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PRELIMINARY RESULTS OF STUDIES ON THE MID-WINTER STREAMFLOW AND ICE REGIME OF THE THIRTY-MILE REACH OF THE YUKON RIVER : OBSERVATIONS IN 1985

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The Thirty Mile River was wide open. Its wild water defied the frost, and it was in the eddies only and in the quiet places that the ice held at all. Six days of exhausting toil were required to cover those thirty terrible miles. And terrible they were, for every foot of them was accomplished at the risk of man and dog. A dozen times, Perrault, nosing his way, broke through the ice bridges, being saved by the long pole he carried, which he so held that it fell each time across the hole made by his body. But a cold snap was on, the thermometer registering fifty below zero, and each time he broke through he was compelled to build a fire to dry his garments...

He skirted the frowning shores on rim ice that bent and crackled under foot and upon which they dared not halt. Once, the sled broke through with Dave and Buck, and they were half-frozen and all but drowned by the time they were dragged out. The usual fire was necessary to save them...

Jack London
The Call of the Wild

Abstract

Due to a combination of lake influence and fast flowing water, the Thirty Mile River in winter is characterized by large areas of open water and thin ice; in turn, the existence of turbulent, open water is conducive to the formation of frazil ice. A reconnaissance of the reach was carried out in 1985 to identify the general features of its ice regime. It was observed that the position of the ice front is highly variable in time and may advance or retreat at a rate of several hundred metres per day. The rate of frazil dam growth is likewise rapid so long as open water leads persist.

The position of the velocity core or axis of maximum velocity strongly influences the ice regime by (a) maintaining an open water lead far down reach; and (b) by serving as both a source and a transport mechanism for frazil ice varieties. There is evidence that when frazil deposition occurs behind and under an advancing ice front the resulting dam may serve to deflect the velocity core, thus increasing the hydraulic resistance of the reach.

INTRODUCTION

The Thirty Mile River is that reach of the Yukon River that runs north from the outlet of Lake Laberge (Figure 1). Due to a combination of lake influence and high flow velocities, the ice regime of Thirty-Mile River is extremely dynamic: it freezes-up late and breaks-up early; it is unusually patchy and subject to rapid change; and it is highly variable from year to year. Also, because the river immediately below the lake is turbulent and remains open a distance of 6 to 12 km, it acts as a high production area of frazil ice. It is these characteristics that makes the ice regime of the Thirty Mile much like that which would be expected downstream of a large hydro-electric dam.

To better understand the effects of lake outflow on the ice cover downstream, a preliminary study of the reach was carried out in 1985 to identify the general features of its ice regime, and to study the relation between ice in the reach and physical processes within the lake (Figure 1A). During the course of the winter five aerial reconnaissances were made to map and photograph surface ice distributions. In addition, a field camp was established on Frazil Island, located 16 km (10 mi) from the outlet of the lake, from 18 to 23 February. From this camp 5 sections of ice thickness and water velocity were obtained using a hand-pulled, internally-heated metering sled (see Alford and Carmack, 1986, for description of instrumentation).

Our purpose here is to report on observations obtained in the winter of 1984-85 of (a) ice cover patterns, (b) frazil dam formation, and (c) flow conditions within the reach. We hope this basic description will allow more detailed research on the governing dynamics of the reach.

STUDY AREA

Geographically, the Thirty Mile begins at the outlet of

Lake Laberge and ends at the mouth of the Teslin River near the abandoned settlement of Hootalingua. Within this reach the gradient is steep (about 0.7×10^{-3}),-the channel is narrow, and there are many shallows and riffles. The bed is clean sand and gravel. The shores are a mix if steep, clay cliffs, and low, forested banks. The reach is an important habitat for fish, for large and small mammals, and for birds of prey, waterfowl, and shorebirds.

Conditions at the outlet of the lake are shown in Figure 1B. Due to the upwelling of warm, subsurface lake water to the surface, and to accelerated flow velocities, a polynya or broad zone of open water forms at the outlet (see Carmack, et al. 1986). Water issuing from the lake in winter is typically about 0.2 to 0.4 ^{o}C. As this mixture moves down stream it is cooled until at some point, depending on air temperature, it reaches 0 C and frazil ice crystals begin to form. Because of the swift current the frazil ice does not attach immediately, but is transported downstream in the form of slush, pans and floes. Eventually, the bridging of ice downstream leads to the formation of an ice front. Continued production of frazil ice may also lead to the formation of hanging dams, defined as massive accumulations of ice particles on the underside of an ice cover (Tsang, 1982).

While the position of the ice front on the Thirty Mile is highly variable from year to year, it is typically located somewhere near U. S. Bend (Figure 1C). This figure also shows frazil drifting in the open water, shear ridges forming along the ice boundary. The upper portion of the study reach is shown in Figure 1D.

Two additional characteristics of the ice regime of the Thirty Mile require comment. First, because of numerous bends in the river, the position of the velocity core (i.e. the line of maximum water velocity) meanders; e.g. it is close to the outer side of each bend and crosses over near the point of inflection between bends. Like velocity, channels of ice-free water follow the same pattern; we will refer to such long, narrow openings in the ice associated with the velocity core as core leads (Figure 2A). Now, the manner by which core leads eventually freeze over is complex. In one extreme the ice may form gradually from local growth, leading to a smooth cover. At the other extreme the core lead may fill with drifting pans and floes, leading to a rough cover. We will refer such features as either smooth-frozen leads or rough-frozen leads; Figure 2B shows examples of both.

OBSERVATIONS

On 5 February (Figure 3A) the reach was completely covered below a point approximately 26 km from the lake outlet. However, due to bridging of floes, a second ice front formed about 1 km north of Frazil Island, 18 km from Laberge. The cover of ice on 18 February (Figure 3B) is strikingly different; in response to extreme air temperatures during the second week of February, the ice front has advanced to U.S. Bend, about 10 km from the lake, giving an average rate of advance of 600 $m \cdot d^{-1}$. However, a number of core leads are evident in the new ice cover. Between 18 and 23 February (Figure 3C) the position of the front remains stable. On 8 March (Figure 3D) the ice front has actually retreated about 3 km, despite the fact that air temperatures remained well below freezing (see Alford and Carmack, 1986, for air temperatures at Whitehorse. This transient behaviour of the ice cover underscores the importance of hydraulic constraints on the position of the ice front (e.g. see Michel, 1971), and emphasizes why the reach is so dangerous to winter travelers.

On 1 April (Figure 3E) the reach is almost ice free with the exception on shore ice and a few local ice jams. By contrast, Lake Laberge remained ice-covered until June.

We next describe sections of streamflow and ice regime.

Here, the cross-sectional distribution of surface and frazil ice thickness is shown along with the corresponding profile of transport per unit width. We begin with the section furthest from the ice front and proceed upstream:

Section T13 (Figure 4A) shows a single, massive accumulation of frazil occupying about 48% of the cross-sectional area. The frazil dam is roughly centered over the thalweg or deepest part of the channel, and below a rough-frozen lead. The transport profile indicates a weak bifrucation in the flow, a feature not present in sections obtained in summer (Inland Waters Directorate, unpublished data). Section T12 (Figure 4B) was obtained approximately 100 m below and open lead. In terms of ice regime and flow patterns it is similar to T13; however, the channel is narrower and the dam occupies only 28% of the section.

Section T11 (Figure 4C) show two frazil deposits; one under shore ice along the left bank, and one above the thalweg of the channel. We will refer to these features as lateral and medial dams, respectively. The velocity core, on the other hand, lies between the two dams. Three lines of evidence suggest that the velocity core has, in fact, been deflected from its initial path. First, in most rivers the velocity core follows the thalweg of the channel; in this case, however, the velocity core lies some 40 m to the left. Second, the ice surface above the medial dam was rougher than elsewhere in the section, suggesting that earlier it was a core lead. Third, areal photographs from previous years show the core lead to indeed be closer to the right bank.

