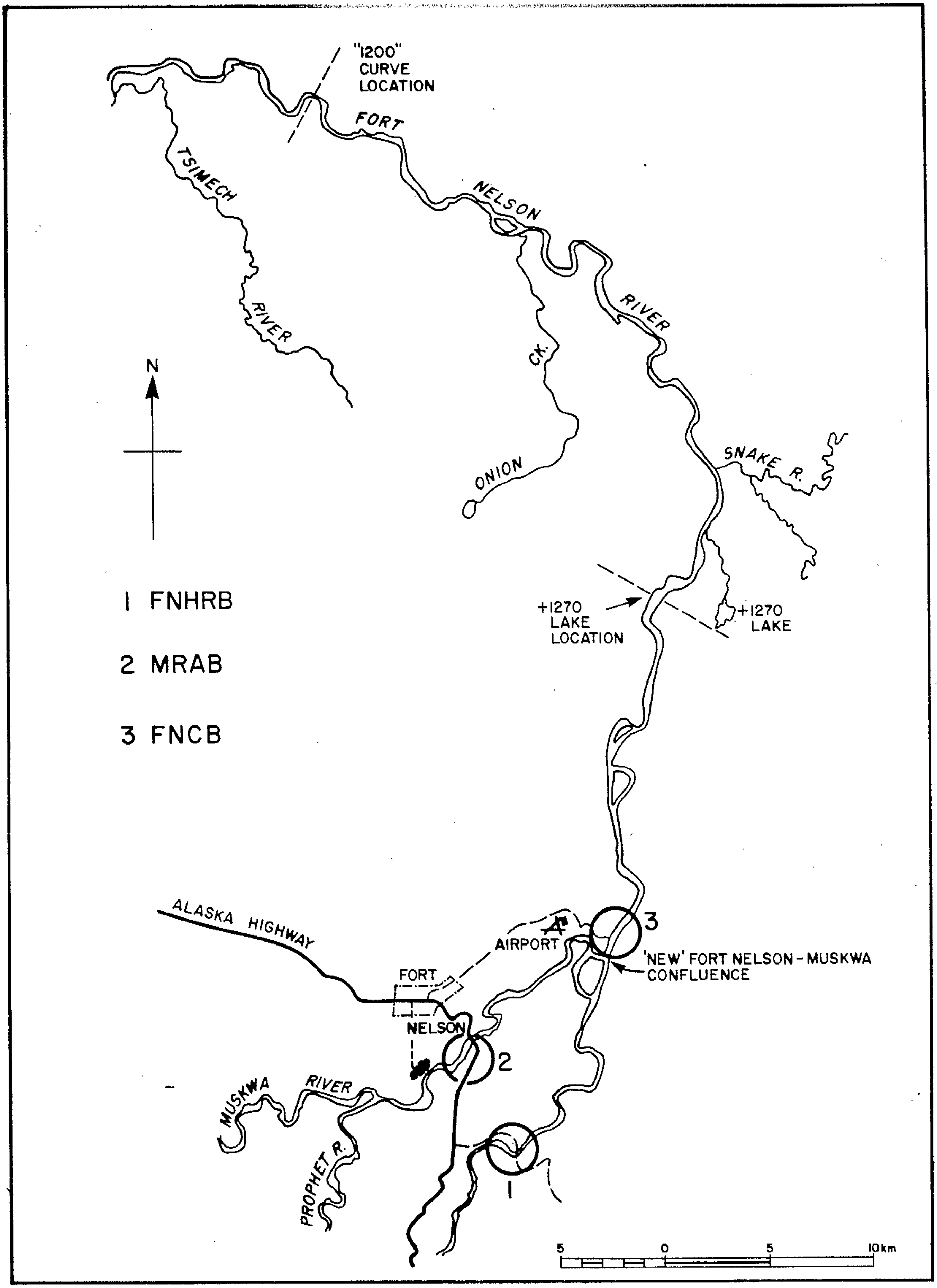


FIGURE 2-LOCATION OF BREAK-UP (GROUND STUDY) SITES NEAR FORT NELSON, B.C.

and the actual residual strength of the ice immediately prior to ice movement is of great importance. The variability of thickness and strength across any given cross-section is also a factor, one which has not been adequately considered in much of the theoretical and/or laboratory study of ice jams (c.f. Michel 1971 and Uzuner and Kennedy, 1976).

The ice thickness variations of the sample sections do not appear related to the depth of water beneath the ice cover (Figure 4 and Table 3). The ice thickness to total depth ratio, $\frac{I_t}{T_d}$, over the two sites sampled ranged from a low of 23% to a high of 75%, while the averages for the sites were 46% (FNHRB) and 39% (MRAB). The ice thickness values were again measured after break-up. In this period, from April 24 to April 30, the ice thickness decreased by approximately 40 - 45%.

The ice thickness variations are of interest in that they result in part from the freeze-up history and the accelerated thawing action prior to the date of the drilling. Hole #3 at the MRAB site had the greatest ice thickness and the most competant ice. The bulk of the ice at both sites was soft and slushy, with the visible lower layers grey and/or candled ice, while that of hole #3, MRAB was hard clear ice throughout. This analomous drill hole, which exhibited a surface layer of 4-5 cm of highly deteriorated snow-ice was located in ice which resulted from winter ice jam / refreeze processes. Evidence of previous ice disturbance in this area was found in the darker, harder ice in the hole and the rough texture of the surrounding ice.

FIGURE 4

ICE THICKNESS AT MRAB AND FNHRB SITES
APRIL 24, 1979

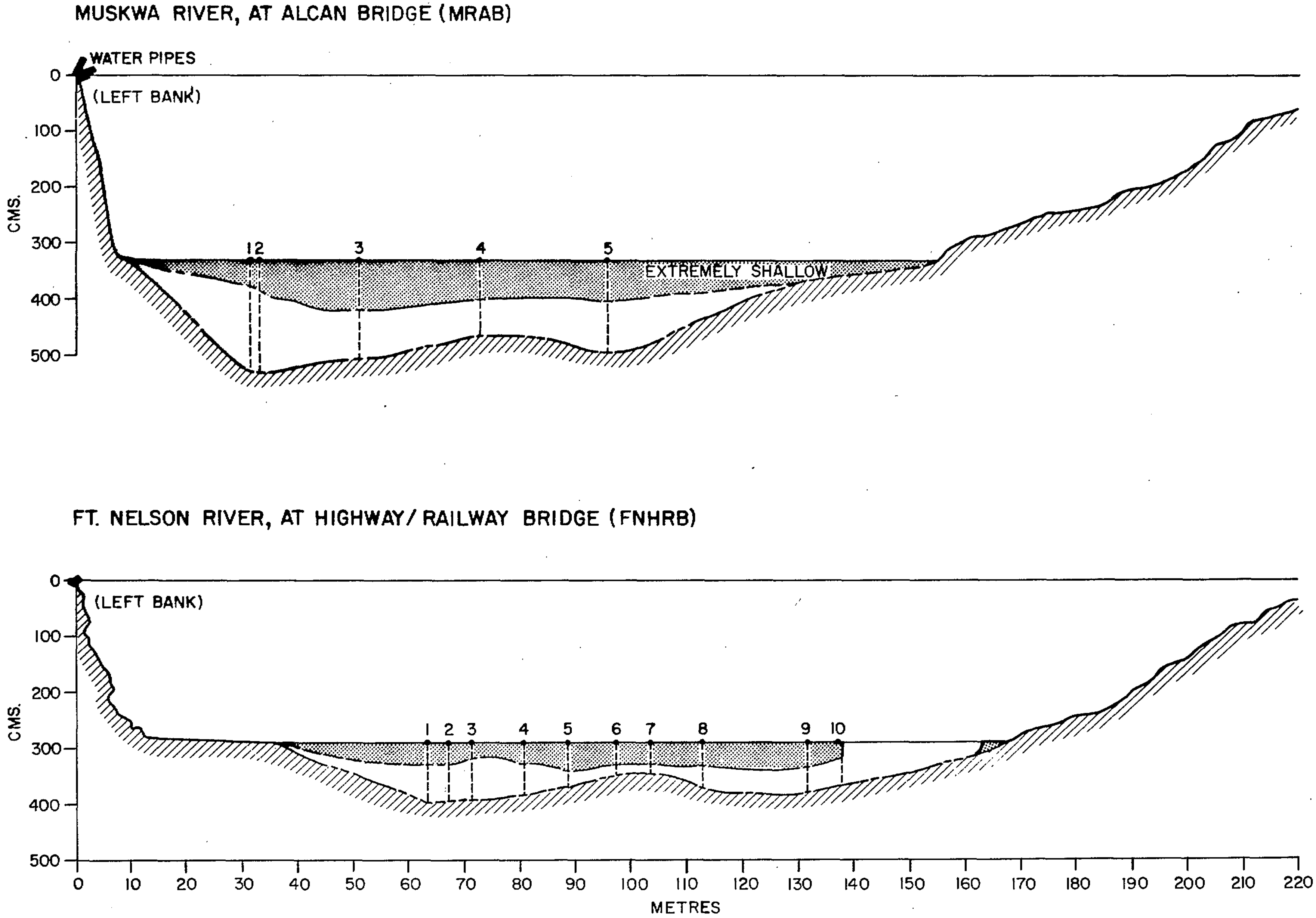


TABLE 3

ICE THICKNESS AND CHANNEL DEPTH FOR PRE-BREAK-UP

DRILLING SITES MRAB AND FNHRB

HOLE #	ICE THICKNESS(cm)	TOTAL PROFILE DEPTH(cm)	$\frac{I_T}{T_D}$ (%)
MRAB SITE			
1	47	207	22.7
2	61	207	29.5
3	91	185	49.2
4	70	137	51.1
5	72	171	42.1
AVERAGE	68.2	181.4	38.9
FNHRB SITE			
1	31	103	30.0
2	31	100	31.0
3	27.5	102	26.9
4	36	95	37.9
5	47	81	58.0
6	38	51	74.5
7	35	53	66.0
8	38	80	47.5
9	46	83	55.4
10	28	76	36.8
AVERAGE	35.8	82.4	46.4

At the FNHRB site the ice cover was of uniform texture and tone, slush covered and heavily candled. The ice along this profile was only marginally capable of supporting a person of 80 kg and a powered ice drill was not required to hole the ice, a sharp 4 kg ice chipper being sufficient.

The important points which can be extracted from the limited information obtained in 1979 are:

1. ice thickness prior to break-up does not appear related to channel depth;
2. ice strength and integrity in the immediate pre-break-up period varies significantly across the channel;
3. significant thinning and deterioration of the ice cover occurs during the final few days prior to ice movement;
4. if discharge levels remain static and low during the spring melt season the ice cover (as evidenced at FNHRB) is reduced to almost uniform thickness and strength prior to initial movement; and
5. where fall or winter jams and refreezing have occurred ice thickness and strength in the refrozen areas may vary significantly from surrounding ice. This may have major consequences in the severity of ice jams at jam prone sites and in the ability of the ice mass to produce sediment for transport. Locally ice movement may be restricted or slowed.

C. Aerial Reconnaissance and Monitoring of Break-up

While the timing and magnitude of jams in the 1979 break-up differed from 1978 the pattern of break-up was similar. In the 1978 report a detailed description of all break-up events was provided. For 1979 a broader description of the break-up is given and differences from previous observations highlighted. Break-up events in the Nelson Forks area are described in greater detail. A detailed chronology of break-up events is provided as Appendix A.

1. Description of Break-Up: Throughout the study area the winter of 1978/79 followed a pattern similar to that of 1977/78. Precipitation and air temperatures were below normal. Air temperatures were particularly low in December and January. In mid-April these circumstances were reflected in the ice conditions of the Liard and Fort Nelson Rivers. The Liard, from Watson Lake, Yukon to Nelson Forks, B.C., was ice covered, except at the confluences with major tributaries and through the Grand Canyon of the Liard. Below Nelson Forks an intact ice cover existed which included the Flett Rapids area, a location usually open throughout the winter. In the Fort Nelson region ice covers were intact and snow covered with some wet spots. Moderately decayed ice was evident in the area of the Fort Nelson - Muskwa confluence.

Near Ft. Nelson warm daytime temperatures (+16 to +18^{o}C) in the period April 22 to 26 caused rapid melting of the ice cover. Break-up of the upper Ft. Nelson occurred rapidly by April 27.

Break-up at FNHRB occurred on April 28 and at MRAB on the morning of April 29. Except for a major jam downstream of MRAB, on the Muskwa, the Fort Nelson system had broken up and was cleared of much of the ice debris by May 2.

The Nelson Forks area broke up in the period May 1 and 2. Liard ice upstream of the Forks remained competant.

At Fort Liard the ice broke up at 2050h on May 2 but a major jam developed upstream of the settlement and remained in place until the afternoon of May 5. From Fort Liard to Flett Rapids (km 255) ice jams were frequent as the cover failed on May 2. Jam creation and failure sequences were frequent along this stretch of the Liard.

Ice from km 255 through the confluence with the South Nahanni to Swan Point (km 170) was not disturbed by the initial spring flood. This cover remained in place despite clearance of ice upstream and downstream. 'In situ decay' continued through May 14 despite the added discharge of the South Nahanni.

Break-up at Fort Simpson, N.W.T., began with failure of the ice at LRFC at 1500h on May 11, followed by a progressive break-up and jamming down to LRSB by 2030h. Low ice levels and discharges caused a retardation in the progress of break-up at the Mackenzie confluence and Liard ice did not initiate Mackenzie ice movement until 1525h on May 13. Major failure of Mackenzie ice began at 1642h on May 14 and a jam formed in front of the town at 1750h. This jam had broken and the head (downstream end) of the jam moved 50-55 km downstream of the Liard confluence by 2145h on May 15.

2. <u>Discussion of Break-up Events</u>: In the 1978 progress report it was noted that river ice break-up had occurred, "...with the lowest river stage levels observed in the Mackenzie system by the author since 1973." (Glaciology Division, 1978, p. 42). This statement is now obsolete since stage levels observed in 1979 were well below those of 1978. Factors other than these reduced water levels which were important to the 1979 break-up included reduced ice thickness (Table 4), despite air temperatures lower than those of 1978 (Table 5), and winter precipitation totals that were below normal.

Break-up at all ground study sites was delayed (Table 6), ranging from 27hrs at MRAB to a maximum of 195.5hrs at LRFM. The time of break-up at various locations is detailed in Figure 5.

Of the factors responsible for break-up the most important appears to be that of maximum discharge. Without adequate discharge, the ice will melt "in situ" rather than break up mechanically. This conclusion was supported by the existence of solid ice cover on the Liard near Nahanni Butte which existed long after the channel upstream and downstream was almost completely ice-free. A review of Table 1 illustrates the reduction in flow in 1979 compared to 1978. The greatest reduction at MRAB, for example, occurred in the period April 27 to 30, the normal break-up period, and may explain the delay in break-up at this location.

At several other locations, the spring freshet, when added to the base flow, was not sufficient to lift and fracture the ice or initiate movement. In the Nahanni Butte area, internal weakening of the ice cover due to combined thermal heat input and fluvial erosion

TABLE 4

ICE THICKNESS AT TEST SITES: PRIOR TO AND AFTER BREAK-UP: 197B and 1979

PRE BREAK-UP: 1978						1979				
LOCATION	DATE	Max. Measured Thickness(cm.)	Min. Measured Thickness(cm.)	Mean Ice Thickness(cm.)	Sample Size	DATE	Max. Measured Thickness(cm.)	Min. Measured Thickness(cm.)	Mean Ice Thickness(cm.)	Sample Size
MRAB	10/4	N.A.	7.0	N.A.	1	24/4	91.0	47.0	6B.2	6
FNHRB	15/4	N.A.	42.0	N.A.	1	24/4	47.0	27.5	35.7	10
LRFC	16/4	N.A.	50.8	N.A.	2					
MRTL						1/5	245.0	150.0	*(1)	

POST BREAK-Up 197B										
MRAB	28/4	50.0	4.5	15.5	16*(2)	30/4	(L.B.)35.0	11.0	25.9	8
						5/5	(R.B.)85.0	19.0	3B.0	14
FNHRB	27/4	48.0	2.0	20.0	10	28/4	12.0	10.0	11.0	5
LRFC	3/5	180.0	60.0	95.1	13	12/5	122.0	N.A.	N.A.	3
LRFM	4/5	60.0	35.0	55.5	6					
LRSB	4/5	83.0	75.0	79.5	5					
MRTL	4/5	123.0	10B.0	110.0	10	13/5	70.0	46.0	59.5	B

*(1) Water Survey data: only max. & min. values recorded
*(2) cumulative data from two separate locations

TABLE 5

MEAN DAILY AIR TEMPERATURES; FORT NELSON B.C., AND FORT SIMPSON N.W.T., APRIL 20 - MAY 20, 1978 and 1979

	DATE	FORT NELSON, B.C. A.E.S. STA. NO. 71945 1978	FORT NELSON, B.C. A.E.S. STA. NO. 71945 1979	FORT SIMPSON, N.W.T. A.E.S. STA. NO. 71946 1978	FORT SIMPSON, N.W.T. A.E.S. STA. NO. 71946 1979
APRIL	20	6.7	0.6	3.7	-4.9
	21	5.9	3.0	-0.3	-0.5
	22	2.7	5.8	-2.2	1.5
	23	5.0	6.5	-2.8	0.7
	24	7.6	6.4	-2.3	2.2
	25	5.9	7.4	-1.2	3.0
	26	9.3	8.4	2.8	4.6
	27	11.7	9.7	7.0	5.0
	28	10.7	8.3	4.4	5.8
	29	10.3	9.6	7.2	5.7
	30	7.9	6.0	6.7	2.6
MAY	1	13.4	-0.6	11.5	-1.8
	2	9.7	-1.0	12.8	-2.0
	3	7.6	3.3	3.7	-0.3
	4	5.3	2.9	1.6	-0.8
	5	5.9	3.6	5.6	1.2
	6	7.9	-0.3	3.6	-5.6
	7	8.7	1.6	0.9	-6.3
	8	11.1	4.3	1.7	-3.3
	9	2.8	6.9	1.2	4.9
	10	1.9	6.7	-0.8	5.4
	11	4.5	8.4	0.8	8.3
	12	10.7	8.2	4.7	8.2
	13	12.2	6.7	6.0	9.2
	14	6.4	9.1	3.8	7.1
	15	7.7	6.8	5.4	8.5
	16	9.4	10.5	11.2	9.7
	17	10.9	10.0	11.7	11.7
	18	10.9	8.1	12.5	7.5
	19	10.0	9.5	10.7	9.3
	20	7.3	8.3	9.2	9.4
	AVERAGE FOR PERIOD	8.0	5.6	4.5	3.4

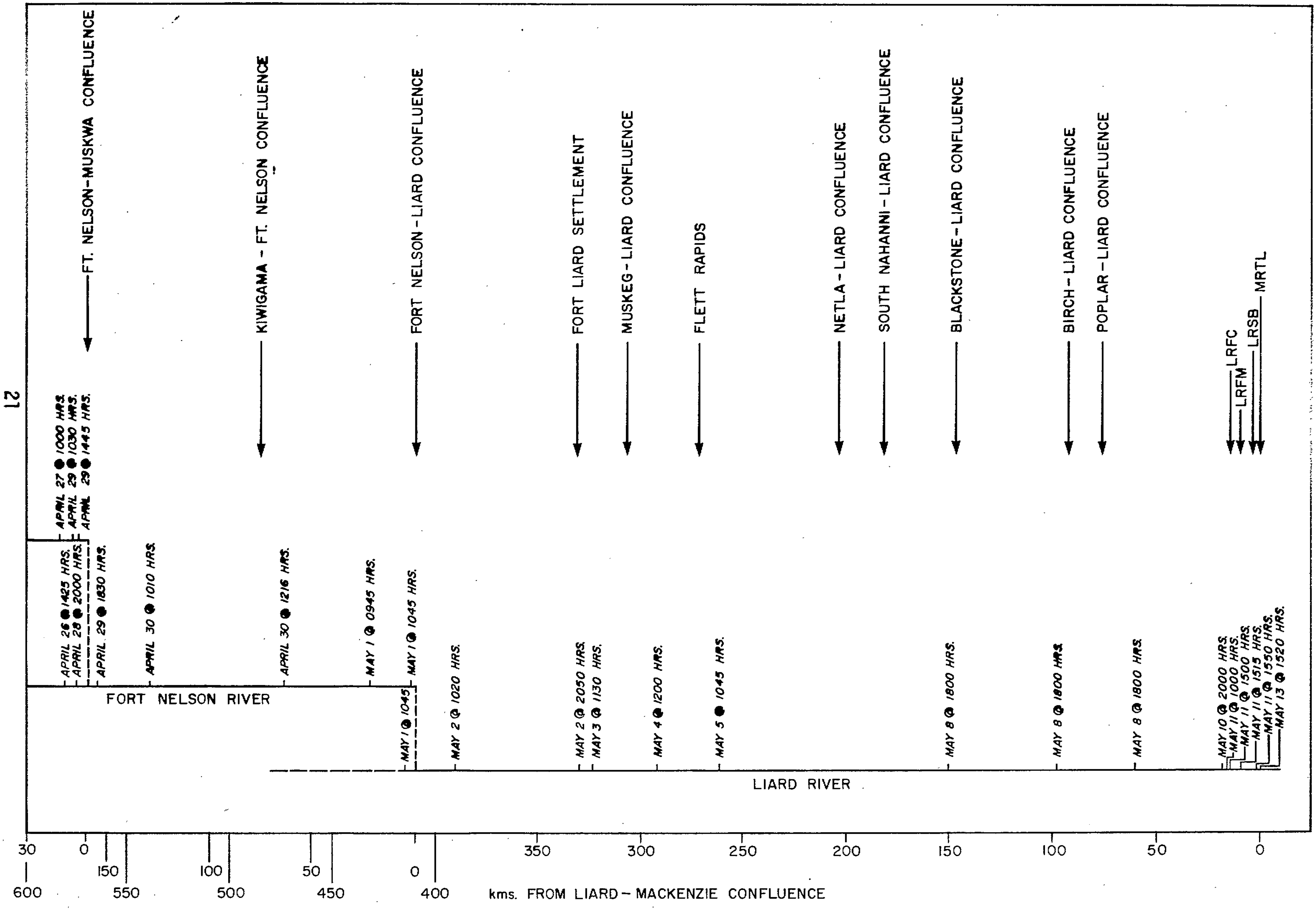
TABLE 6

DELAY IN TIMES OF BREAK-UP AT GROUND SITES : 1978 and 1979

SITE	BREAK-UP DATE 1978	BREAK-UP DATE 1979	DELAY(hrs.)
FNHRB	APRIL 26-1550h	APRIL 28-2000h	52.2
MRAB	APRIL 28-1100h	APRIL 29-1445h	27.9
FNCB	APRIL 26-1745h	APRIL 29-1830h	72.8
FORT LIARD	APRIL 30-1130h	MAY 2-2050h	57.3
LRFC	MAY 3-0800h	MAY 11-1000h	194.0
LRFM	MAY 3-1130h	MAY 11-1500h	195.5
LRSB	MAY 3-1800h	MAY 11-1515h	189.3
MRTL	MAY 4-1100h	MAY 11-1550h	172.8
MRNE	MAY 8-0830h	MAY 13-1712h	128.7

Average delay: Ft. Nelson-Muskwa sites-50.9h
Average delay: Liard River sites- 156.3h
Average delay: All ground sites- 121.1h

FIGURE 5 PROGRESS OF ICE BREAK-UP FRONT (S) THROUGH STUDY REGION - 1979



was eventually responsible for failure by downward collapse of the ice. After initial collapse the flow fragmented the cover and transported it downstream.

Despite extremely low flows the Fort Nelson River again acted as a 'trigger' to inititate Liard ice movement. Liard ice acted similarly at the Mackenzie confluence.

Ice jam locations in 1979 (Figure 6) were similar to those of 1978, and occurred at sites which satellite imagery study indicated were common jam locations in the period 1973-78. Over this period the majority of the ice jams have occurred on the Liard from Fort Liard to Nahanni Butte (km 322 to km 180) an area which the conjoined sediment study has identified as one of the least active bank erosion areas of the Liard (see Appendix B). Thus while ice jam frequency in this area is high the actual effect on the banks is minimized when ice levels are low. Bed scour may increase under low spring flow conditions. Evidence for this is found on exposed shoal areas which were undisturbed in 1978 while extensive ice scour was found in 1979 (Photograph 1).

Low ice levels and small water level increases were also responsible for the delay in break-up at Fort Simpson. In 1978 a large (>3 m) hydraulic head formed between MRTL and LRSB sites due to jamming of the Liard ice against a durable Mackenzie ice cover while in 1979 little increase in water levels occurred. In contrast the 1979 Liard ice at break-up was thinner, had undergone greater decay and abutted thinner Mackenzie ice. This created a stable jam and permitted ice debris to pass beneath the Mackenzie ice. Figure 7 and Tables 7a and 7b summarize the events described above and their effect on break-up in separate river reaches.

