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EFFECTS OF ICE ON THE HYDRAULICS OF THE MACKENZIE RIVER AT THE OUTLET OF GREAT SLAVE LAKE, NWT

BY

XIAOBING CHEN

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The undersigned certify that they have read, and recommend to the faculty of Graduate Studies and Research for acceptance, a thesis entitled EFFECTS OF ICE ON THE HYDRAULICS OF THE MACKENZIE RIVER AT THE OUTLET OF GREAT SLAVE LAKE, NWT submitted by XIAOBING CHEN in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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ABSTRACT

The Mackenzie River at the outlet of Great Slave Lake is affected by ice for up to six months each year. As an important transportation waterway, both for barge traffic from Hay River and as the location of the highway crossing to Yellowknife and other points north, the Mackenzie River plays an important role in northern development. Therefore, an understanding of the effects of ice on the channel hydraulics is quite pertinent.

This study provides a method to estimate the Manning's n for both open water and ice covered conditions. By measuring the water surface profiles in summer and winter time, respectively, the bed and ice undersurface roughness coefficients can be calibrated by gradually varied flow model. The calibrated Manning's bed roughness n_b are in the range of 0.02 to 0.03 from the Great Slave Lake outlet to Mills Lake section. The calibrated Manning's roughness coefficient n_i are 0.015 from the Great Slave Lake outlet to Big River section and 0.05 form the Big River to Dock section for a consolidated ice in April, 1992. Once the roughness for both open water and ice cover are calibrated, the winter discharge can be estimated by using gradually varied flow model. The estimated discharges are from 4350 to 6200 cubic meter per second during the late April to the early May, 1992. This study also provides an alternative method to calculate winter discharges for different ice conditions at Dory Point. Through a family of rating curves with backwater as a parameter, the discharge can be estimated from measurements of the water elevation, ice thickness and ice roughness at Dory Point and the water surface elevation at the Big River section.

This study also confirms that the lake exits to a mild sloping channel which has an irregular geometry. Despite this, the channel displays near uniform flow from the lake outlet to Kakisa River both for the open water case and for the ice conditions which prevailed in late winter of 1992.

It is recommended that further measurements of velocity profiles under the ice cover be conducted to verify bed and ice roughness obtained with the gradually varied flow model.

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A = cross section area, m^2;

A_i = cross section area affected by ice cover, m^2;

A_b = cross section area affected by bed, m^2;

a_I = transfer coefficient from roughness height to Manning's n, equal to 0.0316 (based on k_i in feet);

C = Chezy coefficient under open water conditions, $s/m^{0.5}$;

C_l = expansion (or contraction) loss coefficient;

g = acceleration of gravity, m/s^2;

H = water surface elevation, m;

h_e = the eddy loss between two cross sections, m;

H_g = gage height, m;

K = conveyance coefficient;

k_i = equivalent roughness height for the ice underside, m;

L = reach length, m;

n = Manning's roughness coefficient, $s/m^{0.33}$;

n_i = Manning roughness coefficient for ice underside, $s/m^{0.33}$;

n_b = Manning roughness coefficient for bed, $s/m^{0.33}$;

P = wetted perimeter, m;

P_i = wetted perimeter influenced by ice cover, m

P_b = wetted perimeter influenced by bed, m;

Q = discharge, m^3/s;

q = discharge per unit width, $m^3/s/m$;

R = hydraulic radius, m;

R_i = hydraulic radius for ice cover, m;

R_b = hydraulic radius for bed, m;;

S = energy slope;

$\overline{S_f}$ = representative friction slope for reach;

t = ice thickness, m;

V = cross sectional averaged velocity, m/s;

V_i = cross sectional averaged velocity for ice affected zone, m/s;

V_b = cross sectional averaged velocity for bed affected zone, m/s;

$v(y_i)$ = velocity at location y_i from the ice boundary, m/s;

V_* = shear velocity, m/s;

V_{max} = maximum velocity, m/s;

y_c = critical depth, m;

y_i = water depth from the ice boundary surface, m;

Y_{imax} = maximum water depth from ice boundary surface, m;

Y_{bmax} = maximum water depth from bed boundary surface, m;

α = kinetic energy correction coefficient;

$\Phi = P_i / P_b$;

ρ = water density, kg/m^3.

τ = boundary shear stress, N/m^2;

τ_b = boundary shear stress for bed, N/m^2;

τ_i = boundary shear stress for ice underside, N/m^2.

Chapter 1
Introduction

The Mackenzie River at the outlet of Great Slave Lake is affected by ice for up to six months each year. It is an important transportation waterway, both for barge traffic from Hay River and as the location of the highway crossing to Yellowknife and other points north. Therefore, an understanding of the effects of ice on the channel hydraulics is quite pertinent. The reach of the Mackenzie River considered in this study extends from the outlet of the Great Slave Lake downstream to Mills Lake, a distance of about 100 kilometers (km).

The reduced conveyance capacity occurring under an ice cover may cause an increase in water levels and flooding, particularly when an ice jam forms and releases. In addition, for both hydraulic or ice breakup analysis, the discharge in an ice cover is an essential data to develop such a model. In terms of the specific problem at Ft. Providence, a prolonged breakup can result in a significant interruption in ground transportation. The ferry cannot be operated safely without an adequate model of breakup processes enabling reliable forecasting. Such a model requires knowledge of discharge during the breakup period.

This study has two main objectives. The first is to evaluate the hydraulic conditions which control the lake outflows both under open water and ice conditions. The second aim is to determine whether such an analysis can be used to interpret stage data at the Water Survey of Canada (WSC) gauging station in the reach, to establish more reliable winter rating curves. These objectives are addressed by:

1) undertaking a review of the available literature on ice roughness analysis under ice conditions;
2) carrying out field investigations to collect hydraulic, hydrological and ice characteristics data on the Mackenzie River;

3) determing the Manning's *n* for bed roughness in open water conditions;

4) determing the Manning's *n* for ice cover in ice covered conditions prevalent during the late winter period of 1992;

5) estimating the pre-breakup discharge and the ice roughness in the Ft. Providence Rapids;

6) developing uniform flow rating curves for each cross section and analyzing the measured stage and discharge data; and

7) developing a family of winter rating curves which consider backwater effects and ice conditions at Dory Point.

Chapter 2 presents a review of the pertinent literature, while Chapter 3 describes the field data collection program. The hydraulic analysis is described in Chapter 4 and the interpretation of this analysis as it pertains to the outlet hydraulics is presented in Chapter 5. Conclusions and recommendations are provided in Chapter 6.

Chapter 2

Theoretical background and literature review

2.1 River ice formation, evolution and breakup processes

A brief review of river ice processes from formation to breakup is provided to develop an understanding of the effects of an ice cover on the flow. This review is based on a classification of river ice types which generally reflects the development process of a natural ice cover through the winter. Such a classification also provides a convenient framework to analyze ice roughness because each ice cover form has unique characteristics and resistance effects on the flow.

When the water temperature in a river decreases and becomes supercooled (supercooled water is defined as water at temperatures of a few hundredths of a degree less than 0°C), the first phenomenon that occurs is the formation of minute ice crystals called frazil. The frazil is present throughout the cross section of the flow if the river is sufficiently turbulent (Ashton, 1986). Following the initial formation of frazil, crystals begin to agglomerate into flocs. Because of their buoyancy, frazil flocs float to the surface to form frazil slush. If the slush stays on the surface long enough, the surface freezes and an ice floe or frazil pan is formed. As these floating frazil pans move about and impact upon each other, they often become circular with upturned edges; hence the name pancake ice. These floes are carried downstream in increasing concentrations as ice generation continues. If they meet a barrier, such as a man-made structure or an existing ice cover, the floes begin to accumulate and the ice front propagates upstream forming a continuous ice cover. This form of ice cover growth is an important mechanism of ice cover formation over wide rivers (Ashton, 1986).

When brought to the river bottom by turbulence, the frazil may adhere to the bed, forming anchor ice (Ashton, 1986). Anchor ice can form on a number of materials, such as aquatic weeds and gravel. Anchor ice seldom forms on the river bottoms of fine materials, such as sand, silt and clay, because these particles can be easily lifted off the bottom before the anchor ice can grow to a large size.

There are two kinds of surface ice covers, border (or shore) ice and channel ice. In the slower flow near the banks, where the turbulence is too low to entrain the frazil particles, they accumulate to form a continuous layer of skim ice on the water surface. This skim ice effectively prevents further supercooling, and subsequent ice growth is thermal in nature. The resulting ice cover is typically termed "border ice". Because ice formed by thermal heat exchange across the ice layer usually results in crystal growth in the vertical direction, a characteristic of thermal ice is its columnar crystal structure, easily recognizable in the "candles" of ice seen as this type of ice melts.

As freezeup progresses, the surface concentration of pans increases as does the extent of border ice out from the bank. At some point, the pans bridge and a solid front propagates upstream between the border ice which has developed along the banks. If the flow velocity is large, the accumulation of pans may shove and thicken. Normally once the accumulation has stabilized, the water between the ice floes freezes and gives strength to the accumulation, thereby inhibiting further consolidation. Subsequent ice growth occurs by one of two means: thermal growth, as described above, or through snow ice development. The latter may occur as snow accumulates on the ice surface. The weight of the snow may cause the cover to float lower in the water, resulting in the inundation and subsequent freezing of the saturated snow layer, forming snow ice.

In spring, the increase of solar radiation and air temperature results in snow-melt in the catchment and an increase of heat input on ice covers. Subsequently, the snow-melt may cause a significant increase in stage and the heat input causes the deterioration of ice and snow on the river (Prowse, 1989). Thus, the nature of breakup on a reach can vary from one in which the ice gradually deteriorates and more-or-less melts in place, to one in which breakup occurs suddenly due to the passage of a dynamic breakup front while the ice is still competent. The manner of breakup depends on a subtle trade-off between ice deterioration due to heat input and increased water levels due to snowmelt, ice melt, or ice jams. Figure 2.1 shows a schematic ice jam diagram.

2.2 Description of effects of an ice cover on the flow

The formation of an ice cover over a river channel has two significant effects on a river flow. First, the ice cover increases the wetted perimeter. Second, the underside of ice cover makes an important contribution to the channel resistance causing the river to "stage-up". According to Manning's equation (Henderson, 1966), river discharge is a function of cross sectional area, hydraulic radius, river bed slope and Manning's roughness coefficient n. Comparing the flow in an ice covered channel with flow in an open channel, the hydraulic radius decreases and equivalent Manning's n may increase or decrease depending on the roughness of the underside of the ice cover. Consequently, the river hydraulic conveyance capacity is reduced.

To estimate the discharge under an ice cover, the cross sectional area, hydraulic radius and roughness coefficient have to be computed in a different way as compared to the case of open water. Although it is not difficult to recalculate the cross sectional area and hydraulic radius, determination of an appropriate resistance coefficient which can account for the combined effects of bed and ice resistance is not straightforward.

2.3 Estimate of roughness coefficient in an ice covered channel

Difficulties in estimating an accurate roughness coefficient for an ice covered channel arise from two basic sources. The first is related to the definition of roughness. If for example it is to be represented by a resistance coefficient, such as

Manning's n, then it must incorporate other loss effects such as channel irregularity, alignment, silting and scouring, obstructions etc., as well as roughness (Chow, 1959). Secondly, roughness may not be measured directly. It must be deduced from other parameters describing the flow. These problems are complicated by the fact that the nature of the ice cover and/or bed may vary with time, thus altering the resistance coefficient. Also, resistance effects vary with changing stage and discharge.

Generally, estimates of the roughness coefficients in an ice covered flow, are done by one of two methods. The first method is based on measured velocity profile(s) under an ice cover in which the resistance coefficient of the underside of the ice and of the bed are determined separately and then combined in some way to determine a composite value of roughness. The second is based on measurement of general flow characteristics (such as discharge, cross section shape, and water surface slope), in which case a composite value would determined directly through a simple uniform flow or gradually varied flow analysis. In the latter case, an estimate of the resistance coefficient of the underside of the ice may be obtained if the resistance coefficient of the bed is known, again by using a composite roughness formula.

In the following sections, methods for determining roughness from velocity profiles are presented. Also, a number of methods for considering the combined effects of bed and ice cover resistance are reviewed.

2.3.1. Obtaining resistance coefficients from measured vertical velocity profiles

Because the roughness of the ice under surface is difficult to measure directly, some investigators have used measured velocity profiles to estimate ice or bed roughness height (Larsen, 1969; Calkins et al, 1982). This approach divides a channel cross section into two zones as shown in Figure 2.2, and the Karman-Prandtl velocity distribution is assumed to describe the vertical velocity profile near the wall within each zone.

2.3.1.1 Larsen's method

In this analysis, the Karman-Prandtl velocity distribution is assumed to describe the vertical velocity profile from the ice boundary surface to the location of maximum velocity plane in an ice covered channel (Larsen, 1969). Although the method is described here in terms of obtaining the ice roughness (as originally applied by Larsen) it may be used to estimate the roughness height of the bed as well.

The Karman-Prandtl velocity distribution for the ice affected region is (Larsen, 1969)

$$v(y_i) = 2.5V_* ln(\frac{30}{k_i} y_i) \quad (2\text{-}1)$$

where:

$v(y_i)$ = velocity at location y_i from the boundary, m/s;

V_* = shear velocity defined as $V_* = (\tau_i/\rho)^{1/2}$,

τ_i = boundary shear stress for ice under surface, N/m^2;

ρ = water density, kg/m^3;

k_i = equivalent roughness height for the ice under surface, m;

y_i = water depth from the ice boundary surface, m;

and $k_i/30$ represents the estimated location of the position of zero velocity from the boundary (Larsen,1969).

The average velocity can be obtained by integrating the velocities in the ice affected zone. The equation can be written as (Larsen, 1969):

$$V_i = 2.5V_* \left[ln(\frac{30}{k_i} Y_{i\,max}) - 1 \right] \quad (2\text{-}2)$$

and the maximum velocity can be written as (Larsen, 1969):

$$V_{max} = 2.5V_* ln(\frac{30}{k_i}Y_{imax}) \tag{2-3}$$

where:

V_i = average velocity for ice affected zone, m/s;

Y_{imax} = maximum water depth from ice boundary surface, m;

V_{max} = maximum velocity, m/s.

Combining Equation (2-2) and (2-3), the equivalent roughness height for the ice under surface, k_i, can be found by using following equation.

$$k_i = 30Y_{imax} exp(\frac{-1}{1 - V_i/V_{max}}) \tag{2-4}$$

This form of the equation has the significant advantage of eliminating the shear velocity, which cannot be evaluated for a non-uniform flow since the slope of the energy grade line is unknown.

2.3.1.2 Graphical method

An alternative approach is to fit the Karman-Prandtl velocity distribution to the measured data graphically. This is done by plotting velocity versus the log of the depth. A best-fit line can then be obtained for the measured data either by eye or through least-squares regression. Extending the straight line to $v_i = 0$, the corresponding intercept, y_i, can be obtained. The roughness k_i is simply equal to 30*y_i.

2.3.1.3 Conversion of k_i to Mannings n

After k_i is found, the Manning roughness coefficient may be estimated from the Manning-Strickler equation for the ice affected zone (Larsen, 1969):

$$n_i = a_1 k_i^{1/6} \tag{2-5}$$

where:

$$a_1 = \frac{(Y_{i\max} / k_i)^{1/6}}{21.9\log(12.2\frac{Y_{i\max}}{k_i})} \qquad (2\text{-}6)$$

n_i = Manning roughness coefficient for ice under surface;

a_1 = coefficient, a function of Y_{imax}/k_i (based on k_i in feet) where k_i/Y_{imax} is a measure of the relative roughness on the boundary.

Strickler found that over a wide range of relative roughness values the coefficient a_1 value varied little (Chow, 1959). He therefore proposed a constant value be used for this coefficient. In this study, the constant value of 0.0316 recommended by Ashton (1986) was used for a_1. Calculated estimates of this coefficient for the Mackenzie River data confirmed that no significant variations occurred and that the value 0.0316 was reasonable.

2.3.1.4 Discussion

There are a number of practical difficulties associated with the use of velocity profiles in the determination of boundary roughness. First, is the suitability of using the Prandtl-Karman logarithmic velocity distribution law in a natural channel. Pratte (1979) pointed out the Equation (2-1) was originally applied to turbulent flow in nearly circular rough conduits and for a wide, shallow ice-covered channel. the equation may not be valid. Second, the Prandtl-Karman logarithmic velocity distribution law describes the velocity distribution in the near-wall region. However, because of the limited depth within each of the sub-zones, data extending right to the point of maximum velocity are often employed. This combined with the problem of obtaining accurate depth measurements under ice conditions, may lead to significant error.

Perhaps the greatest inaccuracies are related to the conversion of roughness height to Manning's n. Equation (2-5) implied that n_i is a function of k_i only. Actually, roughness height is a local parameter and thus is not simply correlated to Manning's n, which as stated earlier, must incorporate other loss effects such as channel irregularity, alignment, silting and scouring, obstructions etc.

2.3.2 Estimate of composite roughness

For an ice covered channel, the composite roughness represents the combination of the roughness effects of the under surface ice cover and channel bed. Generally, methods for computing composite roughness values consider the flow in an ice covered channel to consist of two separate flow zones, one affected by the ice cover and one affected by the bed. It is generally assumed that these two zones, separated by the zero shear stress interface, act independently of each other. It is also frequently assumed that this zero shear stress interface coincides with the locus of maximum velocity providing a means of identifying the relative size of the two zones. However, when the roughness of the underside of the ice cover and the bed are different, as is usually the case, the two zones are not independent. This problem was thoroughly investigated by Hanjalic and Launder (1972) who found by experiment that because of turbulent mixing between the rougher boundary affected zone and the smoother boundary affected zone the velocity gradient approximation is not valid for quantifying the Reynolds shear stresses and the locus of maximum velocity will not coincide with the zero shear stress interface.

Table 2.1 summarizes seven commonly cited formula for the calculation of composite roughness as well as their corresponding assumptions. These equations are also compared graphically in Figure 2.3. Each method is discussed in more detail below.

2.3.2.1 Pavlovskiy, Lotter, Belokon, and Sabaneev's analyses

As the original papers describing the analyses of Pavlovskiy (1931), Lotter (1933), Belokon (1938) and Sabaneev (1948) are not generally available, this and other discussions (Uzuner, 1975; Ashton, 1986) have relied upon the comprehensive review presented by Nezhikhovskiy (1964).

Pavlovskiy based his analysis on the assumption that the gravity force along the channel is equal to the sum of the shear forces exerted on the channel bed and the ice cover. This equality was derived based on the assumption that the channel hydraulic radius, R, could be approximated by the average depth (which is an appropriate assumption only for wide open channel, under ice conditions, the hydraulic radius would be better approximated as one-half of the mean depth).

Faced with too many unknowns and too few equations, he further assumed that the hydraulic radius in the ice affected zone was equal to that in the bed affected zone, or $R_b = R_i$, and that both were also equal to the total hydraulic radius. In addition to the fact that such an assumption is clearly not valid, it leads to the further restriction that the average velocity in the two zones must be equal to each other, and to the overall average velocity (Uzuner, 1975), which is also unreasonable. Lotter (Nezhikhovskiy, 1964) also based his equation on the assumption that $R_b = R_i = R$.

Belokon (Nezhikhovskiy, 1964) assumed that the zero stress interface was defined by the locus of maximum velocity (which as discussed above is incorrect if the ice and bed have different roughnesses) and that the velocity distribution within each zone can be described by a parabola with an exponent of 1.5. He also assumed that the average velocities in the ice and bed roughness affected zone are equal to each other and to the channel average velocity, which is an unrealistic assumption. Nezhikhovskiy (1964) also points out that Belokon's formula produces unreasonable results: when the bed and the ice cover have the same roughness, $n_b = n_i = n$ the computed composite value will be $1.58n$.

Nezhikhovskiy describes Sabaneev's equation, also referred to as the Belokon-Sabaneev equation (Uzuner, 1975; Calkins et al, 1982), as a refinement which corrected an unidentified mistake in the Belokon equation and included "a new proposition on the minimum energy losses with the given hydraulic elements of the stress" (Nezhikhovskiy, 1964). Simply put, the Belokon-Sabaneev equation merely differs from the Belokon equation by a factor of 0.63, eliminating the problem noted above such that when the bed and the ice cover have the same roughness, *n*, the computed composite will be equal to that common value.

2.3.2.2 Chow's equation

Chow (1959) utilized $R = R_b + R_i$ in his equation, which is also not strictly valid. According to this assumption,

$$\frac{A_i + A_b}{P_i + P_b} = \frac{A_i}{P_i} + \frac{A_b}{P_b} \qquad (2\text{-}7)$$

which is not mathematically correct.

2.3.2.3 Larsen's analysis

Following the assumptions employed in the determination of roughness based on velocity profiles, Larsen's (1969) equation is based on the assumption that velocity profiles in a natural river comply with the logarithmic velocity distribution. Larsen combined the Karman-Prandtl formula, continuity equation and Manning's equation together to find an expression for composite roughness. The equation, shown in Table 2.1, indicates that the composite roughness is a function of the ratio of water depth Y_{imax} / Y_{bmax} and the roughness coefficients n_i and n_b.

Larsen's equation is important in that it avoids the limiting (and generally invalid) assumptions of the methods described above by introducing an equation for velocity distribution to close the problem. The disadvantage of Larsen's equation is that the depths Y_{imax} or Y_{bmax} are not easy to measure, which makes Larsen's equation difficulty to apply in practice. In addition, application of the logarithmic velocity distribution all the way to the point of maximum velocity is inappropriate.

2.3.2.4 Hancu's analysis

Hancu's analysis, originally published in Romanian (1967) is reported by (Uzuner 1975). Hancu's approach was based on the velocity defect law and logarithmic resistance relation, and a shear stress equation of the Darcy-Weisbach form. It is significant because he too avoided the necessity for assuming $V_i = V_b$ obtaining a system of equations, including velocity distribution, equal to the number of unknowns. In Hancu's equation, the average velocities, V_i and V_b are needed, requiring velocity data. Also, R_i and R_b must be quantified.