Sections T10-B and T10-A (Figures 4D-E) show a pattern made even more complex by the presence of a mid-channel bar. Our experience with flow patterns in summer prompts us to speculate that two flow bifrucation events have occurred; the first due to the large mid-channel dam, and the second due to a second medial dam forming near the left bank.

The T13 Section was repeated three weeks later on 8 March (Figure 5). The only noticeable difference between the two sections was that the area of the dam had decreased as a result of erosion.

Figure 6 is a summary map showing the cross-sectional distribution of frazil ice and the corresponding Froude numbers, defined as $F_r = V/(gh2)^{1/2}$.

DISCUSSION

In is well known that the outlet reaches of lakes are often ice free (Bengtsson, 1978), and that such reaches are also conducive to the formation of frazil ice (Tsang, 1982). Based on our work some more specific remarks on the ice regime of the Thirty Mile River can be made.

Frazil dams appear to grow most rapidly immediately after freeze-up, and then gradually erode to break-up (see Alford and Carmack, 1986). How much frazil ice accumulated along the 8 km stretch of this river that froze between 5 and 18 February? Taking the mean width of the river to be about 120 m, and the mean thickness of the frazil slush to be about 1 m, a total volume of about 1×10^6 m^3 is obtained. Assuming the porosity of the frazil slush to be about 50% (see Beltaos and Dean, 1981), then the average rate of production of frazil ice within the reach for this 13 day period is found to be nearly 40×10^6 kg/day. Taking the latent heat of freezing to be 334×10^3 J/kg, and the area of open water upstream of the ice from to be about 0.5×10^6 m^2, then an rate of heat loss is estimated to be 340 W/m^2. This value for heat loss is similar to that for the Yukon River near Whitehorse (Alford and Carmack, 1986).

The velocity core discussed above effects the ice regime both by maintaining open leads through the reach, and by acting as a mechanism for frazil ice transport. Ice front advance occurs as a progressive upstream advance by the jamming of frazil pans and floes in core leads. This can be extremely rapid during cold periods (also, see Schoch and Bredthauer, 1983).

Finally, we suggest that there are two possible types of frazil deposition during the freeze-up period (Figure 7). First, the lateral deposition which occurs under shore ice; and second, the medial deposition which occurs under the last part of the section to freeze over, i.e. where the velocity is highest and the ice is roughest. It is the latter that may cause the velocity core to bifrucate, and thus most strongly affect the hydraulic resistance of the channel.

There remain several unanswered questions of practical importance regarding the ice regime of a river fed by lake outflow: What factors control the temperature of water entering the reach from lake and the rate of cooling within the reach? Is there a 0^{o}c isotherm within the reach, beyond which the open water is maintained by turbulence, and in which frazil production predominates? If so, to what degree does the position of this isotherm and the rate of frazil production vary with surface heat flux? Is the hydraulic resistance of a reach dependent upon air and water temperature? Finally, how do the various components of the system combine to determine what we commonly refer to as the ice regime?

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Schoch, G. C., and S. R. Bredthauer. 1983. Environmental effects of ice processes on the Susitna River. Report IWR-105, Inst Wat. Resour., Univ. Alaska, Fairbanks, 31 pp.

Tsang, G. 1982. Frazil and anchor ice. NRC Subcommitte on Hydraulics of Ice Covered Rivers, Ottawa, 90 pp.

FIGURES

FIGURE 1 (OVER)

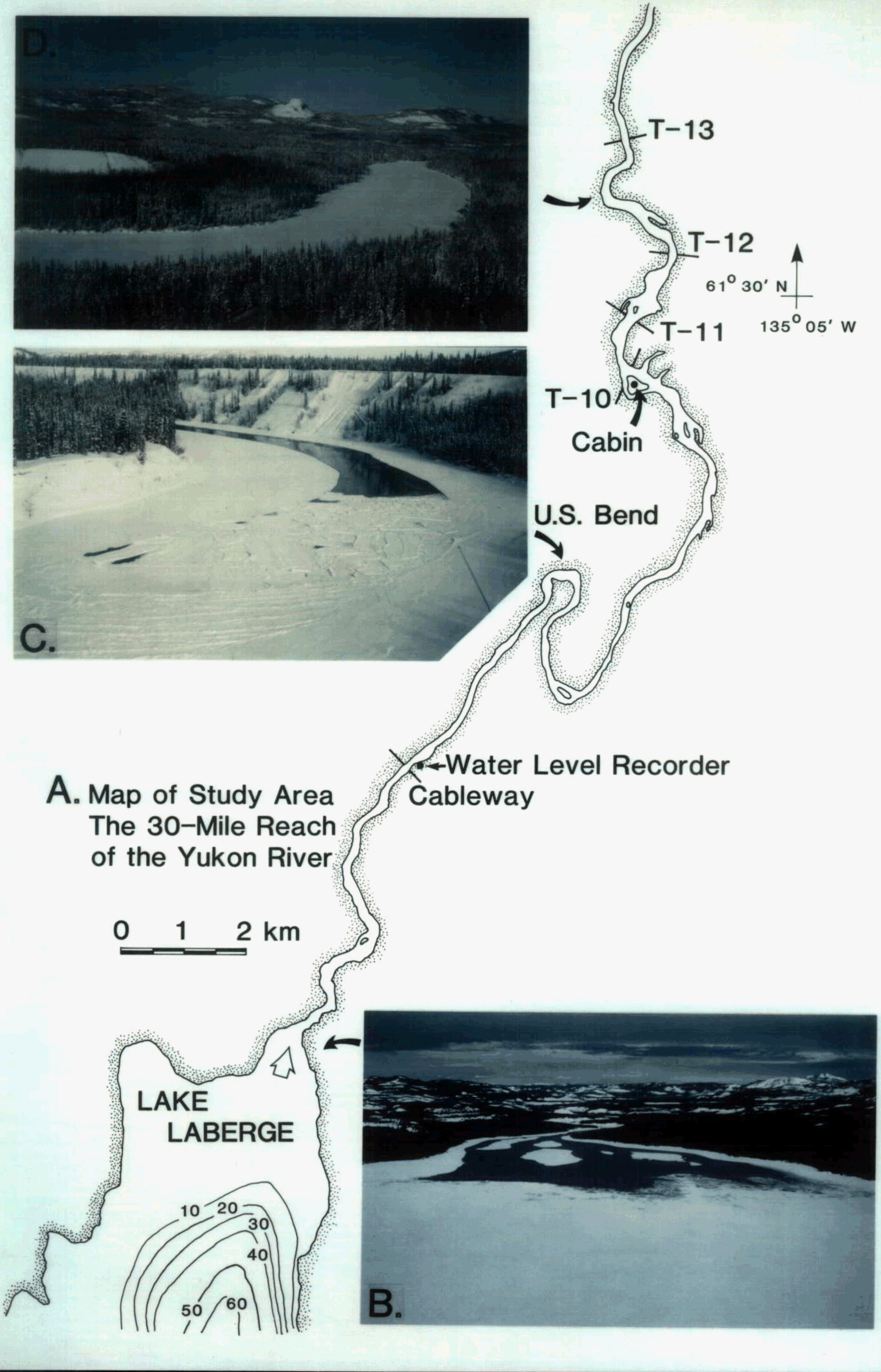
Study area: (A) map of the study area; (B) a photograph of the outlet of the lake, (C) a photograph of U. S. Bend, and (D) a photograph of the reach near Section T12.


A.


B.

FIGURE 2 (OVER)

Photographs of the reach taken (A) near sections T11 and T12 in 1983 and (B) approximately 2 km above Frazil Island in 1985.


D.
T-13
T-12
61° 30′ N
135° 05′ W
T-11
T-10
Cabin
U.S. Bend
C.
Water Level Recorder
Cableway
A. Map of Study Area
The 30-Mile Reach
of the Yukon River
0 1 2 km
LAKE
LABERGE
10
20
30
40
50
60
B.