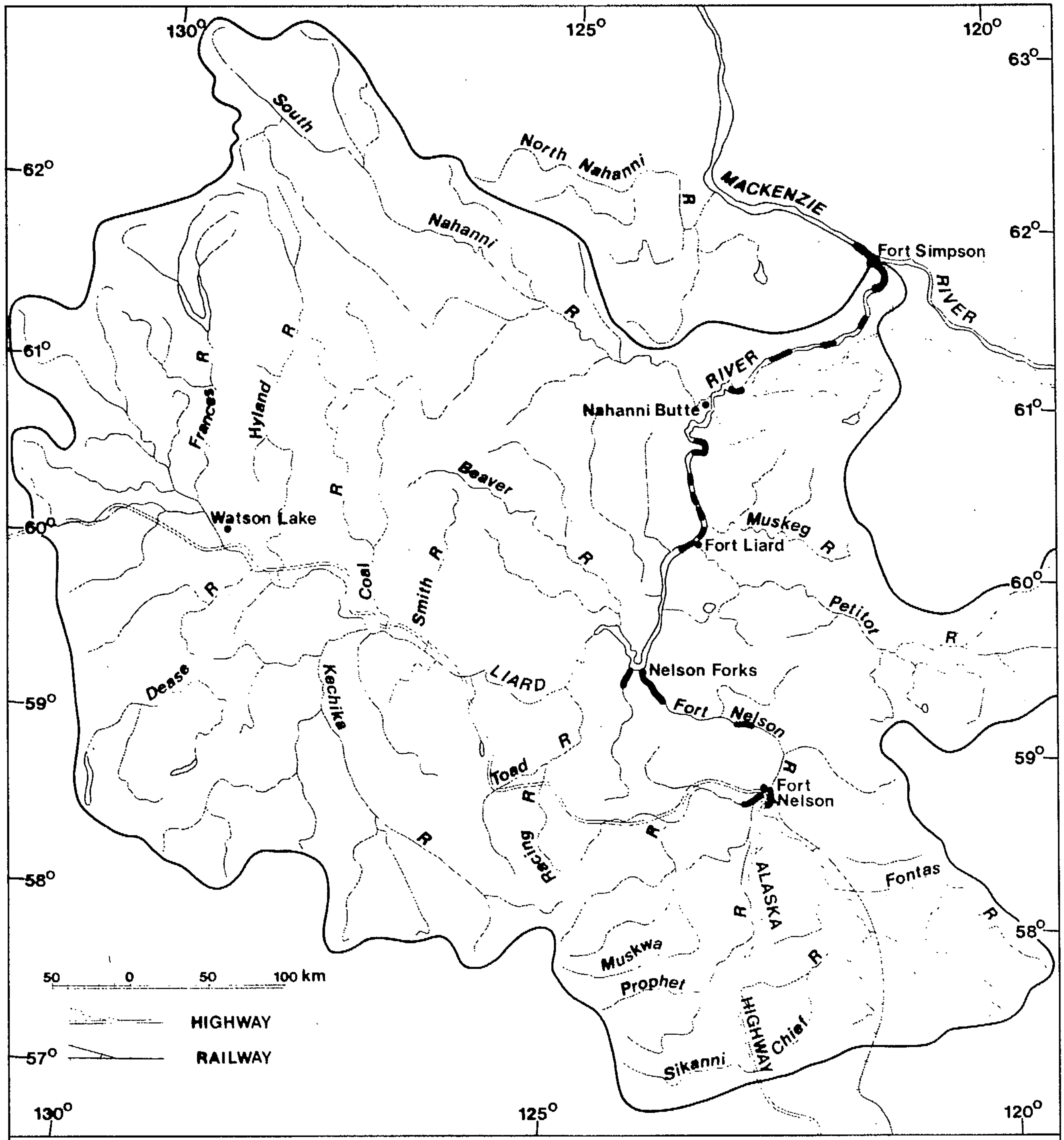


FIGURE 6 LOCATION OF ICE JAMS DURING 1979 BREAK-UP; FROM AERIAL RECONAISSANCE AND GROUND SITE INVESTIGATION

FIGURE 7

RATES OF RIVER ICE BREAK-UP FOR FORT NELSON AND LIARD RIVERS; BY REACH: APRIL/MAY 1979

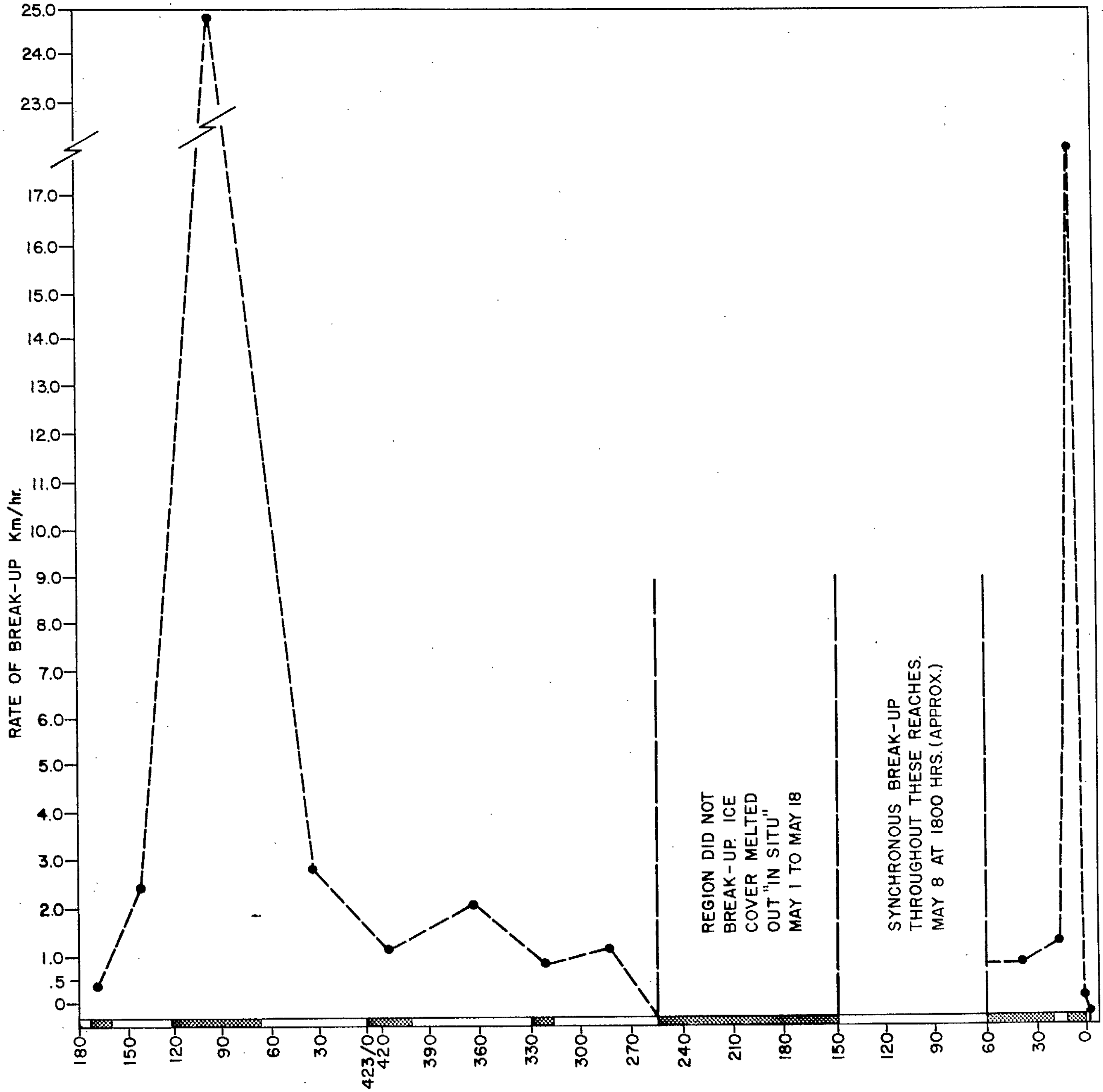


TABLE 7a

TIME REQUIRED FOR RIVER ICE BREAK-UP; 1978 AND 1979

	1978	1979
Fort Nelson River (from FNHRB to Nelson Forks)	66.5h	63.5h
Liard River (from Nelson Forks to LRSB)	105.3h	185.5h
Mackenzie - Liard Confluence (LRSB to MRTL)	.2h	47.3h
Total Time - Entire System (from FNHRB to MRTL)	172.0h	296.3h

TABLE 7b

AVERAGE SPEED OF ICE BREAK BY RIVER REACH: 1979

Ft. Nelson River	:	FNHRB to FNCB site	km 183	to km 167	0.4
Ft. Nelson River	:	FNCB to Shusk Ck.	km 167	to km 121	2.4
Ft. Nelson River	:	Shush Ck. to Liard Highway Crossing	km 121	to km 65	24.9
Ft. Nelson River	:	Liard Highway Crossing to Nelson Forks	km 65	to km 0	2.8
Liard River	:	Nelson Forks to Sandy Ck.	km 0/423	to km 402	1.2
Liard River	:	Sandy Ck. to Fort Liard	km 402	to km 330	2.0
Liard River	:	Fort Liard to Muskeg Confl.	km 330	to km 317	0.9
Liard River	:	Muskeg Confl. to Flett Rapids	km 317	to km 260	1.2
Liard River	:	Flett Rapids to Blackstone Confl.	km 260	to km 150	Did not break-up during study period.
Liard River	:	Blackstone Confl. to Poplar Confl.	km 150	to km 60	Synchronous break-up in this reach
Liard River	:	Poplar Confl. to "12-Mile" Island	km 60	to km 20	0.8
Liard River	:	"12-Mile" Island to LRFC	km 20	to km 17	0.2
Liard River	:	LRFC to LRFM	km 17	to km 10	1.3
Liard River	:	LRFM to LRSB	km 10	to km 1	18.0
Liard River	:	LRSB to MRTL	km 1	to km 0	0.02
AVERAGE	:	Ft. Nelson System (from FNHRB to Nelson Forks)	km 183	to km 0	2.7
	:	Liard River (from Nelson Forks to MRTL)	km 0/423	to km 0	0.6
	:	Total Combined System	km 183	to km 0 +	
			km 423	to km 0	2.0

Once again the phenomenon of large quantities of ice being submerged at the upstream end of a solid ice cover, but not emerging in downstream open shore leads, polynyas, or transverse cracks was observed. Why this occurs is still uncertain. Since the hydraulic head does not increase upstream of the ice edge in most cases, the submerged ice is not becoming attached to the underside of the solid ice cover which would cause increased flow resistance and thus backwater effects. Often ice pans could be heard striking the underice surface at a distance from the point of submergence. It would appear that such ice is finally fragmented and then abraded or melted rapidly and is identifiable only as increased discharge at any downstream location.

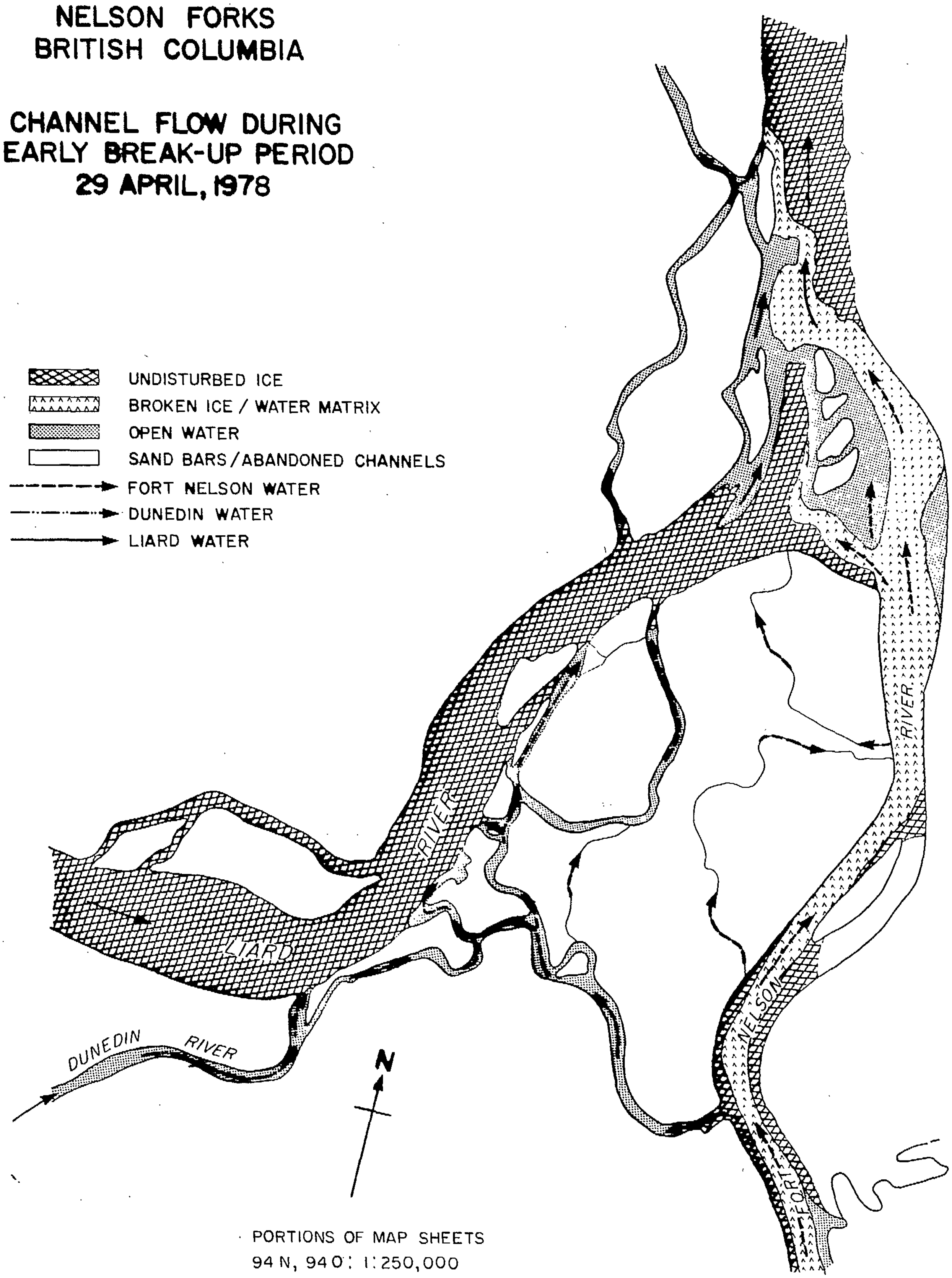
3. Break-up Events in the Nelson Forks Area: In the 1978 report the Nelson Forks area was identified as a site which required detailed study since the water flow and ice break-up in the distributary and main channels is complex. As a result, attempts were made in 1979 to increase surveillance at this location.

In the examination of 1978 break-up at Nelson Forks water from the Fort Nelson River was observed to flow through the distributary channels and join the Liard upstream of the confluence (Figure 8). In an extreme case Ft. Nelson flow joined that of the Dunedin River and entered the main Liard channel 5 km upstream of the major Ft. Nelson junction. If the Liard ice upstream of the confluence were thicker and stronger than that downstream (due to ice production effects upstream on the Liard) then the addition of highly turbid Ft. Nelson discharge may act to hasten ice decay and hence Liard break-up.

FIGURE 8

NELSON FORKS BRITISH COLUMBIA

CHANNEL FLOW DURING EARLY BREAK-UP PERIOD 29 APRIL, 1978



In 1978 the break-up of the Dunedin River was not a factor in the mechanical break-up of Liard ice.

In 1979 the flow patterns observed in 1978 were reversed. In the early break-up period many of the smaller distributary channels contained no water (Figure 9a), further evidence of reduced discharges. The Dunedin River, which had been frozen on April 27 had broken into the Liard by 1130h on April 30 (Photograph 2). In those channels which did contain water, Liard and Dunedin waters flowed to the Fort Nelson River. Such flow at break-up could aid in destruction of the Fort Nelson ice cover.

In late summer (Figure 9b) Liard and Dunedin flows predominated and distributary flow entered the Fort Nelson approximately 5.5 kms upstream of the confluence. Widely varied turbidities made tracing water from each of the streams straightforward.

Conclusions on the importance to break-up of varied quantities and directions of flow in the distributary channels are suspect without knowledge of winter ice conditions. If ice conditions on the Liard in the Nelson Forks area are such that Liard ice thickness decreases through the confluence area then it can be expected that upstream Liard ice will remain in place beyond the break-up of the Fort Nelson.

Water from the Fort Nelson, if added to the Liard via distributary channels may aid in destruction of Liard ice cover in the last 5 kms above the confluence. While this is significant to ice behavior within the Forks areas the effect on Liard ice from Nelson Forks upstream is not known. A rapid increase in the discharge of the Fort Nelson River would be expected to heighten the trigger effect and accelerate Liard break-up

FIGURE 9a

NELSON FORKS
BRITISH COLUMBIA

CHANNEL FLOW DURING LATE BREAK-UP PERIOD
3 MAY, 1979

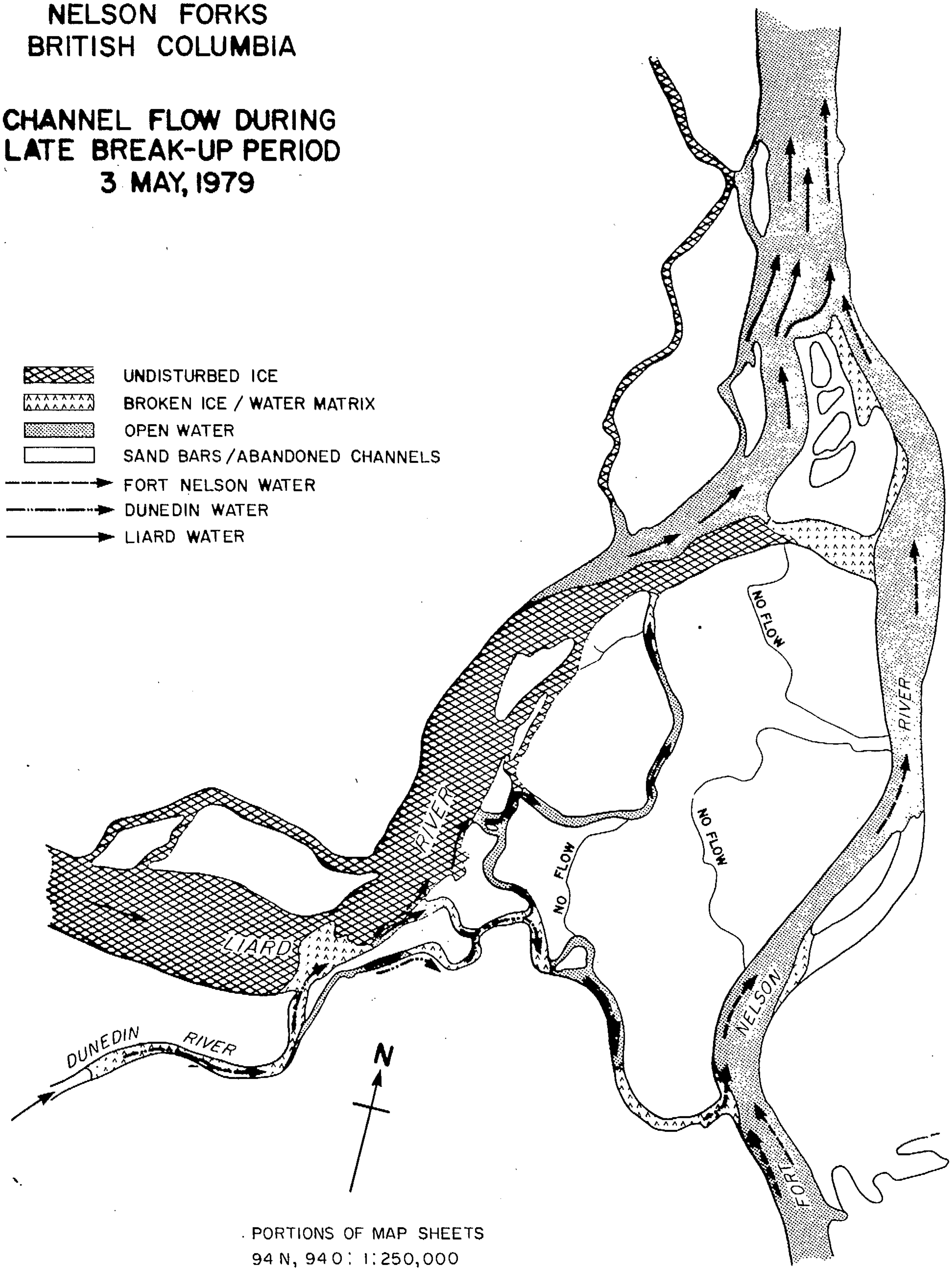
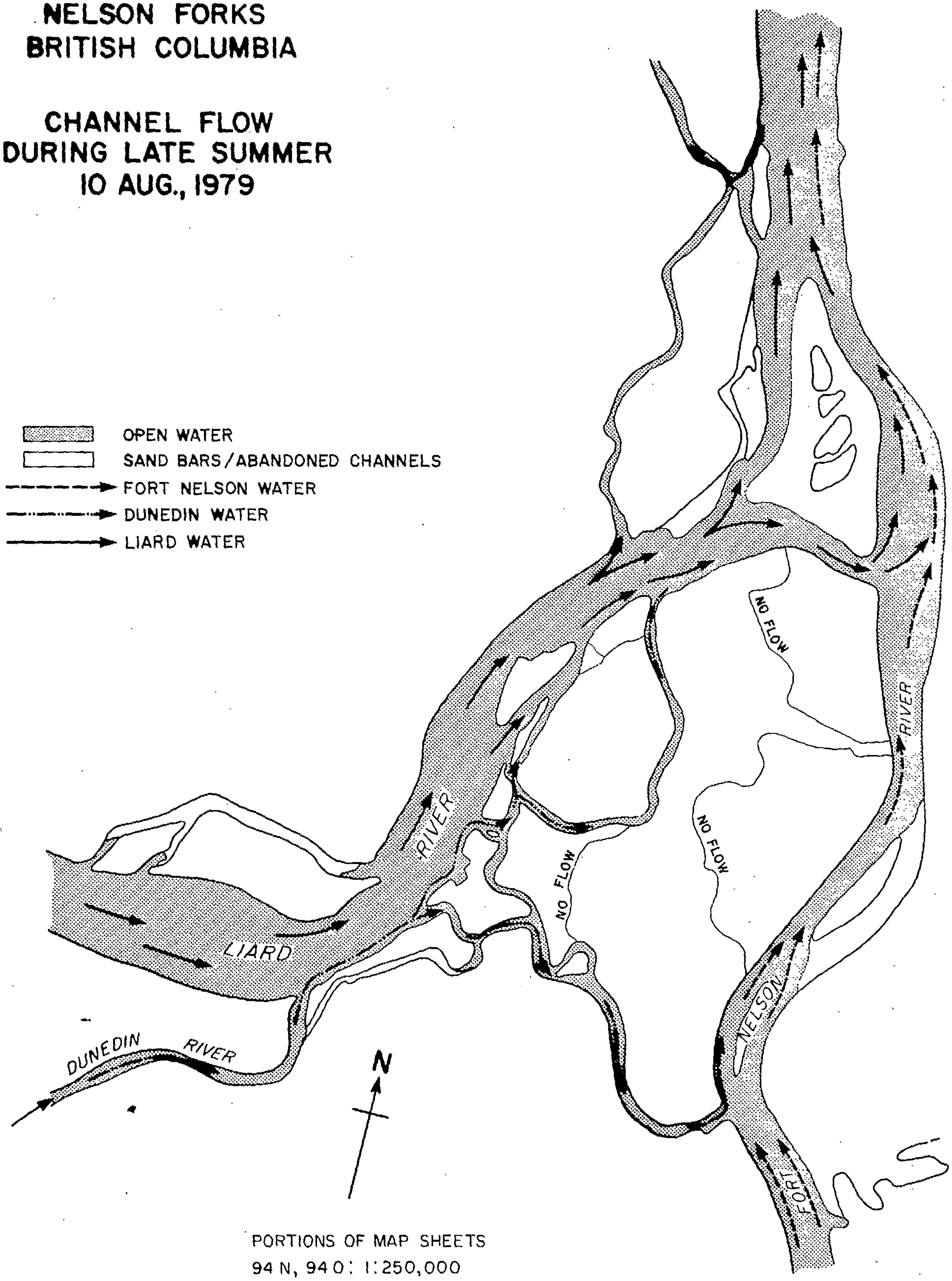


FIGURE 9b

NELSON FORKS BRITISH COLUMBIA

CHANNEL FLOW DURING LATE SUMMER 10 AUG., 1979



PORTIONS OF MAP SHEETS
94 N, 94 O: 1:250,000

If however this increase in discharge was 'bled-off' through the distributary channels then the trigger effect, while still present, may be dampened. This would somewhat reduce the ability of the Fort Nelson break-up to continue down the Liard. Thus distributary channel flow, both directionally and volumetrically, may act as a shock absorber which would prevent Fort Nelson - triggered Liard break-up if the ice downstream of the confluence remains relatively thick and strong. The lack of pre-break-up ice thickness and strength data is a major handicap in determination of the causes of the events observed in 1978 and 1979.

D. Late Summer Low Water Examination of 1979 Ice Jam Sites

Between August 8 and August 11 examination of the locations of spring ice jams on the Liard and Fort Nelson Rivers was made by helicopter. At several locations landings were made to undertake detailed observations.

Throughout the basin extensive areas of sandbars and shoals were exposed and secondary channels, which were responsible for carrying large volumes of water and ice in the spring, were dry. Ice scour, which was evident on shoals and bars after ice clearance (Photograph 1), had been smoothed by high flows associated with higher discharges in June and/or July.