2.3 ?.5 Discussion

In summary, the limitations for the equations in Table 2.1 are as follows: 1) all equations assume that the cross section is divided into two parts with the upper zone being solely affected by the ice cover and the lower zone solely by the bed, this may not be valid; and 2) definition of the zones is difficult because the locus of maximum velocity will not necessarily coincide with the zero shear interface.

Because Larsen's and Hancu's formulae close the system of equations defining composite roughness with velocity data, rather than through restrictive and unrealistic assumptions, they are the most reasonable and recommended for use. However, practically speaking, the data required to apply these two methods are often not available. Of the remaining equations, although the Belokon-Sabaneev equation presents no clear refinement in terms of the underlying assumptions used, it is clearly the most favored in the literature. Nezhikhovskiy considered it the best formula

(Nezhikhovskiy, 1964), possibly because it produced reasonable results where the others did not. A number of other authors also recommend the use of the Belokon-Sabaneev equation (Carey,1967; Calkins et al, 1982). However, as Figure 2.3 illustrates with published data from Carey (1967) such conclusions may reflect the fact that differences in the results obtained with the various equations are within the range of measurement error.

In this investigation, hydraulic analyses were conducted with the Belokon-Sabaneev (as it is the only option available in the Corps of Engineers HEC-2 program used in the computation of the water surface profiles). These results were compared with roughness values computed from velocity profiles, measured on the Mackenzie River under ice conditions.

2.3.2.6 Other considerations in the application of composite roughness formulae

It should be noted that the bed roughness coefficient may change when hydraulic conditions change. For example, the bed roughness coefficient obtained from open channel flow may not be valid in an ice-covered channel. This may be due in part to a sensitivity of the bed roughness coefficient to depth (or more specifically hydraulic radius) variations or might be due to changing bed conditions (i.e., varying bedforms). For example, Carey (1967) applied the bed roughness coefficient obtained from open channel flow to ice covered river calculations on the St. Croix River and obtained incorrect, and sometimes negative, values for the ice cover roughness coefficient, n_i. Larsen (1969) applied the bed roughness coefficient obtained from open channel flow in a canal to the ice covered case and produced quite reasonable results. This indicates that the bed roughness coefficient changed for ice cover conditions in Carey's case as roughness is not normally so sensitive to depth variations.

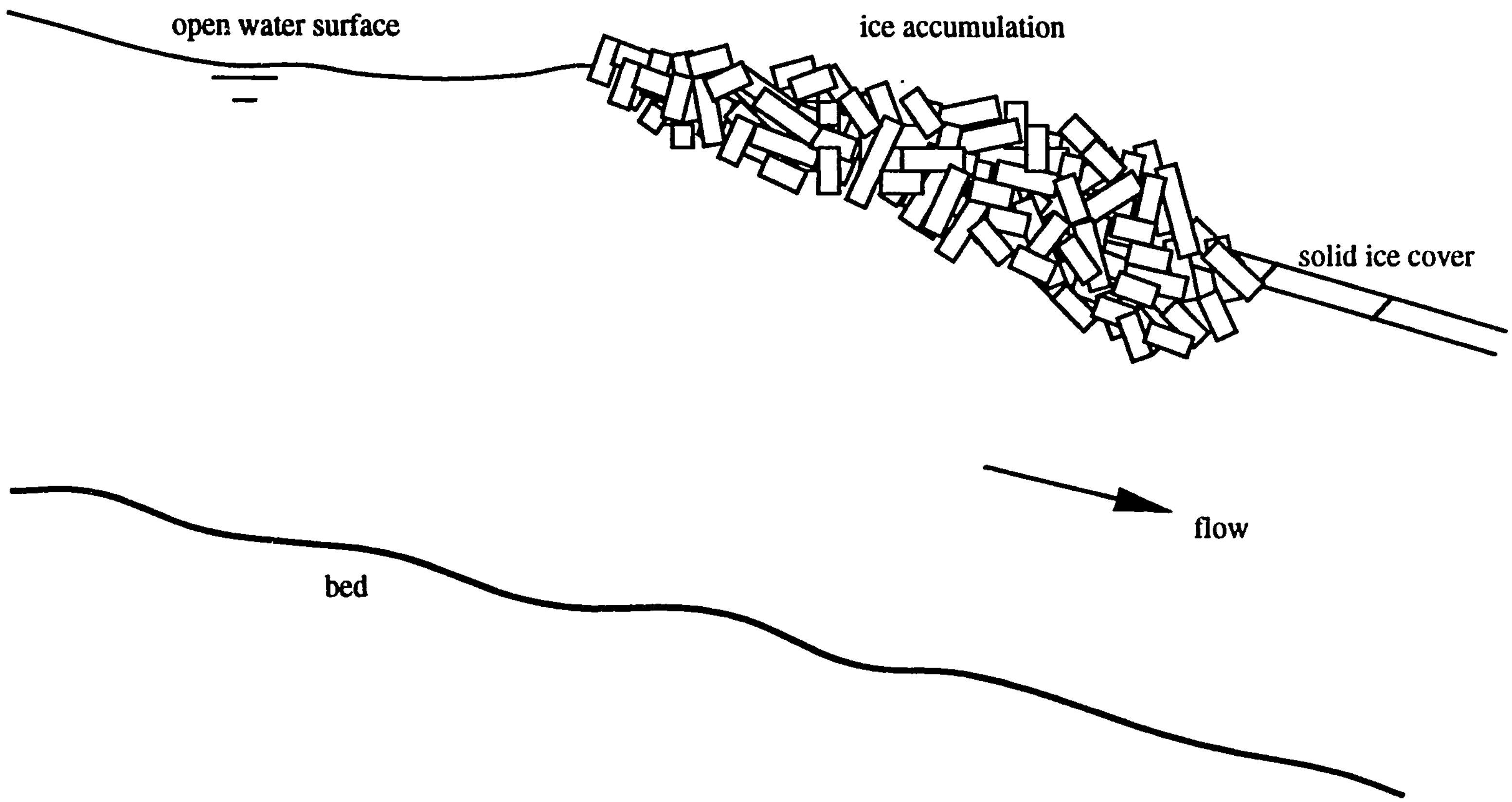


Figure 2.1 Schematic representation of a breakup ice jam diagram.

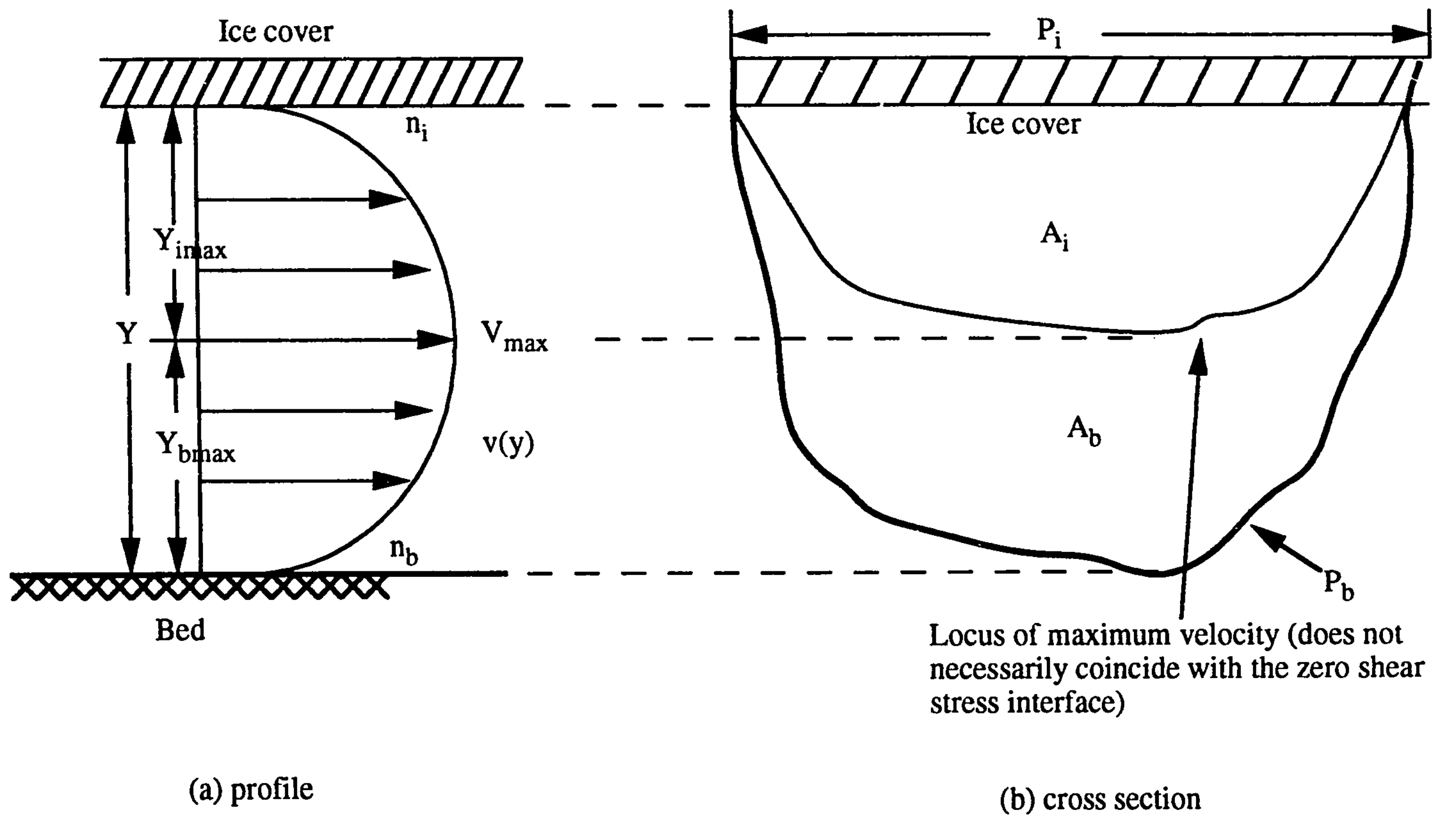


Figure 2.2 Schematic velocity profile and cross section area for flow under an ice cover.

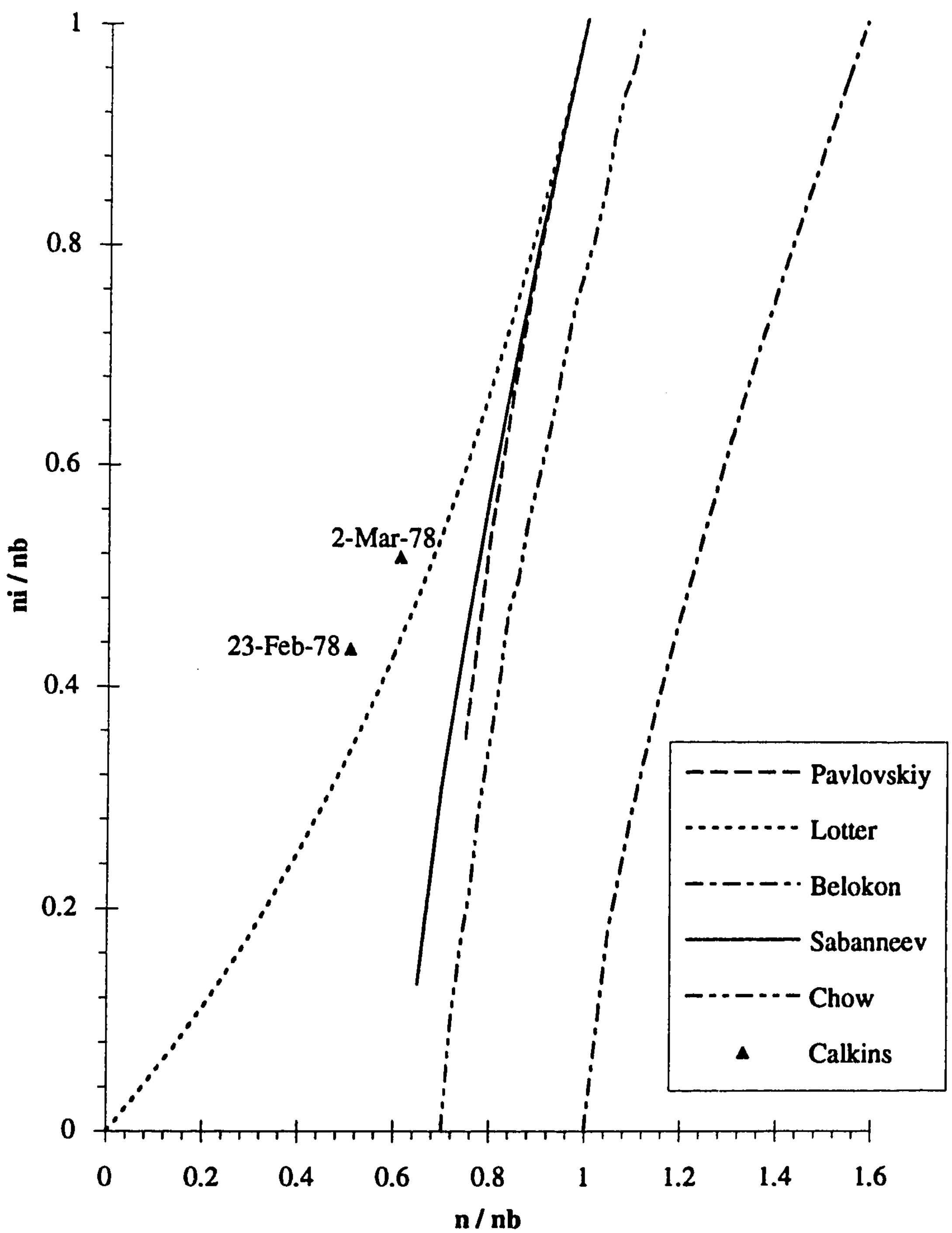


Figure 2.3 Comparison of composite roughness coefficients as a function of ice and bed roughness calculated using various predictors.

Table 2.1 Composite resistance relationships for ice covered channels (after Uzuner, 1975).

Developer	Equation
Pavlovskiy 1931	$\frac{n}{n_b} = \left[\frac{1 + \Phi(\frac{n_i}{n_b})^2}{1 + \Phi} \right]^{1/2}$
Lotter 1933	$\frac{n}{n_b} = \frac{\Phi + 1}{1 + \Phi(\frac{n_b}{n_i})}$
Belokon 1938	$\frac{n}{n_b} = \left[1 + \Phi(\frac{n_i}{n_b})^{3/2} \right]^{2/3}$
Sabaneev 1948	$\frac{n}{n_b} = \left[\frac{1 + \Phi(\frac{n_i}{n_b})^{3/2}}{1 + \Phi} \right]^{2/3}$
Chow 1959	$\frac{n}{n_b} = \frac{1}{\sqrt{1+\Phi}} (\frac{n_i}{n_b}) \left[\Phi^{3/4} + (\frac{n_b}{n_i})^{3/2} \right]^{2/3}$
Larsen 1969	$\frac{n}{n_b} = \frac{0.63 \left(\frac{Y_{i\,max}}{Y_{b\,max}} + 1 \right)^{5/3}}{\frac{n_b}{n_i} \left(\frac{Y_{i\,max}}{Y_{b\,max}} \right)^{5/3} + 1}$
Hancu 1967	$\frac{n}{n_b} = \frac{1}{\sqrt{2}} \left(\frac{R}{R_b} \right)^{1/6} \left[\left(\frac{V_b}{V} \right)^2 + \left(\frac{V_i}{V} \right)^2 \left(\frac{n_i}{n_b} \right)^2 \left(\frac{R_b}{R_i} \right)^{1/3} \right]^{1/2}$

where: *n = Manning's roughness coefficient;*
R = hydraulic radius, defined as R = A/P, m;
A = flow cross section area,
P = wetted perimeter, m; *V = average velocity, m/s;*
Y_{max} = *water depth from boundary surface, m;*
$\Phi = P_i / P_b$;
The subscripts of i and b represent ice cover and river bed respectively.

Chapter 3
Field investigations

3.1 Introduction

The Mackenzie River system is both the largest in drainage area and longest in Canada, flowing approximately 4240 kilometers from the headwaters of the Finlay River to the Arctic Ocean. The drainage area is about 1.8 million square kilometers (Mackenzie River Basin Committee, 1981). The Mackenzie River system contains three major lakes, namely, Great Slave Lake, Athabasca Lake and Great Bear Lake. The three major river tributaries of the system are the Peace, Athabasca and Liard Rivers. The annual precipitation in this system ranges from 460 mm in the south to 130 mm in the north (Mackenzie River Basin Committee, 1981).

The name "Mackenzie River" is applied to that part of the system that extends from Great Slave Lake to Arctic coast. The length of the river is about 1650 kilometers. The river flows through Ft. Providence, Ft. Simpson, Wrigley, Ft. Norman, Ft. Goodhope, and finally passes through Inuvik to the Beaufort Sea. At Ft. Simpson, a major tributary, the Liard River, joins the Mackenzie River. Others sizable tributaries joining the river downstream are the Arctic Red and the Peel Rivers from the mountains to the west and the Great Bear River from Great Bear Lake to the east.

The study reach is the Mackenzie River from the outlet of the Great Slave Lake to Mills Lake, about 100 kilometers long. Due to the complication of flow characteristics at Ft. Providence Rapids during the spring of 1992, the emphasis was put on the outlet of Great Slave Lake to Ft. Providence Rapids, a distance of 70 kilometers. Figure 3.1 is a map of the study reach.

The objectives of the study are as follows: first, to find discharge and roughness both for open water and ice cover conditions in the study reach; and second, to find how the downstream channel controls the flow at outlet of Great Slave Lake, especially when the channel has an ice cover. In order to do that, historical and field data had to be collected. These included details of channel bathymetry, ice characteristics, water surface profile measurements, discharge and velocity profile measurements, and ice movement processes.

3.2 Channel bathymetry

The channel bathymetry is the fundamental data for establishing a hydraulic model. In this section, the cross section surveys in 1991 and 1992 are discussed. The connection of temporary benchmarks to cross sections, the longitudinal distance between sections and the thalweg are also discussed.

The first cross section surveys were conducted during late August and early September, 1991. At that time, nine cross sections were surveyed between Beaver Lake and Ft. Providence. These surveys were based on continuous depth sounding of the channel cross sections. Horizontal control was obtained by maintaining a relatively constant boat speed. Due to the difficulty of approaching the edge in shallow water, the cross section survey did not quite reach the edge of the bank. The Beaver Lake and Burnt Point cross sections were not surveyed in the proper locations owing to the difficulty in finding the original temporary benchmarks. These surveys were used for a preliminary hydraulic analysis.

Additional cross section soundings were undertaken to expand the data base in early July, 1992. A total of twenty cross section surveys were conducted between Great Slave Lake and Mills Lake. These a shown in Figure 3.2. All cross section surveys were extended up onto the bank to facilitate the hydraulic analysis at high water levels. The nine cross sections which were surveyed in 1991 were surveyed again in order to maintain consistency and to provide a comparison.

Improved horizontal control was achieved for most of these cross sections with the use of a portable Global Positioning System (GPS). The GPS is an electronic receiver which provides locations in terms of universal coordinates by triangulation on orbiting satellites. The GPS's error is generally 10 to 40 meters. However, this can be improved to about 3 meters by recording a number of measurements at a single point and then averaging the results. Since this could not be done in a moving boat, an alternative approach was tried. During each cross section survey, a series of readings were obtained as the boat traversed the channel, with a corresponding notation placed on the depth sounding chart. In all cases, an effort was made to keep the boat on a straight course, roughly perpendicular to the flow. The locations obtained from GPS were plotted to scale on a map to check the survey results. A linear regression analysis for the GPS data points on the survey line across the channel at each cross section was then carried out. Figure 3.3 shows an example of the results obtained by this method. Although this regression did not improve the horizontal error of the GPS by a quantifiable amount, it did lend some credibility to the results obtained. As the figure shows, most points plotted on a near perfect straight line, indicating a measure of consistency between readings. Table 3.1 shows the correlation coefficients R obtained for the regression at each section. These coordinates were used in combination with the sounding chart to apportion distances across the channel width.

In order to eliminate "noise" in the cross section soundings, 3, 5, 7 point moving averages of the cross section elevations were computed. The 5 point moving average of the cross section elevations was found to be the most representative of the actual sounding data. Discrete cross section points were taken evenly along the river width and at breaks in grade. The final number of points defining each cross section was equal to or less than 60 in number. Details of the cross section surveys and hydraulic components are presented in Appendix A.

Table 3.1 Regression of GPS data for the cross section surveys.

Location of cross sections	Correlation coefficient R	Remark
Great Slave Lake	~	~ means the GPS data is not available.
South Channel	~	
North Channel	0.96	
Kakisa River	0.98	
Beaver Lake	0.99	
Burnt Point	0.96	
Ice Bridge	~	
Dory Point	0.99	
Ferry	0.94	
Coast Guard	0.93	
Blue Quonset	0.97	
Big River	0.76	
Big Snye	0.85	
Campground	1.00	
Blue House	0.92	
Boat Launch	0.99	
RCMP (South)	0.95	
RCMP (North)	0.98	
Ft. Prov. Dock	0.98	
Orange Cabin	0.72	
Mills Lake	0.95	

To establish a hydraulic model of the study reach, the cross sections had to related to a common datum. In the study reach, there are some monuments established by Geodetic Survey of Canada (GSC). Most are located near the roads and highways. In order to measure the water surface elevation, a number of temporary benchmarks (TBMs) were established along the channel banks adjacent to the cross sections. These TBMs were then tied to the GSC monuments, to establish this common datum. The TBMs at the Ice Bridge, Dory Point, Ferry, and Coast Guard cross sections were tied into GSC benchmarks along the south side of the river in spring, 1991. The TBMs at the Big River, Blue House, RCMP cross sections were tied into the GSC benchmark along the north side of the river in summer, 1991. The TBMs at the Burnt Point and

Beaver Lake cross sections were tied into GSC benchmarks along the south side of the river in December, 1991 and the Kakisa River, South Channel, and Great Slave Lake cross sections were tied in during March, 1992. The TBMs at the Blue Quonset, Boat Launch, Campground, Dock and Mills Lake cross sections were tied into GSC benchmarks along the north side of the river in spring, 1992. To eliminate the expense of crossing the river by helicopter during breakup observation, TBMs were established along the north bank of the river between the Ice Bridge and Coast Guard sections in May, 1992. The accuracy of TBM surveys were confirmed by closed level circuit except at the Great Slave Lake, South Channel, and Kakisa cross sections (due to the expense involved in conducting these surveys). Since these three TBMs were tied in extreme cold weather conditions and it was suspected that the electronic instrument used may have malfunctioned, TBM elevations were checked by comparing the water surface elevation at the Great Slave Lake cross section to the water surface elevation of Great Slave Lake at Hay River. Based on this check, the elevation of the TBM at the Great Slave Lake section was revised by 1 meter. However, the elevations of the TBM at the South Channel and Kakisa cross sections were confirmed based on this check. Table 3.2 shows the TBM descriptions.