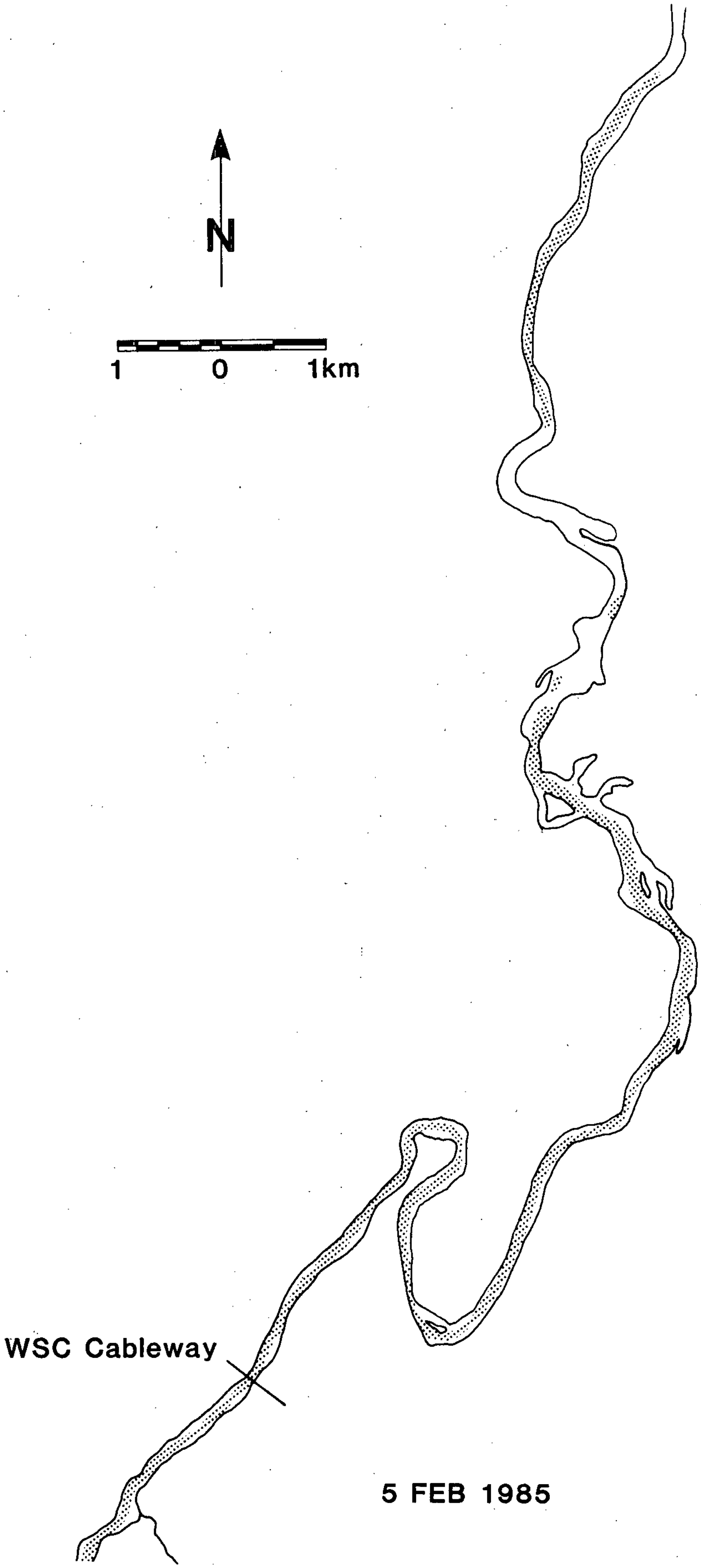


Figure 3A

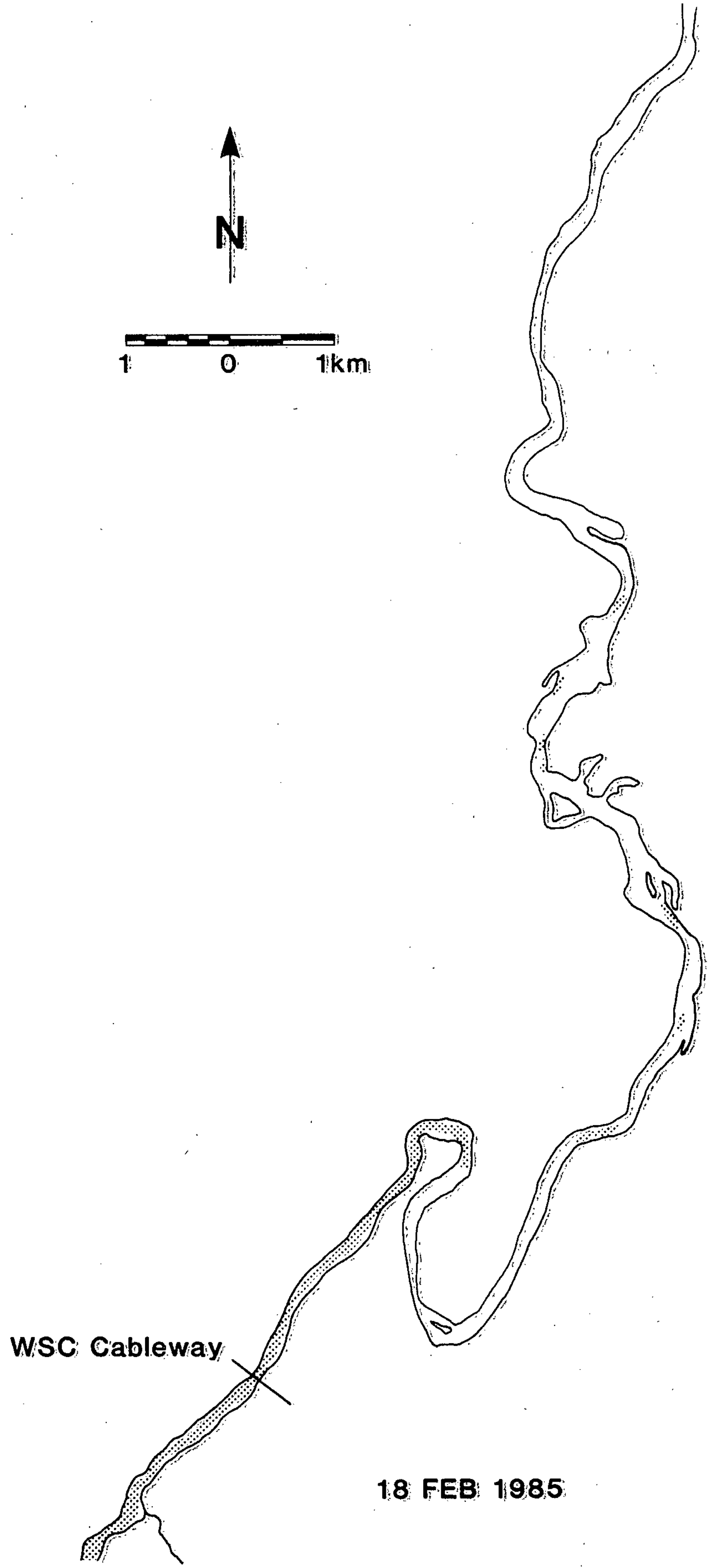


Figure 3B

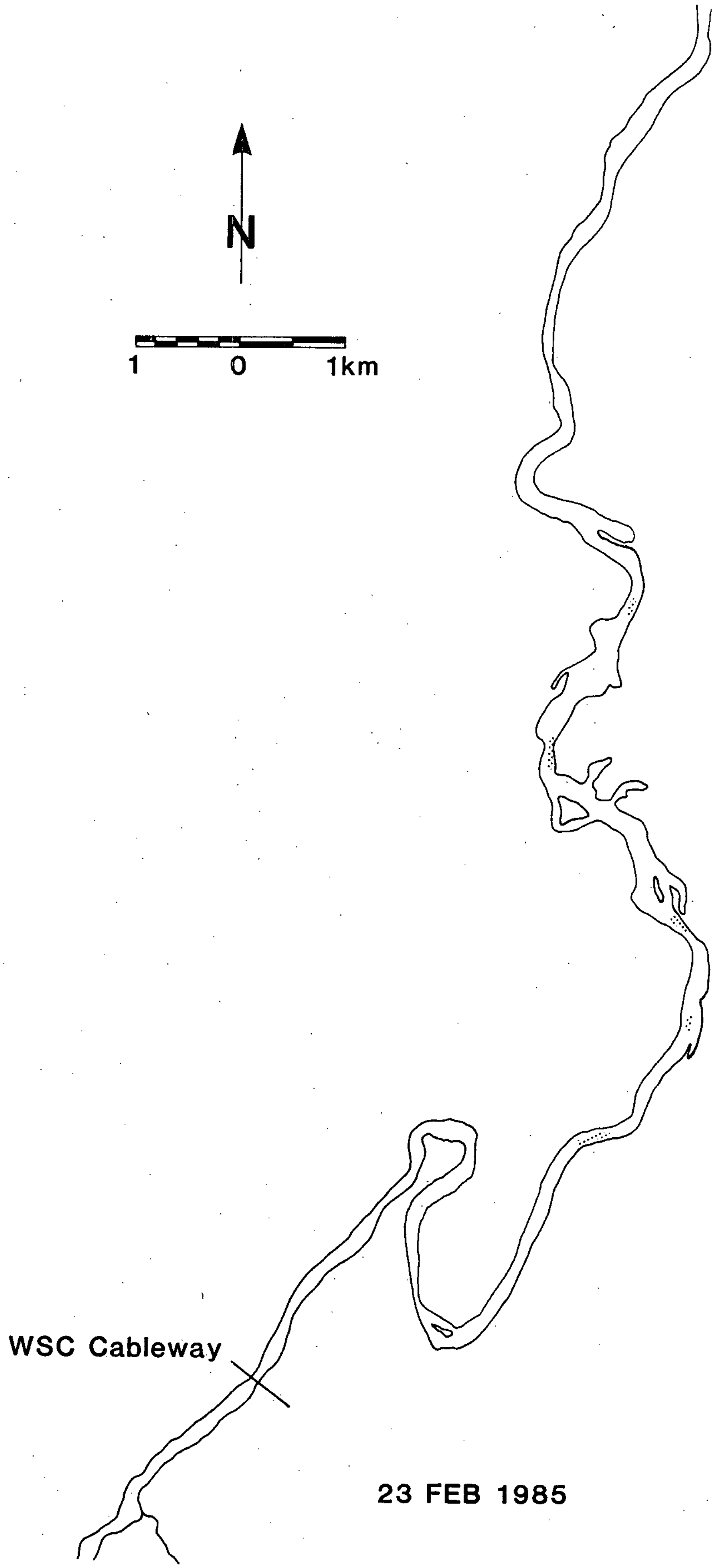