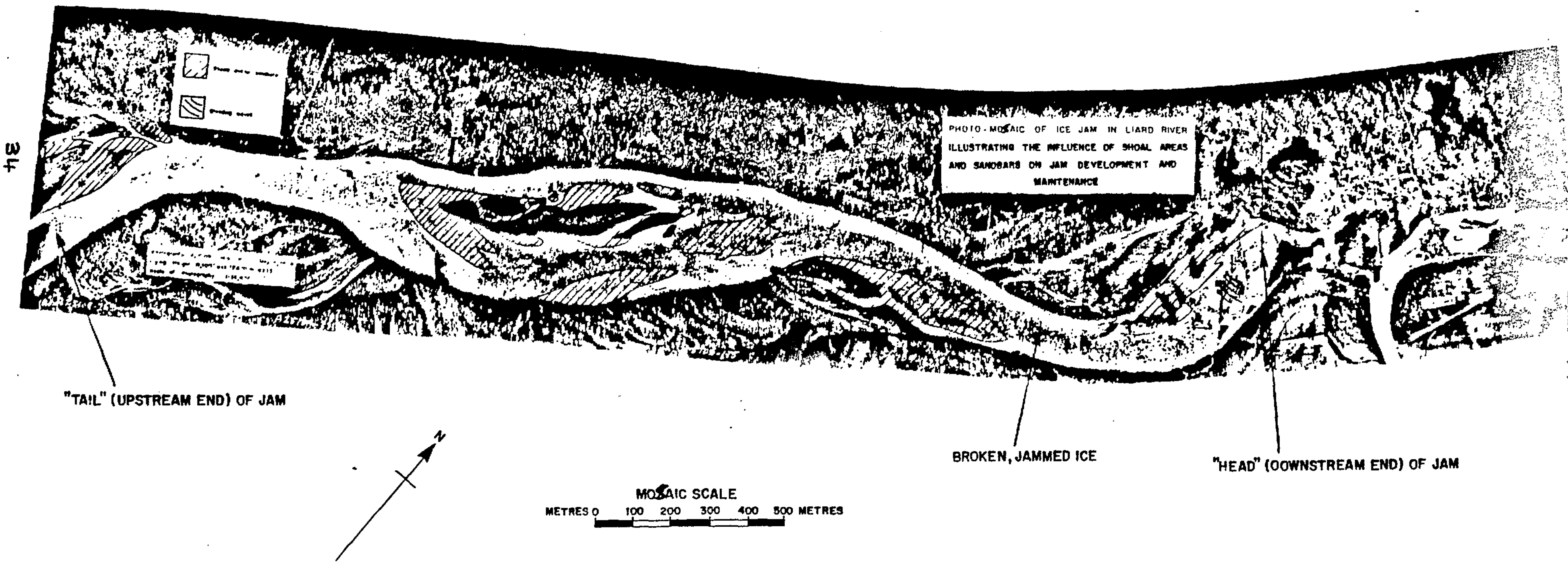
After examination of jam sites it appears that ice jams are most likely to occur at locations such as sharp bends and/or shoal areas. At sharp bends ice cover which initially fractures into large pans will not 'swing' through the curve and restrains upstream ice. Such jams are most likely to occur when ice strength is high. Jams can also occur where shoal areas are deep enough to allow passage of the smaller blocks of ice broken from the edge of longshore leads but cause ice of greater thickness to ground. Where this occurs over a broad shoal or sandbar, resistance at the ice-bed interface can exceed downstream thrust of the broken ice and form a jam. Jams of both types may exist for several days but the majority exist only long enough for backwater to increase and either reduce resistance or mechanically destroy the ice. An example of a shoal-sand bar resistance jam is shown in Figure 10. This jam formed on the Liard near Fort Liard, N.W.T., immediately upstream of the Petitot confluence (km 322 to km 335). The photo-mosaic of the ice jam has been inked to outline shoal areas which existed as exposed sandbars in August. Planimetry of these areas, plus photographic interpretation of grounded ice, reveals that slightly more than 24% of the channel at break-up was of insufficient depth to permit broken ice to move over the shoals.

Finally, reaches of river which have sharp curves with shoal areas upstream or downstream of the curve apex produce a persistent jam. The jam site on the Muskwa, 2.5 km downstream of MRAB, is of this category. The ice cover from the apex of the curve upstream for 1 km remained intact and grounded until May 5 in 1979. Discharge beneath the ice cover cleared upstream ice debris prior to collapse and subsequent destruction of the jammed and stranded ice.

FIGURE 10

ANNOTATED PHOTO MOSAIC OF MAJOR ICE JAM AT FORT LIARD, N.W.T.

MAY 2 TO MAY 5, 1979



E. Selection of Ice Jam Sites for Intensive Study

As part of the aerial reconnaissance phase of the program several sites known to have jammed in 1978 were observed in 1979 with a view to the selection of sites for a detailed ground study of ice jams and any resultant channel geometry modification. Three sites were observed in 1979 at which long-lived or repeated jams occurred. These were: (1) Muskwa River, 2.5 km downstream of MRAB site, (2) Fort Nelson River, upstream of Stanolind Creek confluence (km 84) and, (3) Liard River, downstream of Swan Point (km 165). The first two sites were chosen for further study.

The reasons for selection of these river curves as sites were threefold. Firstly, both sites are close to Ft. Nelson, B.C. and have near-by road access. Study at these sites is thus easier and less expensive than the more remote Liard site. Secondly active erosion faces exist at the apex of both curves. Thirdly the reduced size of the Muskwa and Fort Nelson Rivers compared to either the Liard or Mackenzie provides a more manageable, "half-scale" study, more easily handled by small field parties. Data on a greater number of variables can thus be obtained in a shorter time at reasonable cost.

Additionally the two selected sites are located near the present study sites MRAB and FNHRB. This should provide supportive background on the ice and sediment processes active in the area. Data collection at these sites was achieved in August 1979 (channel geometry - baseline data), and is proposed for March 1980 (ice thickness and type, water depth and sediment loads), April-May 1980 (break-up events and ice action during jamming) and August 1980 (channel geometry - changes). If initial results prove worthwhile for 1979/80, long-term continuation of studies should be considered.

F. Channel Geometry of Long-Term Ice Jam Study Sites

On August 11 to August 13 examination of the two ice jam prone sites (described in section E, above) was completed with boat mounted depth sounders. At both sites, Fort Nelson River at Stanolind Creek (Photograph 3) and Muskwa River, below MRAB (Photograph 4) cross-sectional profiles were obtained at the apex, the upstream approach and the downstream exit of the curve. Figures 11 and 12 illustrate the planimetry of the study sites and the transect locations. Depth readings were taken at 5 m intervals. The data obtained were then used to construct cross-profiles for each transect (Figures 13 and 14 and Photograph 5).

At the Ft. Nelson - Stanolind Creek site a longitudinal bed profile was obtained by taking depth readings at regular intervals along the presumed thalweg from site 4 (Figure 11) to the confluence of Stanolind Creek. The resulting profile is shown in Figure 15.

G. Summary and Proposals for Future Break-up Studies

The most salient points derived from the 1979 ice break-up component of the Spring Flood Study can be summarized as follows:

FIGURE 11

GENERAL ARRANGEMENT OF CROSS PROFILES AND LONGITUDINAL PROFILE FOR ICE JAM PRONE CURVE: FORT NELSON RIVER AT STANOLIND CREEK AUGUST 12, 1979

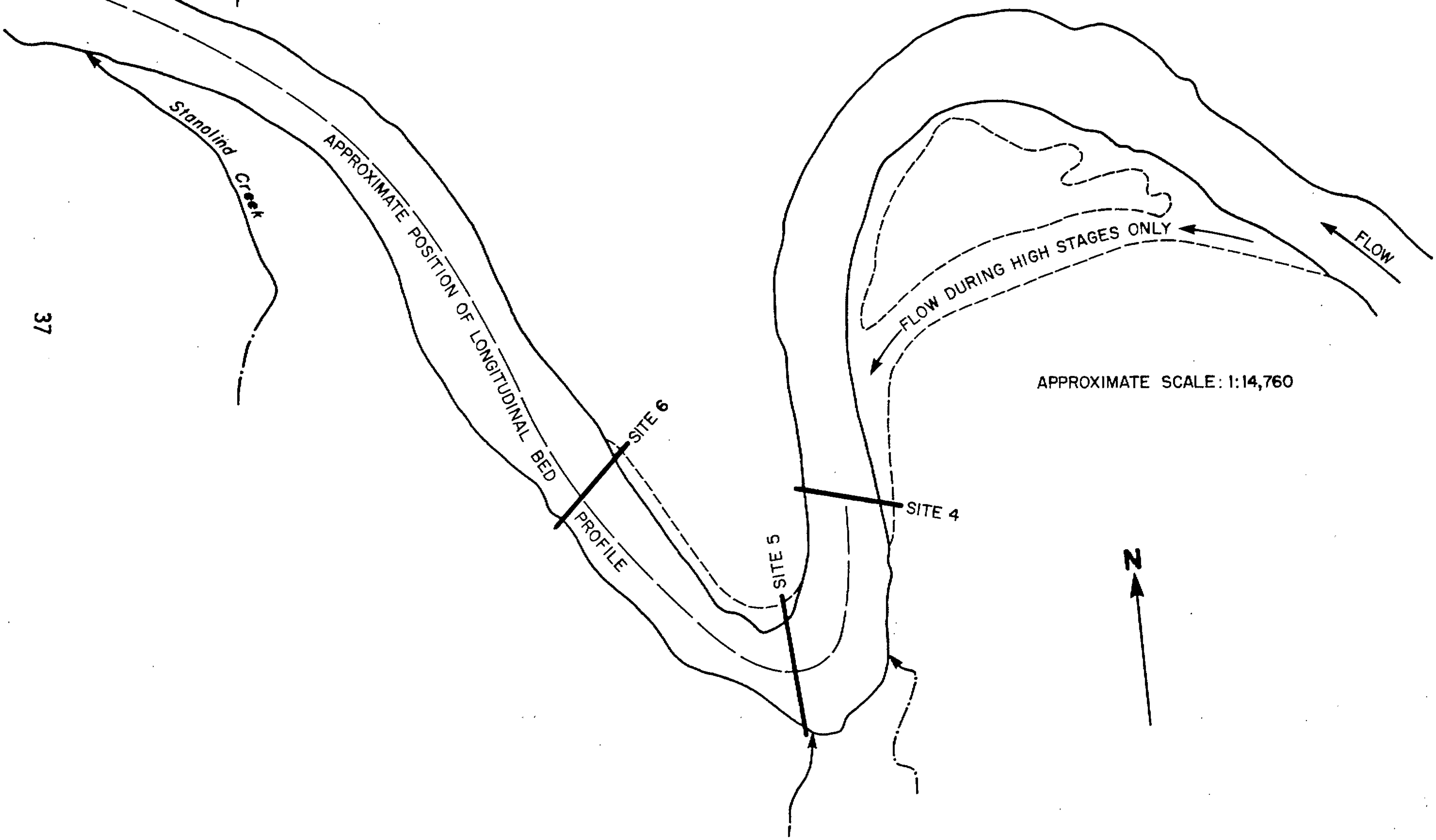


FIGURE 12

GENERAL ARRANGEMENT OF CROSS PROFILES FOR ICE JAM PRONE CURVE: MUSKWA RIVER NEAR FORT NELSON AIRPORT, B.C.

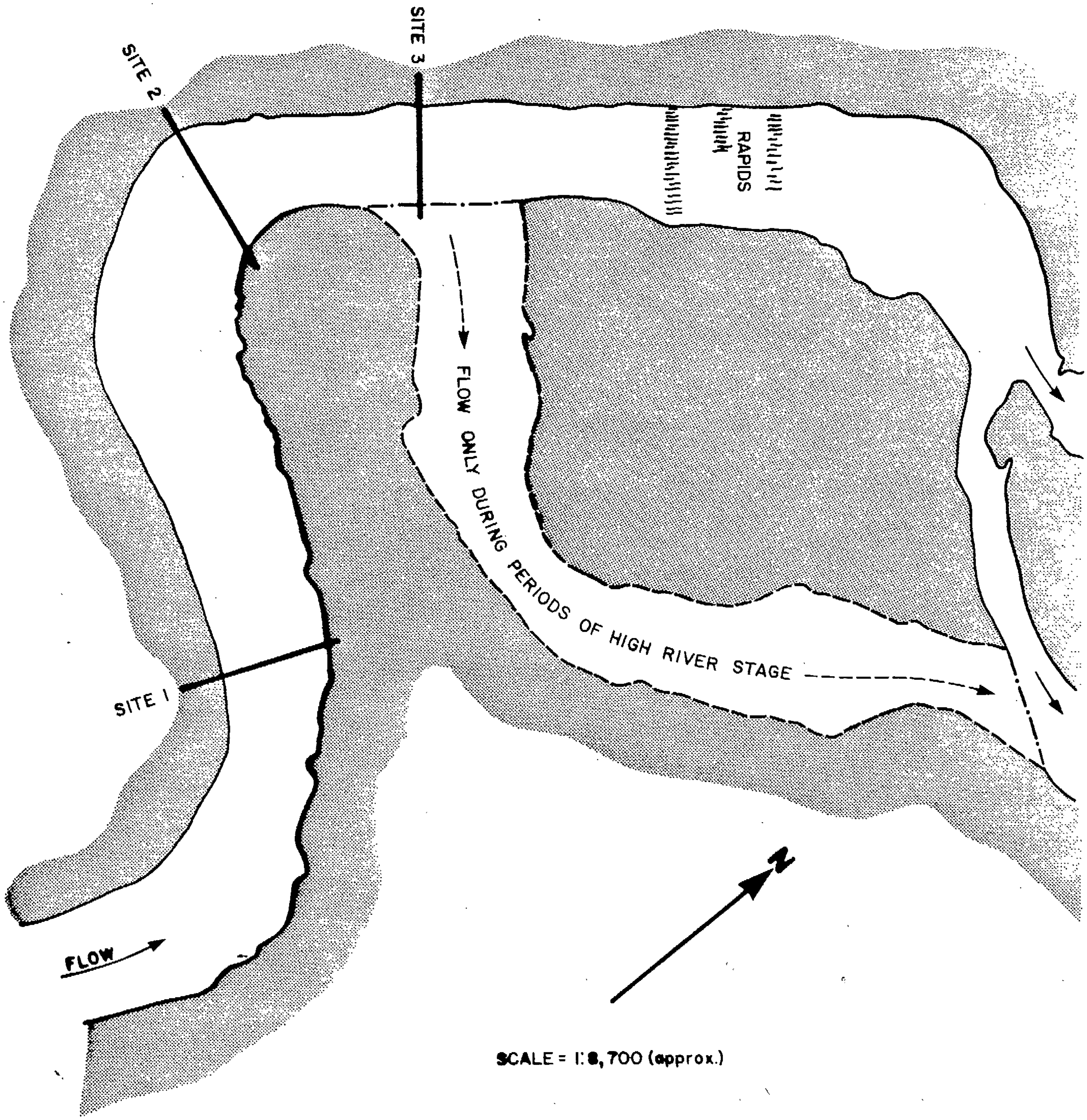


FIGURE 13

BED PROFILES: FORT NELSON RIVER AT STANOLIND CREEK
DATA ACQUIRED AUG. 12, 1979

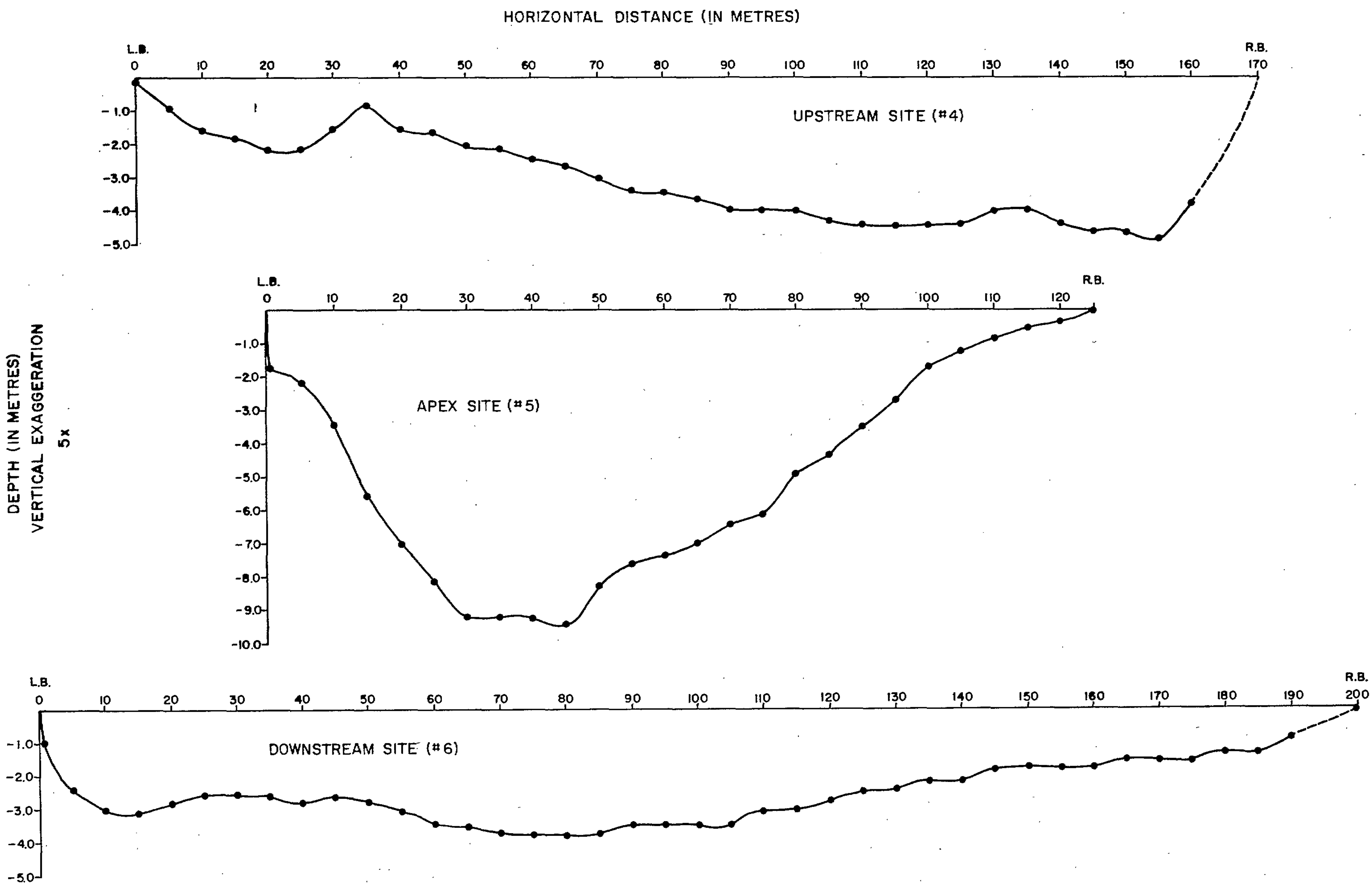


FIGURE 14

BED PROFILES: MUSKWA RIVER SITES NEAR FORT NELSON AIRPORT, B.C.

DATA ACQUIRED AUG. 13, 1979

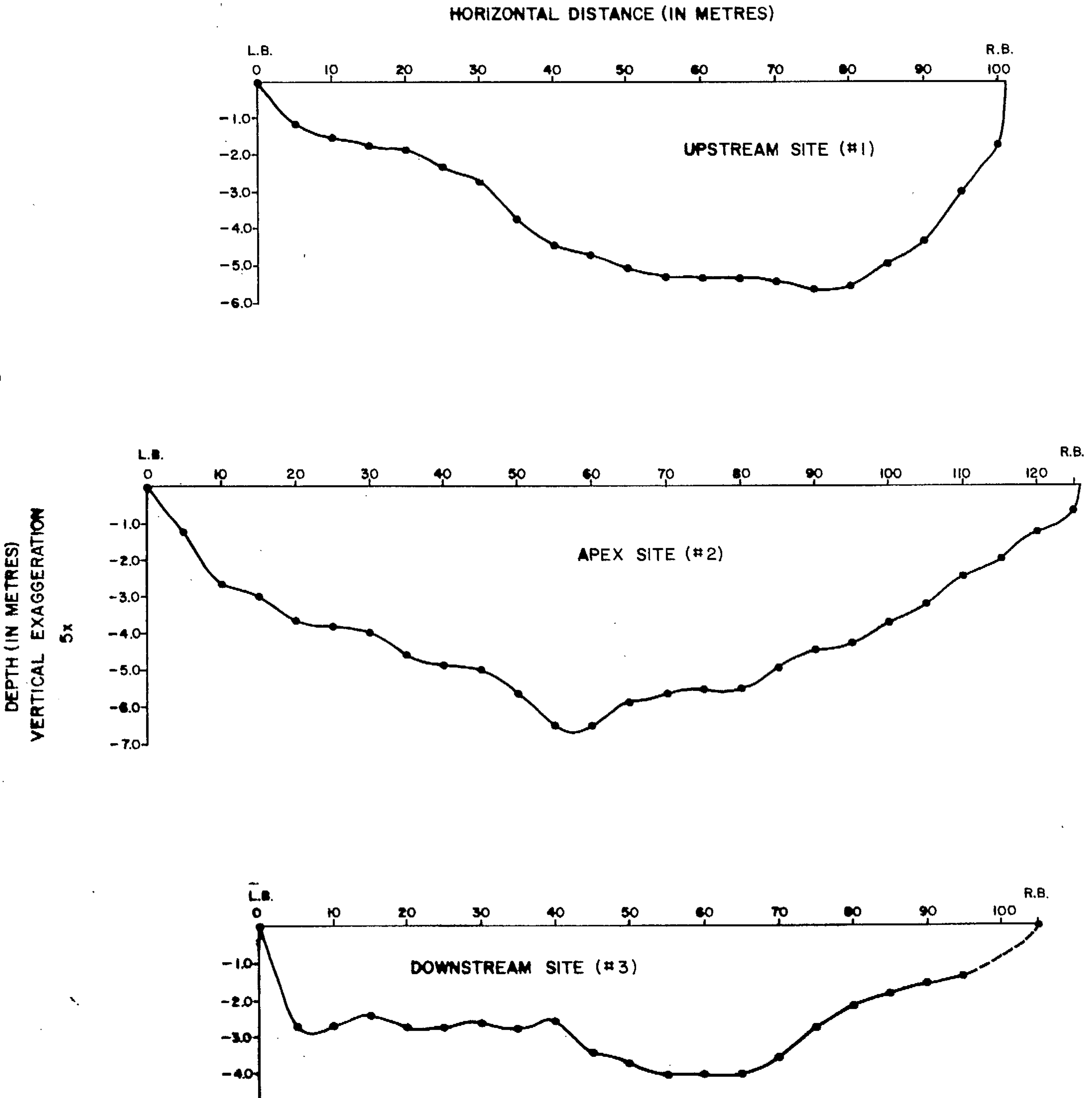
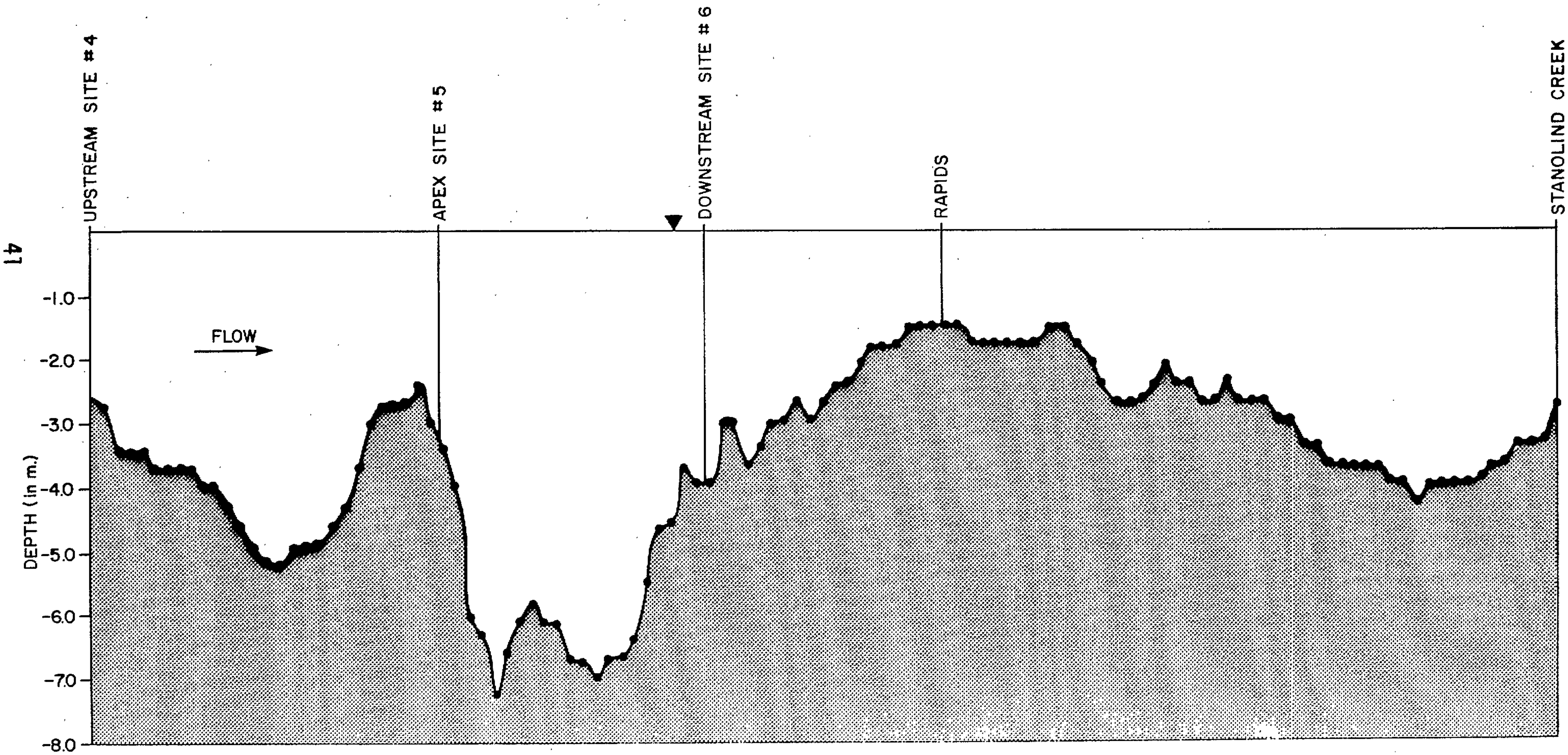


FIGURE 15

DOWNSTREAM PROFILE: CENTRE (THALWEG) CHANNEL: FORT NELSON RIVER, B.C.
STANOLIND CREEK AREA

READINGS TAKEN EVERY 10 SEC. FROM START OF CROSS PROFILE # 4



HORIZONTAL SCALE: EACH DIV. = 10 SEC. INTERVAL OR (APPROX.) 28 METRES

VERTICAL SCALE: EACH DIV. = .2 METRES

1. ice thickness decreases rapidly in the immediate pre-break-up period;
2. ice thickness and strength vary markedly across the channel at any given location;
3. variations in the ice at break-up are in part a reflection of the freeze-up history at any given locations;
4. discharge increases appear to be the most important single factor in initiating and sustaining break-up. Temperatures also affect the timing of initial break-up but are not sufficient, by themselves, to control the progress of break-up once started;
5. below normal precipitation in the winter months in 1977/78 and 1978/79 resulted in reduced flood levels in the spring flood period. As a result discharges were not sufficient in 1979 to break up and flush out the ice from some reaches of the Ft. Nelson and Liard systems;
6. low winter ice levels and reduced discharges at break-up limit ice action on the banks but probably cause increased shoal, sand-bar and bed modification;
7. ice jams observed in 1979 were more frequent than in 1978 but their magnitude was reduced. Ice jam locations were similar to those of 1978 and agree well with those locations identified by satellite imagery analysis for the period 1973-1978;

8. break-up in the Nelson Forks area remains incompletely understood. The lack of ice thickness and discharge data for this area hinders detailed analysis, but it appears that the widely varied flow patterns in the distributary channels may have a moderating or dampening effect on extreme break-up events;

9. the identification of ice jam prone sites amenable to detailed study provides an opportunity to obtain information on the processes responsible for ice jams, the effect of such jams on channel geometry and the resultant production of sediment.