The establishment of a common datum provides key information for determining bed and water surface slope. Based on this and the cross section surveys, a quantitative description of the study reach can be presented. The study reach from the outlet of Great Slave Lake to Mills Lake can be divided into four distinct sub-reaches. The first sub-reach extends from the Great Slave Lake section to the Beaver Lake section. The channel length is 43.3 kilometers. The channel is wide and the bed slope is mild. The typical channel width is about 6000 meters (Great Slave Lake and Beaver Lake sections). The average bed slope in this reach is 0.00008. From the Beaver Lake section to the Ferry Crossing, the river length is 17.8 kilometers. The average bed slope steepens slightly and has a value of 0.00027. The river width varies from 6000 meters (Beaver Lake) to 1000 meters (Ferry Crossing) and the typical river width is about 1800 meters (Dory Point). From the Ferry Crossing to Dock section, the river length is 14.2 kilometers. The bed slope increases further and has an average value of 0.00051. The river becomes narrow and the typical width is about 800 meters (Big River). Downstream of the Dock to the Mills Lake section, the bed slope decreases again and the average value is 0.00014. The river length is 24.4 kilometers. The typical river width varies from 1100 meters (Dock) to 3700 meters (Mills Lake).

3.3 Ice characteristics, Spring, 1992

The ice thickness for the channel and border ice was measured at 18 cross sections between the Great Slave Lake section and Dock section at Ft. Providence in 1992. These measurements were first performed in late winter (late March and early April) and repeated three times during the initial period of the breakup season. After the ice started to move, some sections were not accessible. Tables 3.3 and 3.4 show the variation of ice thickness in both border ice and channel ice respectively.

The trend in variation of channel ice thickness can be seen in Figure 3.4. The ice thickness increased systematically from the Great Slave Lake section to the Ice Bridge section. At the outlet of Great Slave Lake, most of the water surface was open by late April, 1992. Downstream of the outlet, the ice thickness increased gradually. The ice thicknesses at Beaver Lake and Burnt Point were about 1.0 and 1.2 m, respectively. At the Ice Bridge section, the ice thickness exceeded 1.7 m. Downstream of the Ice Bridge section to upstream of the Big River section, the ice thickness was about 1.0 to 1.2 m. Between the Big River and the Dock sections, the ice thickness ranged from 0.7 to 1.5 m. From Figure 3.4, one can see that these measurements show no significant trend towards ice thinning during the period of pre-breakup. This was likely because initial ice movements occurred before any appreciable thermal deterioration had taken place.

Figure 3.5 shows the border ice variation along the study reach. The thickness of border ice varied from 0.6 to 1.6 m. The thickest border ice occurred at Beaver Lake and Burnt Point and the thinnest occurred at the outlet of Great Slave Lake. Most of the border ice was about one meter thick.

Variations in the ice thickness are closely related to the nature of ice formation and accumulation, heat transfer between the interface of the ice and water, and the flow velocity (Ashton, 1986). In the study reach, the reason for the thin ice upstream of Burnt Point is probably due to warm water released from the lake. At the Ice Bridge cross section, the heat transfer between the water and ice interface probably decreased because the ice upstream had absorbed all the available heat. The flow velocity was not high due to the width of the cross section. The artificial method to build the ice bridge may also have its contribution. All of these made the ice very thick at the Ice Bridge cross section. Down to the Big River cross section, the channel narrows and the flow velocity increase. Thus, the ice was thin again.

3.4 Water elevation measurements

The measurement of water surface elevations was an essential part of the field investigation. Water surface elevations were measured along the study reach during the pre-breakup period in 1991, and the summer, freezeup, winter and breakup periods in 1992. In 1991, the measurements were limited to the reach from the Beaver Lake section to the RCMP section in Ft. Providence. When an ice cover was present, water surface elevations were obtained by cutting a hole in the border ice and surveying to the water level in the hole. Care was taken to avoid areas of shorefast ice. In 1992, as breakup progressed and ice movement increased, the water surface profile measurements were increased in frequency from 1 time per day to 3 or 4 times per day. In total, more than 45 water surface profiles were measured in the study reach between 5 April and 20 May, 1992. Several water surface profiles were measured from the Great Slave Lake section to the Dock section in Ft. Providence. Most of them were measured from the Ice Bridge section to the Ft. Providence Dock section.

Figure 3.6 illustrates the stage hydrograph at the Ferry Crossing section between March 22 and May 24, 1992. As the figure shows, the water elevation at the Ferry Crossing was relatively stable during late March and early May, with only a gradual increase in water level over the period between April 22 and May 3. On May 4, a substantial increase in water level occurred during the initial movement in the ice cover at the Ferry Crossing. Subsequently, the water surface elevation increased rapidly and continuously until May 18. The fluctuations in water level at the Ferry Crossing section were associated with major ice movements in the reach and in particular, the formation and repeated consolidation of an ice jam in the reach through Ft. Providence Rapids. Breakup, which occurred between May 19 and May 21, was associated with a final water level increase, the release of ice and water through the Big Snye, and a subsequent rapid reduction in stage over a period of 24 hours.

Figure 3.7 illustrates the stage hydrographs measured through Ft. Providence Rapids from the Big River section to the Dock section. There was only a gradual increase in water elevation before May 2, as was the case at the Ferry Crossing section. After that, the water level started to increase and fluctuated until May 22. The biggest fluctuation occurred on May 8. It was probably a consequence of the ice jam toe moving downstream from Blue House section to the Dock.

3.5 Discharge measurements and rating curves

3.5.1 Discharge estimation at Dory Point

In the study reach, discharge data were collected at Dory Point by Water Survey of Canada (WSC) staff from 1961 to 1978. The measured discharge data for open water are presented in Table 3.5. The rating curve for open water, based on the data surveyed by WSC staff at Dory Point, was developed in this analysis. The discharge and water elevation were plotted, and a best fit curve was obtained using a least squares power law regression. The resulting rating curve equation can be written as:

$$H_g = 0.0153 * Q^{0.6069} \qquad (3\text{-}1)$$

where;

H_g = gage height, m, (zero height is 148.806 m); and

Q = discharge, m^3/s.

The resulting coefficient of determination R^2 was equal to 0.95.

The exponent for Q in Equation (3-1) is very close to the exponent 3/5 obtained for a theoretical rating curve based on Manning's equation assuming a rectangular cross section shape. The coefficient of 0.0153 then is a function of river width, Manning's n and bed slope. Typical values of width, roughness and bed slope at Dory Point of 1700 m, 0.02 and 0.00027, respectively, were used in Manning's Equation. The coefficient computed from Manning equation for Dory Point was 0.013, which is very close to the value in Equation (3-1).

Another approach to get discharge during open water is to use the discharge data at Ft. Simpson, located 250 kilometers downstream of Ft. Providence. The flow travel time from Ft. Providence to Ft. Simpson, based on average velocity estimates and the distance between Ft. Providence and Ft. Simpson, is estimated to be about 48 hours. To get discharge at Ft. Providence, the discharge at Liard River was subtracted from the discharge at Ft. Simpson. Considering the travel time, the discharge at Ft. Providence can be estimated based on records 2 days after the day in question with relative accuracy during times when discharge is not changing rapidly. Table 3.6 illustrates the relative values obtained for discharge at Ft. Providence determined for these dates on which cross section surveys were undertaken.

Table 3.6 Discharge estimates of Mackenzie River near Ft. Providence.

Date	Discharge (cms) rating curve at Dory Point	Discharge (cms) Ft. Simpson- Liard River
29-Aug.-91	7000	6890
11-Jul.-92	8500	8460

Discharge had also been measured by WSC staff for ice covered cases. These discharge measurements are presented in Table 3.7. Due to backwater effects which vary with changing ice conditions, there is not a simple relationship between discharge and water elevation. Therefore, in order to quantify discharge during the spring of 1992, three measurements were performed. Two measurements were taken at the Ferry Crossing (located just downstream of the Dory Point site) and a third was taken at the Orange Cabin section (downstream of Ft. Providence). The measurements of water depth were inaccurate because of the influence of the flow velocity on the metering device. To improve the results, the cross section area at Dory Point and Orange Cabin surveyed in summer, 1992 was used for the discharge calculation instead of using the surveyed water depth during the velocity measurements. The results are presented in Table 3.8.

Table 3.8 Discharge measurements of Mackenzie River near Ft.Providence.

Date	Location	Discharge (cms) measured
27-Apr.-92	Ferry section	4350
1-May-92	Ferry section	4780
6-May-92	Orange Cabin section	5340

3.5.2 Discharge estimation at Big Snye and North Channel

Besides the estimated discharge at Dory Point on the Mackenzie River, the discharges in two major anabranch channels along the study reach, namely, the North Channel and the Big Snye, had to be considered. Due to the lack of surveyed data, uniform flow conditions were assumed in these channels and Manning's equation was used to obtain the corresponding rating curves. The Manning's n in the North Channel and the Big Snye were assumed to be the same as the Manning's n at the South Channel and Big River sections, respectively. The water elevations at the North Channel and Big Snye were assumed to be the same as the water elevations at the South Channel and Big River sections, respectively. The bed slope was approximated by the water surface slope. The cross section area was obtained from the cross sectional surveys conducted in July, 1992. Figure 3.8 illustrates the discharge relationship developed from this analysis between the North Channel and Big River sections and Dory Point section for the open water period. Table 3.9 shows the computed discharge for the North Channel and Big Snye for different Manning's n, indicating the relative sensitivity of the results to the assumed roughness. It is hoped that coincident measurements of discharge in the Big Snye and at the Ferry Crossing upstream will refine that relationship in the future.

3.6 Velocity profile measurements

Three velocity profiles were measured in late April and early May, 1992. Two of them were at the Ferry Crossing section and the third one was measured at the Orange Cabin section, downstream of Ft. Providence. The velocity profile measurements were conducted at only one location each time, using a magnetic flow meter. Representative velocities at each measurement point were obtained by averaging the metered values over a period of 30 to 60 seconds. Table 3.10 and Figure 3.9 show the measured velocity profiles taken at the Ferry Crossing section. From the velocity profile plots, one can see the shape of velocity profile measured on April 27, 1992 is poorly defined due to too few data measurement points. The velocity profile measured on May 1, 1992 is better defined although there are still very few points.

The two methods mentioned in Chapter 2 were used in the analysis of the velocity profiles to estimate the roughness height and Manning' *n* for the ice and the bed. Table 3.11 presents the results calculated using Larsen's method. Figure 3.10 and 3.11 show the plot of velocity and log y. The regression equations are also presented. Table 3.12 presents the results of the two methods. Larsen's method produced higher values than the regression method. Calkins et al (1982) reported a similar trend when comparing the two methods.

Table 3.12 Larsen and regression methods to calculate roughness from a velocity profile both for bed and ice cover, Mackenzie River at Dory Point, 1992.

	Date	Equivalent roughness		Manning's coefficient	
		Larsen's method Roughness k (m)	Regression method Roughness k (m)	Larsen's method Manning's n	Regression method Manning's n
Bed	27-Apr.	9.53	25.50	0.056	0.066
	1-May	1.22	3.00	0.033	0.046
Ice cover	27-Apr.	3.85	0.0045	0.048	0.016
	1-May	4.34	1.20	0.049	0.040

The results of this analysis, particularly for the April 27, 1992 profile are questionable given that the calculated roughness heights are greater than the flow depth in some cases. Given that the analysis is based on so few measured points, it is not surprising that unrealistic values resulted.

3.7 Observations of major ice movements

All major ice movements were observed and documented in the spring, 1992. On April 29, the initial development of open water leads and overflow between these leads were observed from the Blue Quonset section to the Dock section. On May 3, initial ice movements were observed between the Big River and Campground sections, and the channel was open at the Big River section. On May 4, the thin ice in the ferry passage channel crushed and the ice cover shifted downstream. On May 8, the ice cleared from Dory Point to the Blue Quonset, moving to Ft. Providence Rapids. By late afternoon the channel was open from just downstream of the Ice Bridge to upstream of the Big River section. The toe of the ice accumulation was located at the Dock and the entire channel through Ft. Providence Rapids was filled with the ice accumulation. On May 12, the cracks were observed in Beaver Lake, and the channel was open from Burnt Point downstream. On May 16, open water appeared in Beaver Lake. On May 19, the onset of breakup downstream of the Ferry Crossing was observed, and on May 21, the ice has gone out along the north side of Ft. Providence Island. Details of the report of the ice movements can be found in Hicks and Andres (1992).

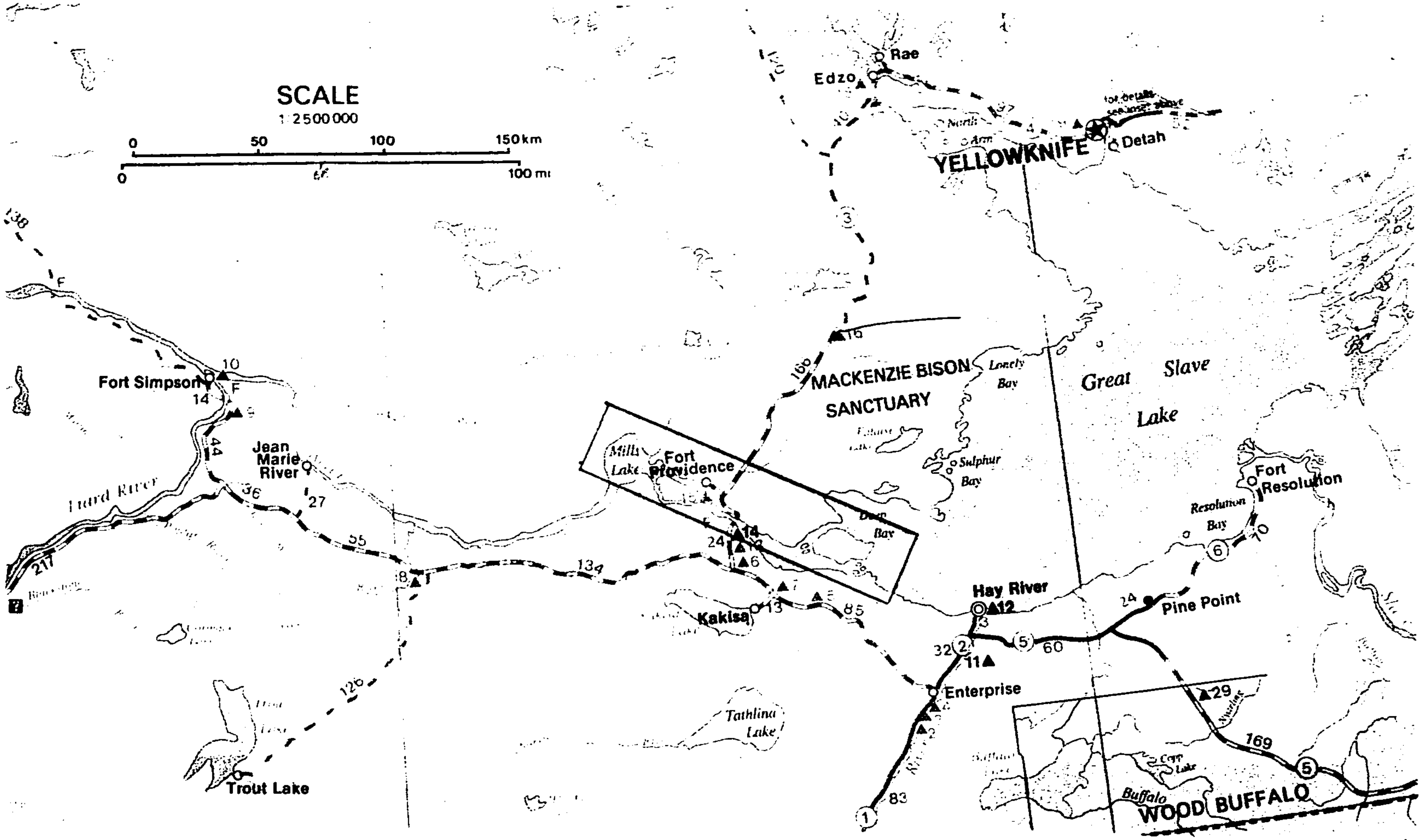


Figure 3.1 Location of study reach.

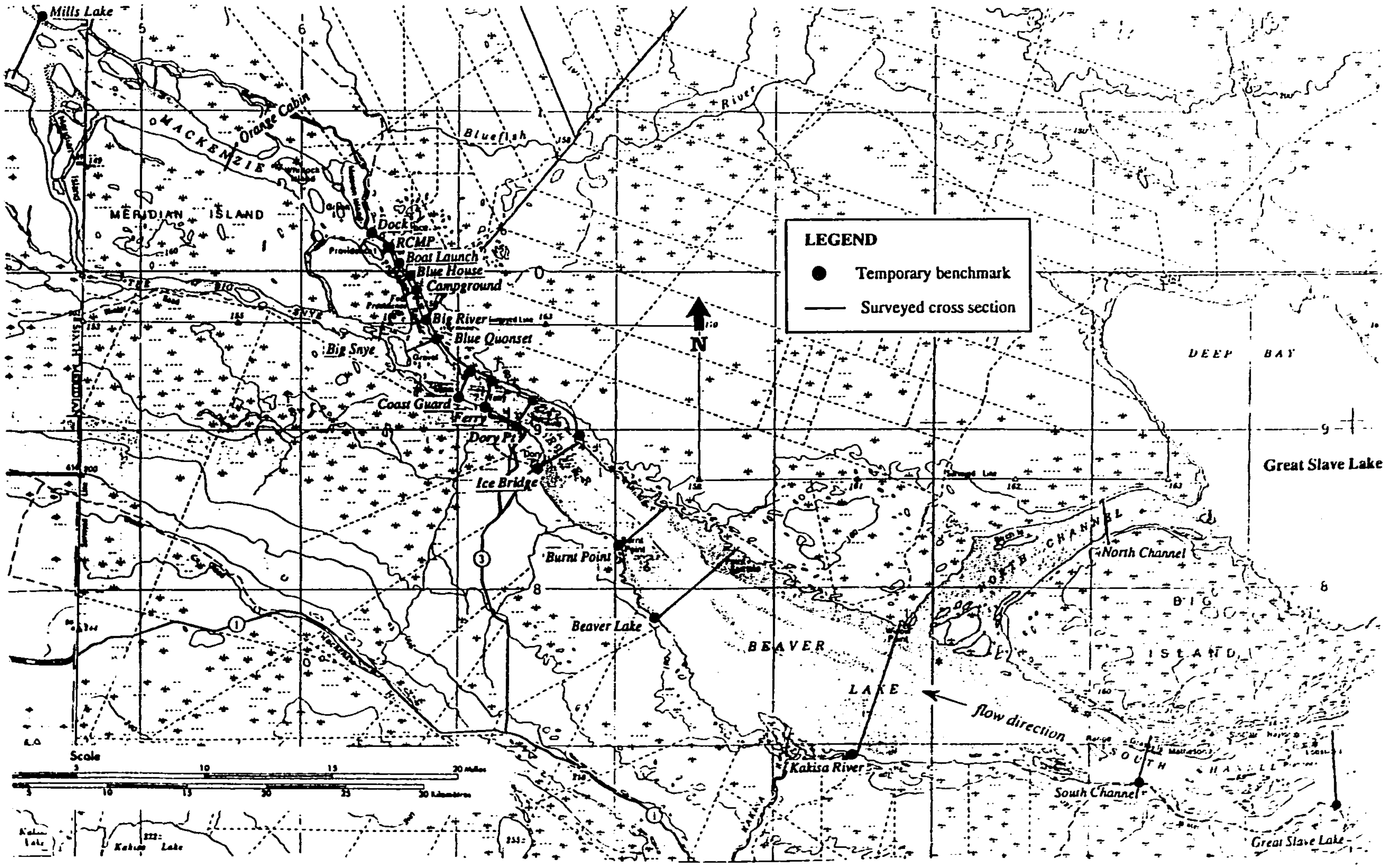


Figure 3.2 Location of cross sections and temporary benchmarks on the Mackenzie River near Ft.Providence.