Figure 3C

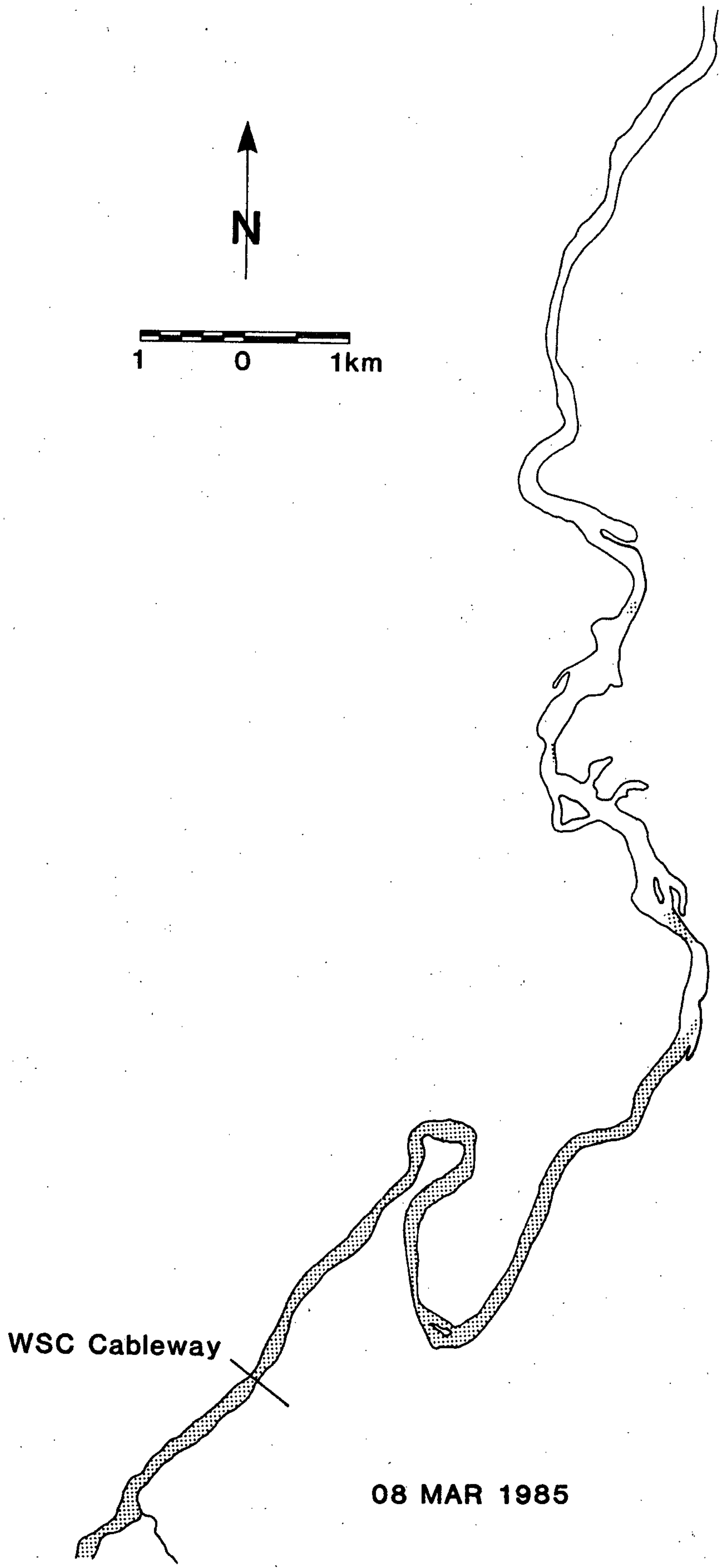


Figure 3D

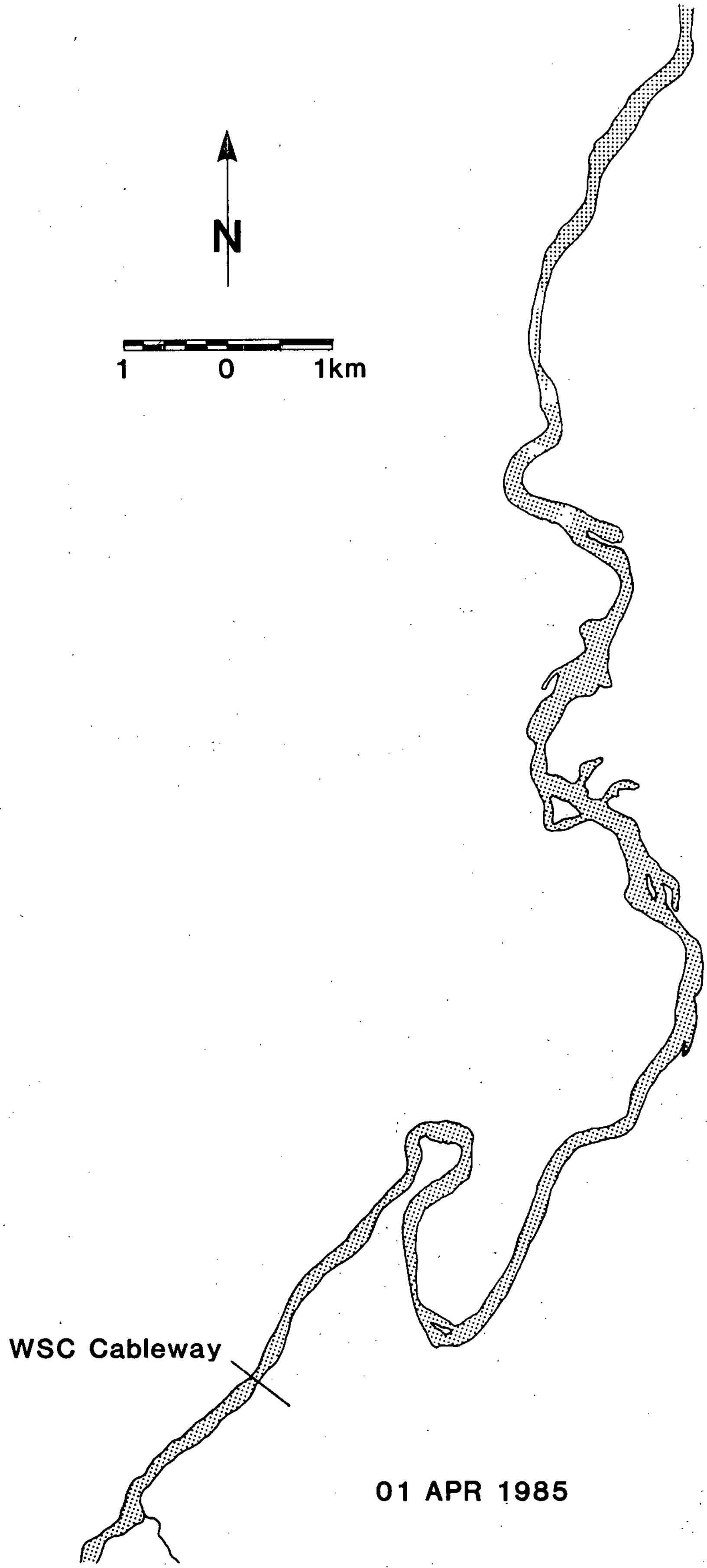


Figure 3E

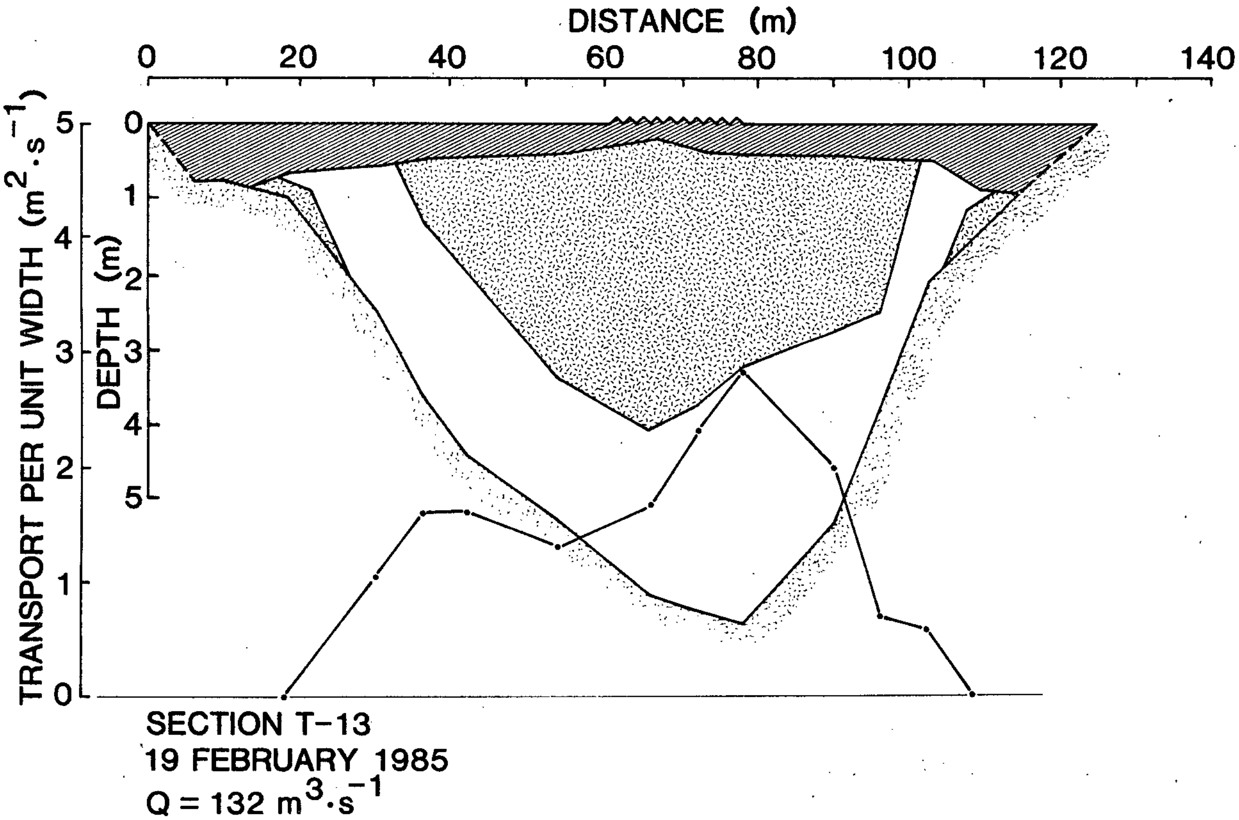

DISTANCE (m)
0
20
40
60
80
100
120
140
TRANSPORT PER UNIT WIDTH (m²·s⁻¹)
DEPTH (m)
SECTION T-13
19 FEBRUARY 1985
Q = 132 m³·s⁻¹