As a result of the 1978 and 1979 field programs the following proposals are outlined which should provide increased understanding of ice break-up processes within the Liard basin. Further, the data obtained would increase the information that is required to permit analysis of the ice regime over long periods of time and permit prediction of any system changes. For the ice regime, break-up portion of the Liard Spring Flood study it is proposed that:

1. a field program similar to that described above for 1979, be carried out in 1980;

2. measurement of maximum winter ice thickness should be carried out at selected sites. Such work should include the Nelson Forks area;

3. continued aerial and ground monitoring should be undertaken to extend the data base for location and timing of ice break-up events. This will also assist in compilation of a complete photographic record of ice

jams for future analysis;

4. post break-up examination of ice jam locations should be made to determine the importance of ice jams and break-up events on channel morphology and sediment production.

CHAPTER III

SUSPENDED SEDIMENT, 1979

B.J. Grey

A. Introduction

The 1978 reconnaissance of tributaries to the Liard accessible from the Alaska Highway, revealed great differences between several types of streams as potential contributors of suspended sediment to the Liard. The Fort Nelson River and its major tributary the Muskwa, which join near Fort Nelson B.C., displayed sediment concentrations much higher than any of the other sampled rivers. A few samples from the Liard River at Lower Crossing indicated the potential for high sediment transport rates due to the high water discharge, even though the sediment concentrations were low to moderate. However, no analysis of the data was possible, because the sediment concentrations obtained were from single profiles over a very short sampling period. Also, very little previous sediment data were available for comparison.

Accordingly, it was proposed to undertake a more thorough suspended sediment data collection and analysis program in 1979, from those sites likely to provide the data needed to explain the sediment regime of the upper Liard Basin. In order to allow for daily sampling, it was necessary to rely on road access, and hence, the Fort Nelson and Muskwa Rivers near Fort Nelson, and the Liard River at Lower Crossing, were selected as representatives of the main sub-basins of the upper Liard. Also, at each site, full cross-sectional sediment profiles were proposed to obtain mean daily suspended sediment concentrations for computation of total load, over a large portion of the spring/summer period. No spring break-up sediment data are available for any river in the Mackenzie Basin because of the inherant difficulties of sampling through a decaying or broken ice surface. However, the sites chosen for the 1979 sediment program allowed such sampling from bridge platforms. Because of the general south to north flow within the Mackenzie Basin, break-up has a greatly extended duration, from late April in the headwaters to early June in the Delta, and therefore, the early summer sediment data from the upper part of the Basin can still be a factor in break-up downstream.

B. Field Operations

1. Equipment and Methodology: In an attempt to make the data collected from the upper Liard in 1979 compatible with the proposed sediment program at the mouth of the Liard, near Fort Simpson (Water Survey of Canada), and with previous data collected at the latter site, the equipment and methodologies used were as similar as possible to those of Sediment Survey of Canada. Two suspended sediment samplers were used, both of the depth-integrating type. For low velocity or shallow conditions the DH-59 was utilized, while the DH-49 was needed for faster and deeper situations. The samplers were suspended from bridges on a cable attached to a crane, which allowed for smooth

transect rates. River discharge was gauged periodically in order to subdivide the flow into five equal zones across the cross-section. Each of the five zones had a single sediment profile for each sampling date. The samples were filtered in the field, and the filter papers containing the sediment were sent to a Sediment Survey laboratory for gravimetric analysis.

The first samples were taken on April 24, sampling under the ice cover, in association with the break-up program. Three samples each were taken on the Fort Nelson and Muskwa Rivers, near the regular sampling sites. Regular sampling began on April 29 at the Fort Nelson site, and on May 2 at the Muskwa site. Occasional samples were obtained during ice movement and jamming at both sites, a situation which lasted longer at the Muskwa site. Sampling continued almost daily until June 24 at both sites, and covered a range of flow conditions. Three visits were made to the Liard - Lower Crossing site in late May and early June

2. Sampling Sites: As mentioned above, regular sampling was undertaken at two sites in the vicinity of the town of Fort Nelson, B.C., near which the Muskwa River joins the mainstem Fort Nelson. It was not feasible to measure the river below this junction, but both rivers are bridged a short distance upstream. These sites are shown on Figure 16. The Fort Nelson River is spanned by a bridge of the British Columbia Railway (B.C.R.), and this site is shown in Photographs 6 and 7. These photographs show pre and post-break-up conditions, and in the latter the river was approximately 150 m wide. The Muskwa River was sampled from the Alaska Highway bridge, (Photograph 8). The bridge surface is the lowest elevation of the entire length of the highway,

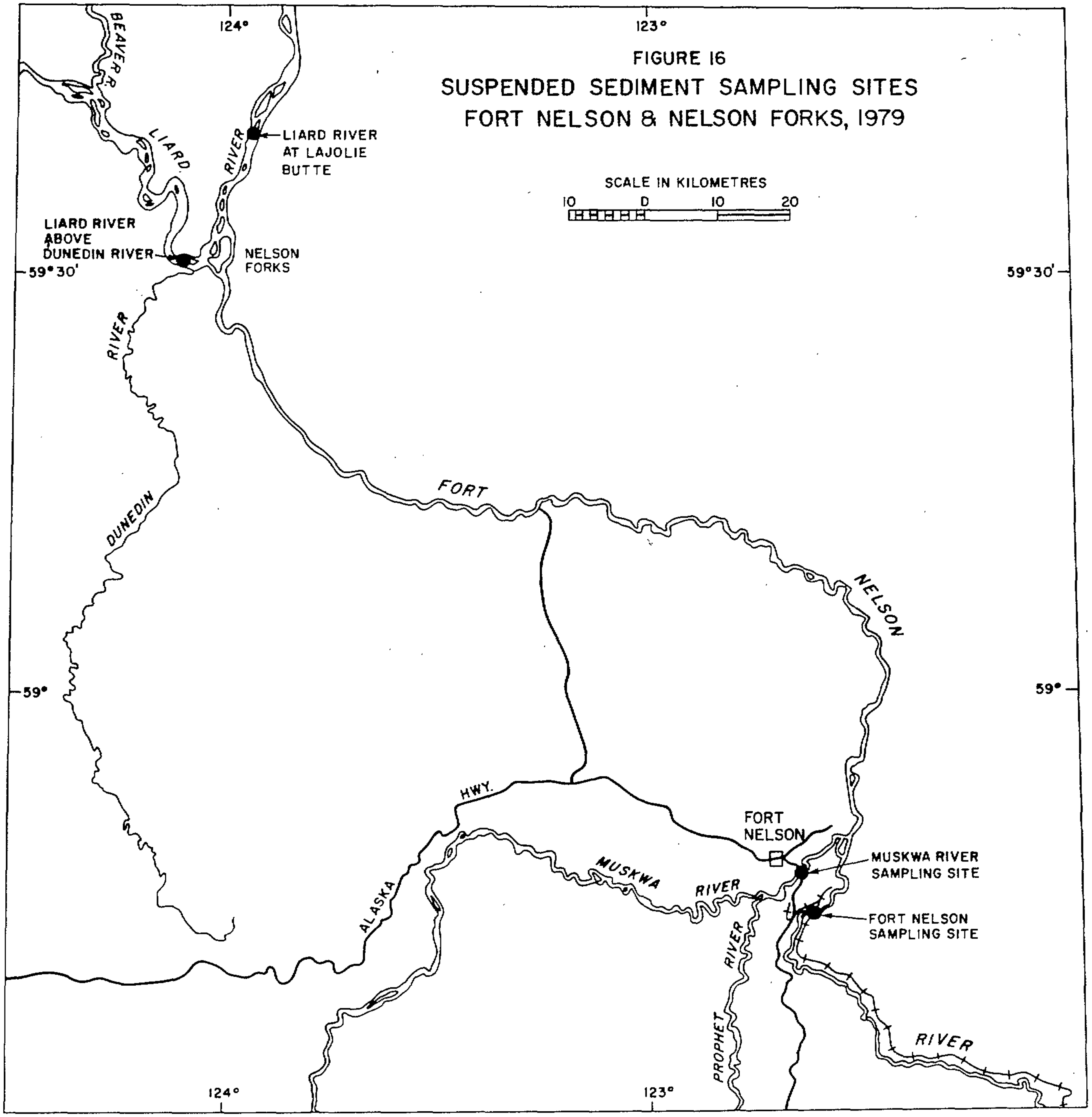


FIGURE 16
SUSPENDED SEDIMENT SAMPLING SITES
FORT NELSON & NELSON FORKS, 1979

a reflection of the degree to which the Muskwa is incised. The only repeated sampling of the Liard was at the Lower Crossing of the Alaska Highway (Photograph 9), approximately 120 km due west of Nelson Forks, (Figure 17). Two further sampling sites of the Liard are shown on Figure 16; the Liard above Dunedin River is above the junction with the Fort Nelson River, while the Liard at La Jolie Butte is below. These latter sites were only visited once each, and samples were taken from the upstream ends of midstream islands. The Liard at the mouth, near Fort Simpson (Figure 17), was regularly sampled from June onwards by personnel of Water Survey of Canada (W.S.C.), and the preliminary data have been provided for comparative purposes.

C. Results of 1979 Field Operations

1. Fort Nelson Area: The first samples were taken at both rivers on April 24, through intact, decaying ice covers. Both rivers exhibited suspended sediment concentrations less than 50 mg/L, and although insufficient samples were taken to compute a mean cross-sectional concentration, the available data do indicate that very low sediment transport occurred under the ice, in the period just prior to break-up. The concentrations measured for the Fort Nelson and Muskwa Rivers are shown in Figures 18 and 19, respectively. They exhibit similar trends; a rapid build-up to the spring sediment peak, followed by an early summer period of low sediment transport, and finally, a mid-summer period of greatly fluctuating peaks and troughs of sediment, as a result of summer

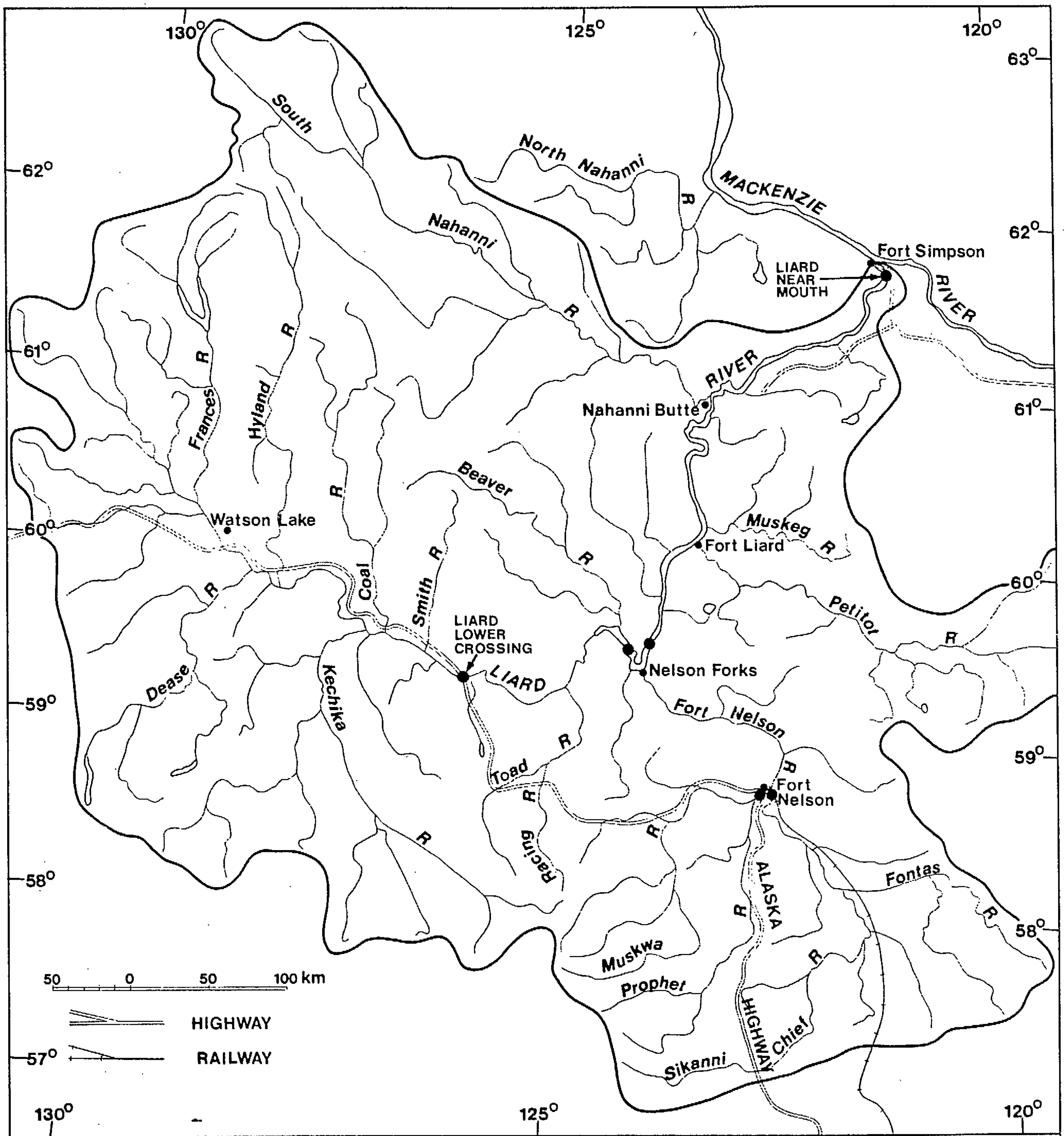


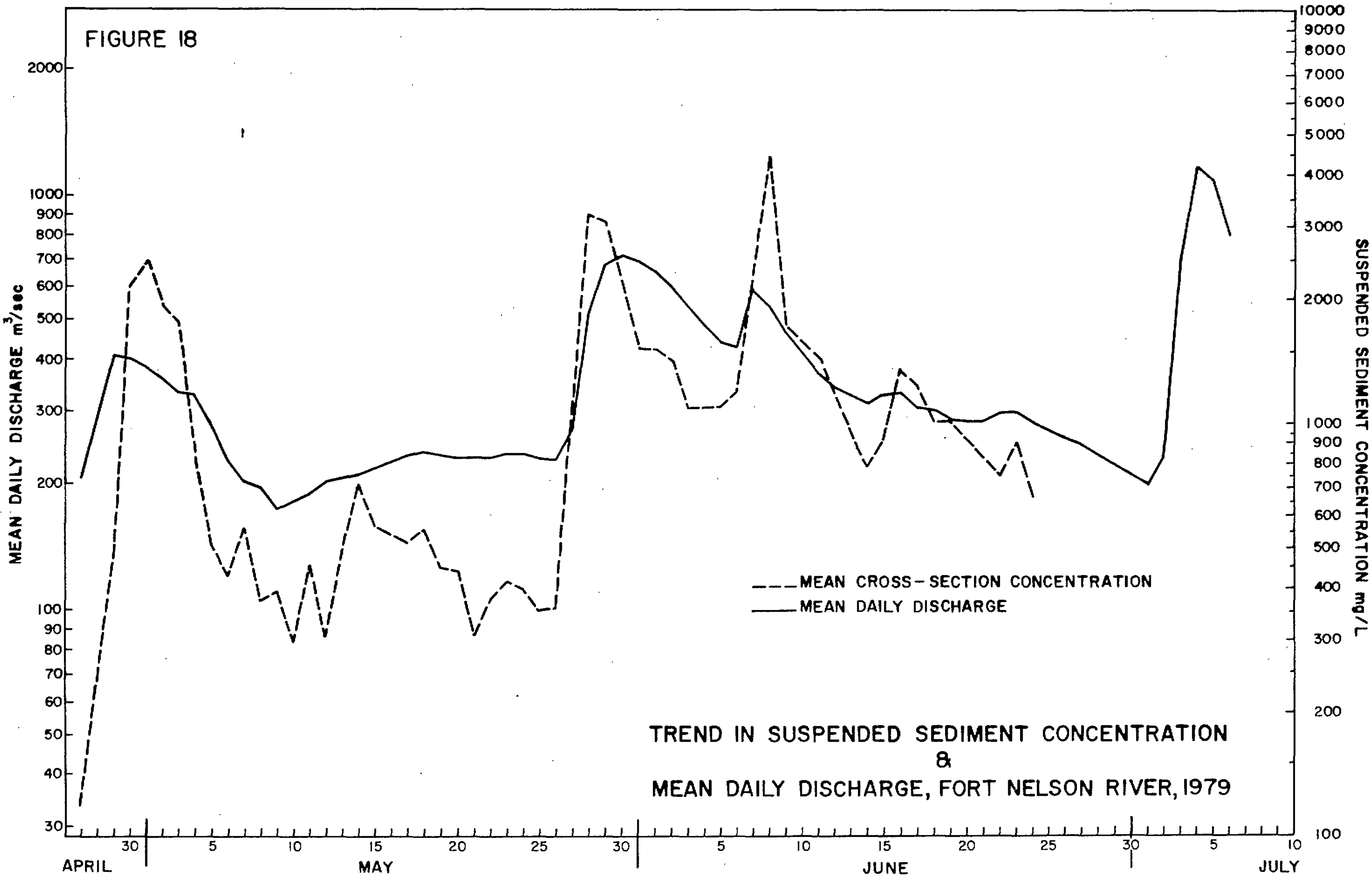
FIGURE 17
LIARD BASIN SUSPENDED SEDIMENT SAMPLING SITES, 1979

storms. All the major peaks of concentration occurred on both rivers, and the values on the Fort Nelson exceeded those of the Muskwa for most dates, as did the water discharge. However, in mid-June the flow of the Muskwa exceeded that of the Fort Nelson, and continued to do so through July, as indicated by the preliminary records provided by the W.S.C., Fort St. John.

It is not possible to tell whether the sediment concentration peaked prior to water discharge because only one sample per day was feasible, and a continuous flow record was not available. However, it is apparent that such occurred on the Fort Nelson for the peak of late May, and may have happened on the Muskwa for the same event. On the other hand, it is probable that sediment concentration peaked after that of water discharge on the Fort Nelson for the break-up event and in early June. This timing factor is important in explaining the immediate source of sediment, in that, if concentration peaks much before discharge it is indicative of a large amount of transportable sediment readily entrained during the early part of the rising flow, which becomes exhausted before the flow has peaked. This ready supply of suspended sediment was made ready for transport by previous high flows, and exposure during recession. Thus, much of the sediment transported in late May could have resulted from the flows of the break-up period. Also, when the peaks of sediment concentration and water discharge are coincident, it is a reflection of a material source from the bed, probably deposited on previous recessions (Arnborg et al., 1967).

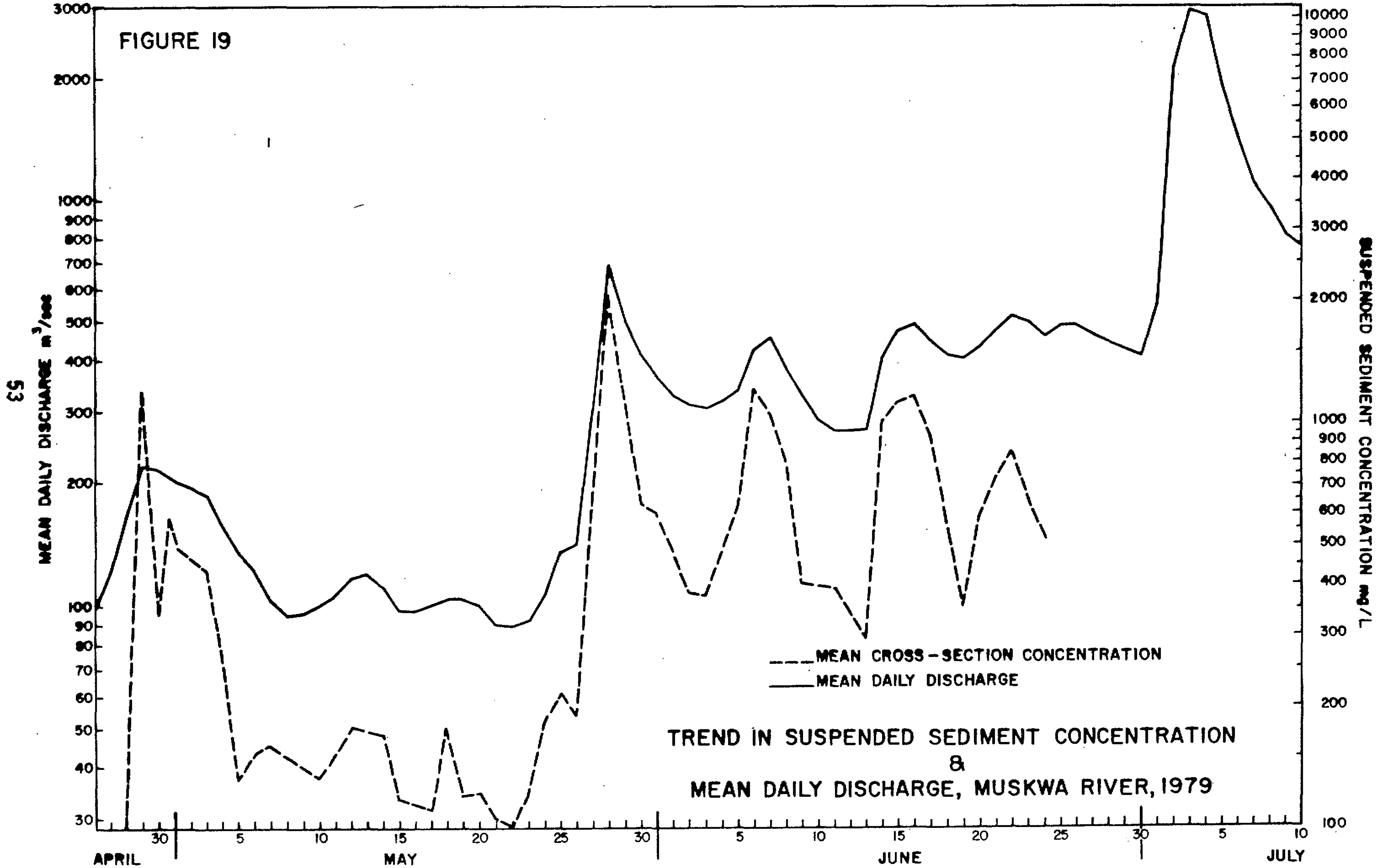
At both sites, the break-up period was accompanied by dramatic

FIGURE 18



TREND IN SUSPENDED SEDIMENT CONCENTRATION & MEAN DAILY DISCHARGE, FORT NELSON RIVER, 1979

FIGURE 19



TREND IN SUSPENDED SEDIMENT CONCENTRATION & MEAN DAILY DISCHARGE, MUSKWA RIVER, 1979 rises in sediment concentration, and recessions almost as severe. However, the peak concentrations encountered during the sampling period (i.e. until June 24) occurred in late May and/or mid-June, possibly as an indirect consequence of the spring flows. Nonetheless, the peak flow and sediment event for 1979 occurred in early July, when peak flows on the Muskwa were more than three times the discharge achieved in late May. The flow of the Fort Nelson in early July was also the peak for the year, but less than twice the late May value. The suspended sediment concentrations measured in early July (preliminary data provided by W.S.C., Fort St. John) were 5640 and 4780 mg/L for the Muskwa and Fort Nelson, respectively. These exceeded values measured earlier in the year, even though they were samples taken on the falling limb of the storm peak.