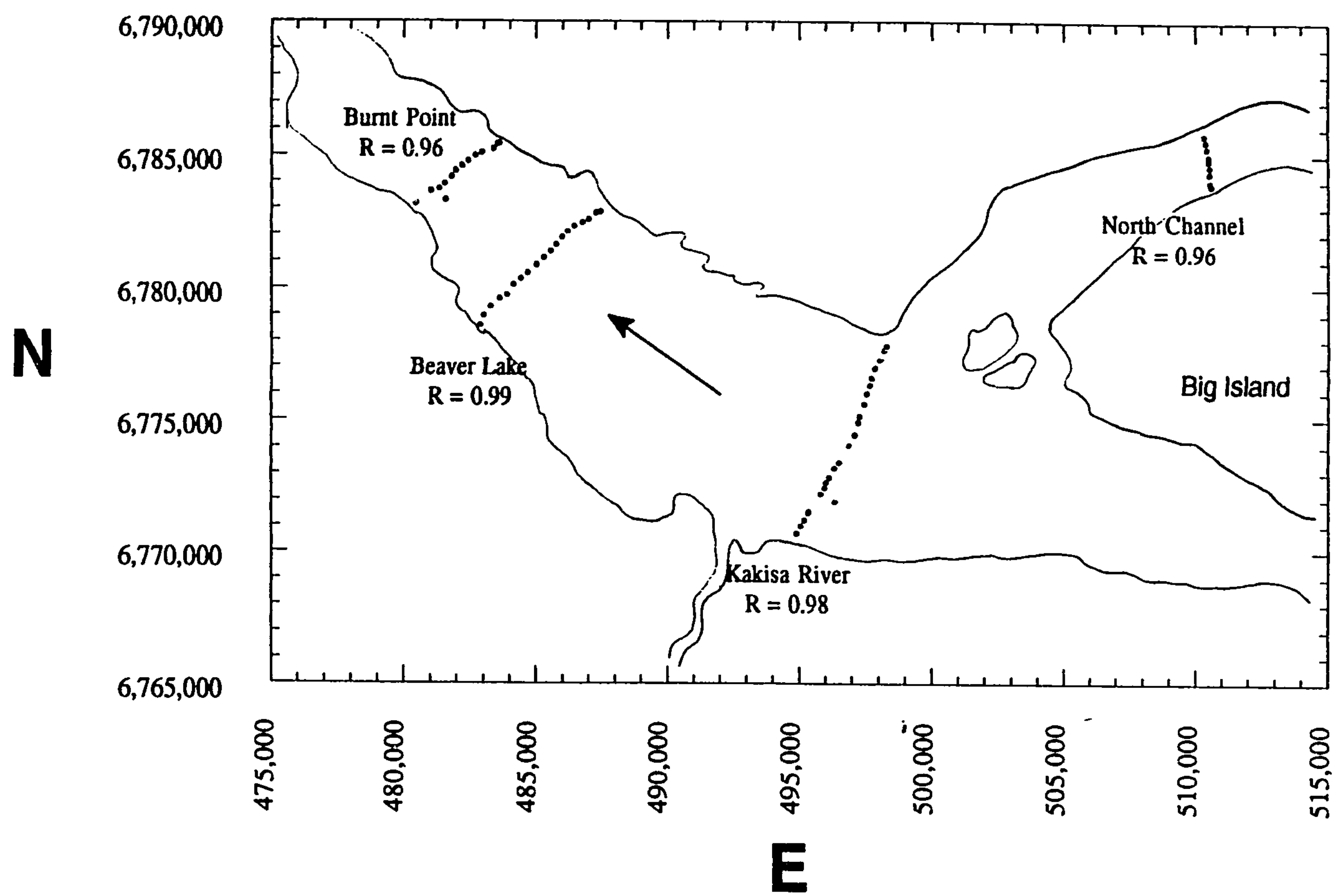


Figure 3.3 An example of GPS cross sections obtained on Mackenzie River.

Table 3.2. Elevation of temporary benchmarks established on the Mackenzie River near Ft. Providence, as of April 1, 1993.
(all elevations G.S.C.)

TBM Name	Elevation	Remarks
Great Slave Lake	158.427	nail in tree
South Channel	158.577	nail in tree
Kakisa River	155.881	nail in tree
Beaver Lake	155.352	nail in tree
	154.474	rock
Burnt Point	154.426	nail in tree
	154.303	rock
Ice Bridge S	154.605	TBM #1 - nail in tree, SE side road
	154.710	TBM #2 - nail in tree, NW side road
Ice Bridge N	155.884	nail in tree
Dory Point S	155.900	nail in tree (confirmed by WSC 3-Jun-92)
Dory Point N	155.752	bolt - N corner of tower (to be confirmed)
Ferry S	153.358	TBM#1 - on SW corner sheet pile
	153.569	TBM#2 - bolt on 2nd lamp standard
	153.307	TBM#3 - on sheet pile
	153.138	TBM#4 - on bracket
Ferry N	156.080	GSC 86T040 (under green plate)
	156.543	GSC 66T132
Coast Guard S	152.492	TBM #1 - bolt
	152.474	TBM #2 - top of sheet pile
Coast Guard N	155.522	nail in 3" tree (requires confirmation)
Blue Quonset	155.383	nail in tree
Big River	157.477	TBM #2 - spike in power pole behind restaurant
Campground	157.791	nail in tree at end of runway
Blue House	153.817	marker on concrete pad behind plant
Boat Launch	153.762	spike in power pole
RCMP	154.171	spike in power pole
Dock	146.021	on sheet pile
Mills Lake	143.718	HBM 86C9986E (based on tie in to P11B-E)
	144.343	Public Works P11B-5

Table 3.3 Border ice thickness (m) - Mackenzie River near Ft. Providence, 1992.

Location	Station (km)	22 to 25-Mar	5 to 9-Apr	25 to 28-Apr	29 to 30-Apr	3 to 4-May
Great Slave Lake	4.5	0.8	0.64	0.62	0.75	0.51
South Channel	16.8		0.74	0.78	0.78	0.00
Kakisa River	34.7	0.7	0.69	1.04		0.00
Beaver Lake	47.3		1.57	1.10	0.98	0.00
Burnt Point	52.8	1.0	1.09	0.96	0.94	0.86
Ice Bridge	59.2	0.8				
Dory Point	63.7	0.6		0.66		
Ferry	65.3	0.9		0.94	0.92	
Coast Guard	67.3		0.76	0.70		
Big River	72.7		0.75			
Ft. Prov. dock	79.5		1.07	0.75		
Mills Lake	103.9			0.59		
Averages		0.79	0.91	0.81	0.87	0.69

Table 3.4 Channel ice thickness (m) - Mackenzie River near Ft. Providence, 1992.

Location	Station (km)	22 to 25-Mar	5 to 9-Apr	25 to 28-Apr	29 to 30-Apr	3 to 4-May
Great Slave Lake †	4.5	0.00	0.00	0.00	0.00	0.00
Matheson Island	12.2		*0.51*	*0.60*	0.00	0.00
South Channel	16.8		*0.75*	*0.45*	0.40	0.00
d/s Range Island	24.8		*0.87*	**1.11**	1.07	0.99
North Channel	30.3		*1.13*	**1.27**	1.30	1.04
Kakisa River	34.7		1.17	**1.26**	1.22	1.18
d/s Kakisa River	41.1		*0.59*	**1.38**	*0.78*	>1.4††
Beaver Lake	47.3		1.04	**1.63**	1.66	1.57
Burnt Point	52.8	1.55	*0.81*	**>1.7††**	1.75	>1.6††
Ice Bridge	59.2	>1.7††	**1.76**	1.70	**>1.7††**	>1.7††
Dory Point †	63.7	0.00	0.00	0.00		0.00
Ferry	65.3		1.04	**1.08**	1.03	
Coast Guard	67.3		1.07	1.30		
Blue Quonset	71.5					0.00
Big River	72.7		0.72			
Blue House	76.7		1.10	**1.19**		0.00
Boat Launch	77.4			1.22		
RCMP	77.9		1.42	**>1.7††**		
Ft. Prov. dock	79.5		1.57	1.50		

† Open lead at the centre of the channel at Dory Point and Great Slave Lake

†† ">" indicates that the actual ice thickness exceeded the thickness stated

Italics indicate that the measurements were taken in pan ice adjacent to the rough ice

Bold indicates that measurements were taken in a different hole from previous

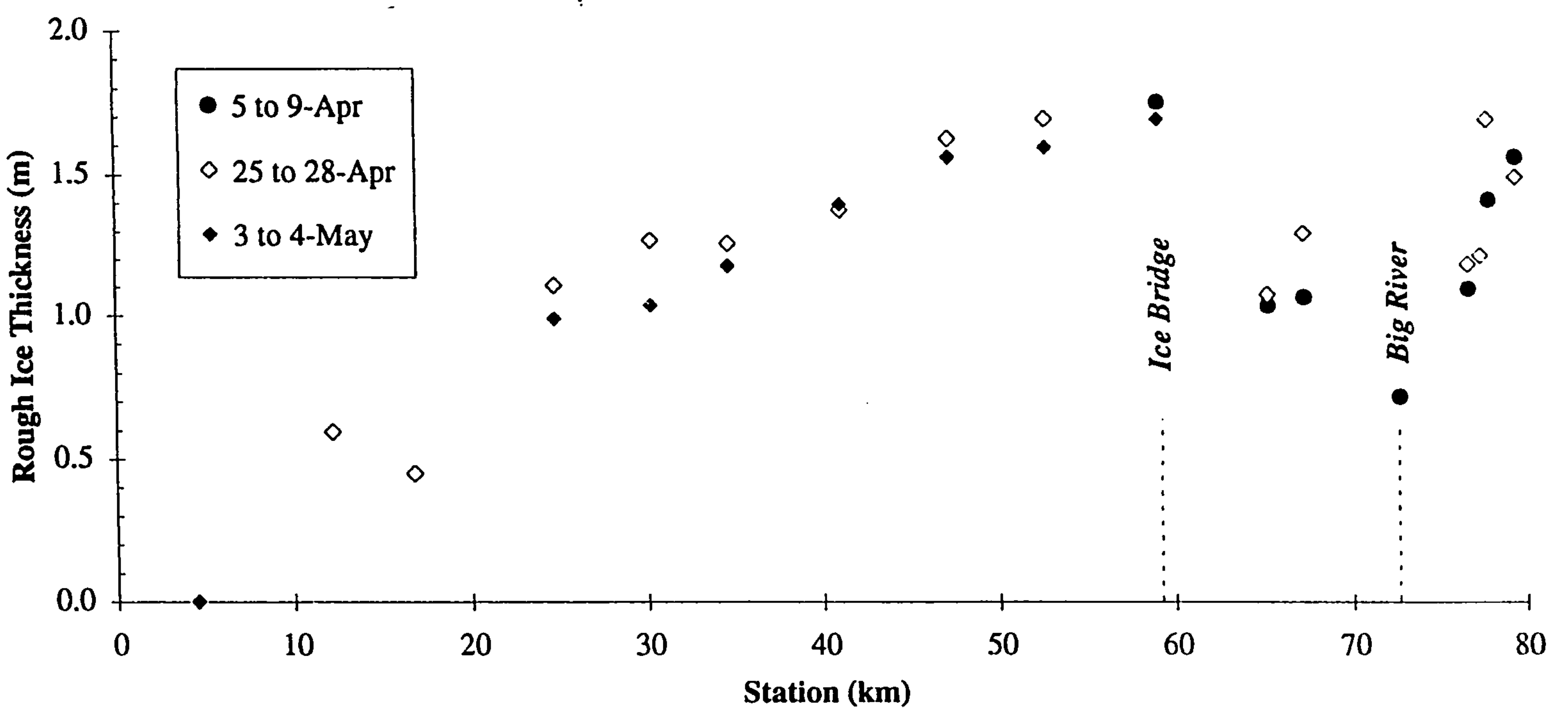


Figure 3.4 Variation in channel ice thickness, Mackenzie River at Ft. Providence, 1992.

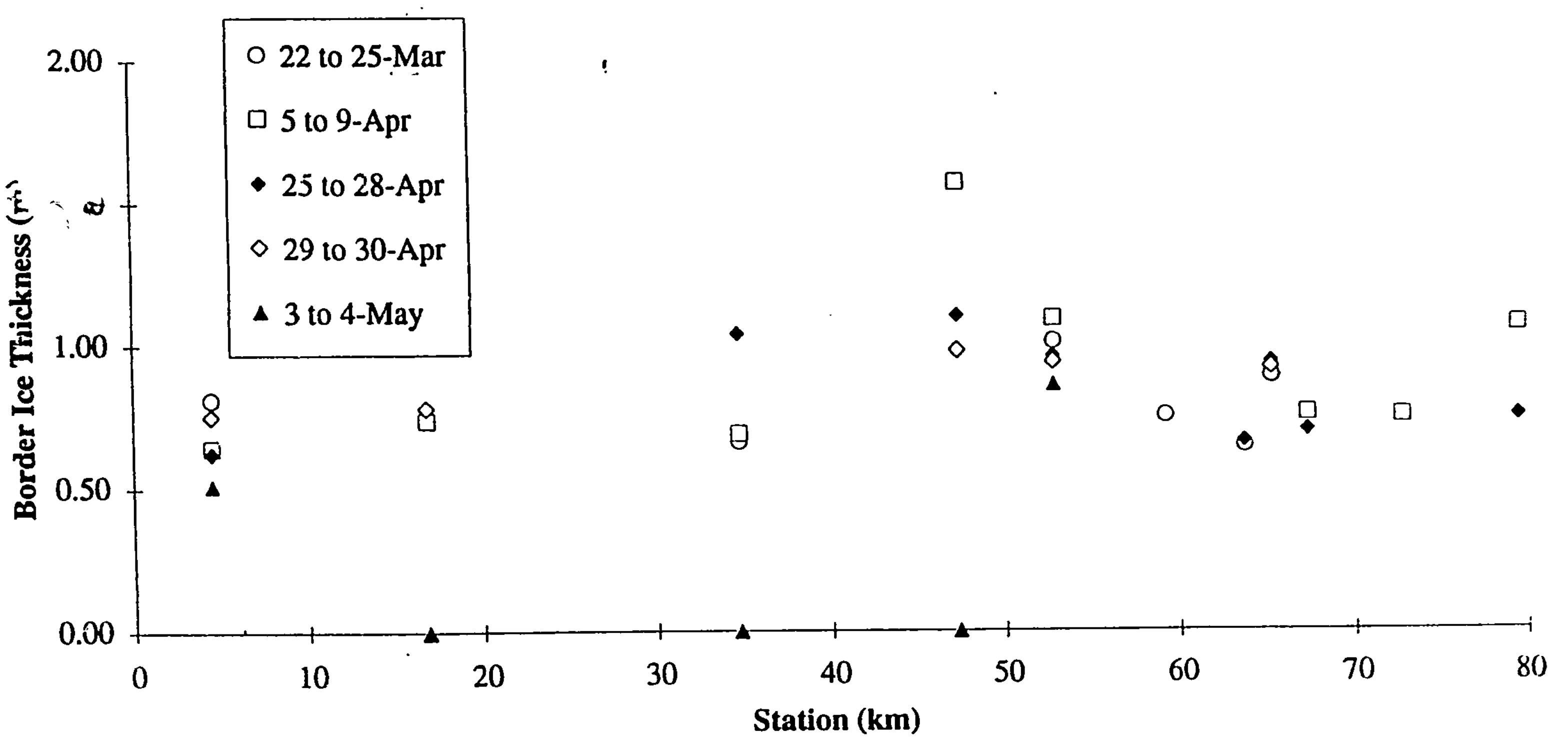


Figure 3.5 Variation in border ice thickness, Mackenzie River at Ft. Providence, 1992.

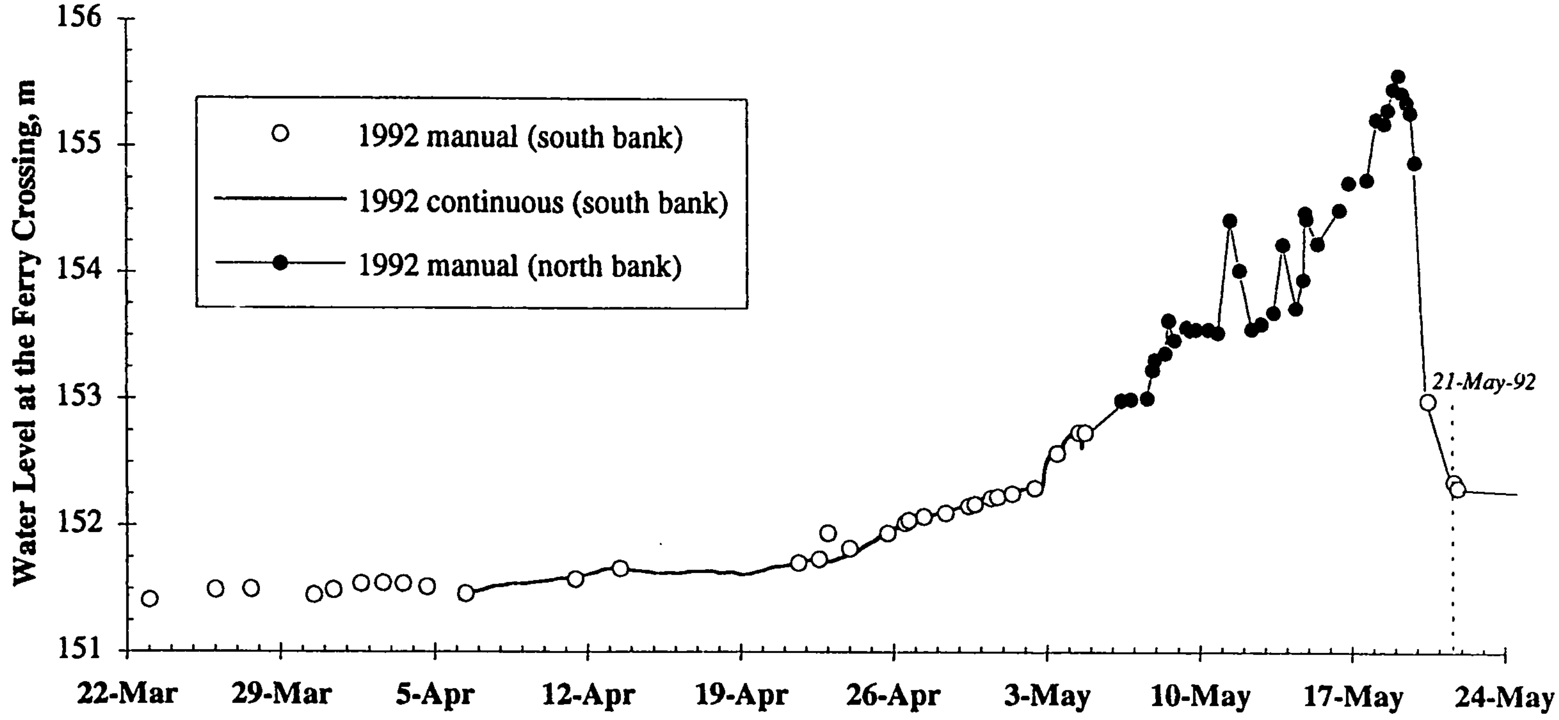


Figure 3.6 Water elevation hydrograph at Ferry Crossing section, 1992.

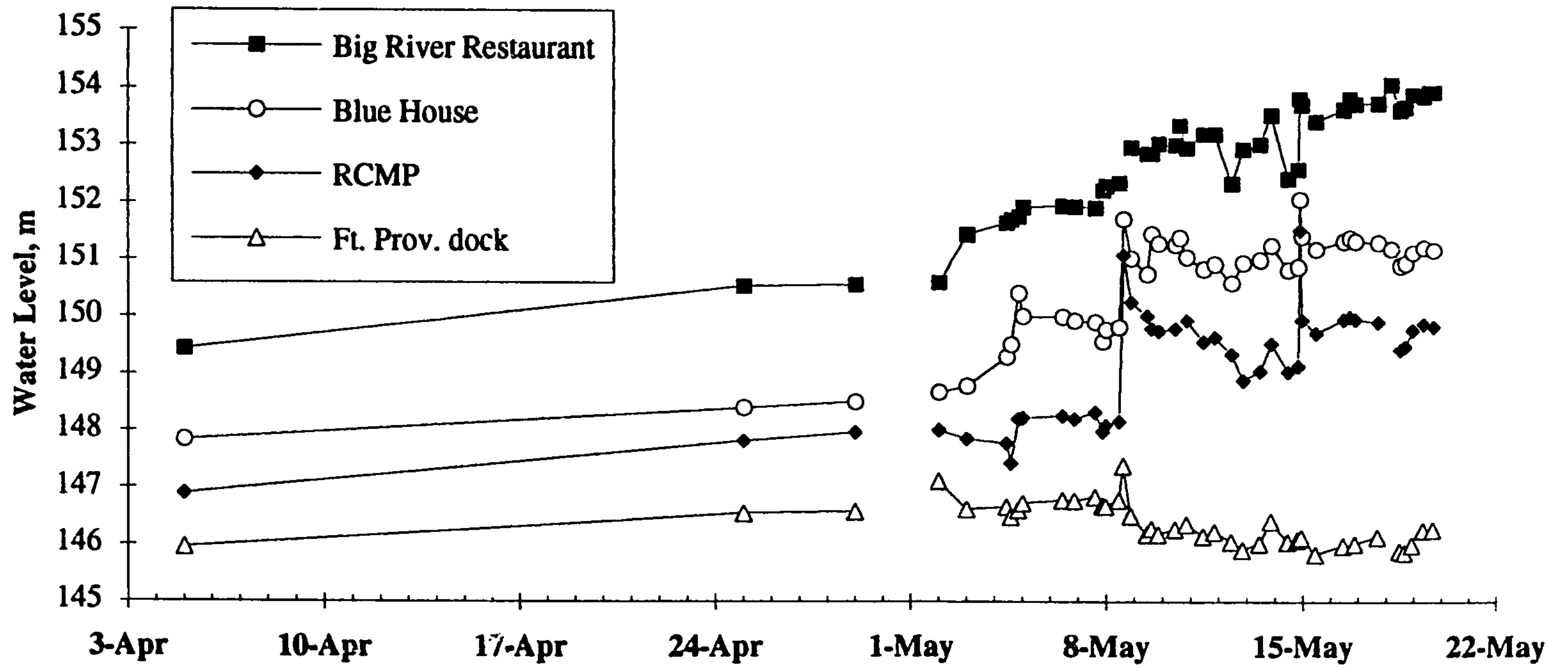


Figure 3.7 Water elevation hydrographs at four cross sections near Ft. Providence, 1992.