Figure 4A

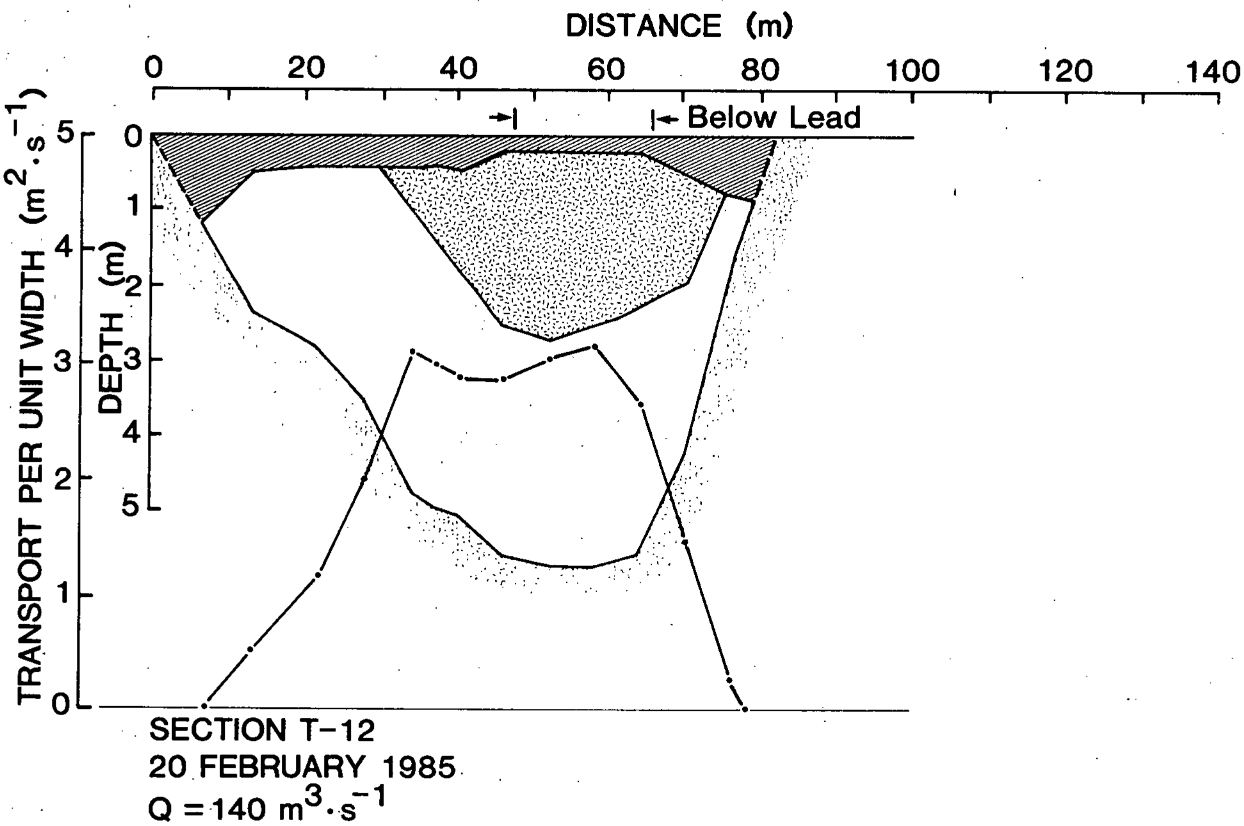

DISTANCE (m)
0
20
40
60
80
100
120
140
Below Lead
TRANSPORT PER UNIT WIDTH ($m^2 \cdot s^{-1}$)
5
4
3
2
1
0
DEPTH (m)
0
1
2
3
4
5
SECTION T-12
20 FEBRUARY 1985
$Q = 140\ m^3 \cdot s^{-1}$

Figure 4B

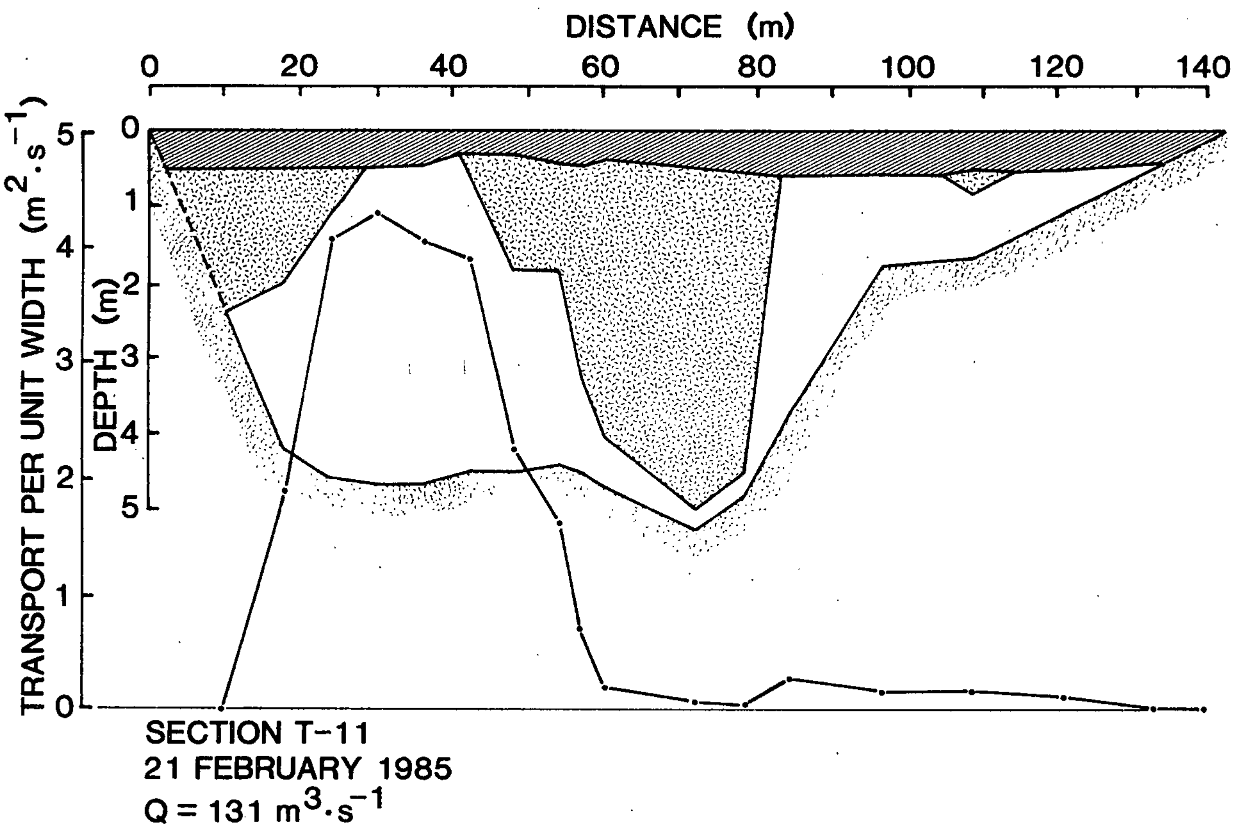

DISTANCE (m)
0
20
40
60
80
100
120
140
TRANSPORT PER UNIT WIDTH ($m^2 \cdot s^{-1}$)
5
4
3
2
1
0
DEPTH (m)
0
1
2
3
4
5
SECTION T-11
21 FEBRUARY 1985
$Q = 131\ m^3 \cdot s^{-1}$

Figure 4C

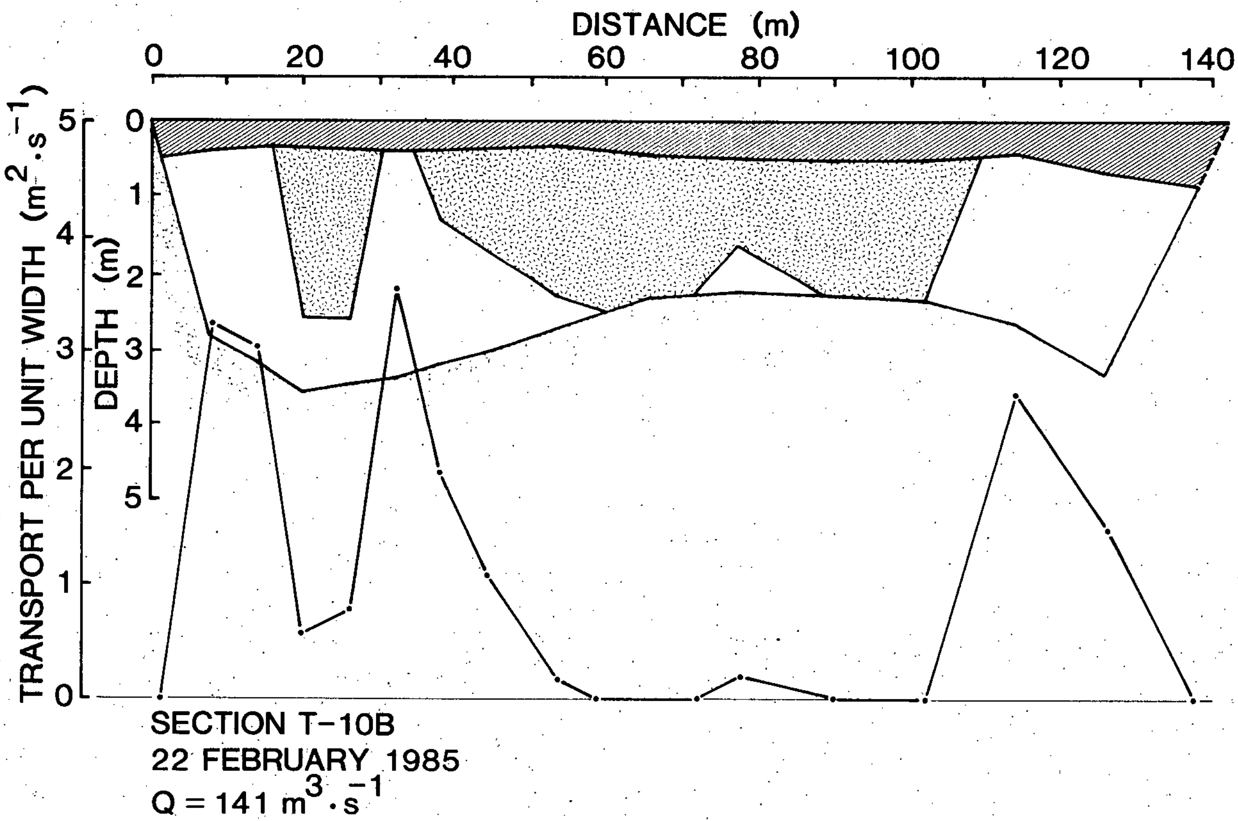

DISTANCE (m)
0
20
40
60
80
100
120
140
TRANSPORT PER UNIT WIDTH (m2·s-1)
5
4
3
2
1
0
DEPTH (m)
0
1
2
3
4
5
SECTION T-10B
22 FEBRUARY 1985
Q = 141 m3·s-1