The data for mean daily concentrations and mean daily loads are provided in Appendix B1. The computations were made according to the methods prescribed by Sediment Survey of Canada, (Environment Canada, 1978 a and b). Interpolation of missing values was facilitated by the sediment rating curves for the Fort Nelson and Muskwa Rivers shown in Figures 20 and 21, respectively. The relationship between water discharge and sediment discharge rate was strong for both rivers, and the closeness between rising and falling water level conditions is a confirmation of the situation shown by temporal concurrence of water and concentration peaks.

Appendix B1 also contains water temperatures for both rivers, and shows a warming trend after break-up, followed by a sudden fall in values in late May. This drop is associated with the large peak in

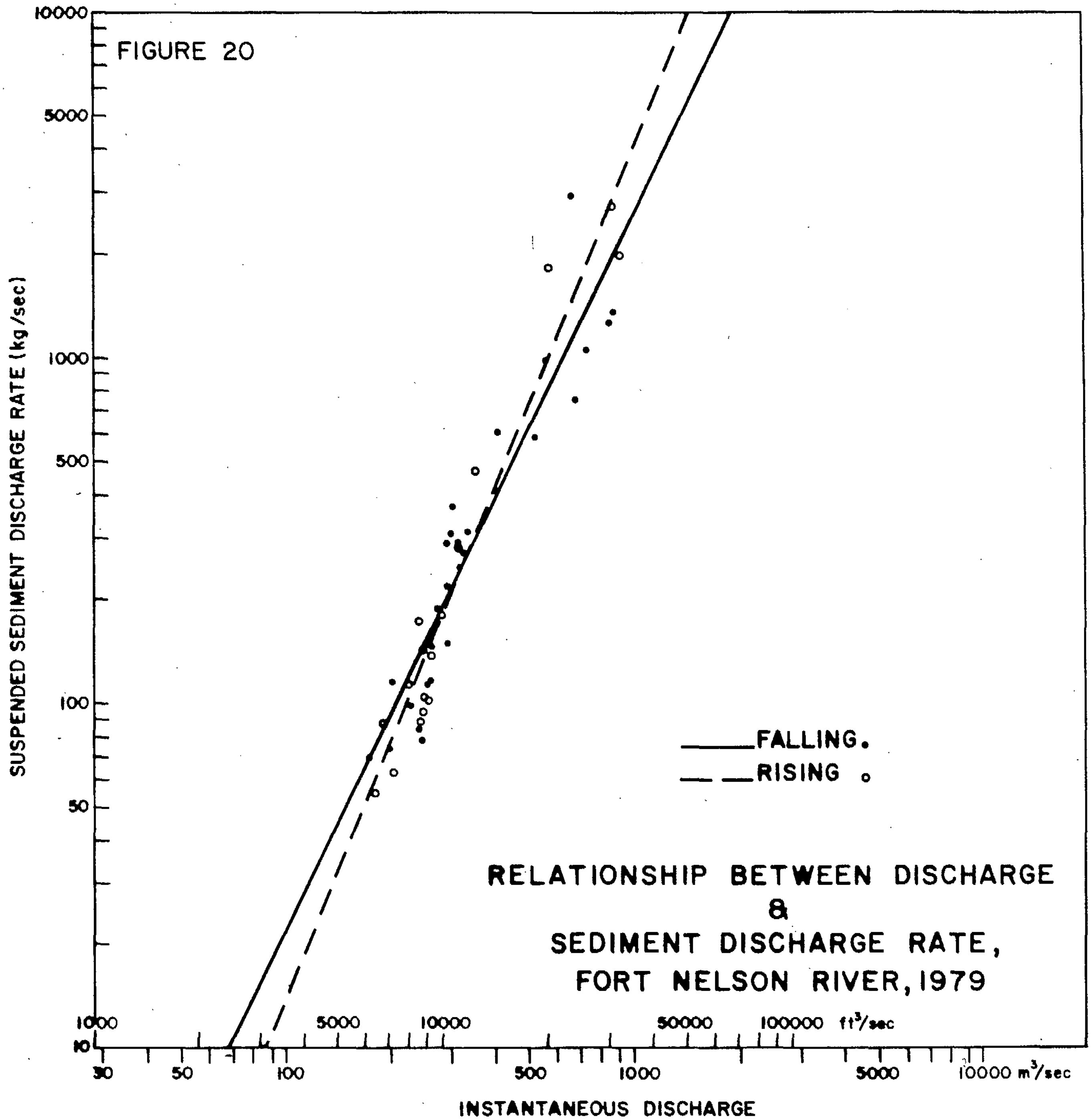


FIGURE 20
SUSPENDED SEDIMENT DISCHARGE RATE (kg/sec)
10000
5000
1000
500
100
50
10
FALLING •
RISING o
RELATIONSHIP BETWEEN DISCHARGE
&
SEDIMENT DISCHARGE RATE,
FORT NELSON RIVER, 1979
1000
5000
10000
50000
100000 ft³/sec
30
50
100
500
1000
5000
10000 m³/sec
INSTANTANEOUS DISCHARGE

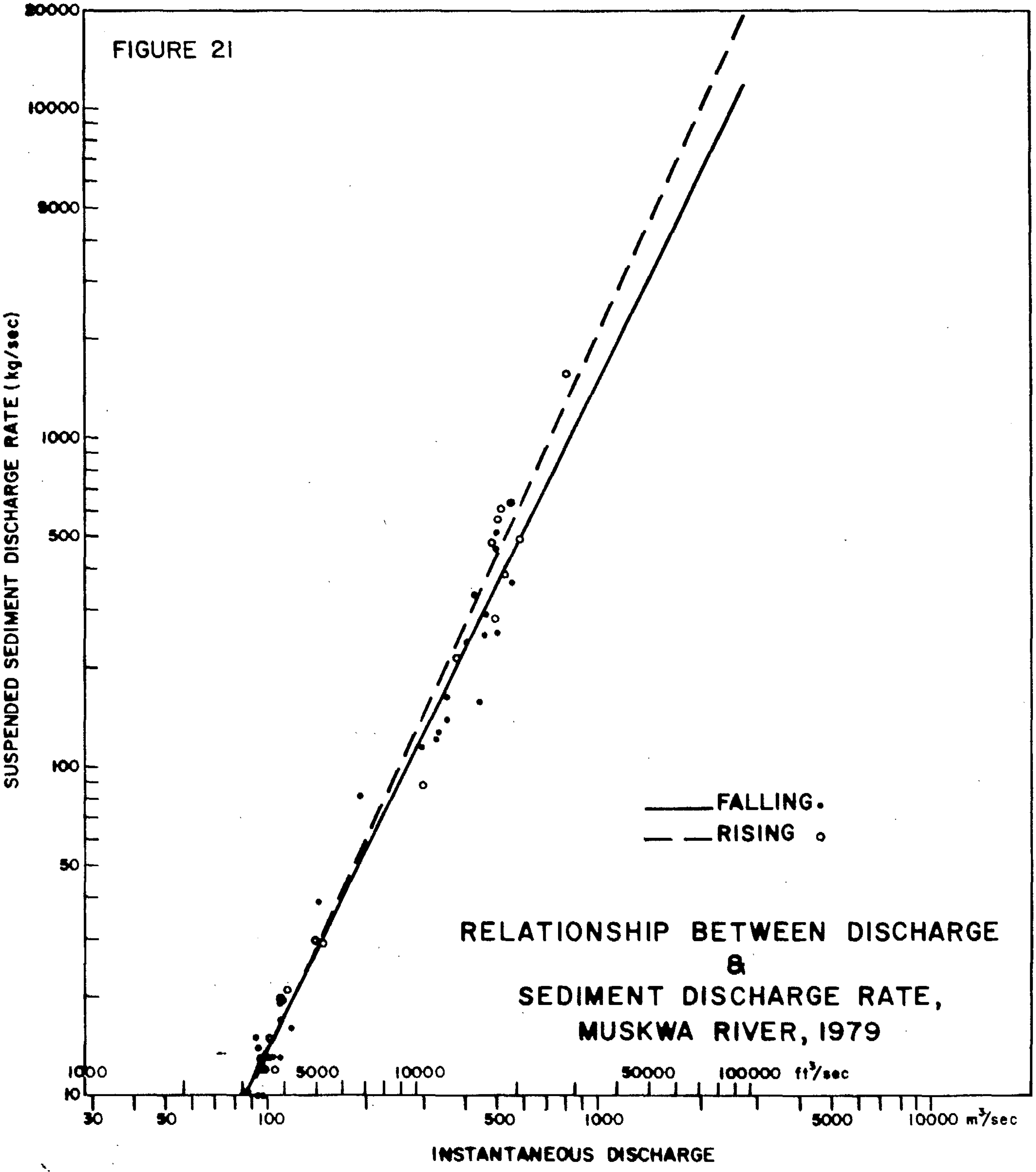


FIGURE 21
SUSPENDED SEDIMENT DISCHARGE RATE (kg/sec)
20000
10000
5000
1000
500
100
50
10
FALLING •
RISING o
RELATIONSHIP BETWEEN DISCHARGE
&
SEDIMENT DISCHARGE RATE,
MUSKWA RIVER, 1979
1000
5000
10000
50000
100000 ft³/sec
30
50
100
500
1000
5000
10000 m³/sec
INSTANTANEOUS DISCHARGE

flow following a rainstorm, which apparently triggered further snowmelt in the high elevation portions of both river basins. Further minor periods of lower water temperatures are also associated with later flow peaks, particularly on the Muskwa.

2. Liard River: As mentioned above, the Liard River was sampled sporadically at three sites. The three samples taken at the Lower Crossing were on the slow, rising limb of spring discharge, which generally peaks in early to mid-June at this site. The sediment concentrations also showed a slow increase between May 16 and June 4. These values are provided in Appendix B2, along with the estimated daily loads. Table 8 shows the results of an attempt to elucidate the spatial variability of sediment concentration on the Liard. The main feature is the increase in concentration on the Liard after the junction with the Fort Nelson. This result is not unexpected, although the sampling date was very close to that of the minimum concentrations measured on the Fort Nelson upstream at Fort Nelson. However, this table is based on very few samples, and the sampling method was less rigorous than that used at Lower Crossing and Fort Nelson.

D. Discussion of Field Results

The results of the sediment transport computations presented for the Fort Nelson area, and the Liard at Lower Crossing will be discussed separately, as will those for the Liard at Fort Simpson (to be presented below). The interrelationships between the results from these

TABLE 8

MISCELLANEOUS SUSPENDED SEDIMENT CONCENTRATIONS ON THE LIARD RIVER, LATE MAY, 1979

STATION[a]	DATE	SUSPENDED SEDIMENT CONCENTRATION mg/L	WATER TEMP. °C
LIARD RIVER AT LOWER CROSSING	MAY 27	516[b]	7.0
LIARD RIVER ABOVE NELSON FORKS	MAY 26	508[c]	7.3
LIARD RIVER BELOW NELSON FORKS	MAY 26	764[c]	7.5

a Stations listed in downstream order; the Fort Nelson and Dunedin Rivers join the Liard at Nelson Forks: see Figure 16

b Mean cross-sectional concentration.

c Mean of 2 midstream samples

widespread points of the same river system will, however, be made apparent in this section.

1. <u>The Fort Nelson and Muskwa Rivers:</u> These two rivers have basins of roughly the same size, the Fort Nelson being the larger - 23300 km^2, compared to 20300 km^2 for the Muskwa. The southernmost drainage boundaries of both basins are at almost the same latitude, but whereas the Muskwa drains to the north and east, the Fort Nelson has major drainage lines from the east and west; the Sikanni Chief drains east before flowing north, and the Fontas west before flowing north. The great width (and hence, stream length) of the headwater portion of the Fort Nelson basin is reflected in the travel time of streamflow to the junction with the Muskwa. This is shown in Table 9, which presents the correlation coefficients between the flow values of the two rivers at Fort Nelson, for different lag times of the Muskwa. Similar results would be expected for sediment delivery rates. The time series have been analysed for several hydrologic periods, described at the bottom of the table. The early summer (May/June) and mid-summer (June/July) periods are those that most closely reflect travel times, since the events occurring were due to rainstorms throughout the basins, thereby involving the maximum streamflow length. For both of the above periods the strongest correlation was for the Muskwa lagged one day. However, during the break-up period (April/May), the flows of both rivers were strongly correlated at the same travel times, perhaps a reflection of the similarity of snowmelt elevation bands, and the more localized nature of snowmelt compared with rain-induced peaks.

TABLE 9

AUTOCORRELATION MATRIX FOR TIME SERIES OF MEAN DAILY FLOWS OF MUSKWA AND FORT NELSON RIVERS AT FORT NELSON, B.C., 1979

TIME PERIOD	NO TIME LAG	MUSKWA LAGGED 1 day	MUSKWA LAGGED 2 days
April 21-May 5 n = 15	r = 0.99	r = 0.96	r = 0.86
May 6 - June 13 n = 39	r = 0.85	r = 0.93	r = 0.87
June 14-July 10 n = 27	r = 0.78	r = 0.98	r = 0.88
May 6-July 10 n = 66	r = 0.67	r = 0.81	r 0.74

April 21 - May 5 - Break-up period.

May 6 - June 13 - Early summer, one major storm-induced flood

June 14 - July 10 - Mid summer, one major storm - induced flood

Daily, monthly and seasonal sediment loads for both rivers are shown in Appendix B1, and great monthly and seasonal disparities are apparent. These are clearly evident in Figure 22, which is a plot of the cumulative daily loads. During the break-up period, the Fort Nelson transported a much greater volume of suspended sediment than did the Muskwa. Both water discharge and suspended sediment concentrations were greater on the former. Major hydrologic and sediment events are apparent from the steep increases of each curve, separated by longer periods of lesser sediment transport. The difference between the Fort Nelson and Muskwa sediment loads during the break-up period was maintained throughout May, and even increased through June. However, the major storm of early July had a greater effect on sediment transport of the Muskwa, as shown by the very steep increase in cumulative sediment load of that river. The Fort Nelson reacted later, and less markedly. This resulted in the total load of the Muskwa for the period of record being almost twice that of the Fort Nelson, a reversal of the situation that had prevailed up until the end of June.

The combined load of both rivers for the period April 28 to July 15 was almost 13 million tonnes, of which just less than half a million tonnes were transported during the break-up period April 28 to May 5. Although the amount of sediment transported during break-up appears small, its importance should not be underestimated. The Fort Nelson River breaks up at Nelson Forks before the Liard, and it was seen that under-ice sediment transport on the Fort Nelson was very low. Presumably this is also true on the Liard above Nelson Forks. Accordingly, any increase in turbidity of the Liard waters below Nelson Forks during

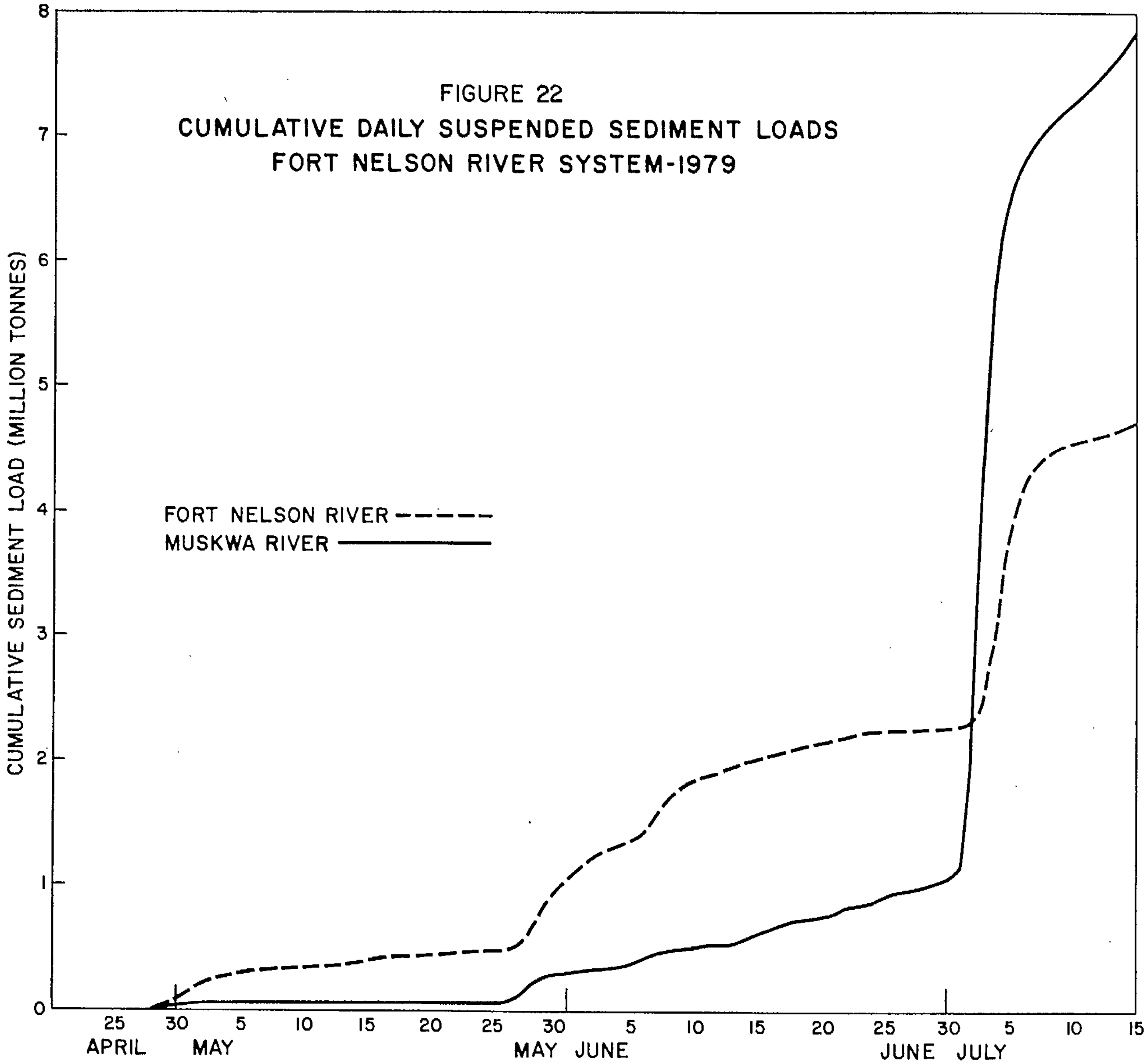


FIGURE 22
CUMULATIVE DAILY SUSPENDED SEDIMENT LOADS
FORT NELSON RIVER SYSTEM-1979

break-up is mainly due to Fort Nelson sediment input. Also, this turbid water is instrumental in aiding and accelerating break-up through albedo reduction of downstream ice covers.

It is important to remember that the sediment loads have been computed for the Fort Nelson and Muskwa Rivers at Fort Nelson, and these are probably only minimum estimates of the amount entering the Liard at Nelson Forks. Although it is probable that some of the sediment would have been deposited between Fort Nelson and Nelson Forks, it is more likely that the load would have been augmented from further riverbank erosion. A survey of the river over this section was conducted during the period of low summer flows in 1979, and the resulting maps of erosion are shown in Appendix C. Although there were some sites of slip-off-slope sand accumulation, approximately half the total riverbank length was estimated to be undergoing active erosion. At the start of break-up these sections of active erosion can have accumulated large amounts of transportable sediment (prepared by winter and pre-break-up thaws), and together with material deposited on the bed by the last flood of the previous summer, the spring flood could transport a much greater load past Nelson Forks than was measured at the bridge sites further upstream.

2. <u>The Liard River Upstream of Nelson Forks:</u> The data in Appendix B2 consist of the mean cross-sectional concentrations for sample days at the Lower Crossing of the Liard, along with estimates of associated daily loads. The only comparative date available resulted

from a sediment sampling program conducted by B.C. Hydro personnel at various sites on the Liard in 1977 and 1978. The data are presented in Table 10. The sites sampled are listed in downstream progression. Each sample is presented under the mean date of the three-day sample period required to cover most sites at any one survey. For each date there was an increase in load downstream on the Liard, although there was great variation in loads between sample dates. The daily yield values are given as a basis for comparison of inputs between stations and sampling periods. The station identified as Liard River above Beaver River was the sampling site nearest to Nelson Forks, and is therefore, the best representative of the sediment transport condition of the Liard before the Fort Nelson input. For the five available sample dates, it can be seen that the sediment load of the Liard above Beaver River was two to four times that of the Liard at Lower Crossing. It should also be noted that the computations of the combined load of the Fort Nelson and Muskwa Rivers for 1977 and 1978 exceeded the loads of the Liard-Lower Crossing for each date.

The data for 1979 revealed a different picture, especially the values for late May and early June, at which times, the load of the Liard at Lower Crossing exceeded that carried by the Fort Nelson below the Muskwa. The dichotomy appears to result from the streamflow pattern of the upper Liard. Figure 23 is a plot of portions of the hydrographs of flow at the Lower Crossing site for part of 1977 and 1978, and with some preliminary flow values for sample days during 1979 (provided by W.S.C., Whitehorse). The Liard at this site experiences snowmelt throughout may from the upper basin, and the integration of snowmelt flow inputs

TABLE 10

LIARD BASIN MISCELLANEOUS DAILY SEDIMENT LOADS (TONNES) AND YIELDS (TONNES/KM^2)

FOR 1977, 1978 and 1979

DATE	June 23, 1977	July 20, 1977	Sept. 28, 1977	June 29, 1978	July 25, 1978	May 16, 1979	May 27, 1979	June 4, 1979
LIARD above[a] Kechika R.	15900[c] (0.3)[d]	8710 (0.1)	687 (0.01)					
LIARD at Lower Crossing	51000[a] (0.5)	37100[a] (0.4)	707[a] (0.01)	5760[a] (0.1)	1650[a] (0.02)	11700 (0.1)	154000 (1.5)	252000 (2.4)
LIARD above[a] Beaver R.	182000 (1.5)	217000 (1.8)	3000 (0.03)	10700 (0.1)	4010 (0.03)			
MUSKWA at Fort Nelson	39600[a] (2.0)	1380000[a] (68.2)	3020[a] (0.2)	4490[a] (0.2)	3890[a] (0.2)	987 (0.1)	11000 (0.5)	12000 (0.6)
FORT NELSON above Muskwa R.	21800[a] (0.9)	89900[a] (3.9)	2730[a] (0.1)	3810[a] (0.2)	376[a] (0.02)	10700 (0.5)	13700 (0.6)	47400 (2.0)
LIARD at Mouth				67700[a] (0.2)				787000[b] (2.8)

a Data Provided by B.C. Hydro

b Data Provided by W.S.C., Calgary

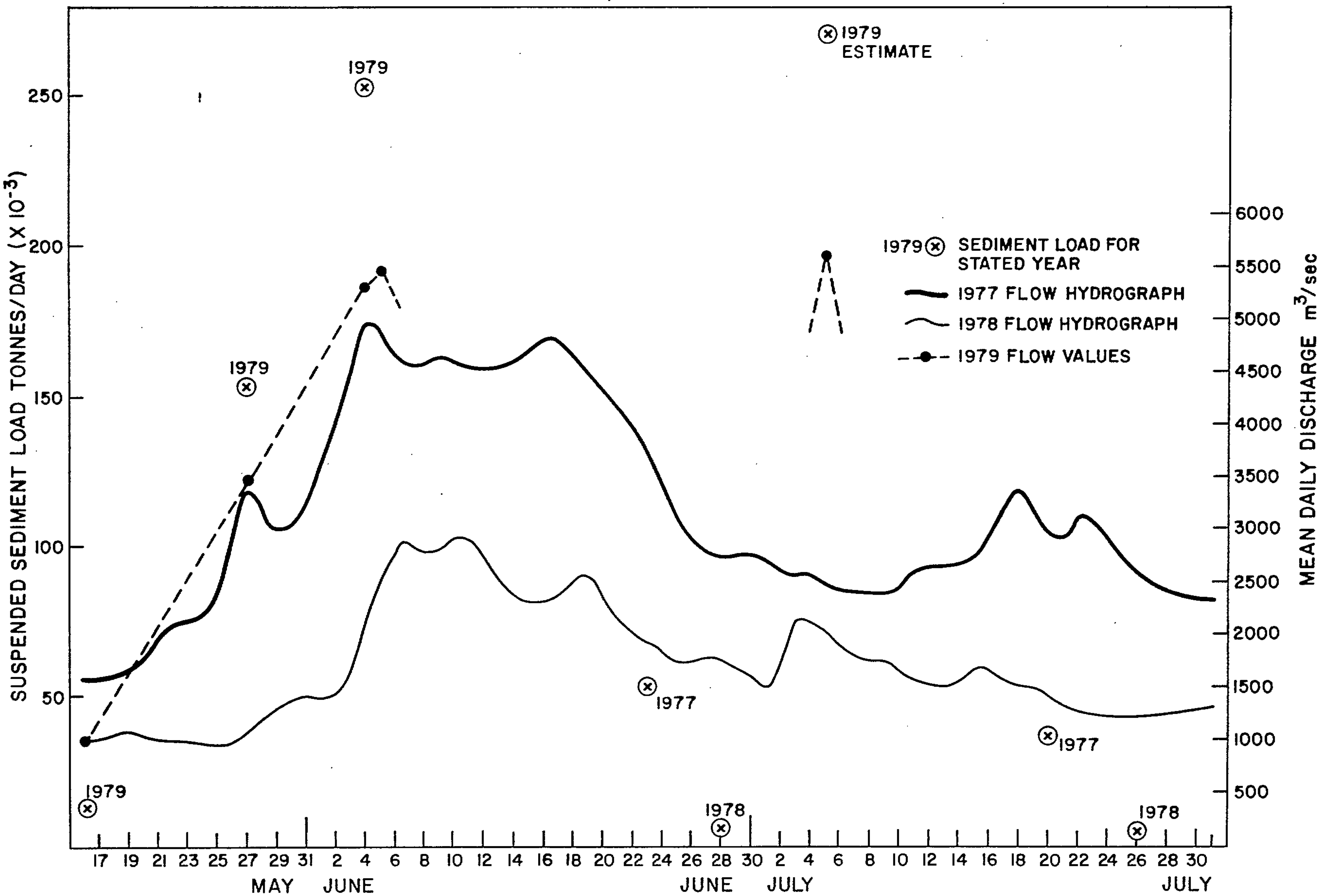
c Load in Tonnes

d Yield in Tonnes/km^2

FIGURE 23

LIARD AT LOWER CROSSING

MEAN DAILY FLOWS & MISCELLANEOUS SUSPENDED SEDIMENT LOADS FOR 1977, 1978 AND 1979



from various elevations generally results in spring peak flow occurring in early to mid-June. This pattern is faily consistent for the flow records examined for the 1970's. In addition, the spring peak is often the annual peak flow, although summer storm peaks are also evident. In 1979, the annual peak flow at Lower Crossing occurred in early July, (concurrent with the peaks in the Fort Nelson area), and this peak was marginally higher than the spring peak of June 5.