Table 3.5 Discharge measurements for open water conditions, Mackenzie River at Dory Point.

Source: Inland Water Directorate, NWT (No copyright)

Date	Discharge (cms)	Gauge Height (m)	Water Stage (m)	Remarks
Gauge zero = 21.280 m.				
19-Jul-61	7836	3.48	152.28	
21-Sep-61	6083	2.92	151.73	
13-Jun-62	7080	3.27	152.08	
5-Aug-62	8836	3.89	152.70	
15-Sep-62	8354	3.70	152.50	
27-Jun-63	8241	3.59	152.40	
17-Sep-63	7476	3.43	152.23	
Gauge zero = 148.806 m.				
3-Sep-64	8354	3.69	152.49	
10-Jun-65	7675	3.42	152.23	
27-Jul-65	7788	3.69	152.50	
30-Sep-65	6938	3.22	152.03	
25-Jun-66	7731	3.40	152.21	
30-Aug-66	7193	3.26	152.07	
6-Oct-66	7080	3.22	152.02	
11-Jul-68	6938	3.27	152.08	
13-Aug-68	5862	2.92	151.73	at Ferry Crossing
26-Sep-68	5041	2.63	151.44	
16-Oct-68	4956	2.48	151.29	
17-Jun-69	6400	3.16	151.97	
23-Jul-69	5551	2.82	151.62	
27-Aug-69	5296	2.69	151.50	
16-Jun-70	5749	2.88	151.68	
13-Aug-70	5296	2.58	151.39	
8-Oct-70	4418	2.42	151.23	at Ferry Crossing
8-Jul-71	5551	2.96	151.77	
22-Sep-71	5098	2.67	151.47	
6-Oct-72	4984	2.83	151.64	at Ferry Crossing
4-Sep-75	6004	3.06	151.87	
6-Jul-76	7307	3.44	152.25	
23-Sep-76	6967	3.44	152.25	
23-Sep-77	5891	3.17	151.98	at Ferry Crossing
12-Jul-78	5947	3.26	152.07	at Ferry Crossing
27-Sep-78	4475	2.69	151.50	

Notes: Measurement was taken at Dory Point unless otherwise noted.

Table 3.7 Discharge measurements for ice covered conditions, Mackenzie River at Dory Point.

Source: Inland Water Directorate, NWT
(No copyright)

Date	Discharge (cms)	Gauge Height (m)	Water Stage (m)	Remarks
Guage zero = 21.280 m.				
31-Jan-62	2209	3.67	152.48	
26-Mar-62	1778	3.36	152.16	
Gauge zero = 148.806 m.				
25-Feb-64	2294	3.82	152.63	
15-Apr-64	1880	3.21	152.02	
27-Jan-65	2515	2.98	151.79	
11-Mar-65	2203	2.67	151.47	
15-Jan-66	2713	4.12	152.92	
23-Feb-66	2662	3.53	152.34	
5-Apr-66	2464	3.34	152.15	
15-Dec-66	3030	4.24	153.04	
25-Jan-67	2801	3.69	152.50	
9-Mar-67	2008	3.16	151.97	
13-Apr-67	1776	3.03	151.83	
30-Jan-68	1674	3.44	152.24	
21-Mar-68	1436	3.05	151.86	
17-Apr-68	1526	2.71	151.51	
20-Feb-69	1410	3.22	152.02	
12-Mar-69	1240	2.99	151.80	
10-Apr-69	1240	2.81	151.61	
4-Mar-70	1368	3.35	152.16	
14-Apr-70	1374	2.77	151.58	
4-Feb-71	1498	3.26	152.06	Ave Ice 0.80 m
16-Mar-71	1382	3.03	151.84	Ave Ice 1.00 m
15-Apr-71	1325	2.83	151.64	Ave Ice 0.90 m
16-Feb-72	1784	3.22	152.02	Ave Ice 0.80 m
15-Mar-72	1821	2.88	151.68	Ave Ice 1.0 m
28-Apr-72	1685	3.10	151.91	Ave Ice 1.2 m
27-Apr-92	4351	3.97	152.78	Measured by U of A
1-May-92	4777	4.10	152.91	Measured by U of A

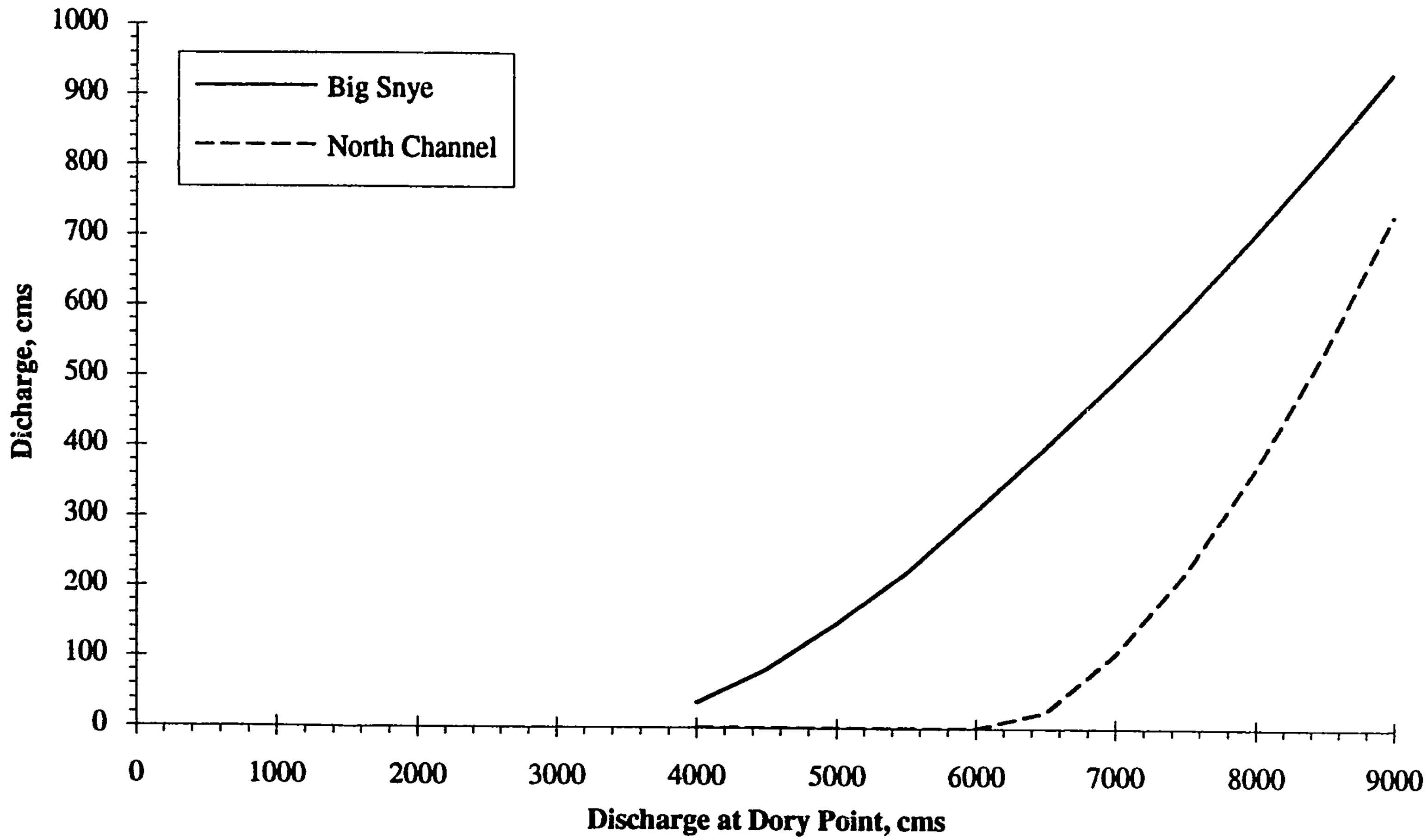


Figure 3.8 Discharge correlation between Dory Point and Big Snye & North Channel during open water period.

Table 3.9 Estimate of discharge in Big Snye and North Channel.

Location	River length (km)	Water stage difference (m)	Average depth (m)	River width (m)	Cross sectional area (m^2)	River surface slope	Discharge (cms)		
							n=0.020	n=0.025	n=0.030
Big Snye	33.75	7.78	1.56	652	1017	0.00020	967	774	645
North Channel	20.75	3.43	0.60	2063	1238	0.00017	574	459	383

Notes: The Manning Equation was used to estimate discharge, assuming flow is uniform.
The discharge was 8500 cms in Mackenzie River on July 11,1992 (based on the power law regression of the guage data).
Water stage at Big Snye was estimated to be 150.032 m on July 11,1992.
Water stage at Mills Lake was 142.538 m on July 11,1992.
Water stage at Great Slave Lake was 158.147 m on July 11,1992.
Water stage at Kakisa was 154.716 m on July 11,1992.

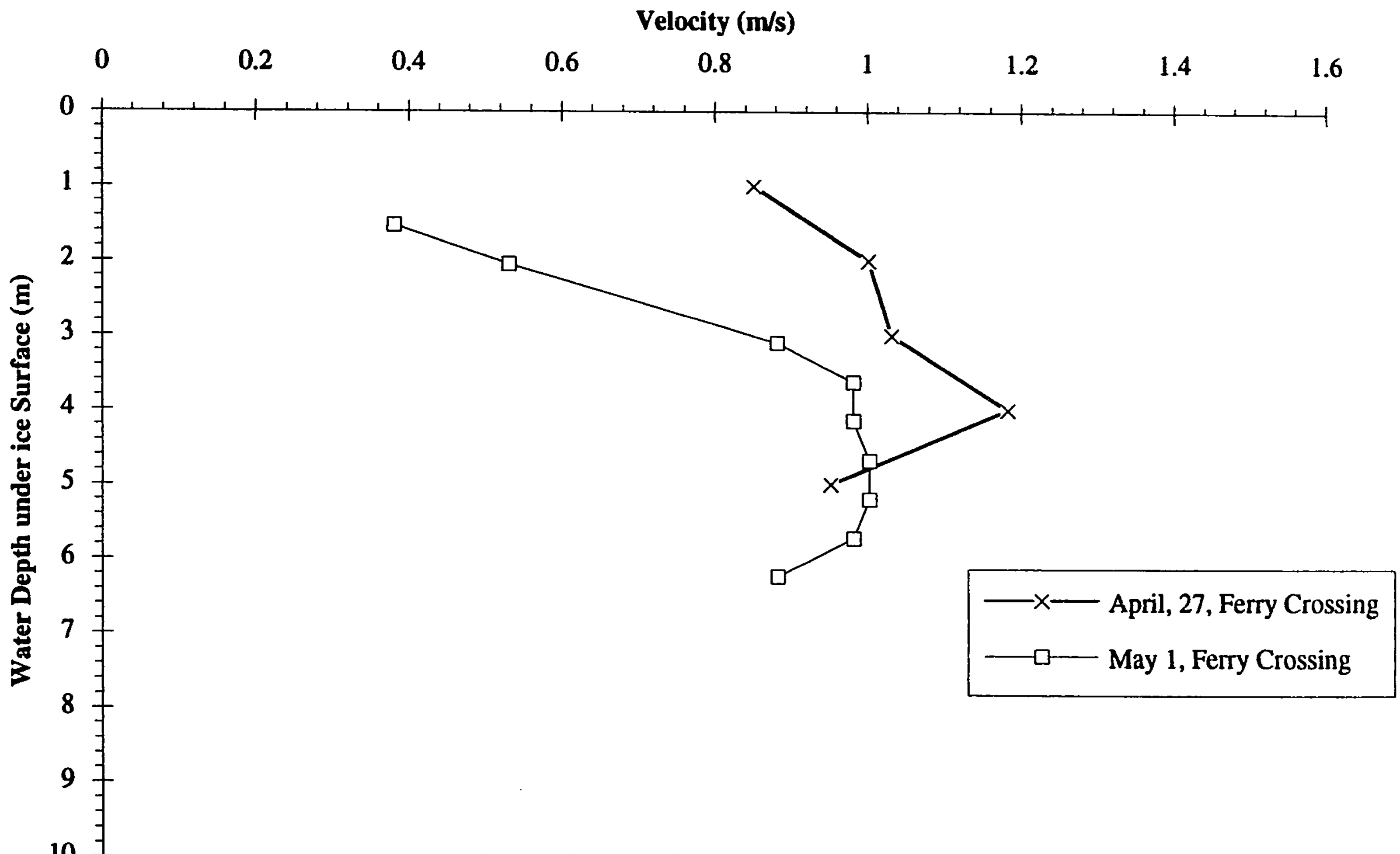


Figure 3.9 Velocity profiles under ice conditions, Mackenzie River at Ft. Providence, 1992.

Table 3.10 Measured velocity profiles, Mackenzie River at Ft. Providence, 1992.

Date	Location	Total depth (including ice thickness) (m)	Ice thickness (m)	Distance below top of ice (m)	Velocity Reading #1 m/s	Velocity Reading #2 m/s	Velocity Average m/s
27-Apr	Ferry Crossing 71.2 m from north bank	7.91	0.82	1.00	0.80	0.90	0.85
				2.00	0.95	1.05	1.00
				3.00	1.00	1.05	1.03
				4.00	1.20	1.15	1.18
				5.00	0.95	0.95	0.95
1-May	Ferry Crossing 500 m from south bank	8.48	1.38	1.53	0.40	0.35	0.38
				2.05	0.55	0.50	0.53
				2.58	1.30	0.90	1.10
				3.10	0.85	0.90	0.88
				3.63	0.95	1.00	0.98
				4.15	1.00	0.95	0.98
				4.68	1.00	1.00	1.00
				5.20	1.00	1.00	1.00
				5.73	0.95	1.00	0.98
				6.25	0.90	0.85	0.88
6-May	Orange Cabin 620 m from north bank	6.80	0.73	1.00	0.45	0.50	0.48
				1.50	0.55	0.65	0.60
				2.00	0.70	0.65	0.68
				2.50	0.75	0.75	0.75
				3.00	0.80	0.80	0.80
				3.50	0.80	0.85	0.83
				4.00	0.85	0.90	0.88
				4.50	0.85	0.95	0.90
				5.00	0.95	0.90	0.93
				5.50	0.70	0.75	0.73
				6.00	0.75	0.70	0.73
				6.35	0.65	0.60	0.63

Table 3.11 Larsen's method to calculate roughness and Manning's n, 1992.

Date [1]	Location [2]	Affected zone [3]	Maximum velocity (m/s) [4]	Average velocity (m/s) [5]	Coefficient α [6]	[illegible] [7]	Roughness k (m) [8]	Manning's n [9]
27-Apr	Ferry Crossing	Ice cover	1.18	0.81	3.21	3.18	3.85	0.048
1-May	Ferry Crossing		1.00	0.68	3.13	3.30	4.34	0.049
27-Apr	Ferry Crossing	Bed	1.18	0.71	2.51	3.91	9.53	0.056
1-May	Ferry Crossing		1.00	0.77	4.39	3.28	1.22	0.033

Note: [6] = [4] / ([4]-[5])
[8] = 30* [7] *exp(-[6])
[9] = 0.0316* [8]

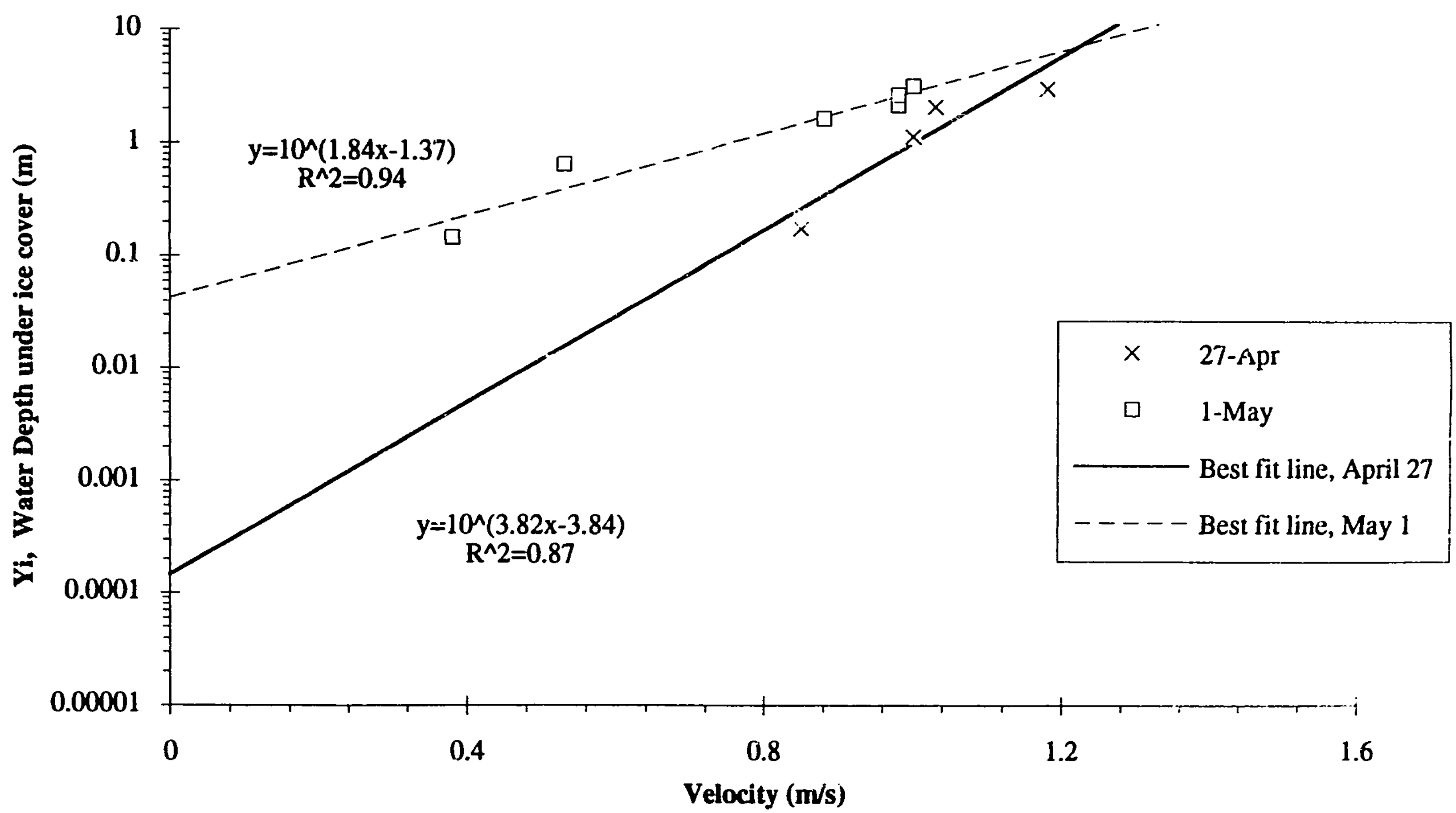


Figure 3.10 Regression method to analyzing velocity profiles in ice zone, Mackenzie River at Ft. Providence, 1992.

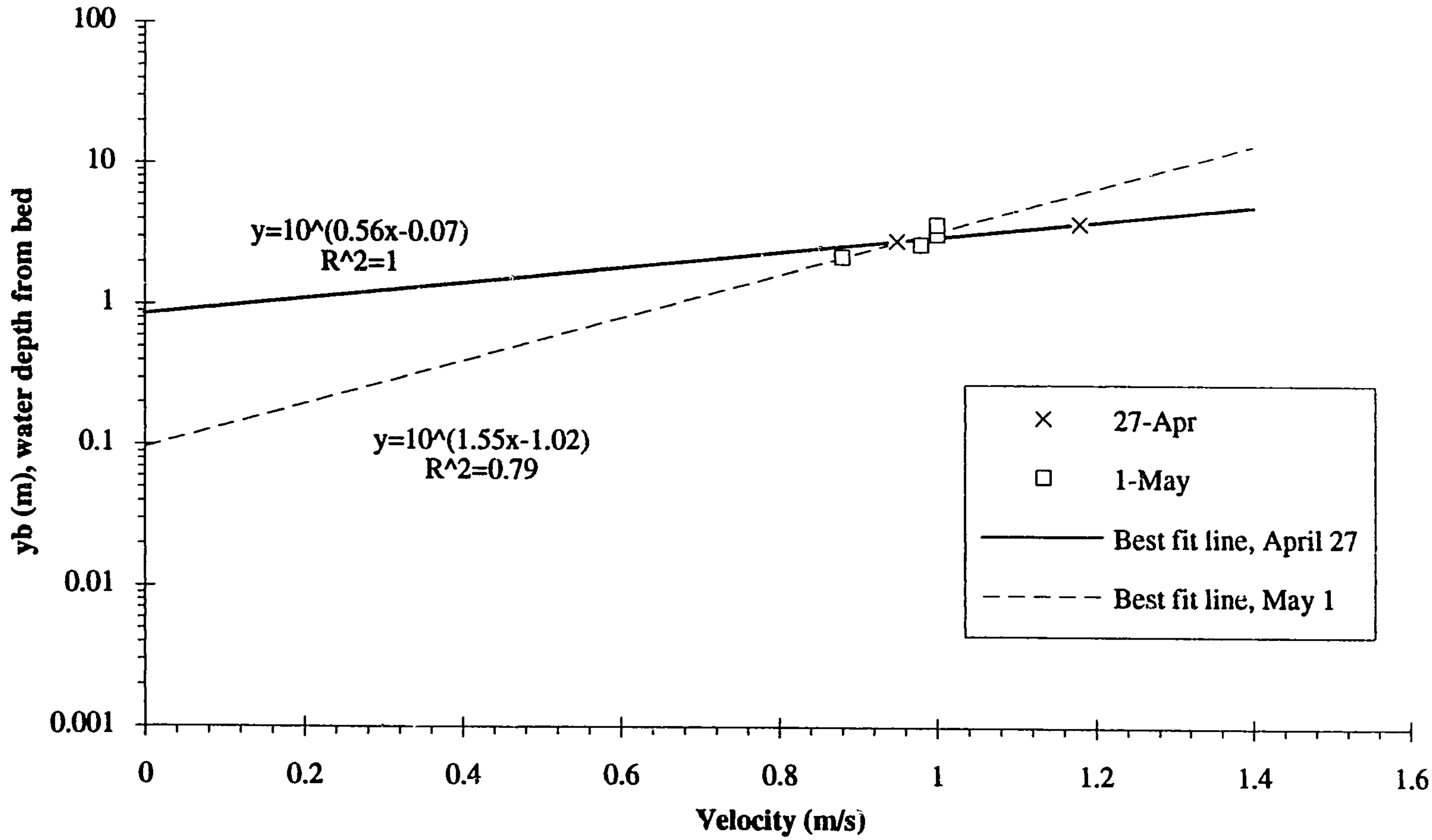


Figure 3.11 Regression method to analyzing velocity profiles in bed zone, Mackenzie River at Ft. Providence, 1992.