Figure 4D

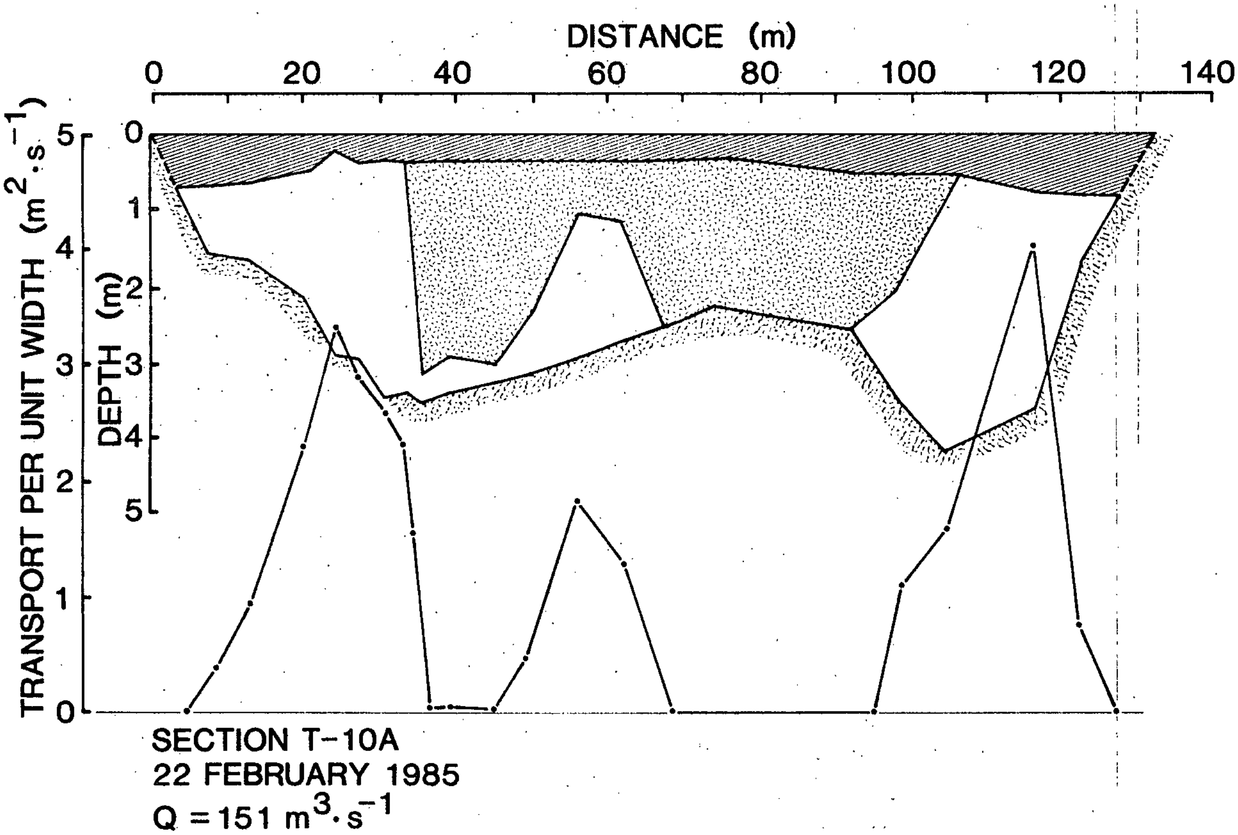

DISTANCE (m)
0
20
40
60
80
100
120
140
TRANSPORT PER UNIT WIDTH ($m^2 \cdot s^{-1}$)
5
4
3
2
1
0
DEPTH (m)
0
1
2
3
4
5
SECTION T-10A
22 FEBRUARY 1985
Q = 151 $m^3 \cdot s^{-1}$