It can be seen from Figure 23 that the daily sediment loads estimated from the B.C. Hydro data for 1977 and 1978 were all samples of recession flow, or late summer low flow events. On the other hand, the values for 1979 were taken from flows on the rising limb of the spring peak (which occurred one day after the final sampling), and the picture of sediment transport that is revealed is quite different to that obtained from the previous data. Thus, the importance of choosing sediment sampling dates that reflect streamflow variation becomes apparent. Also, from an admitedly meagre data source, it appears that the upper Liard (as represented by the Lower Crossing) has a suspended sediment regime closely resembling that of flow; steadily increasing sediment transport during snowmelt into mid-June, low sediment transport during spring recession and summer baseflow, with possible short-duration peaks in sediment transport during summer storm peaks. If this pattern does hold from year to year, then the majority of the annual suspended sediment load of the upper Liard would be transported in the period mid-May to mid-June, at a time when sediment inputs to the lower Liard from the Fort Nelson could be relatively low.

The sediment load of the Liard - Lower Crossing for June 4, when the flow was only slightly lower than the spring peak of the following day, was computed to be 250000 tonnes per day, and the estimated load for the July 5 peak at 265000 tonnes per day. It was mentioned above that there was an approximately three-fold increase in load between Lower Crossing and Beaver River. If this factor is applied to the 1979 data it produces the estimates shown in Table 11.

TABLE 11

SEDIMENT LOAD ESTIMATES ON LIARD AT NELSON FORKS, 1979

	LIARD at Lower Crossing (tonnes)	LIARD at Nelson Forks (tonnes)	FORT NELSON at Fort Nelson (tonnes)
June 4	250 000	750 000	60 000
July 5	265 000	800 000	1 250 000

Therefore, although the loads on the Liard are estimated to be similar for both dates, it is apparent that the sediment load of the upper Liard would be more influential on the sediment regime of the lower Liard during early June, than it would in July.

3. The Sediment Loads of the Liard at Fort Simpson and the Fort Nelson River: During the summer of 1979, Water Survey of Canada conducted a suspended sediment sampling program on the Liard near the mouth, (Fort Simpson, N.W.T.). In order to compare the sediment loads from the Fort Nelson Basin with that of the entire Liard Basin, it was

necessary to obtain a measure of the flow travel time between the towns of Fort Nelson and Fort Simpson. Accordingly, correlations were computed for a time series of Fort Nelson River flows (at Fort Nelson), with flows of the Liard River (near Fort Simpson). The matrix of coefficients is shown as Table 12. The coefficients do not reveal a great strength of association, especially when consideration is given to the longest period analysed (April to July). However, for each period it appears that the appropriate travel time is between two to three days. The greater strength of association for the June 29 to July 20 period is perhaps a reflection of the importance of the Fort Nelson Basin as a streamflow contributor to the Liard during the summer storm period.

A similar matrix was produced for sediment loads on the Fort Nelson and Liard Rivers, and the results are shown in Table 13. The time periods analysed are a reflection of the different sampling periods - April 28 to July 15 on the Fort Nelson, and June 1 to October 31 on the Liard. For the maximum concurrent record, i.e. May 25 to July 22, a strong correlation exists for a three-day travel time, and with a two-day travel time in the second rank. There is almost an identical pattern for the late summer time period, and this is possibly because of the importance of the late summer storm peak to sediment transport on the Fort Nelson, and hence, the Liard. The coefficients for early summer are very low, and indicate negligible association between the sediment loads of the Liard and Fort Nelson Basins. This appears to be confirmation of the results from the Lower Crossing data, namely, that the upper Liard is more important for suspended sediment input

TABLE 12

AUTOCORRELATION MATRIX FOR TIME SERIES OF MEAN DAILY FLOWS OF FORT NELSON RIVER AT FORT NELSON AND LIARD RIVER AT FORT SIMPSON, 1979.

TIME PERIOD	NO TIME LAG	FORT NELSON FLOWS LAGGED BY 1 DAY	2 DAYS	3 DAYS	4 DAYS
April 21 - July 20	r = 0.59 n = 91	0.64 90	0.67 89	0.67 88	0.63 87
May 24 - July 20	r = 0.45 n = 58	0.64 58	0.76 58	0.77 58	0.66 58
June 29 - July 20	r = 0.40 n = 22	0.66 22	0.84 22	0.85 22	0.69 22

TABLE 13

AUTOCORRELATION MATRIX FOR TIME SERIES OF DAILY SUSPENDED SEDIMENT LOADS OF THE FORT NELSON RIVER AT FORT NELSON AND LIARD RIVER AT FORT SIMPSON, 1979.

TIME PERIOD	NO LAG	FORT NELSON SYSTEM LAGGED BY						
		1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS	6 DAYS	7 DAYS
FORT NELSON May 25-July 15 LIARD June 1-July 22	r = 0.25 n = 45	0.56 46	0.86 47	0.97 48	0.77 49	0.44 50	0.18 51	0.02 52
Early summer FORT NELSON May 25-June 24 LIARD June 1-June 28	r = 0.53 n = 24	0.51 25	0.46 26	0.42 27	0.43 28	--	--	--
Late summer FORT NELSON June 25-July 15 LIARD June 25-July 22	r = 0.13 n = 21	0.50 22	0.86 23	0.98 24	0.76 25	0.39 26	0.11 27	--

to the lower Liard than the Fort Nelson Basin, for this early summer period (mid-May to mid-June). A comparison of Tables 12 and 13 will indicate that the correlation coefficients point to the same travel times, but are stronger for sediment load than streamflow, especially in late summer. A possible inferrance is that Fort Nelson streamflow input is a major influence on downstream Liard streamflow only as a result of severe summer storms, and other tributaries are more important to Liard streamflow for the rest of the open-water season. On the other hand, the suspended sediment input of the Fort Nelson has a much greater effect on the timing and intensity of sediment on the Liard at Fort Simpson, even allowing for a period of reduced transport in early summer.

From the foregoing, a three-day travel time was assumed, and comparison of the sediment loads of the two rivers was made by lagging the flows of the Fort Nelson River by three days. The data are shown in Table 14. The final column presents the Fort Nelson load as a percentage of Liard load, this value can be viewed as an indicator of daily fluctuations. This is valid even though it is realised that deposition is probable downstream, because the load should be kept in equilibrium with flow conditions by further sediment entrainment on the Fort Nelson and Liard. As might be expected from a basin as large as the Liard, the daily load at the mouth changes slowly, unlike the rapid fluctuations shown by the Fort Nelson. Accordingly, the changes shown in the percentage column are mainly a reflection of peaks and troughs in Fort Nelson load. For the majority of the record, covering June, the greatest contributions rose to about 30%, and fell to less than 10%.

TABLE 14

COMPARISON OF DAILY SUSPENDED SEDIMENT LOADS OF THE FORT NELSON[a] AND LIARD[b] RIVERS-1979.

LIARD R.[c] tonnes	FORT NELSON R.[d] tonnes	FORT NELSON AS % OF LIARD
732000(June 1)	240000(May 29)	33
756000	165000	22
807000	117000	14
874000	101000(June 1)	12
877000(June 5)	84400	10
883000	64200	7
787000	59400	8
887000	62200(June 5)	7
748000	89300	12
714000(June 10)	166000	23
662000	210000	32
606000	98200	16
486000	67500(June 10)	14
406000	55100	14
358000(June 15)	43300	12
340000	34700	10
328000	52300	16
303000	72800(June 15)	24
270000	85700	32
239000(June 20)	69900	29
238000	49300	21
250000	39100	16
297000	42400(June 20)	14
442000	49700	11
596000(June 25)	55900	9
678000	50900	8
628000	38600	6
513000	50000(June 25)	10
426000	51400	12
344000(June 30)	39800	12
272000	32700	12
254000	28700	11
477000	29500(June 30)	6
1310000	81700	6
3130000(July 5)	1050000	34
5200000	2440000	47
4660000	2140000	46
2900000	1240000(July 5)	43

TABLE 14(cont'd)

LIARD	FN	%
1790000	650000	36
1180000(July 10)	363000	31
812000	223000	27
603000	154000	26
443000	121000(July 10)	27
326000	105000	32
270000(July 15)	128000	47
276000	149000	54
287000	167000	58
275000(July 18)	168000(July 15)	61
TOTAL 40940000	11700000	29
YIELD 148 tonnes/km^2	269 tonnes/km^2	

N.B. [a] Combined sediment load of Muskwa and Fort Nelson Rivers at Fort Nelson, B.C.

[b] Liard River measured near Fort Simpson, N.W.T., close to its mouth.

[c] Liard River data is of a preliminary nature (subject to correction), provided by W.S.C., Calgary Office.

[d] Fort Nelson data are lagged 3 days to correspond with Liard data.

This is the period when the upper Liard is thought to be transporting much of the load passing the Fort Simpson sampling site. However, the projected fall in the upper Liard transport rate, and the increase in sediment from the Fort Nelson as a result of summer storms, was reflected in the percentages for the final third of the record (July). For this period the Fort Nelson contributed up to 60%, and was never less than 25%. For the entire period of available record the Fort Nelson potentially contributed almost 30% of the suspended load passing through the mouth of the Liard. Unfortunately, it is not possible to sample suspended sediment at Fort Simpson during break-up, so no direct comparison is possible. Nonetheless, as explained above, the fact that the Fort Nelson Basin undergoes break-up before the Liard upstream of Nelson Forks, and the observed pulse of sediment during this period, are probably sufficient to imply the overwhelming importance of the Fort Nelson River to the sediment load of the Liard at Fort Simpson throughout the spring break-up (early May).

E. Relationship to the Mackenzie Basin

In order to assess the role of the Fort Nelson River as a sediment contributor to the Liard, and hence the Mackenzie, it would be necessary to have simultaneous sediment surveys on all three rivers, for all periods of interest. Therefore, such an assessment cannot be made for the spring break-up because no data are available other than those presented above for Fort Nelson. The only approach that seems possible is to identify important periods of sediment production from the various contributing areas, and extrapolate the findings to the period of interest for which no data are available. A measure of the sediment transported out of various basins and sub-basins is the sediment yield, expressed as the load transported per unit area, which allows inter-basin comparison. When considered over a period of time that integrates several hydrologic events, this measure should reflect accurately the rate of erosion within a basin, but can be more suspect when considered for only short durations (see Table 10).

In Appendix B1 the suspended sediment yields for the computation period (April 28 to July 15) are given for the Muskwa and Fort Nelson Rivers as 386 and 202 tonnes/km^2, respectively. The combined yield of these two rivers for the same period is 288 tonnes/km^2. These yields would increase if considered over the entire open-water season, even though the load accumulated from late July to the end of October would not equal that accumulated by July 15. This can be seen from the values at the end of Table 14, since the yield of the combined Fort Nelson/Muskwa is 269 tonnes/km^2 for the period June to mid-July, compared to the 288 tonnes/km^2 stated above for a longer period (includes May). Therefore, the yield given for the Liard at Fort Simpson is only a minimum, and the addition of the sediment transported in May would increase the yield above 148 tonnes/km^2, as stated in Table 14.

The ideal situation of simultaneous sediment surveys of the Fort Nelson, Liard at mouth, and Mackenzie downstream of Fort Simpson has never occurred. However, partial comparison is possible from data collected in 1973 and 1974 (Mackenzie and Liard), and 1979 (Liard and Fort Nelson). The data from former years are presented in Table 15, and generally, the yields were calculated for the period early June to

TABLE 15 MACKENZIE BASIN SUSPENDED SEDIMENT YIELDS*

YEAR	BASINS 1+2+3+ tonnes/km^2	BASIN 2+3+ tonnes/km^2	BASIN 2+ tonnes/km^2	BASIN 3+ tonnes/km^2
1973	31	78	132	40
1974	110	276	209	325
1976	-	-	222	-

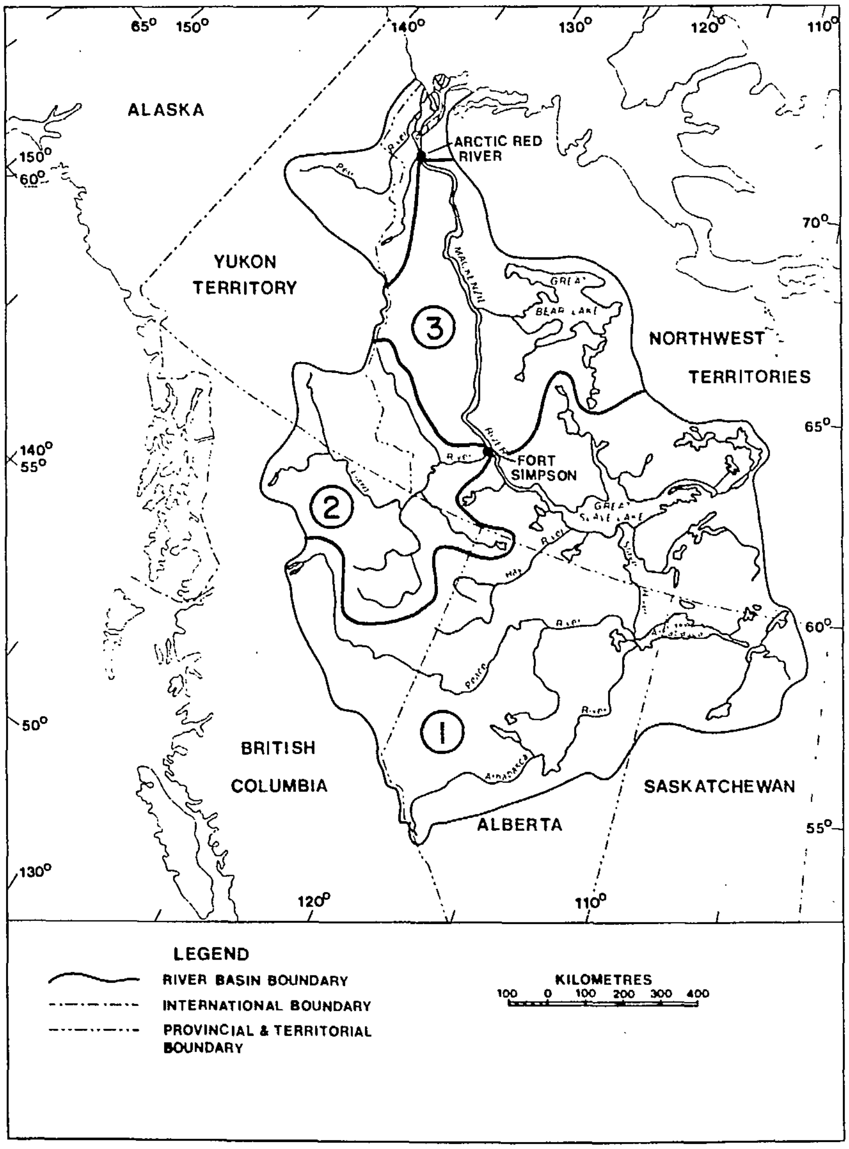
* Sediment loads accumulated over equivalent time periods assuming flow travel time of 8 days between Fort Simpson and Arctic Red River.

\+ See map below for basin explanation.

BASIN ①
Mackenzie River upstream of Liard River.

BASIN ②
Liard River

BASIN ③
Mackenzie River upstream of Arctic Red River and excluding Liard and Great Slave Basins.



end of September. The assumed flow travel time of 8 days between Fort Simpson and Arctic Red River (near the Delta) is based on the work of Mackay (1963). For both 1973 and 1974, the Liard Basin had sediment yields greatly in excess of those calculated for the entire Mackenzie Basin, and this indicates the importance of the Liard (if not the primacy) as a sediment source to the Mackenzie near the Delta. The shortness of record is a hindrance to any analysis. In 1974, Basin 3 (see Table 15) had a seasonal yield greatly exceeding that of 1973, and a review of the sediment and flow data suggests this was the result of a severe summer storm in the Mackenzie Mountains. Such an influx of suspended sediment into the Mackenzie close to the Delta could be very important, but the frequency of such events is not obtainable from the sparse and short records. However, such intense summer storms are relatively frequent in the upper Liard Basin, which is closer to Pacific airmasses.

An additional sediment survey of the Liard at the mouth occurred in 1976, and this provided a three-year record against which to compare the 1979 data. The suspended sediment yield of the Liard at the mouth for the period June to end of September, 1979, was 171 tonnes/km^2. Therefore, in 1979 the Liard was transporting suspended sediment out of the basin at a rate close to the average of the three prior years of record. This exceeded the yield of 1973, but less than 1976. Thus, just as the Fort Nelson has been shown to be a high yield basin to the Liard, the Liard has the same role within the Mackenzie Basin.

F. Summary and Conclusions

As a result of the 1978 reconnaissance of suspended sediment sources in the Liard Basin, the 1979 field program concentrated on the Fort Nelson and Muskwa Rivers at Fort Nelson, B.C., where suspended sediment sampling took place almost daily from break-up through to mid-summer. Also, occasional samples were taken at the Lower Crossing of the Liard River. At Fort Nelson three main periods of high suspended sediment transport were noted; (i) spring break-up, (ii) late May-early June, caused by several rainstorms, and (iii) early July, resulting from a severe rainstorm. On the Liard at Lower Crossing a steady increase in suspended sediment was noted through the protracted snowmelt rise of the hydrograph, and a much reduced rate of sediment discharge is postulated after mid-June, on the basis of a meagre available record. An analysis of the 1979 sediment regimes of the Fort Nelson River (at Fort Nelson) and the Liard River (of Fort Simpson) revealed a strong statistical relationship between timing and amounts of sediment, especially during late June and July. This suggests the likelihood that the sediment load of the Liard below Nelson Forks is largely contributed by the Fort Nelson Basin during this period. Comparison of the 1979 Liard sediment data with a small number of previous records, indicates that 1979 was an average sediment transport year, and therefore, that it was a major high-yield sub-basin of the Mackenzie River.

The following are the main conclusions drawn from the 1979 data and associated analyses:

1. Both rivers in the vicinity of Fort Nelson experienced a rapid and intense increase in suspended sediment discharge during the spring break-up period of late April - early May. The lack of any other break-up sediment data for either of these sites, or any other location within the Mackenzie Basin, make spatial and temporal comparisons impossible. Nonetheless, the early break-up of the Fort Nelson at Nelson Forks, and observed sediment increase indicate the likelihood that the Fort Nelson is the prime suspended sediment input to the Liard River in late April and early May (spring break-up).
2. The available data for the Liard River above Nelson Forks indicate that suspended sediment discharge peaks in early to mid-June, with the snowmelt flood. In the period mid-May to mid-June the sediment discharge of this section of the Liard generally exceeds that of the Fort Nelson at Nelson Forks. This could become significant to downstream break-up on the Mackenzie (which can last until early June) if developments on the Liard curtail the transport of this sediment.
3. In late summer (late June and July), as a result of severe storms, the sediment discharge of the Fort Nelson and Muskwa increase sharply. In 1979 peak sediment concentrations and loads for early July

greatly exceeded those observed in spring. Several instances of these severe summer floods have been evident in recent years. During early July, even though the sediment discharge of the Liard above Nelson Forks is projected to have risen above the June peak (based on flow records at Lower Crossing), the sediment load of the Fort Nelson at Nelson Forks was likely to have been a much more important source of suspended sediment to the downstream Liard.

4. The importance of Fort Nelson sediment to the sediment regime of the Liard at Fort Simpson was confirmed by a correlation analysis of various time series for the months of June and July.

5. A comparison of Liard Basin suspended sediment yields revealed that the 1979 value was close to the average of the previously available data (three-year record). The very sparse record of Mackenzie Basin sediment yields appears to indicate the importance of the Liard to the sediment regime of the Mackenzie near the Delta, at least during summer. Although no sediment data are available for the break-up periods on either river, it is probable that the early break-up influence of the Fort Nelson at Nelson Forks on downstream sediment discharge is repeated on a larger scale at the junction of the Liard and Mackenzie.

G. Recommendations

1. The great scarcity of break-up sediment data in the Mackenzie Basin, and the advantage of the Fort Nelson area for such work (bridge sampling sites), would suggest the need for another period of spring sediment sampling to provide comparative data, especially since conclusions based on a single record can be misleading.
2. Because much of the analysis of sediment regimes within the Liard and Mackenzie Basins depends upon assumptions of prevailing conditions, a survey of pre-break-up sediment discharge conditions is necessary, especially in the Nelson Forks area.
3. It is essential that further suspended sediment sampling be carried out at Fort Nelson and Liard - Lower Crossing during the summer storm period, because of the short data record obtained to date.
4. The sediment sampling achieved so far has been static, observing temporal trends at fixed sites. A spatial sampling scheme (downstream from the fixed sites on the Fort Nelson), should be attempted during moderate flows of summer, in order to elucidate the spatial relationships between the Fort Nelson and Liard at Nelson Forks. Also, to examine the downstream trend in suspended sediment concentration with respect to the mapped erosion zones.

CHAPTER IV

CONCLUSIONS

A. Break-up

1. Late winter ice thickness and strength was found to vary markedly across the channel at two locations, and ice thickness decreased rapidly in the immediate pre-break-up period. Variations in the ice at break-up are in part a reflection of the freeze-up history.

2. Discharge increase appears to be the most important single factor in initiating and sustaining break-up. Air temperature affects the timing of initial break-up, but is not sufficient, by itself, to control the progress of break-up once started.

3. Below normal winter precipitation in 1977/78 and 1978/79 resulted in reduced flood levels in the spring flood period. Consequently, discharges were not sufficient in 1979 to break-up and flush out the ice from some reaches of the Fort Nelson and Liard systems. Also, the low winter ice levels and reduced break-up discharges limited ice action on the banks, but probably caused increased shoal, sand-bar and bed modification.

4. Ice jams observed in 1979 were more frequent than in 1978, but their magnitude was reduced. Ice jam locations were similar to those of 1978 and agree well with those locations identified by satellite imagery analysis for the period 1973-1978.

5. Break-up in the Nelson Forks area remains incompletely understood. The lack of ice thickness and discharge data for this area hinders detailed analysis, but it appears that the widely varied flow patterns in the distributory channels may have a moderating or dampening effect on extreme break-up events.

6. The identification of ice jam-prone sites amenable to detailed study provides an opportunity to obtain information on the processes responsible for ice jams, the effect of such jams on channel geometry, and the resultant production of sediment.

B. Suspended Sediment

7. Both the Fort Nelson and Muskwa Rivers experienced a rapid and intense increase in suspended sediment discharge during the spring break-up period of 1979, and during this period (late April - early May) the Fort Nelson River system is probably the main suspended sediment input to the Liard Basin.

8. On the Liard River at Lower Crossing, snowmelt is prolonged and water and sediment discharge apparently peak in early to mid-June (June 5 in 1979). During the period mid-May to mid-June the upper Liard probably has a higher sediment discharge than the Fort Nelson River system, at the junction of the two at Nelson Forks.

9. In 1979 peak water and sediment discharge occurred in early July for both the Fort Nelson and Muskwa Rivers at Fort Nelson. Evidence suggests that severe summer storms recur frequently in

the Fort Nelson and Muskwa Basins, with the result that the Fort Nelson system is often the major source of suspended sediment to the Liard during late June and July, and statistical analysis confirmed this fact for the 1979 data.

10. On the basis of a meagre available record, it was shown that the Liard Basin is a (if not the main) high sediment yield basin within the Mackenzie Basin. Also, the basin yield of the Liard at the mouth for 1979 was close to the average of a three-year record, and hence in 1979 it was probably a major sediment input to the Mackenzie.

C. Recommendations

1. Ice Break-up:

a. A field program similar to that described above for 1979 should be carried out in 1980, because the data obtained would increase the information that is required to permit analysis of the ice regime over long periods of time, and permit prediction of any system changes, especially since both years studied to date have been ones of low spring discharge.

b. Measurement of maximum winter ice thickness should be carried out at selected sites, particularly the Nelson Forks area and the sites identified as ice jam-prone.

c. Continued aerial and ground monitoring should be undertaken to extend the data base for location and timing of ice break-up events in the Liard Basin, particularly above Nahanni Butte, for which there is only a two-year record. This will also assist in compilation of a complete photographic record of ice jams for future analysis.

d. Post-break-up examination of ice jam locations should be made to determine the importance of ice jams and break-up events on channel morphology and sediment production.