Chapter 4
Gradually varied flow (GVF) analysis

4.1 Introduction

In this chapter, the application of a gradually varied flow (GVF) model, specifically the HEC-2 (Hydrologic Engineering Center, 1982) program, to the Mackenzie River near Ft. Providence is discussed. In section 4.2, the HEC-2 GVF model is described. The data requirements for this model are discussed in section 4.3. In section 4.4, the application of the GVF model to calibrate the Manning's *n* for an open water condition and the verification of the calibrated results are given. The application of the GVF model to calibrate the Manning's *n* for the ice cover upstream of the Big River section, estimate of discharges in ice conditions and the estimate of ice roughness for the accumulation in Ft. Providence Rapids are presented in section 4.5. The discussion of the results is presented in section 4.6.

4.2 HEC-2 program

The HEC-2 computer program was developed in the 1970s at the Hydrologic Engineering Center, U. S. Army Corps of Engineers (Hydrologic Engineering Center, 1982). This program is capable of calculating water surface profiles for one-dimensional, steady, gradually varied flow in natural or man-made channels. The computational procedure, generally known as the Standard Step Method (Henderson, 1966), has the advantage of computing the water surface profiles in natural channels and is capable of accounting for the effects of an ice cover.

The basic equations which HEC-2 uses for profile calculation are as follows (Hydrologic Engineering Center, 1982):

$$H_2 + \frac{\alpha_2 V_2^2}{2g} = H_1 + \frac{\alpha_1 V_1^2}{2g} + L\overline{S}_f + C_l\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (4\text{-}1)$$

$$V = \frac{1}{n} R^{2/3} S_f^{1/2} = K S_f^{1/2} \quad (4\text{-}2)$$

where;

H = water surface elevation, m;

V = cross sectional averaged velocity, m/s;

α = kinetic energy correction coefficient;

g = acceleration of gravity, m/s^2;

L = reach length, m;

$\overline{S_f}$ = representative friction slope for reach;

C_l = expansion (or contraction) loss coefficient;

n = Manning's roughness coefficient;

R = hydraulic radius, m;

S_f = friction slope; and

K = conveyance coefficient.

Subscripts 1 and 2 refer to the downstream and upstream cross sections, respectively, in the computation of a subcritical flow. The energy equation (Equation 4-1) is used to balance the energy between the two cross sections and the Manning equation (Equation 4-2) is used to evaluate the energy losses other than expansion and contraction losses.

Manning's equation is applicable only to fully developed turbulent flow. To verify the flow is fully turbulent in the Mackenzie River, the Dory Point is chosen as a typical cross section. Henderson (1966) gave a criterion of application of Manning's equation, that is:

$$n^6\sqrt{RS_f} \geq 1.9 * 10^{-13} \quad (4\text{-}3)$$

At Dory Point, the average water width and depth are 1800 m and 3.0 m, respectively. The Manning n and energy slope S_f are assumed as 0.02 and bed slope, 0.00027, respectively. The calculated value 1.8×10^{-12} meets the criterion of fully turbulent flow in open channel.

The HEC-2 program deals with the flow in an ice covered channel by including two parameters, ice thickness and ice roughness. With the ice thickness known, the hydraulic radius can then be computed based on flow area (not counting that portion occupied by ice) divided by the wetted perimeter. With the ice roughness, the composite Manning's n is calculated by the Belokon-Sabaneev formula.

4.3 Data input for GVF model

The data needed to perform the GVF computation include: flow regime, loss coefficients, the water surface elevation at the starting cross-section, discharge, cross section geometry, ice thickness and reach length. The flow regime and loss coefficients are discussed in this section. The others have been discussed in Chapter 3 already.

4.3.1 Flow regime

The flow regime may be supercritical or subcritical. For subcritical flow, the calculations start from downstream and progress to upstream. For supercritical flow, the calculations start from upstream and progress to downstream. Gradually varied flow analysis cannot deal with subcritical and supercritical flow together. In order to determine the flow regime, the normal depth and the critical flow depth have to be considered. The normal depth can be calculated by Manning's equation. The critical depth is that at which the specific energy head is a minimum. For a rectangular cross-section channel, the critical water depth can be written as:

$$y_c = \left(\frac{q^2}{g}\right)^{1/3} \tag{4-4}$$

where:

y_c = critical depth, m, and;

q = discharge per unit width, $m^3/s/m$

However, in a natural river, the cross-section area does not have a simple relationship with water depth, so it is difficult to have an explicit solution for critical depth. Therefore the HEC-2 GVF model determines the critical water depth with an iterative procedure by changing the water depth until the water depth corresponding to a minimum specific energy is reached.

To determine the flow regime of the Mackenzie River, typical values of hydraulic geometry were used. Based on a rectangular channel approximation and an average width, bed slope and discharge of 3000 m, 0.0002 and 5000 cubic meters per second (m^3/s), along with an estimate of the Manning resistance coefficient of 0.03 (typical of gravel bed rivers), a uniform flow depth of 2 m was computed. This was compared to a critical depth of about 0.7 m calculated based on the same parameters using Equation (4-4). Therefore, the GVF model was set up to proceed with calculations in the upstream direction. Subsequent runs with the GVF model confirmed that the flow was subcritical throughout the study reach.

4.3.2 Energy loss coefficients

As stated in Chapter 2, Manning's n is usually employed as a resistance coefficient, accounting for other losses in addition to friction (such as channel irregularity, planform variability, silt and scour, etc.). In the HEC-2 model (Equation (4-1)), expansion and contraction losses have been considered separately. This is a poor feature because this extracts one of these other losses leaving all of the rest to be lumped with the roughness. If other losses are to be separated from the friction losses then all should be considered separately, not just one.

The eddy loss refers to the energy loss caused by the flow expansion and contraction due to the change of river cross section shape between the two cross sections. The eddy loss is a function of velocity head and can be written as

$$h_e = C_1 \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \qquad (4\text{-}5)$$

where;

h_e = the eddy loss between two cross sections.

Due to flow separation, the loss due to expansion of flow is usually much larger than the contraction loss (Hydrologic Engineering Center, 1982). The loss from a short abrupt transition is larger than loss from a gradual transition. Typical contraction and expansion coefficients are as follows: for gradual transitions, they are 0.1 and 0.3, respectively; and for abrupt transitions, they are 0.6 and 0.8, respectively (Hydrologic Engineering Center, 1982). The Mackenzie River is dominated by gradual transitions. Therefore contraction and expansion coefficients of 0.1 and 0.3, respectively, were used. A sensitivity analysis was conducted and it was determined that the model was not sensitive to variations in these coefficients.

4.4 Calibration of the GVF model for open water conditions

The objective for applying the GVF model in open water, was to quantify the bed roughness through the study reach by calibrating a measured water surface profile with a known discharge. Two suitable water surface profiles were available, allowing for both calibration and verification of the open water model. The first data set was based on an open water profile taken from Beaver Lake to the RCMP section in Ft. Providence during the cross section surveys conducted from August 29 to

September 1, 1991. A second profile, extending from Great Slave Lake to Mills Lake, was taken while surveying cross sections on July 11, 1992. Discharges measurements were not conducted on either of these dates so the discharge was obtained from the rating curve established by power law regression of the measured stage discharge data at the WSC station at Dory Point (Equation (3-1)) as described in Section 3.5.1.

Given that the HEC-2 GVF model represents a one-dimensional approximation to the flow, a decision had to be made as to how to handle flow around islands. For the two major islands in the study reach: Big Island, at the outlet of Great Slave Lake; and, Meridian Island, which divides the flow between the Big Snye and Ft. Providence Rapids, only the main channel was modeled. That is, the South Channel at Great Slave Lake, and the Ft. Providence Rapids downstream. To account for the proportion of flow carried by the neglected channels, the discharge was decreased in these two reaches based on Figure 3.8 in Chapter 3.5.2. Smaller islands in the main channel at Ft. Providence and downstream were not explicitly considered in the model. Therefore, their effects are incorporated in the calibrated loss coefficients.

There are also numerous small tributaries which contribute streamflow throughout the modeled reach, as well as one large one: the Kakisa River. Based on estimated peak flows from the small tributaries (observed to be in the order of 1 m^3/s during spring runoff) their total input to the flow in the modeled reach would be in the order of 100 m^3/s. The Kakisa River has recorded peak floods in the order of 100 to 200 m^3/s, based on published WSC records. Therefore, if all tributaries were peaking simultaneously (an unlikely occurrence) the combined inflow would still be less than 300 m^3/s, (approximately 4% of the Mackenzie River discharge) which is of the order of the accuracy of the discharge estimate itself. Therefore, these inflows were not considered in the model.

The calibration was achieved by trial and error, inputting values of Manning's *n* and checking to see if the computed water surface profile was close to the surveyed one. In order to improve the calibration results, three interpolated cross sections were generated by the GVF model between the Ice Bridge cross section and the Coast Guard cross section. The criterion for successful calibration between the computed and measured water surface profiles at any cross section was set at 0.3 m (based on the estimated accuracy of the measured water level profiles).

The final range of Manning's *n* was from 0.02 to 0.03 along the study reach. From the Great Slave Lake section to Ice Bridge section, the river channel is very wide and the calibrated Manning's *n* was 0.022. Downstream of the Ice Bridge section to upstream of the Big River section, the calibrated Manning's *n* was 0.020, which is not significantly different from the Manning's *n* upstream. Once the flow passes through the Ft. Providence Rapids, the river channel becomes very narrow. The calibrated Manning's *n* in this reach varied from 0.025 to 0.030. Downstream of Ft. Providence Rapids, the river becomes wide again and the Manning's *n* obtained in the calibration from the Dock to Mills Lake section was 0.020. Figure 4.1 and Table 4.1 show the calibrated results for this open water condition. From Table 4.1, one can see the maximum difference between measured water surface elevation and computed water elevation at a cross section is 0.25 m. Figure 4.2 and Table 4.2 present the verification results for open water case. Table 4.2 shows the maximum difference between measured water surface elevation and computed water surface elevation at a cross section is only 0.29 m for the verification run.

Manning's *n* represents the integrated effect of a large number of factors contributing to the energy loss in a reach. Some important factors are bed material, vegetation, cross section irregularity, irregular alignment of channel and obstructions in the flow such as the islands mentioned above. The channel irregularity includes variations in cross section, size, and shape along the study reach (Chow, 1959). The variation of Manning's *n* along the study reach, especially when flow passes the Big River cross section, may be explained by the following reasons. First, since the velocity and bed slope increase at the Big River cross section, the size of bed materials probably are larger than upstream, that causes the change of Manning's *n* along the study reach. The second reason is probably that the presence of the island at Big River induces losses.

The Manning's *n* values obtained in the calibration are within a reasonable range. This can be proven by a literature review. Chow (1959) presented a summary table and photographs for estimating Manning's *n*. He recommended Manning's *n* from 0.025 to 0.060 for large gravel bed rivers. Barnes (1967) provided a number of illustrative photographs and corresponding values which also indicate that the values obtained here are reasonable (based on comparable sites in that reference). A comparison of the calibration results with the resistance values presented in Table 3.12 (based on measured velocity profiles under ice) might be taken to indicate that the calibrated bed roughness at the ferry crossing is too low. However, given the problems encountered in measuring the velocity profiles, the limited amount of data, and the generally inconsistency of the results obtained (Table 3.12) the GVF analysis is considered superior.

4.5 GVF analysis for late winter, 1992

4.5.1 Calibration of the reach upstream of Big River

The GVF model was applied in ice covered conditions to find the ice roughness through the study reach by calibrating a measured water surface profile. The water surface profile measured from April 25 to 27, 1992, was used for this purpose. Due to the unknown proportions of the split in flow between the Big Snye and Ft. Providence Rapids under ice conditions, the calibration of Manning's *n* for the ice was initially limited to the reach from the Great Slave Lake section to the Big River cross section. As discussed in Section 3.5.1, a discharge measurement was conducted on April 27, 1992.

The bed roughness was based on the calibration for open water conditions. This approach would be invalid if roughness/resistance were found to vary strongly with depth as the effective hydraulic roughness is reduced under ice conditions (and at lower discharges). In the absence of data confirming or denying the validity of this assumption, it was used, recognizing that confidence in results are somewhat diminished.

The variation of ice thickness is a three dimensional phenomenon. In order to use the measured ice thicknesses in the one dimensional hydraulic model, a simplification had to be made. The ice thickness of border and channel ice at each cross section was apportioned into one representative ice thickness. This apportionment was done in a qualitative way, given the sparse nature of the data. The representative ice thickness used was generally closer to the value of channel ice thickness because channel ice covered a larger more fraction of the total active channel width. Table 4.3 presents both the measured data and the ice thicknesses used in the model.

The Manning's n_i for the ice cover was obtained by trial and error calibration. In order to improve the calibration results, an additional three cross sections were interpolated by the HEC-2 program between the Ice Bridge cross section and the Coast Guard cross section. The criterion for calibration between the computed and measured water surface profiles at any cross section was again taken as 0.3 m. The resulting calibrated Manning's n_i for the ice cover was 0.015. The maximum difference between the surveyed water elevation and computed water elevation at a cross section was 0.30 m at the Great Slave Lake section. This can be attributed in part, to the fact that the discharge was not reduced (as it had been in the open water case) to account for the proportion of flow in the north channel around Big Island. Figure 4.3 and Table 4.3 present the calibrated result for the ice cover profile. Table

4.4 shows the hydraulic components computed by the GVF model at different cross sections.

A range of reasonable ice roughness can be also found from the literature. Nezhikhovskiy (1964) found that for sheet ice covers, the Manning's n_i was from 0.010 to 0.015. Ohashi and Hamada (1970) measured velocity profiles in four rough, ice covered streams in Hokkaido, Japan, and determined Manning's n_i for the under surface of the ice to be between 0.012 and 0.062. Tesaker (1970) calculated the ice roughness in three Norwegian rivers and obtained values from 0.013 to 0.020. Table 4.5 presents a comparison of the ice roughness in different rivers. Furthermore, an upturned ice floe, found at the Big River section in late April, 1992 is shown in Figure 4.4. The observed ripples averaged 5 cm in amplitude and about 20 cm in spacing. Qualitatively, the value $n_i = 0.015$ does not appear unreasonable based on this photo. It was considered inappropriate to compare these results to those obtained from the velocity profiles (as discussed for the open water calibration).

4.5.2 Estimation of discharge during the pre-breakup period

After obtaining a calibrated GVF model of late winter ice conditions, discharge estimates were computed based on water surface profiles measured from April 29 to May 13, 1992. Since the downstream water elevation, Manning's n for the river bed and ice cover (assuming it does not change in a short time), ice thickness, and cross section area are known, the only unknown is discharge. The procedure employed was to assume a discharge, calculate a water profile, and compare the calculated profile with the measured water surface profile. When the two profiles were close to each other, the corresponding discharge was taken as the estimated discharge. Generally, the criterion for accepting the two water surface profiles as matched was a maximum difference between the two water levels of 0.3 m. It should be noted changes in ice thickness and roughness which may have occurred with time were not considered. During the period of discharge estimation, ice movements occurred between some cross sections and some temporary open water areas developed as ice moved downstream and jammed in the channel through Ft. Providence. However, attempts to account for these effects by adjusting the ice thickness (to zero in some case) resulted in erratic water surface profiles. It was concluded that such refinements could not be handled with this simple, one-dimensional flow model. Therefore, when these effects became significant, the model could no longer be applied. Detailed results of these analysis can be seen in Figure 4.5 to Figure 4.15 and Table 4.6 to Table 4.16. Figure 4.16 and Table 4.17 present the discharge hydrograph and estimated discharge summary table. The result shows good agreement between the estimated and measured discharges.

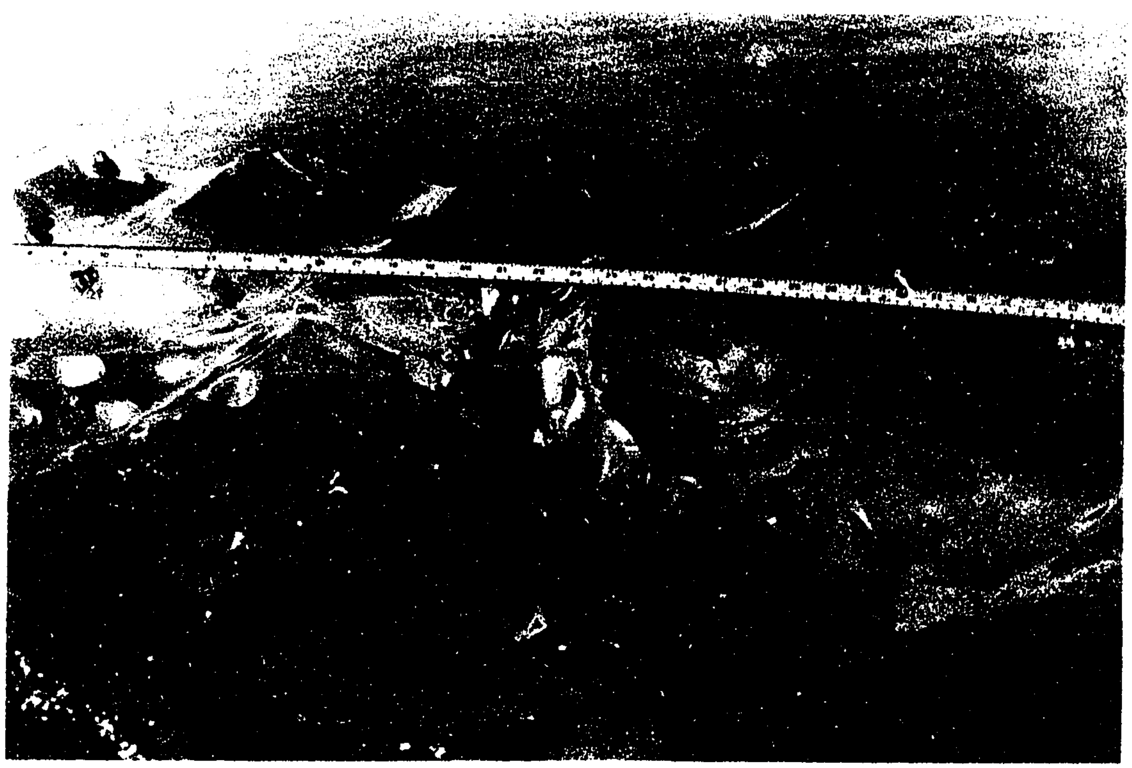


Figure 4.4 Ripple configuration of undersurface of ice cover.

It is interesting to note that the third discharge measurement (taken downstream of Ft. Providence at the Orange Cabin section) was in good agreement with the computed discharge upstream of the split in flow between the main channel and the Big Snye. This implies that little or no discharge was passing through the Big Snye at that time. This conclusion is supported by field observations. An alternative explanation might be that the ice roughness increased with time and since the model did not take this into account the discharge was overpredicted (thus balancing any component of flow in the Big Snye). The former reason is considered to be more likely.

Substantial changes in ice characteristics were observed after May 13, 1992. During this period, the ice was shoved from Great Slave Lake to Dory Point and began piling up at the Big River cross section. Since the ice blocked the water flow, the water level started rising but the discharge did not increase much. The ice cover was no longer a simple ice sheet but a fragmented ice cover. The GVF model was no longer suitable for this situation since discharge, ice thickness and ice roughness were all unknown.

4.5.3 Calibration of the accumulation through Ft. Providence Rapids

As stated earlier, when the calibration for the ice cover was initially conducted, the Big River section was chosen as the starting cross section. However, after the estimate of the discharge for late April and early May was achieved, the ice roughness calibration along Ft. Providence Rapids became possible. This was only because the discharge measurement on May 6, 1992 downstream of Ft. Providence indicated no flow down the Big Snye. For this extended ice roughness calibration, the input data included discharge, ice thickness, and bed roughness. The discharge was obtained from the estimate of discharge described in section 4.5.2. The ice thickness was obtained by averaging measured ice thicknesses in a manner similar to that done for the initial calibration. The bed roughness was again obtained from the open water calibration. Three water surface profiles were used for this calibration. They were April 27, April 29 and May 4. The calibrated Manning's *n* for ice roughness was 0.05 from the Campground section to the dock at Ft. Providence. Table 4.18 to Table 4.20 present the calibration results. The calibration of Manning's *n* for an ice cover in Ft. Providence Rapids indicates the ice was rougher than the one upstream as would be expected from the rough nature of the freezeup accumulation in this reach. After May 4, the ice cover consolidated and formed an ice jam along the Ft. Providence Rapids. As it was no longer possible to determine accurate ice thickness values, no further profiles could be calibrated.

4.6 Discussion of results

The water surface profiles for open water and ice covered conditions had a similar slope along the study reach. Figure 4.17 illustrates this with two of the water surface profiles. From this figure, one can see that the water surface elevations were almost constant at Great Slave Lake in the two water surface profiles. These profiles had a similar mild water surface slope from Great Slave Lake to the Ice Bridge cross section. From the Ice Bridge to the Big River cross section, they had similar, steeper, mild slopes. This character can be used to develop the rating curves from GVF model.