Figure 4E

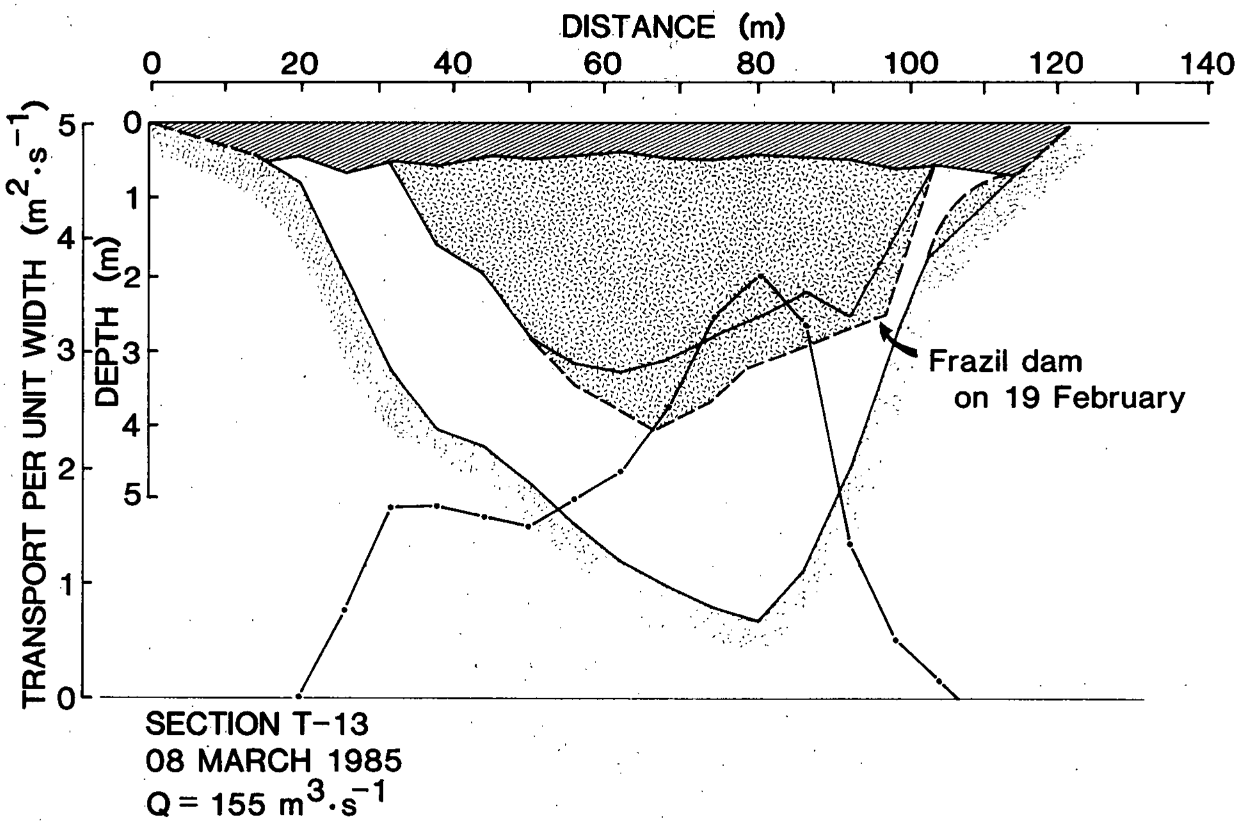
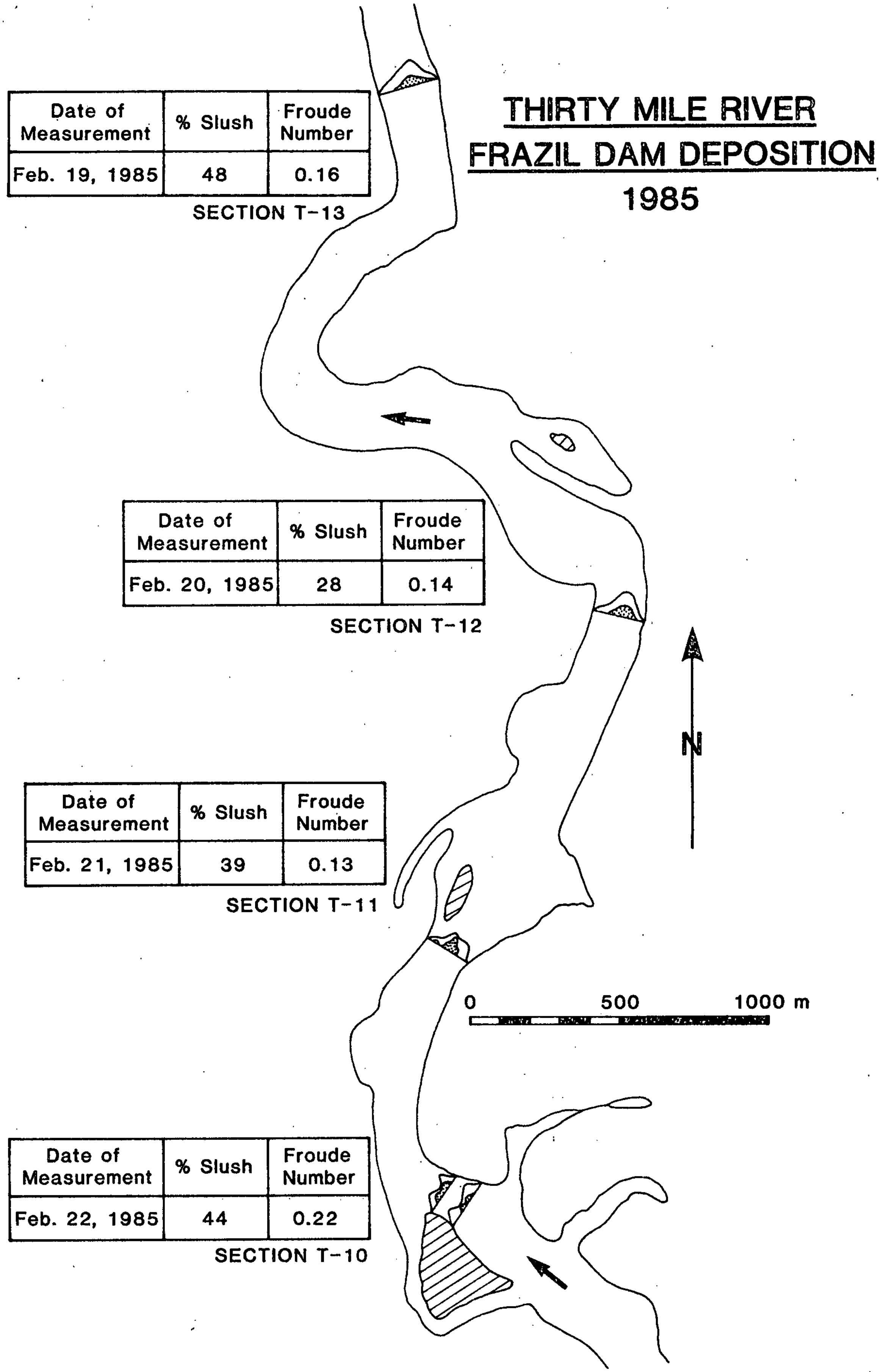

DISTANCE (m)
0
20
40
60
80
100
120
140
TRANSPORT PER UNIT WIDTH (m2·s−1)
DEPTH (m)
Frazil dam
on 19 February
SECTION T-13
08 MARCH 1985
Q = 155 m3·s−1

Figure 5



Date of Measurement	% Slush	Froude Number
Feb. 19, 1985	48	0.16

SECTION T-13

Date of Measurement	% Slush	Froude Number
Feb. 20, 1985	28	0.14

SECTION T-12

Date of Measurement	% Slush	Froude Number
Feb. 21, 1985	39	0.13

SECTION T-11

Date of Measurement	% Slush	Froude Number
Feb. 22, 1985	44	0.22

SECTION T-10

Figure 6

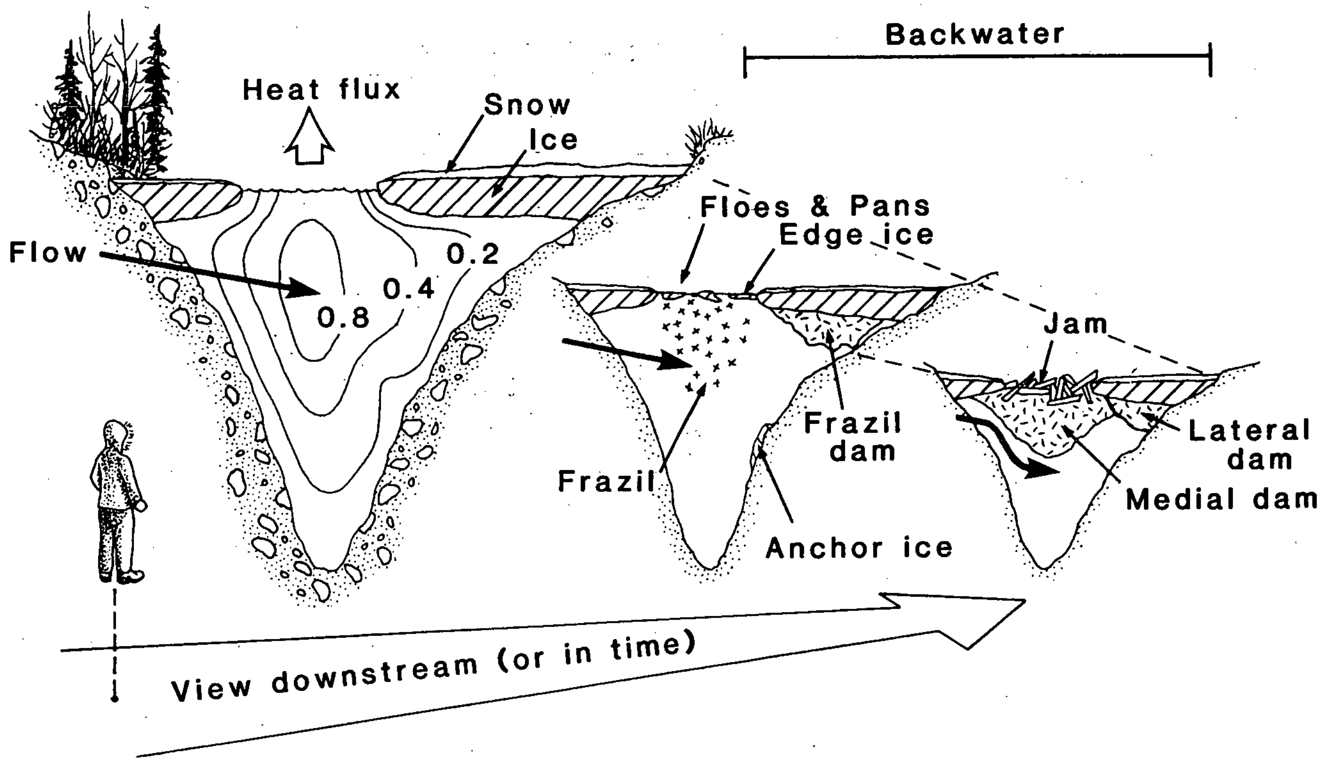

Backwater
Heat flux
Snow
Ice
Flow
0.2
0.4
0.8
Floes & Pans
Edge ice
Jam
Frazil
Frazil
dam
Lateral
dam
Medial dam
Anchor ice
View downstream (or in time)

Figure 7