2. Suspended Sediment:

e. Sediment sampling programs are necessary in the Fort Nelson and Liard - Lower Crossing areas during break-up, because conclusions drawn from the available one-year record of systematic sediment sampling can be misleading.

f. A survey of pre-break-up suspended sediment discharge (under the ice) is needed, particularly at Nelson Forks, in order to check assumptions on prevailing conditions at break-up. These assumptions have to be made because it is not possible to sample sediment during break-up, other than at the bridge sites.

g. Further suspended sediment sampling at Fort Nelson and Liard - Lower Crossing is needed in mid-summer in order to assess the relative importance of the two to the lower Liard, in view of the short data base and projected changeability through the open-water season.

h. An attempt should be made to evaluate the spatial variation in sediment discharge by sampling downstream on the Fort Nelson and then the Liard, during moderate flow periods in the summer.

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APPENDICES

APPENDIX A

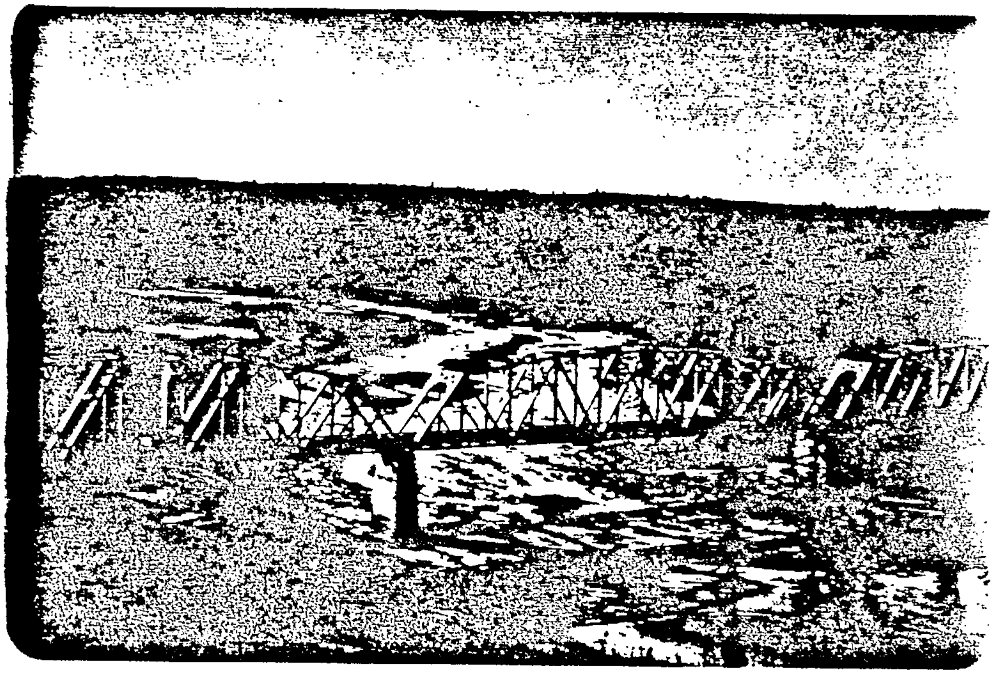
SUMMARY OF DAILY RECORD OF BREAK-UP EVENTS

A. April 21-23

Throughout the Liard and Fort Nelson River basins late winter/early spring conditions prevailed. The Liard River from Watson Lake downstream to Nelson Forks was ice-covered with the exception of the following locations: Cranberry Rapids near Fireside, B.C.; the confluences with the Coal and Smith Rivers; and stretches of the Grand Canyon of the Liard.

While winter precipitation in this region was below normal, average air temperatures were severe, particularly in December and January. Local residents at Fireside reported temperatures as low as -55^{o}C (-67^{o}F) on January 1, 1979. The Liard, from Nelson Forks to Fort Simpson, N.W.T. was solidly frozen including Flett Rapids, an area which normally remains open.

In the Fort Nelson region ice cover was intact and snow covered but with some wet spots. Winter ice levels were extremely low. In general the Fort Nelson River ice exhibited greater decay than the Liard due to snow melt and through-ice percolation of melt-water. The lower reaches of the Muskwa contained significantly more open patches than the Fort Nelson, but were extensively frozen in the upper reaches. The area of weakest ice centred on the Muskwa-Ft. Nelson confluence. The channel width of the Muskwa upstream of the confluence appeared equal to that of 1978 while the Fort Nelson appeared considerably narrower.



PHOTOGRAPH A1. DETERIORATION OF ICE COVER ON FORT NELSON RIVER AT FNHRB SITE. EXTENSIVE MELTING TOOK PLACE PRIOR TO INITIAL ICE MOVEMENT. PHOTOGRAPH TAKEN AT 1650 h, APRIL 26, 1979.

B. April 24-26

With daytime high temperatures near +16° to +18°C at Fort Nelson, ice decay was rapid. Measurement of the ice thickness indicated the extent of ice thinning (see Chapter II). Surprisingly water levels on the Fort Nelson River declined in this period despite significant melting of river ice (Figure A1). By late afternoon of the 26th (1650h) approximately 50% of the channel surface at FNHRB was ice free but no movement of the ice had occurred (Photograph A1). There were no major changes in the remainder of the basin.

C. April 27

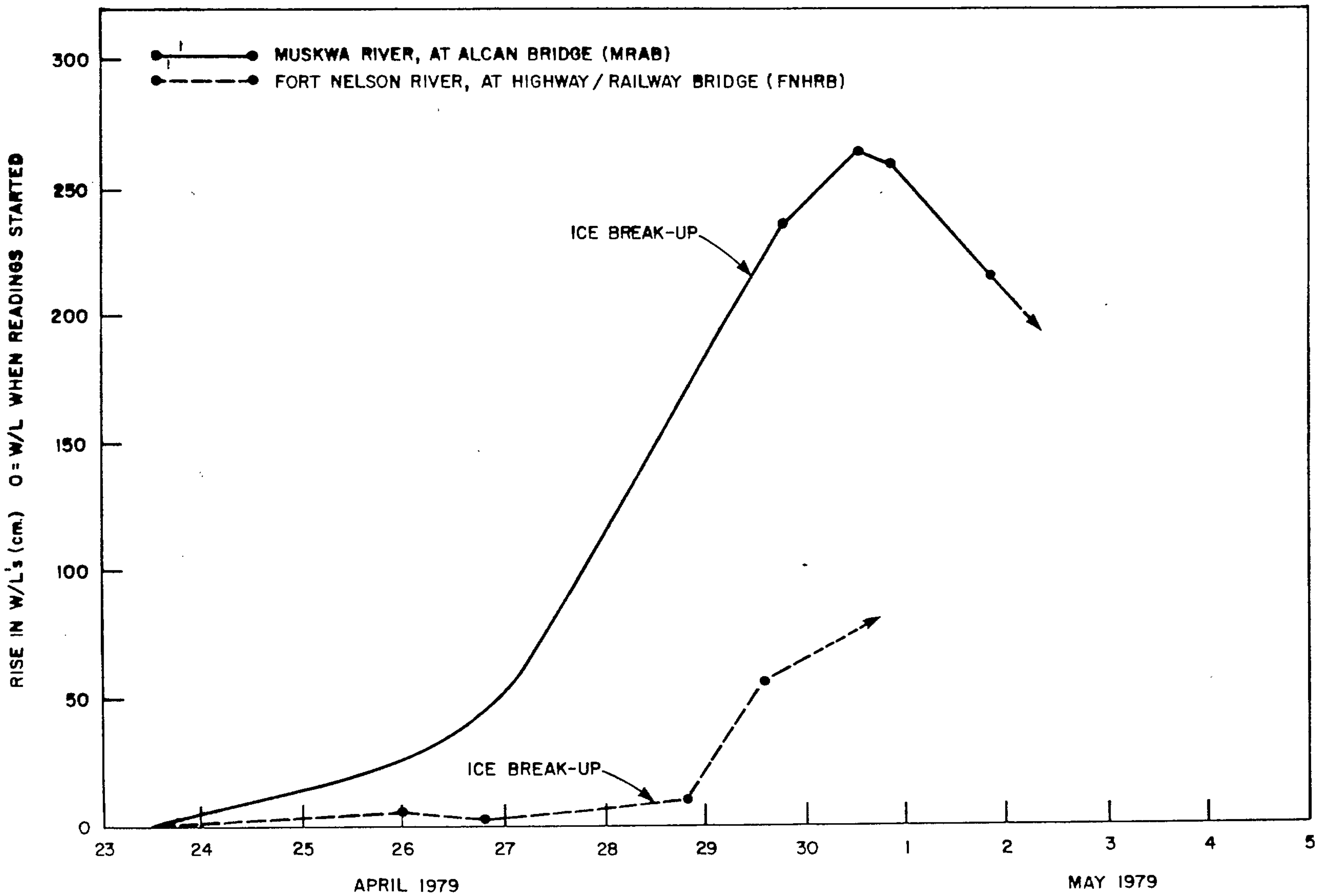
Ice throughout the Fort Nelson basin appeared considerably weakened. The Muskwa had rapidly broken to within 2 km of the MRAB site and ice debris passed beneath the decayed but intact cover downstream. The Fort Nelson was broken and almost ice free 15 km upstream of FNHRB. Throughout the remainder of the basin, but particularly on the Liard upstream of Nelson Forks, little change was evident save for an increase in the size of longshore leads and a decrease in the quantity of shorefast ice in the Grand Canyon region.

D. April 28-29

On April 28 the ice broke up at FNHRB and downstream as far as the old Muskwa - Ft. Nelson confluence. Water levels rose only 10 cm prior to ice movement. Ice block size at FNHRB at 2000h had an average size of only .25 x .25 m, and flow velocity was estimated at 3.0 to 5.5 km/h. The ice pushed onto the banks was

FIGURE AI

WATER LEVEL INCREASES & BACKWATER EFFECTS: FORT NELSON AREA



approximately 10-12 cm thick and was predominantly clear and hard.

At the MRAB site break-up began in the morning of April 29 and by 1445h an ice jam had formed, with the head (i.e. downstream end) of the jam at a curve 1500 m downstream of MRAB. This jam extended about 1100 m upstream of MRAB. The largest ice pans in the jam matrix averaged 2 m x 7 m near the midpoint and the largest blocks observed at the head of the jam reached a size of 35 m x 40 m.

E. <u>April 30 - May 1</u>

While the jam at MRAB remained in place a rapid break-up of the Fort Nelson River down to the Liard confluence took place. The broken ice front moved rapidly along the Fort Nelson (from km 145 to km 0) as a series of synchronous break-up events which caused rapid ice clearance. This is reflected in the apparent high rate of break-up shown for this portion of the basin on Figure 7. At several locations jams were observed reforming as each distinct mass of broken ice arrived. This was particularly true of a series of curves upstream of the Ft. Nelson - Stanolind Creek confluence (20 km upstream of the Liard Highway crossing). By May 1 broken ice existed within 5 km of Nelson Forks.

The ice cover on the Liard, upstream of the Forks remained intact. Large open areas had appeared in the Liard ice cover between Nelson Forks and Fort Simpson. The largest of these were located at La Jolie Butte, the mouth of Sandy Creek, upstream of Flett Rapids, Nahanni Butte, and the mouths of the Matou, Grainger, Birch and Poplar Rivers.

The Mackenzie River ice on May 1 was reported by Water Survey of Canada staff to be between 150-245 cm thick, and Liard ice at LRFC even thicker.

F. May 2 - 5

The ice cover on the Liard from Nelson Forks to Flett Rapids (km 408 to km 270) was destroyed and a series of multiple jams formed. The ice broke at Fort Liard at 2050h on May 2, but a major jam developed immediately upstream of the Petitot junction at the settlement. This jam remained in place until the late afternoon of May 5.

By May 5, water levels had dropped on the Fort Nelson River, and, except for the Fort Liard ice jam, ice was cleared from the Liard to km 255. At this location hard ice remained competant, possibly due to augmentation by frazil ice produced prior to freeze over of Flett Rapids. Below Nahanni Butte (km 180) wet spots had appeared on the ice.

G. May 6 - 10

Break-up events stagnated from May 6 to May 8; only minor increases in longshore and transverse leads were noted on the Liard from km 255 to the mouth. At 1800h on May 8 a rapid break-up of ice from the mouth of the Blackstone River (km 150) to below the mouth of the Birch River (near km 60) began and the channel cleared rapidly. Ice upstream of the Blackstone, to km 255, remained in place.

Water levels observed at LRSB began to decline on May 7 and dropped 50 cm by late evening, May 10. Mackenzie levels dropped 15 cm in the same period (Figure A2). Daytime temperatures had fallen after a snow storm on May 5 and highs during this period were between $+1^{o}$ to $+4^{o}$ C. By 2200hrs on May 10 the break-up front was approximately 4 km upstream of the LRFC site.

H. May 11

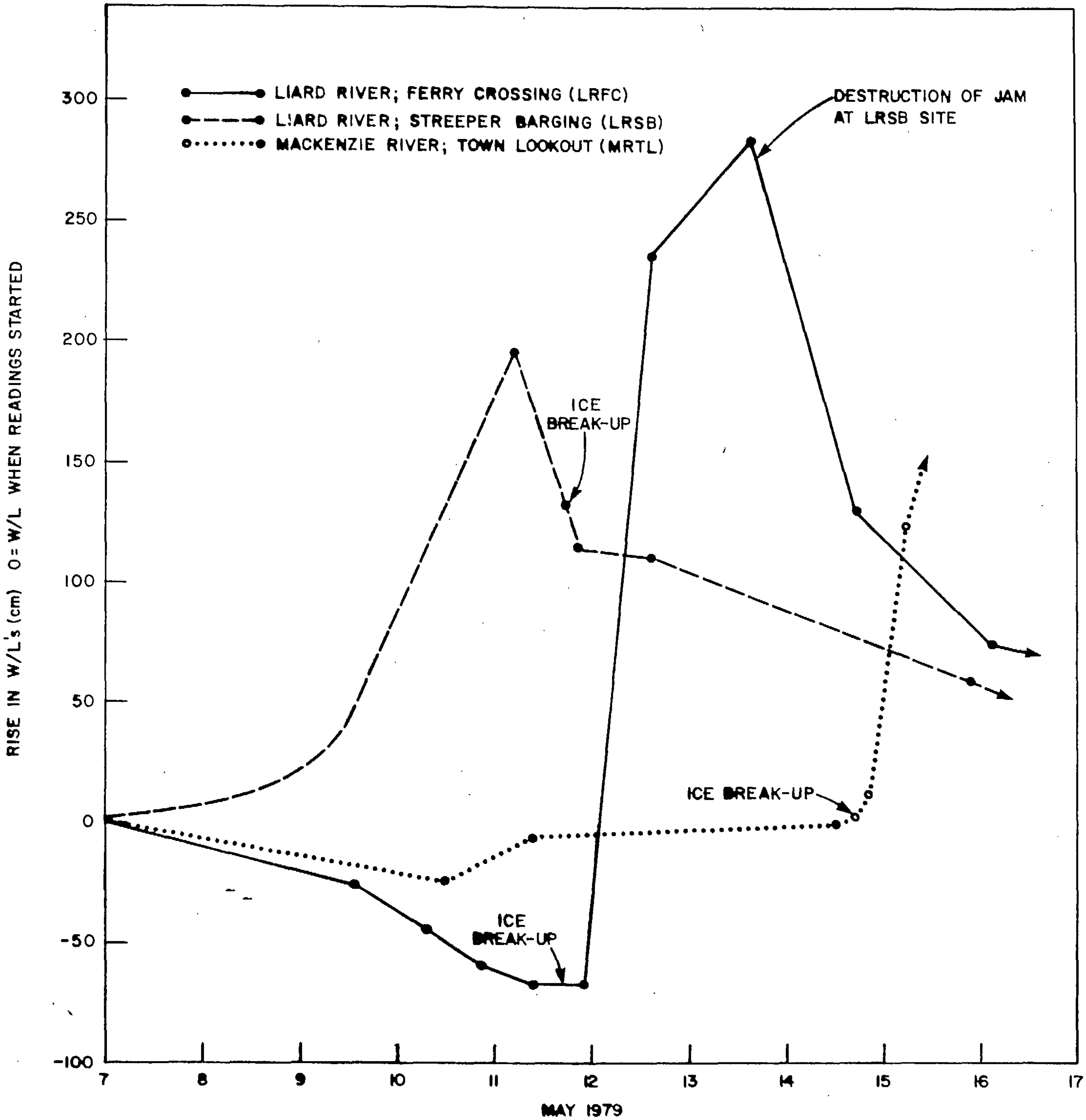
Ice cover in the large bends of the Liard upstream of the South Nahanni confluence (km 170 to km 255) remained undisturbed while the balance of downstream ice moved through the channel toward LRFC as a series of breaking and reforming jams. These jam creation - failure sequences continued until 1500h when the impact of ice debris against the ice cover at LRFC caused failure at this site. By 2030h the ice was broken at LRSB site. Water levels dropped approximately 120 cm from values recorded at the time of peak ice shove. A stationary jam extended from the mouth of the Laird to a point 700 m downstream of LRFC. Throughout the night of May 11/12 jam consolidation continued. Individual ice block size was significantly below that observed in previous years, an indication of weak ice which failed rapidly under the compressive stresses present in the jam.

I. May 12 - 13

The LRSB to LRFC jam continued to compact and water levels increased 200 - 250 cm. Ice blocks in the jam had an average thickness of 122 cm. The jam broke at 1525h on May 13 when Liard ice thrust into the Mackenzie main channel. Mackenzie ice was thrust downstream a distance of 110 - 115 m at MRTL. Mackenzie ice block

FIGURE A2

WATER LEVEL INCREASES & BACKWATER EFFECTS: FORT SIMPSON AREA



thickness ranged from 46 cm to 70 cm (average 60 cm). These values were considerably less than those recorded in 1978 (Table 4).

J. May 14 - 17

Considerable melt of the ice near Nahanni Butte (km 170 to km 255) took place but the solid ice cover remained upstream of Swan Point. Upstream ice upon reaching this obstruction failed completely and passed beneath the ice cover as slush or candled ice. In the Fort Simpson area the increased water levels of the May 12 -13 period, which resulted from the LRSB to LRFC jam backwater, refloated much of the stranded ice. In 1979 more stranded ice was removed from the banks after initial break-up than in the past and as a result ice debris continued to move through the channel of the Liard.

At 1642h on May 14 Liard ice moved at LRSB and at 1700h Mackenzie ice, triggered by release of the Liard jam began a rapid break-up. Water levels did not increase until 1704h when a slight rise began. This coincided with the appearance of large quantities of Liard ice in the main Mackenzie channel. At 1707h the first highly fragmented Liard ice passed MRTL. Liard ice completely occupied the Mackenzie channel from MRTL to MRNE by 1712h. Water levels continued to rise slowly. No hard, clear ice was evident. Speed of the moving ice was approximately 5.5 km/h (1.5 m/sec).

At 1750h backwater began to increase rapidly, the ice velocity decreased, lateral thrusting of the ice increased and, at 1830h, movement ceased. The head of the jam was located 8 km downstream of MRTL.

Downstream of this location pressure ridges and transverse cracks had developed as far as Camsell Bend. A large ice floe had shifted at the mouth of the North Nahanni River and acted as a jam 'key', which prevented additional ice movement.

By 2145h on May 15 water levels from MRNE to LRFM had dropped considerably and the head of the jam on the Mackenzie was located 50 - 55 kms downstream of Fort Simpson. Little ice remained to move through the Liard River at LRFC. Ice at Nahanni Butte continued to decay. Mackenzie ice, upstream of the Liard confluence, to Strong Point remained coherent but appeared weak and darkened with large open patches. Beyond this region, to Great Slave Lake, little deterioration of the winter ice covers had taken place. This was due to cool air temperatures which prevailed in the southern Mackenzie District through much of late April and early May.

APPENDIX B1

1979 SUSPENDED SEDIMENT DATA FOR MUSKWA AND FORT NELSON RIVERS (B.C.)

DATE	MEAN DAILY WATER DISCHARGE(Q) m^3/sec	MEAN DAILY CONCENTRATION(c) mg/L	DAILY LOAD (L) tonnes	WATER TEMP. (T) °C
MUSKWA RIVER (Basin Area 20250 km^2)				
April				
28	170	349 E	5120 E	I
29	221	993 E	18900 E	I
30	218	551 S	10400	I
May				
1	204	516 S	9090	I
2	195	473 S	7980	0.9
3	190	422 S	6910	1.2
4	158	302 S	4110	2.6
5	135	166 S	1940	3.4
6	124	153 S	1640	3.1
7	103	157 S	1400	3.2
8	95	156	1280	
9	95	155 S	1270	6.1
10	100	147 S	1270	5.2
11	106	154 S	1410	6.2
12	116	168 S	1690	7.4
13	120	168	1740	
14	112	158 S	1530	7.5
15	95	132 S	1080	8.2
16	98	117	987	
17	101	109 S	951	10.2
18	105	140 S	1270	9.5
19	104	126 S	1140	8.9
20	101	110 S	960	9.4
21	90	98 S	765	10.0
22	89	77 S	593	12.0
23	92	123 S	981	12.9
24	106	170 S	1560	14.2
25	136	214 S	2520	13.7
26	142	193 S	2360	14.2
27	286	444	11000	
28	691	1630 S	97200	6.0
29	507	1370 S	60000	8.0
30	419	762 S	27600	9.5
31	368	596 S	18900	11.2

	Q	c	L	T
June				
1	331	507 S	14500	12.4
2	314	406 S	11000	12.7
3	306	385 S	10200	13.3
4	320	433	12000	
5	340	642 S	18800	11.5
6	427	1090 S	40200	11.0
7	456	1070 S	42100	11.5
8	388	819 S	27400	11.3
9	331	500 S	14300	11.6
10	292	413	10400	
11	273	394 S	9310	11.8
12	271	345	8070	
13	272	348 S	8170	11.9
14	405	860 S	30100	10.5
15	470	1110 S	45100	10.8
16	492	1140 S	48500	11.6
17	447	953 S	36800	12.8
18	413	611 S	21800	13.5
19	405	407 S	14200	13.0
20	430	523 S	19400	11.9
21	478	699 S	28900	12.5
22	512	809 S	35800	13.0
23	498	666 S	28700	13.4
24	459	549 S	21700	12.9
25	490	857	36300	
26	492	935	39800	
27	461	760	30300	
28	444	662	25400	
29	425	622	22800	
30	410	673	23900	
July				
1	552	1570 E	74900 E	
2	2097	5680 E	1030000 E	
3	3028	8550 E	2240000 E	
4	2858	5820 S	1440000	
5	1961	3630	615000	
6	1435	2510	312000	
7	1104	1890	180000	
8	959	1580	131000	
9	832	1380	99200	
10	764	1240	81900	
11	710	1220	74900	
12	744	1590	102000	
13	787	1740	118000	
14	826	1840	131000	
15	843	1820	133000	

MUSKWA RIVER - SUMMARY OF DATA

Montly Totals - April 34420 tonnes
May 273127 tonnes
June 735950 tonnes
July 6762900 tonnes

Total Suspended Load for Period April 28 - July 15

7,810,000 tonnes

Suspended Sediment Yield for Period April 28 - July 15

386 tonnes/km^2

FORT NELSON RIVER ABOVE MUSKWA RIVER (Basin Area 23260 km^2)

	Q	c	L	T
April				
28	292	269	6780	I
29	410	527 S	18700	1.3
30	402	1740 S	60400	0.5
May				
1	385	2340 S	77800	0.8
2	362	1980 S	62000	1.0
3	337	1680 S	49000	1.6
4	331	903 S	25800	2.0
5	283	553 S	13500	
6	234	461 S	9310	3.4
7	207	518 S	9270	4.1
8	199	392 S	6730	5.3
9	179	372 S	5770	7.0
10	184	346 S	5500	6.7
11	192	425 S	7050	12.7
12	206	367 S	6530	8.8
13	208	518 S	9310	9.1
14	211	663 S	12100	8.5
15	220	575 S	10900	9.2

	Q	c	L	T
May				
16	229	542	10700	
17	236	522 S	10600	9.8
18	241	548 S	11400	10.0
19	237	484 S	9920	8.9
20	235	444 S	9000	9.5
21	234	361 S	7310	9.6
22	232	390 S	7820	10.6
23	238	435 S	8960	11.6
24	238	416 S	8540	12.5
25	232	388 S	7780	13.1
26	231	390 S	7790	14.7
27	273	580	13700	
28	521	2820 S	127000	9.0
29	682	3060 S	180000	7.2
30	713	2220 S	137000	8.7
31	696	1630 S	98000	9.2
June				
1	657	1530 S	86800	10.8
2	603	1410 S	73400	11.7
3	543	1150 S	54000	12.6
4	490	1120	47400	
5	444	1130 S	43400	12.7
6	427	1330 S	49100	12.8
7	594	2410 S	124000	12.4
8	541	3910 S	183000	10.7
9	467	2080 S	83900	11.4
10	413	1600	57100	
11	371	1430 S	45800	12.5
12	345	1180	35200	
13	328	935 S	26500	13.5
14	314	818 S	22200	12.1
15	328	977 S	27700	12.8
16	331	1300 S	37200	13.7
17	309	1240 S	33100	15.2
18	303	1050 S	27500	15.8
19	289	1000 S	24900	15.9
20	289	923	23000	15.2
21	289	833	20800	15.2
22	297	781 S	20100	15.8
23	300	857 S	22200	16.4
24	282	693 S	16900	16.3
25	268	593	13700	
26	260	515	11600	
27	249	439	9460	
28	235	360	7310	
29	224	303	5870	
30	212	303	5560	

	Q	c	L
July			
1	201	394	6840
2	233	916 E	18500 E
3	693	3280 E	197000 E
4	1180	6830 E	696000 E
5	1084	6720 E	629000 E
6	812	4810 S	338000
7	662	3190	183000
8	535	2000	92400
9	456	1380	54300
10	408	1110	39100
11	379	923	30200
12	348	859	25800
13	359	998	31000
14	399	1050	36200
15	408	980	34500