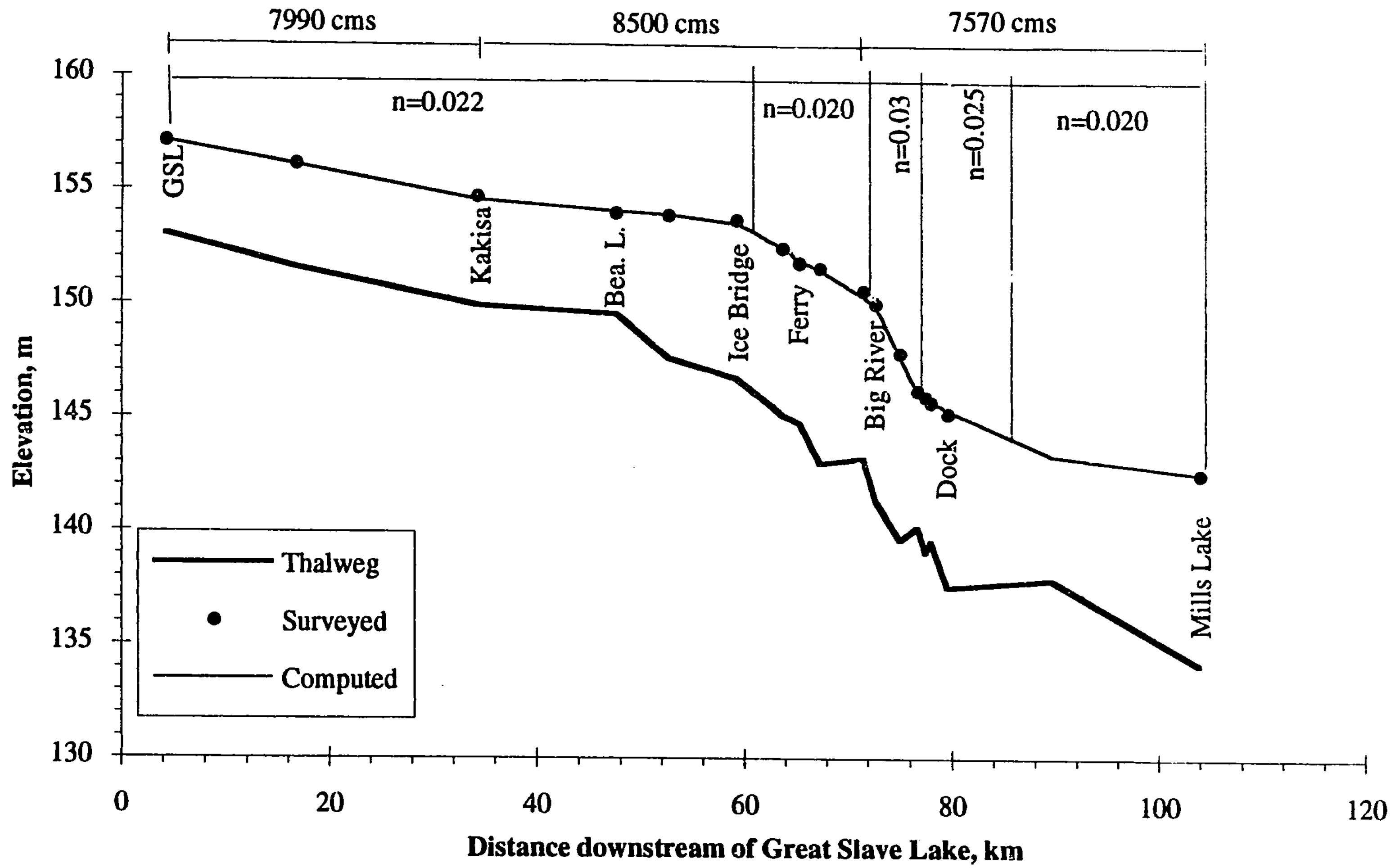


Figure 4.1 Water surface profile along the Mackenzie River between Great Slave Lake and Mills Lake, July 11, 1992.

Table 4.1 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Mill Lake, July 11, 1992.

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 11-Jul-92 (m)	Calibrated Manning's n †	Computed Water Level		
					Discharge (cms)	Water stage (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03	157.11	0.022	7990	157.10	-0.01
South Channel	16.7	151.57	156.11	0.022	7990	156.07	-0.04
Kakisa River	34.2	149.92	154.72	0.022	8500	154.55	-0.17
Beaver Lake	47.5	149.56	153.98	0.022	8500	154.06	0.08
Burnt Point	52.6	147.59	153.89	0.022	8500	153.90	0.01
Ice Bridge	59.2	145.70	153.69	0.022	8500	153.51	-0.18
Dory Point 4 ††	60.7	146.17		0.020	8500	153.21	
Dory Point 3 ††	62.2	145.64		0.020	8500	152.81	
Dory Point	63.7	145.10	152.46	0.020	8500	152.47	0.01
Dory Point2 ††	64.5	144.96		0.020	8500	152.26	
Ferry2 ††	65.2	144.79		0.020	8500	151.83	
Ferry	65.3	144.79	151.80	0.020	8500	151.93	0.13
Coast Guard	67.3	142.97	151.59	0.020	8500	151.50	-0.09
Blue Quonset	71.5	143.19	150.60	0.020	8500	150.35	-0.25
Big River	72.7	141.37	150.03	0.030	7570	149.94	-0.09
Campground	75.0	139.61	147.85	0.030	7570	147.72	-0.13
Blue House	76.7	140.18	146.20	0.030	7570	146.12	-0.08
Boat Launch	77.4	139.06	145.93	0.025	7570	145.97	0.04
RCMF	77.9	139.57	145.70	0.025	7570	145.71	0.01
Ft. Prov. Dock	79.5	137.50	145.19	0.025	7570	145.35	0.16
Orange Cabin	89.5	137.84		0.020	7570	143.31	
Mills Lake	103.9	134.25	142.54	0.020	7570	142.54	0.00

† Calibrated roughness based on a discharge of 8500 cms at Dory Point and surveyed water levels on July 11,1992.
†† Interpolated cross sections.
Note: 'cms' means 'cubic meters per second'.

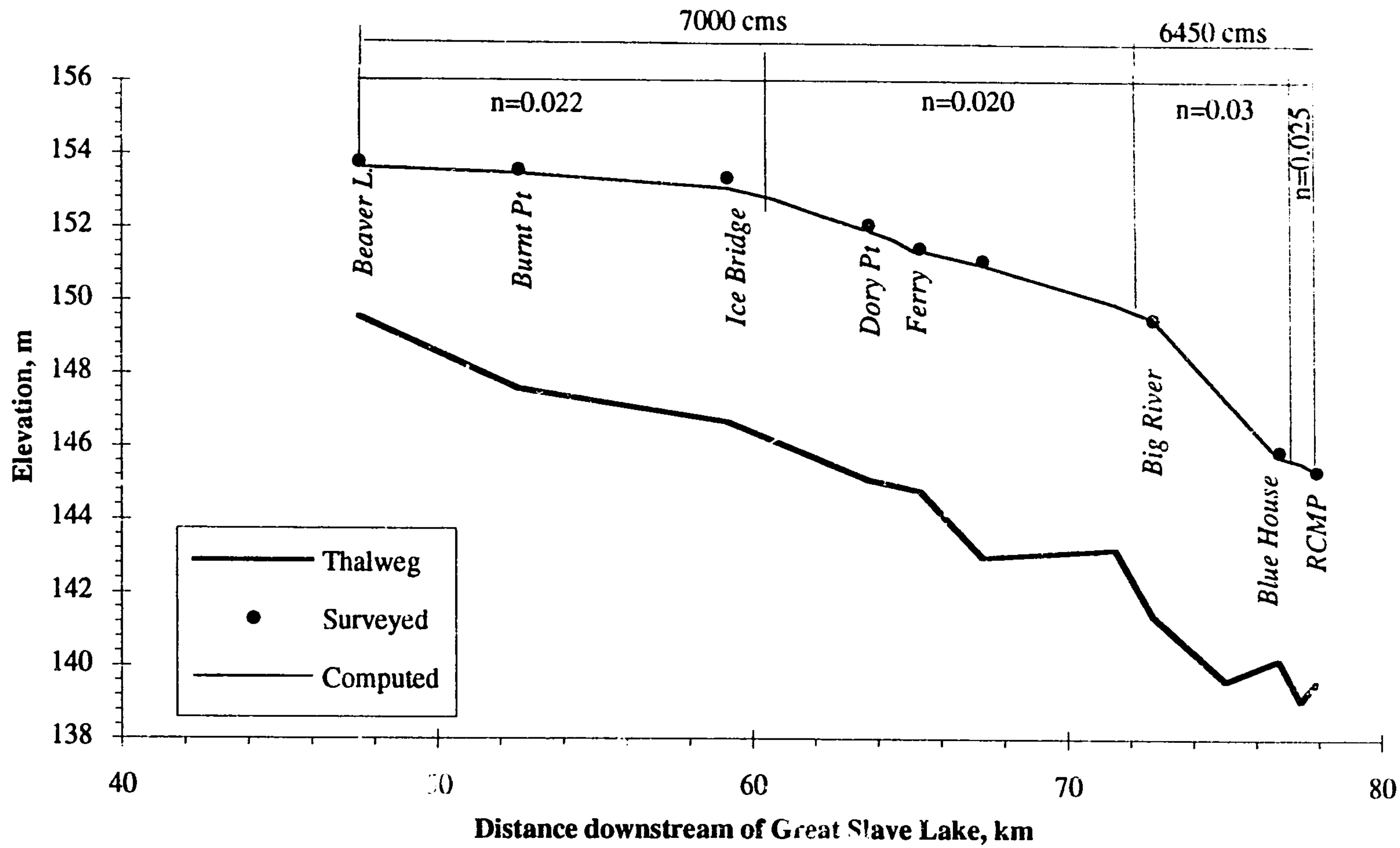


Figure 4.2 Water surface profile along the Mackenzie River between Beaver Lake and RCMP, August 29, 1991.

Table 4.2 Calculated water surface profiles on the Mackenzie River between Beaver Lake and RCMP, August 29, 1991.

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 29-Aug-91 (m)	Manning's n †	Discharge (cms)	Calculated water level (m)	Calculated minus surveyed water level (m)
Beaver Lake	47.5	149.56	153.80	0.022	7000	153.65	-0.15
Burnt Point	52.6	147.59	153.60	0.022	7000	153.48	-0.12
Ice Bridge	59.2	146.70	153.39	0.022	7000	153.10	-0.29
Dory Point 4 ††	60.7	146.17		0.020	7000	152.80	
Dory Point 3 ††	62.2	145.64		0.020	7000	152.36	
Dory Point	63.7	145.10	152.13	0.020	7000	151.96	-0.17
Dory Point2 ††	64.5	144.96		0.02[illegible]	7000	151.70	
Ferry2 ††	65.2	144.81		0.020	7000	151.36	
Ferry	65.3	144.81	151.48	0.020	7000	151.41	-0.07
Coast Guard	67.3	142.97	151.14	0.020	7000	151.01	-0.13
Blue Quonset	71.5	143.19		0.020	7000	149.93	
Big River	72.7	141.37	149.53	0.030	6450	149.53	0.00
Campground	75.0	139.61		0.030	6450	147.33	
Blue House	76.7	140.18	145.90	0.030	6450	145.75	-0.15
Boat Launch	77.4	139.06		0.025	6450	145.60	
RCMP	77.9	139.57	145.36	0.025	6450	145.36	0.00

† Calibrated roughness based on a discharge of 7000 cms at Dory Point and surveyed water levels on Aug. 29,1991.
†† Interpolated cross sections.
Note: 'cms' means 'cubic meters per second'.

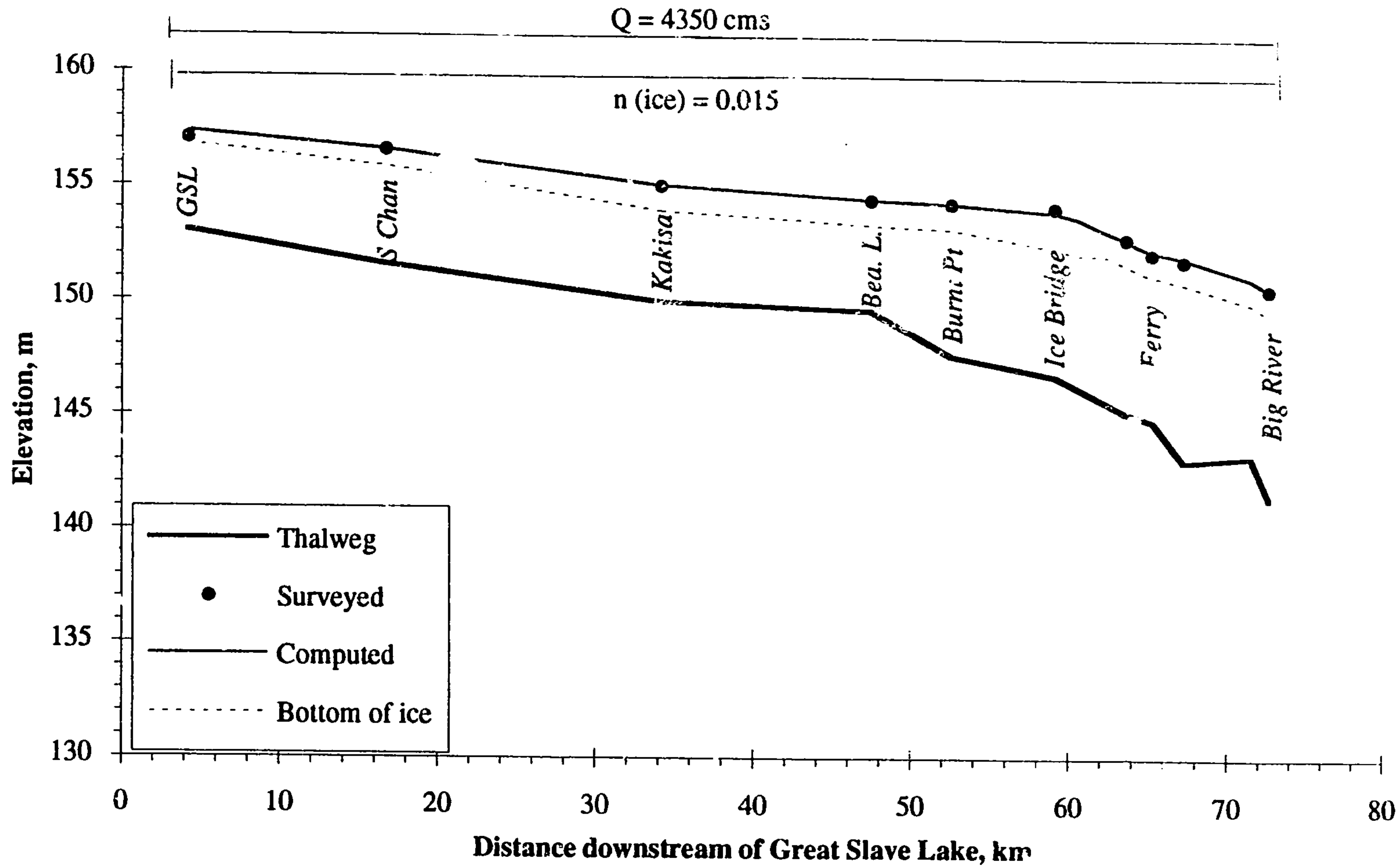


Figure 4.3 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, April 27, 1992.

Table 4.3 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, April 27, 1992.

Discharge = 43[illegible]0 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 27-Apr-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03	157.06	0.022	0.62		0.6	0.015	157.36	0.30
South Channel	16.7	151.5[illegible]	156.59	0.022	0.[illegible]	0.45	0.8	0.015	156.59	0.00
Kakisa River	34.2	149.92	155.03	0.022	1.04	1.26	1.2	0.015	155.05	0.02
Beaver Lake	47.5	149.56	154.44	0.022	1.10	1.63	1.2	0.015	154.44	0.0[illegible]
Burnt Point	52.6	147.59	154.30	0.022	0.96	>1.7	1.2	0.015	154.2[illegible]	-0.0[illegible]
Ice Bridge	59.2	146.70	154.10	0.022		1.70	1.7	0.015	153.[illegible]	-0.20
Dory Point	63.7	145.10	152.77	0.020	0.66		1.2	0.015	152.[illegible]	-0.03
Ferry	65.3	144.79	152.10	0.020	0.94	1.08	1.2	0.015	152.26	0.16
Coast Guard	67.3	142.97	151.80	0.020	0.70	1.[illegible]	1.2	0.015	151.92	0.12
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.02	
Big River	72.7	141.37	150.54	0.030			1.2	0.015	150.54	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

Table 4.4 Summary of hydraulic components in the study reach on April 27, 1992.

Discharge = 4350 cms

Location of cross sections [1]	Distance downstream of G S Lake (km) [2]	Surveyed water level 27-Apr-92 (m) [3]	Maxinum water depth (m) [4]	Average velocity (m/s) [5]	Cross sectional area (m^2) [6]	Top width (m) [7]	Manning's roughness coefficients: Bed nb [8]	Manning's roughness coefficients: Ice ni [9]	Manning's roughness coefficients: Composite n [10]	Hydraulic radius R (total) (m) [11]	Energy slope [12]
Great Slave Lake	4.2	157.06	4.33	0.36	12160	6460	0.022	0.015	0.019	0.94	0.00005
South Channel	16.7	156.59	5.02	0.59	7400	2800	0.022	0.015	0.019	1.32	0.00008
Kakisa River	34.2	155.03	5.13	0.42	10440	8900	0.022	0.015	0.019	0.59	0.00010
Beaver Lake	47.5	154.44	4.98	0.30	14490	6580	0.022	0.015	0.019	1.10	0.00003
Burnt Point	52.6	154.30	6.68	0.40	10790	4450	0.022	0.015	0.019	1.21	0.00004
Ice Bridge	59.2	154.10	7.20	0.69	6270	2870	0.022	0.015	0.019	1.09	0.00010
Dory Point	63.7	152.77	7.78	1.12	3900	1580	0.020	0.015	0.018	1.23	0.00028
Ferry	65.3	152.10	7.48	0.90	4850	1620	0.020	0.015	0.018	1.50	0.00015
Coast Guard	67.3	151.80	8.95	1.09	3990	1650	0.020	0.015	0.018	1.21	0.00018
Blue Quonset	71.5		6.42	1.03	4210	1790	0.020	0.015	0.018	1.18	0.00026
Big River	72.7	150.54	9.17	1.48	2950	810	0.030	0.015	0.023	1.82	0.00050

Notes: Columns [4], [5], [6], [7] and [12] were obtained from GVF model.
Columns [8] and [9] based on open water and ice cover calibrations.
Column [10] was calculated by Sabaneev equation.
Column [11] = [6] / (2*[7]).

Table 4.5 Comparison of ice roughness and Manning's n in different rivers.

Date	Name of river	Discharge	Mean velocity	Cross section area	Wetted perimeter	Hydraulic radius	Energy slope	Manning's roughnesss coefficient			Ripples on underside of solid ice	
								n	nb	ni	Wavelength	Amplitude
		m^3/s	m/s	m^2	m	m					m	m
21-Feb-66	St. Croix	31	0.56	55	138	0.40	0.00028	0.016	0.024	0.004	0.15	0.01
4-Mar-66	St. Croix	35	0.59	59	138	0.42	0.00031	0.017	0.024	0.006	0.18	0.02
10-Mar-66	St. Croix	37	0.57	65	139	0.47	0.00032	0.019	0.025	0.013	0.20	0.02
1974-1981	St. Lawrence at Cardinal	*6200*	*0.72*	8585	*1636*	*2.62*			0.026	.015-.055		
25-Apr-92	Mackenzie at Dory Pt.	4350	1.12	3869	3153	1.23	0.00024	0.018	0.020	0.015	0.20	0.04

Note: Italic means estimated values.
St. Croix River data based on Carey (1966).
St. Lawrence River data based on Shen (1982).

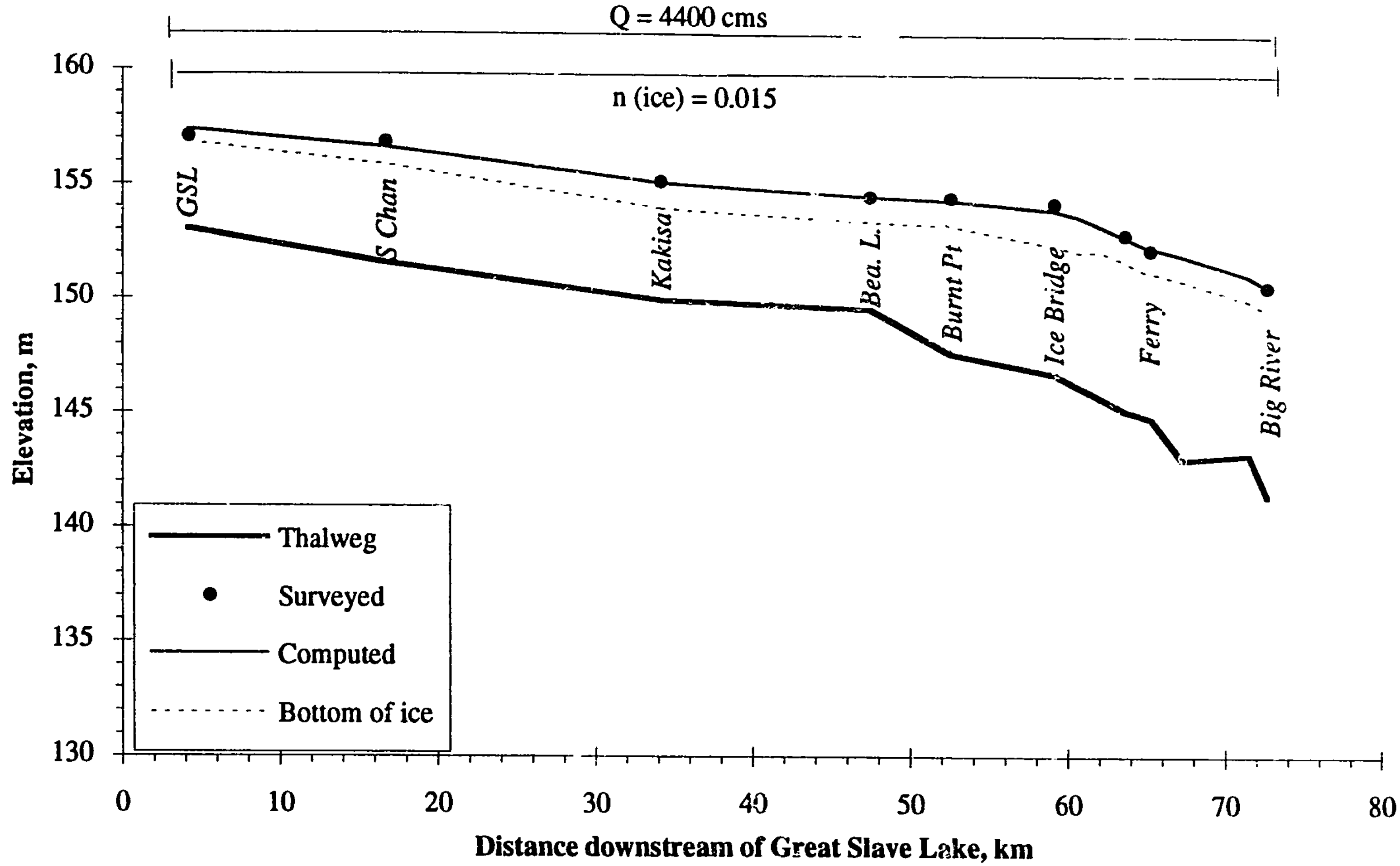


Figure 4.5 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, April 29, 1992.