FORT NELSON RIVER - SUMMARY OF DATA

Monthly Totals -	April	85880	tonnes
	May	966090	tonnes
	June	1238700	tonnes
	July	2411840	tonnes

Total Suspended Load for Period April 28 - July 15

4,700,000 tonnes

Suspended Sediment Yield for Period April 28 - July 15

202 tonnes/km^2

N.B. S - Sample collected this day
E - Estimated
I - Ice or ice jam at sampling section

APPENDIX B2

1979 SUSPENDED SEDIMENT DATA FOR LIARD RIVER AT LOWER CROSSING (B.C.)

DATE	MEAN DAILY WATER DISCHARGE(Q) m^3/sec	MEAN CROSS-SECTIONAL CONCENTRATION mg/L	DAILY LOAD ESTIMATE tonnes	WATER TEMP. ^oC
May 16	971	139	11700	6.4
27	3450	516	154000	7.0
June 4	5320	548	252000	9.2

APPENDIX C

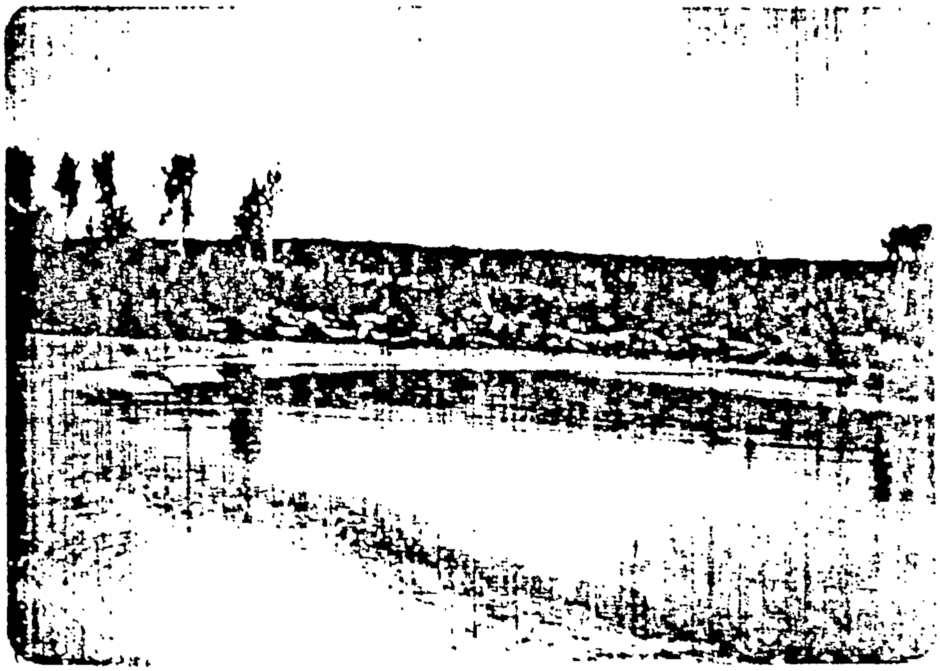
NOTES ON EROSION MAPS OF LIARD & FORT NELSON VALLEYS

A. Introduction

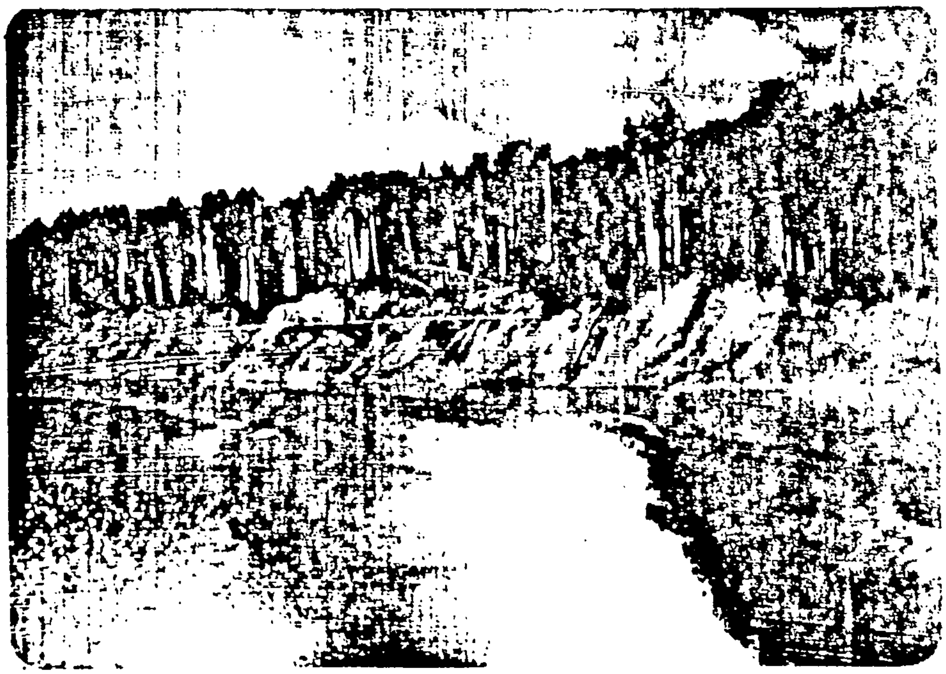
The mapping was originally undertaken on the available maps of 1:50,000 scale during helicopter traverses from Fort Simpson, N.W.T. to Fort Nelson, B.C., during early August 1979. In order that mapping could be carried out for both banks of the rivers, all observed erosion was classified into one of three types, as defined in the section below. Several sites were observed from the ground, and this proved useful in estimating the height of the various features. The maps are contained in the end pocket.

B. Symbol Definition

1. Bank Sloughing: The most widespread type of erosion observed in this area, in which extensive lengths of river bank were undergoing planar failure, (Photograph C1). The failure mechanism is related to active undercutting by the river, and the action of the flow in removing the collapsed debris results in generally parallel retreat, thereby preserving a clean, near-vertical face in cohesive materials. Unlike the two other types of erosion this is essentially a linear feature, and is especially prominent around the outer curves of river bends. The height of this erosion feature was found to be between 2 and 7 m.



PHOTOGRAPH C1. RIVERBANK SLOUGHING, LEFT BANK OF FORT NELSON RIVER, AUGUST 12, 1979.

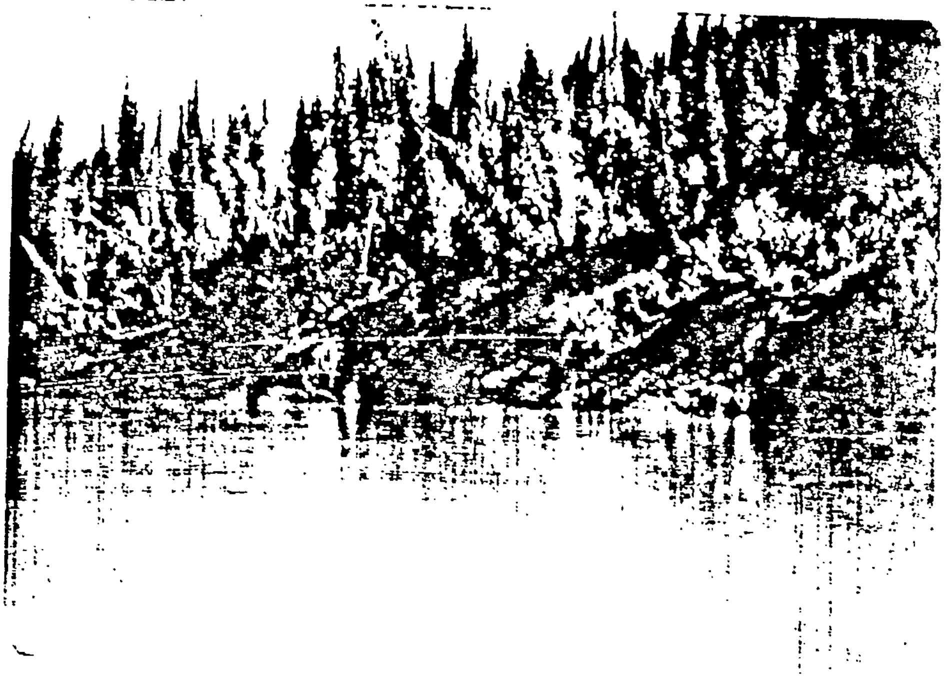


PHOTOGRAPH C2. COLLUVIAL FACE, RIGHT BANK OF FORT NELSON RIVER, AUGUST 12, 1979.

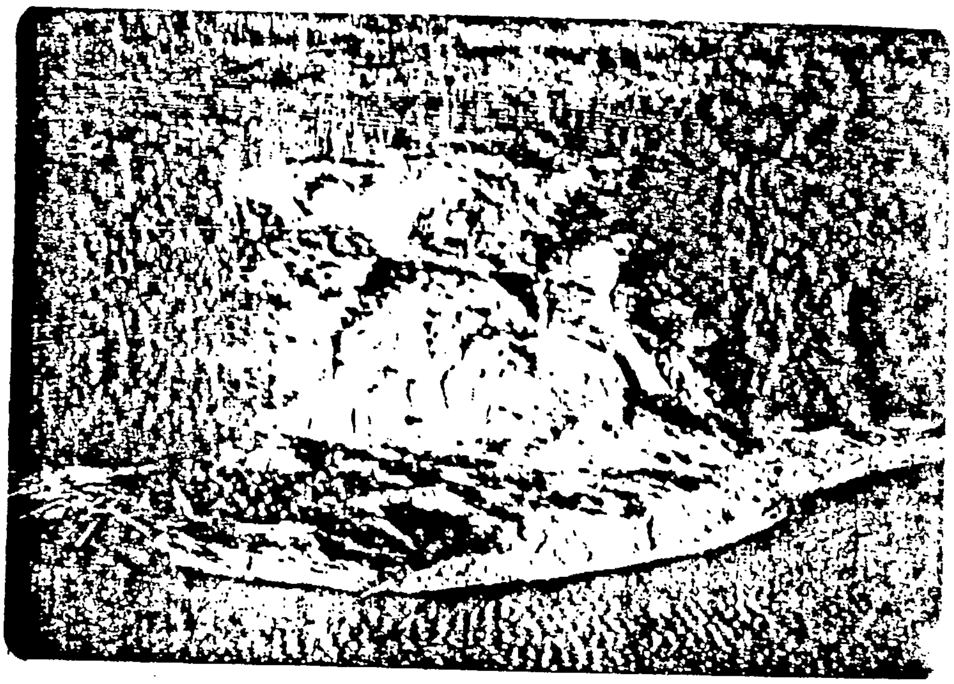
2. <u>Colluvial Faces</u>: These occur at discrete sites and rarely extend along the river for more than 100 m. The features have planar surfaces, are free of vegetation, and slope at angles related to internal friction of the bank material, (Photograph C2). The base of the slope often shows evidence of river undercutting, and this can lead to the removal of material in planar layers, causing parallel retreat of the face. Frequently, tree debris accumulates at the base of the face, having skidded down the face as a result of undercutting of the turf mat at the top of the slope. The observed examples of this erosion type were generally greater than 5 m in height but less than 35 m. The material seemed to be a mix of sand, cobbles and some silts.

3. <u>Rotational Slides</u>: These are also discrete erosion types rarely extending more than 50 m along the river, although at some sites several rotational slides coalesced along the outer curve of a river bend. Unlike the above two erosion types, the mode of failure is not planar, but translational, usually involving the rotation of a large mass of the river bank, (Photograph C3). The distinguishing feature of this type is a large semi-circular scar at the top of the slope, and the hummocked debris cones at the base, where it is under the erosive action of the river. The degree of rotation can usually be identified by the angles of rest of trees that remain rooted in the failed material. The material of this erosion type is mainly silt and clay, and it appears that the mechanism of failure is related to saturation and pore-water pressure. The observed features were greater than 5 m in height but less than 35 m.

4. <u>Active/Inactive</u>: All features that were apparently undergoing erosion at the time of observation, i.e. clean faces and/or active undercutting, were classified as active. All sites mapped as bank



PHOTOGRAPH C3. ACTIVE ROTATIONAL SLIDE, STANOLIND CREEK SITE ON FORT NELSON RIVER, AUGUST 12, 1979.



PHOTOGRAPH C4. INACTIVE ROTATIONAL SLIDE, NEAR POPLAR RIVER ON LIARD RIVER, AUGUST 8, 1979.

sloughing are active. Some of the features identified as colluvial faces, especially in the lower Liard Valley, showed signs of inactivity such as revegetation of part of the face, and boulder pavements at the base, (armouring the slope from the influence of the river), and these were considered inactive. A few of the rotational slide features were also inactive since they displayed revegetation of the basal debris, (Photograph C4), and in one case, the debris did not extend to the water's edge.

C. Erosion Zones Of The Liard Valley

Five erosion zones have been identified and are shown on the maps. Within each zone the length of river bank undergoing active erosion was measured, and the results, expressed as a percentage of the total length of river bank, are shown in Table C1. An attempt has been made to obtain an expression of the area of erosion within each zone by assuming a standard height of 4 m for bank sloughing sections, and 20 m for both colluvial faces and rotational slides. The resulting estimates are shown in Table C2. The five identified erosion zones are briefly described below.

1. Zone 1 - Fort Nelson River, Fort Nelson to Nelson Forks (190 km): This zone has extensive bank sloughing and significant colluvial face erosion, and especially rotational slides where the river impinges on the valley wall. A large percentage of both banks is eroding, and this zone provided the largest estimate of eroding bank area. A short (13 km) subzone along the Muskwa between the Alaska Highway bridge and the junction with Fort Nelson River also provides sediment input to the Fort Nelson River zone, but has not been included in the areal estimates.

2. Zone 2 - Liard River, Nelson Forks to Fort Liard (97 km): This zone has extensive bank sloughing especially on the islands, and the channels around these islands. There is very little evidence of the larger features of bank erosion. However, the areal estimate of bank sloughing is second only to Zone 1.

3. Zone 3 - Liard River, Fort Liard to Flett Rapids (60 km): There is only moderate bank sloughing in this zone, and large erosion features are almost non-existant. The sloughing is concentrated on the islands and the highly curved sections of the river banks.

4. Zone 4 - Liard River, Flett Rapids to Blackstone River (118 km): There is moderate to extensive bank sloughing, but this zone also displays many very active colluvial faces and some rotational slides. Overall, it is the zone with the second highest eroding area. In this zone the South Nahanni River joins the Liard at Nahanni Butte. The lower part of the South Nahanni, from the junction up through the Splits, has extensive bank sloughing, but the values for Zone 4 shown in the two tables do not include the South Nahanni.

5. Zone 5 - Liard River, Blackstone River to Fort Simpson (150 km): This is the zone with the least evidence of active erosion of any of the three types. There are many examples of inactive colluvial faces, and one large inactive rotational slide near the Poplar River. The total eroding area for this zone is small.

TABLE C1

EROSION ZONES OF MID & LOWER LIARD VALLEY

Zone No.	Zone Description	Estimated % Left bank Eroding	Estimated % Right bank Eroding	Estimated % Both banks Eroding
1	Fort Nelson to Nelson Forks	58	42	50
1A	Muskwa River (Alaska Hwy. to Fort Nelson R. junction)	42	32	37
2	Nelson Forks to Fort Liard	53	65	59
3	Fort Liard to Flett Rapids	44	20	33
4	Flett Rapids to Blackstone Riv.	51	42	46
5	Blackstone River to Fort Simpson	6	6	6
TOTAL	*Liard Valley (Fort Nelson to Fort Simpson)*	*42*	*35*	*38*

TABLE C2

ESTIMATES ON ZONAL AREAL EROSION - LIARD VALLEY

Zone No.	Length Sloughing (km)	Area Sloughing[a] (m^2)	Length Other Erosion (km)	Area Other[b] Erosion (m^2)	Total Eroding Area (m^2)
1	150	599,000	38	766,000	1,365,000
2	111	443,000	3	64,000	507,000
3	39	156,000	1	13,000	169,000
4	80	319,000	30	602,000	921,000
5	14	57,000	4	77,000	134,000

N.B.

a - height estimate of 4 m.

b - height estimate of 20 m.

GB 1398.5 .L5 G74 1980
Liard River Basin spring flood: progress report / B.J. Grey, D.A. Sherstone: prepared by Snow & Ice
4001594

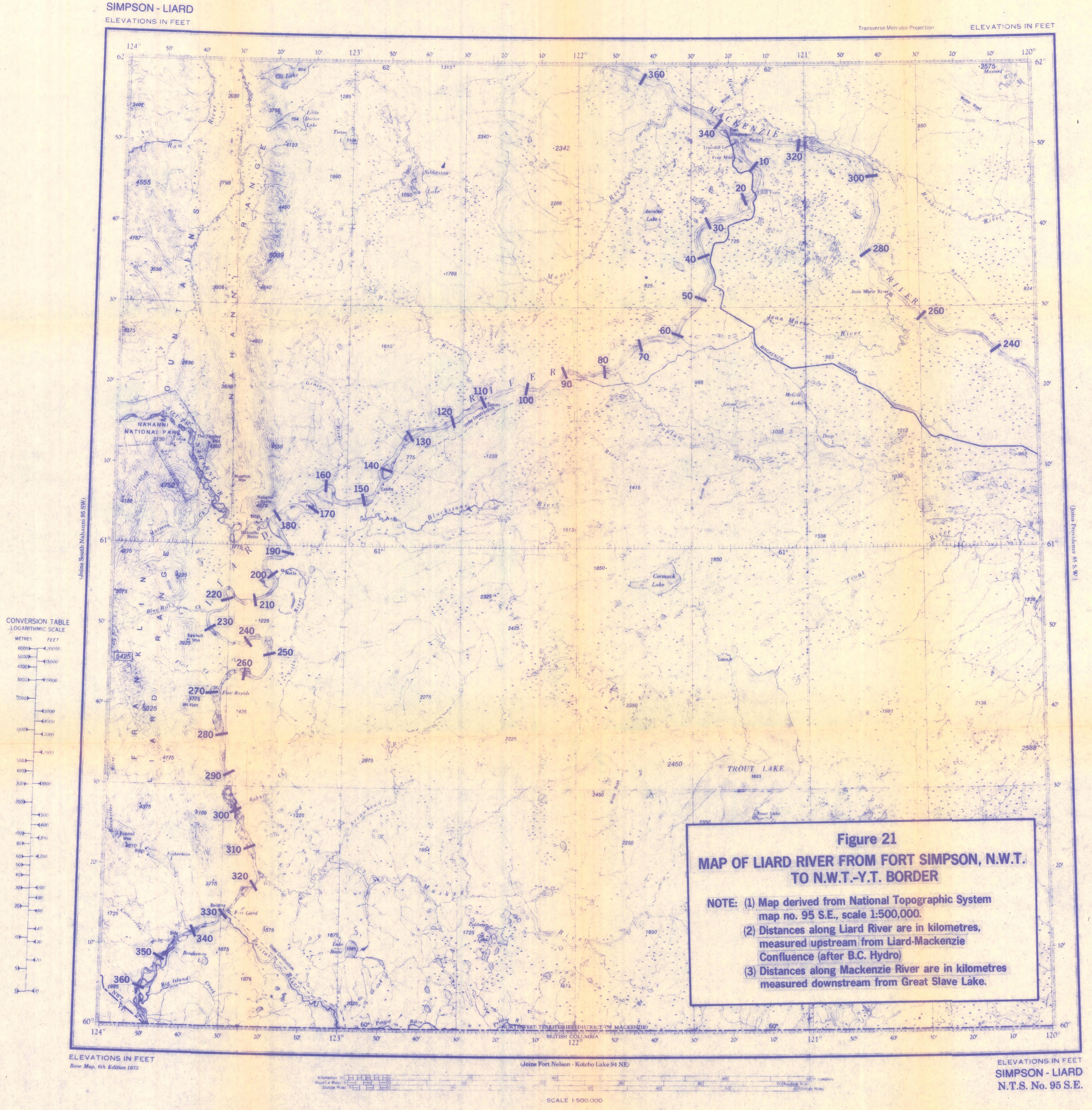
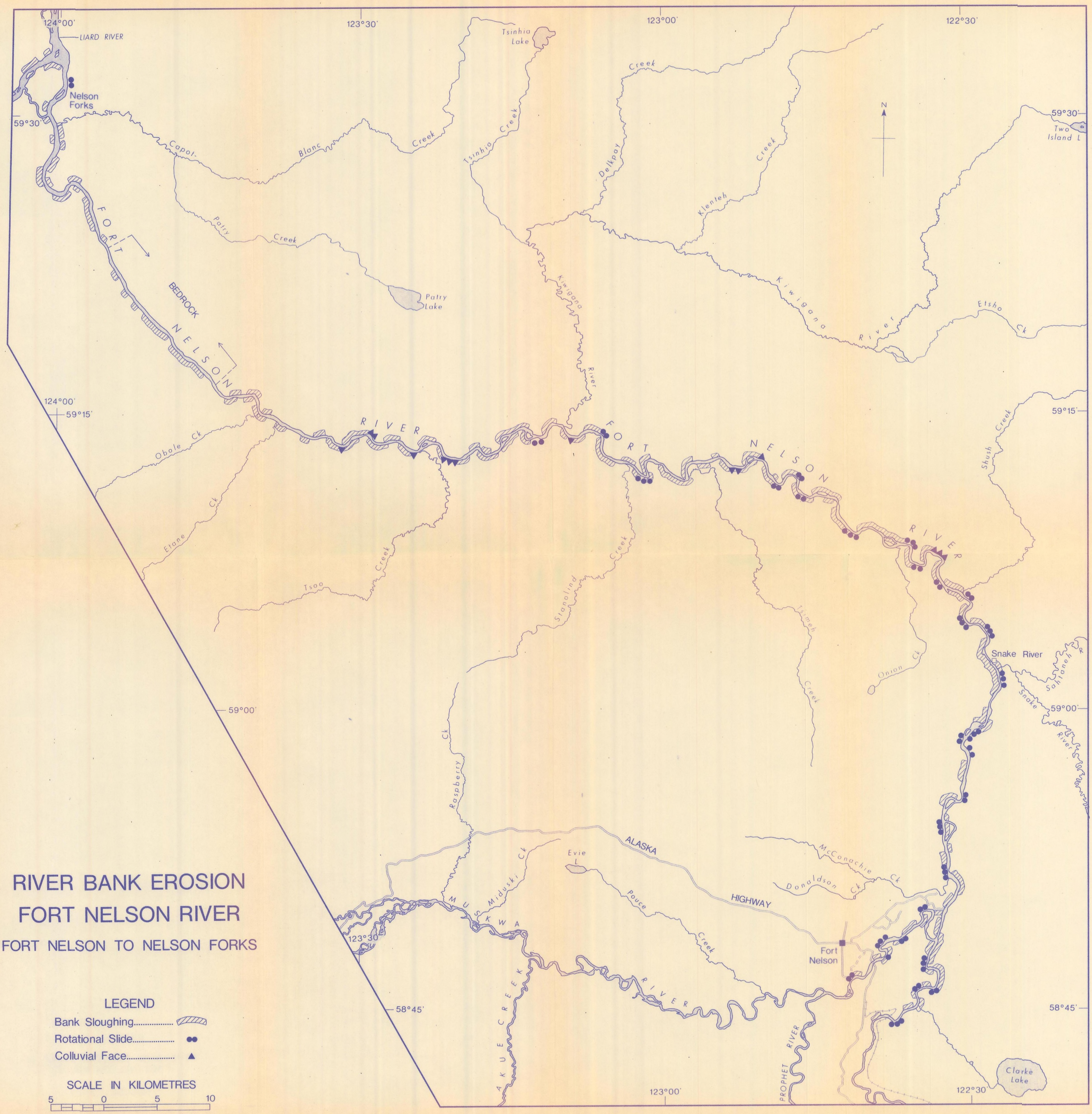


Figure 21

MAP OF LIARD RIVER FROM FORT SIMPSON, N.W.T. TO N.W.T.-Y.T. BORDER

NOTE: (1) Map derived from National Topographic System map no. 95 S.E., scale 1:500,000.
(2) Distances along Liard River are in kilometres, measured upstream from Liard-Mackenzie Confluence (after B.C. Hydro)
(3) Distances along Mackenzie River are in kilometres measured downstream from Great Slave Lake.



RIVER BANK EROSION FORT NELSON RIVER

FORT NELSON TO NELSON FORKS

FIGURE E-1

RIVERBANK EROSION ZONES OF
FORT NELSON VALLEY

AUGUST, 1979

Figure 22

MAP OF LIARD RIVER FROM N.W.T.-Y.T. BORDER TO NEAR BARNEY LAKE, AND FORT NELSON RIVER FROM NELSON FORKS TO FORT NELSON, B.C.

NOTE: (1) Map derived from National Topographic System map nos. 94 N.E. and 94 N.W., scale 1:500,000.
(2) Distances along Liard River are in kilometres, measured upstream from Liard-Mackenzie Confluence (after B.C. Hydro)
(3) Distances along Fort Nelson River are in kilometres, measured upstream from Fort Nelson-Liard Confluence.

RIVER BANK EROSION
LIARD VALLEY, B.C. & N.W.T.

LEGEND

	ACTIVE	INACTIVE
Bank Sloughing	[hatched symbol]	
Rotational Slide	●●	○○
Colluvial Face	▲	△

SCALE IN KILOMETRES

10 0 10 20

FIGURE E-2

RIVERBANK EROSION ZONES OF
LIARD VALLEY

AUGUST, 1979

Grey, Bryan J.
Liard River Basin spring flooc

FIGURES 21 & 22

FIGURES E-1 & E-2