Table 4.6 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, April 29, 1992.

Discharge = 4400 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 29-Apr-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03	157.08	0.022	0.62		0.6	0.015	157.38	0.30
South Channel	16.7	151.57	156.87	0.022	0.78	0.45	0.8	0.015	156.60	-0.27
Kakisa River	34.2	149.92	155.14	0.022	1.04	1.26	1.2	0.015	155.07	-0.07
Beaver Lake	47.5	149.56	154.51	0.022	1.10	1.63	1.2	0.015	154.48	-0.03
Burnt Point	52.6	147.59	154.47	0.022	0.96	>1.7	1.2	0.015	154.32	-0.15
Ice Bridge	59.2	146.70	154.21	0.022		1.70	1.7	0.015	153.92	-0.29
Dory Point	63.7	145.10	152.85	0.020	0.66		1.2	0.015	152.76	-0.09
Ferry	65.3	144.79	152.18	0.020	0.94	1.08	1.2	0.015	152.28	0.10
Coast Guard	67.[illegible]	142.97		0.020	0.70	1.30	1.2	0.015	151.94	
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.[illegible]	
Big River	72.7	141.37	150.57	0.030			1.2	0.015	150.57	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

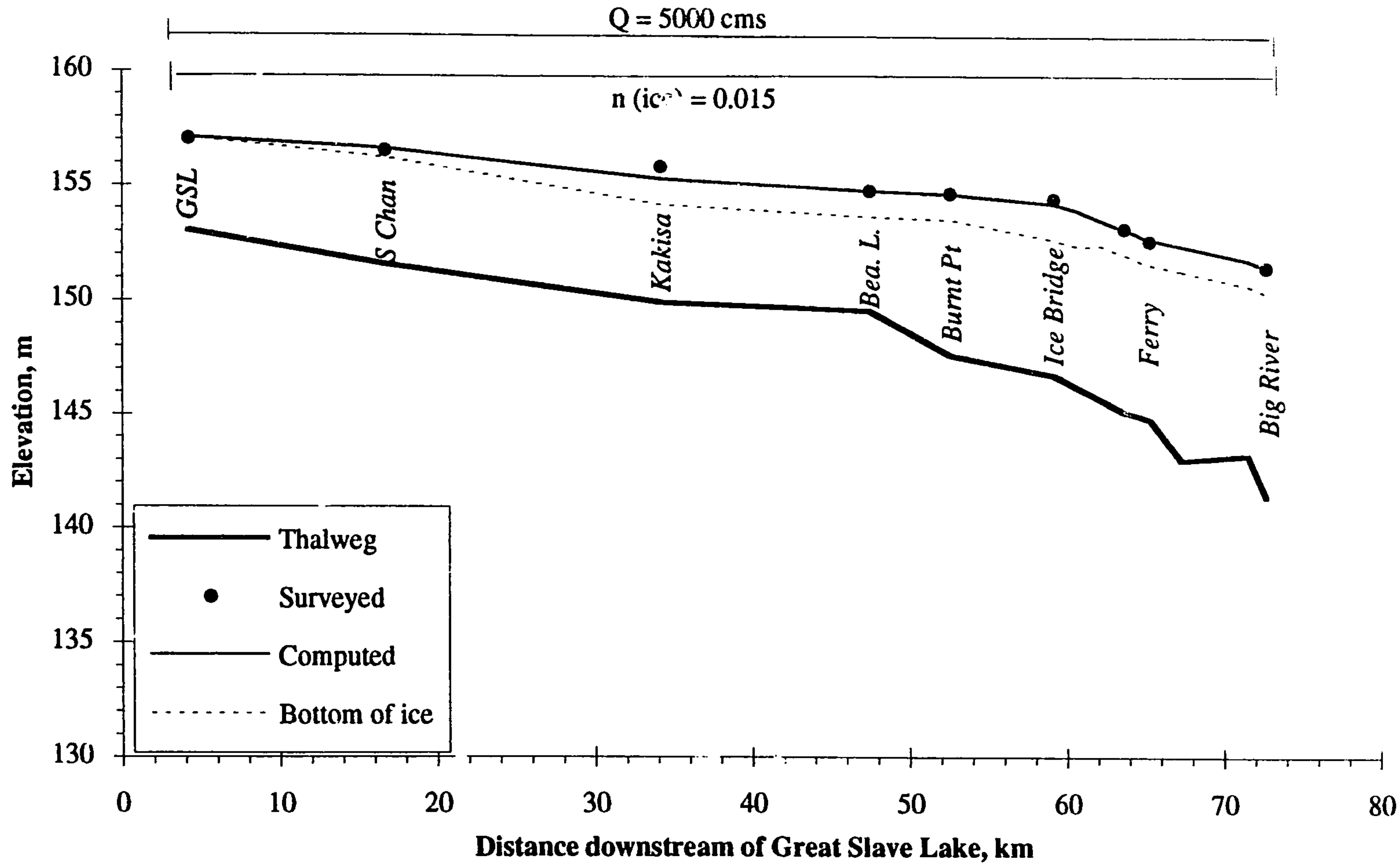


Figure 4.6 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 3, 1992.

Table 4.7 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 3, 1992.

Discharge =5000 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 3-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03	157.03	0.022	0.62		0.0	0.000	157.08	0.05
South Channel	16.7	151.57	156.54	0.022	0.73	0.45	0.4	0.015	156.61	0.07
Kakisa River	34.2	149.92	155.85	0.022	[illegible]	1.26	1.2	0.015	155.29	-0.56
Beaver Lake	47.5	149.56	154.81	0.022	1.10	1.63	1.2	0.015	154.77	-0.04
Burnt Point	52.6	147.59	154.68	0.022	0.95	>1.7	1.2	0.015	154.62	-0.06
Ice Bridge	59.2	146.70	154.45	0.022		1.70	1.7	0.015	154.21	-0.24
Dory Point	63.7	145.10	153.13	0.020	0.66		1.2	0.015	153.11	-0.02
Ferry	65.3	144.79	152.61	0.020	0.94	1.08	1.2	0.015	152.68	0.07
Coast Guard	67.3	142.97		0.020	[illegible]	1.30	1.2	0.015	152.38	
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.76	
Big River	72.7	141.37	151.45	0.030			1.2	0.015	151.45	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

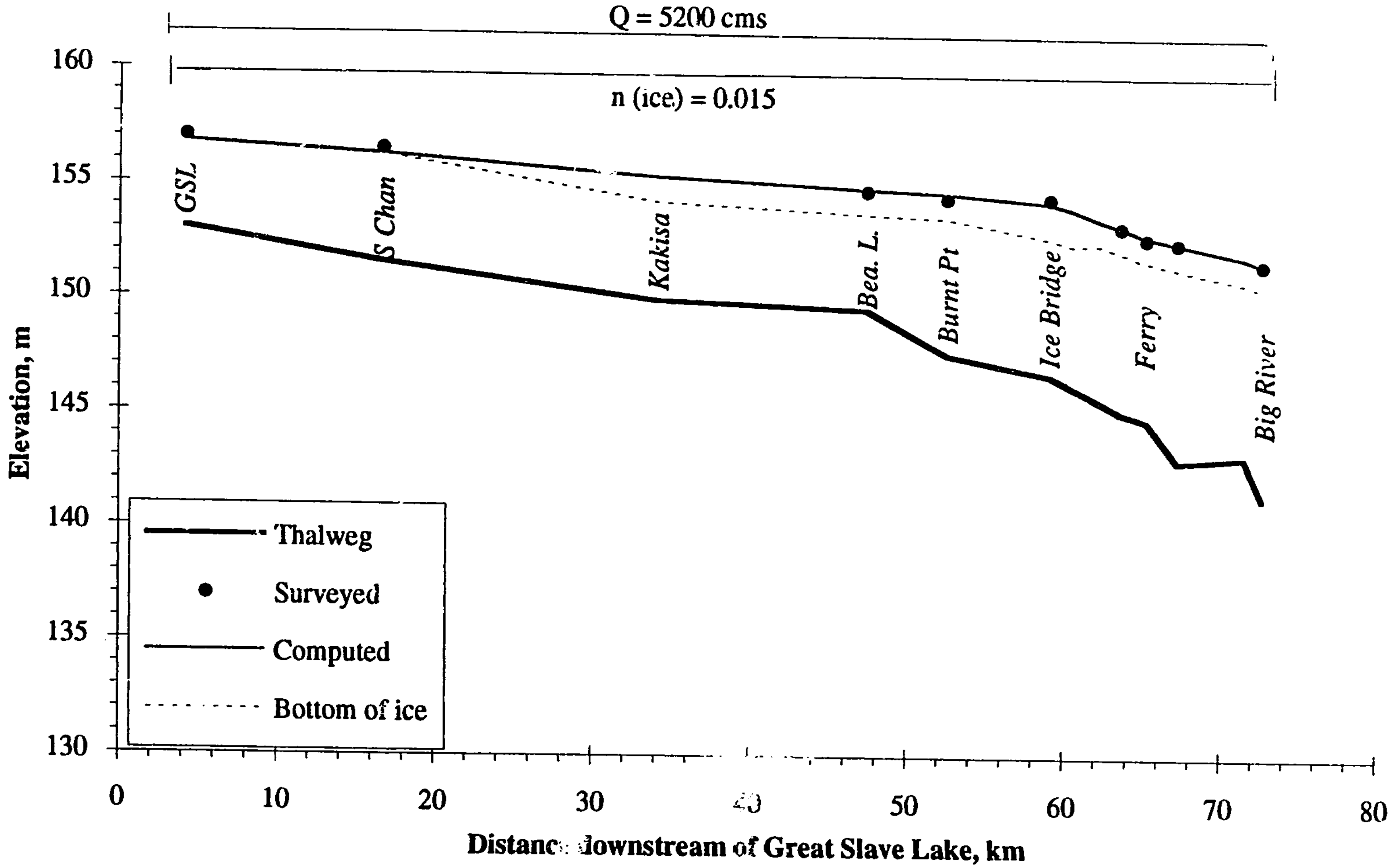


Figure 4.7 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 4, 1992.

Table 4.8 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 4, 1992.

Discharge =5200 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 4-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03	157.03	0.022	0.62		0.0	0.000	156.79	-0.24
South Channel	16.7	151.57	156.54	0.022	0.78	0.45	0.0	0.000	156.30	-0.24
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.35	
Beaver Lake	47.5	149.56	154.77	0.022	1.10	1.63	1.2	0.015	154.86	0.09
Burnt Point	52.6	147.59	154.49	0.022	0.96	>1.7	1.2	0.015	154.71	0.22
Ice Bridge	59.2	146.70	154.50	0.022		1.70	1.7	0.015	154.30	-0.20
Dory Point	63.7	145.10	153.27	0.020	0.66		1.2	0.015	153.28	0.01
Ferry	65.3	144.79	152.77	0.020	0.94	1.08	1.2	0.015	152.88	0.11
Coast Guard	67.3	142.97	152.56	0.020	0.70	1.30	1.2	0.015	152.57	
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.95	
Big River	72.7	141.37	151.67	0.030			1.2	0.015	151.67	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

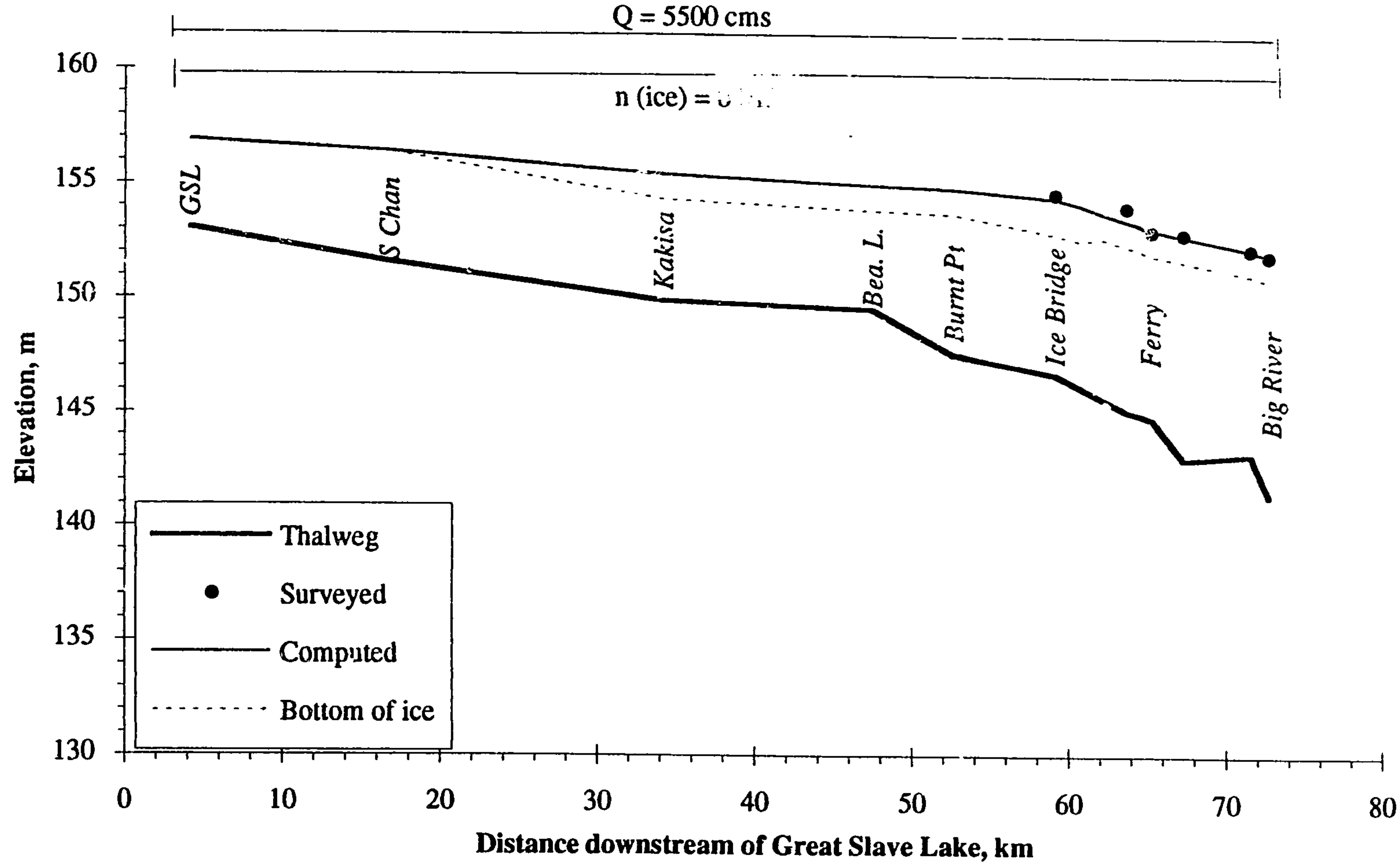


Figure 4.8 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 6, 1992.

Table 4.9 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 6, 1992.

Discharge =5500 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 6-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.88	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.38	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.46	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	154.98	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	154.84	
Ice Bridge	59.2	146.70	154.64	0.022		1.70	1.7	0.015	154.44	-0.20
Dory Point	63.7	145.10	154.06	0.020	0.66		1.2	0.015	153.47	-0.59
Ferry	65.3	144.79	153.01	0.020	0.94	1.08	1.2	0.015	153.09	0.08
Coast Guard	67.3	142.97	152.89	0.020	0.70	1.30	1.2	0.015	152.80	-0.09
Blue Quonset	71.5	143.19	152.23	0.020			1.2	0.015	152.21	-0.02
Big River	72.7	141.37	151.95	0.030			1.2	0.015	151.95	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

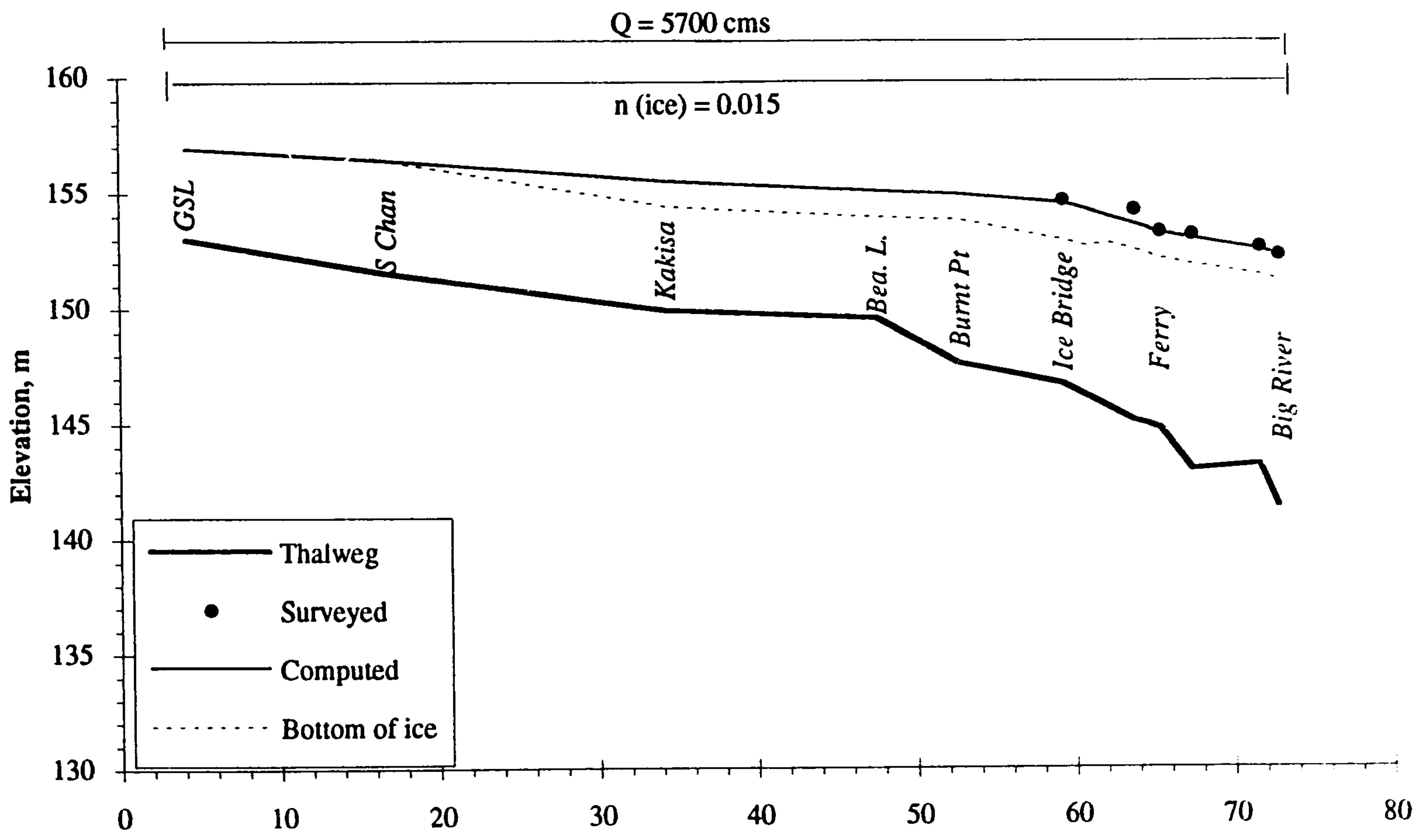


Figure 4.9 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 7, 1992.

Table 4.10 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 7, 1992.

Discharge =5700 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 7-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.93	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.43	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.53	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.07	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	154.94	
Ice Bridge	59.2	146.70	154.69	0.022		1.70	1.7	0.015	154.54	-0.15
Dory Point	63.7	145.10	154.27	0.020	0.66		1.2	0.015	153.64	-0.63
Ferry	65.3	144.79	153.32	0.020	0.94	1.08	1.2	0.015	153.27	-0.05
Coast Guard	67.3	142.97	153.20	0.020	0.70	1.30	1.2	0.015	153.01	-0.19
Blue Quonset	71.5	143.19	152.66	0.020			1.2	0.015	152.53	-0.13
Big River	72.7	141.37	152.31	0.030			1.2	0.015	152.31	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

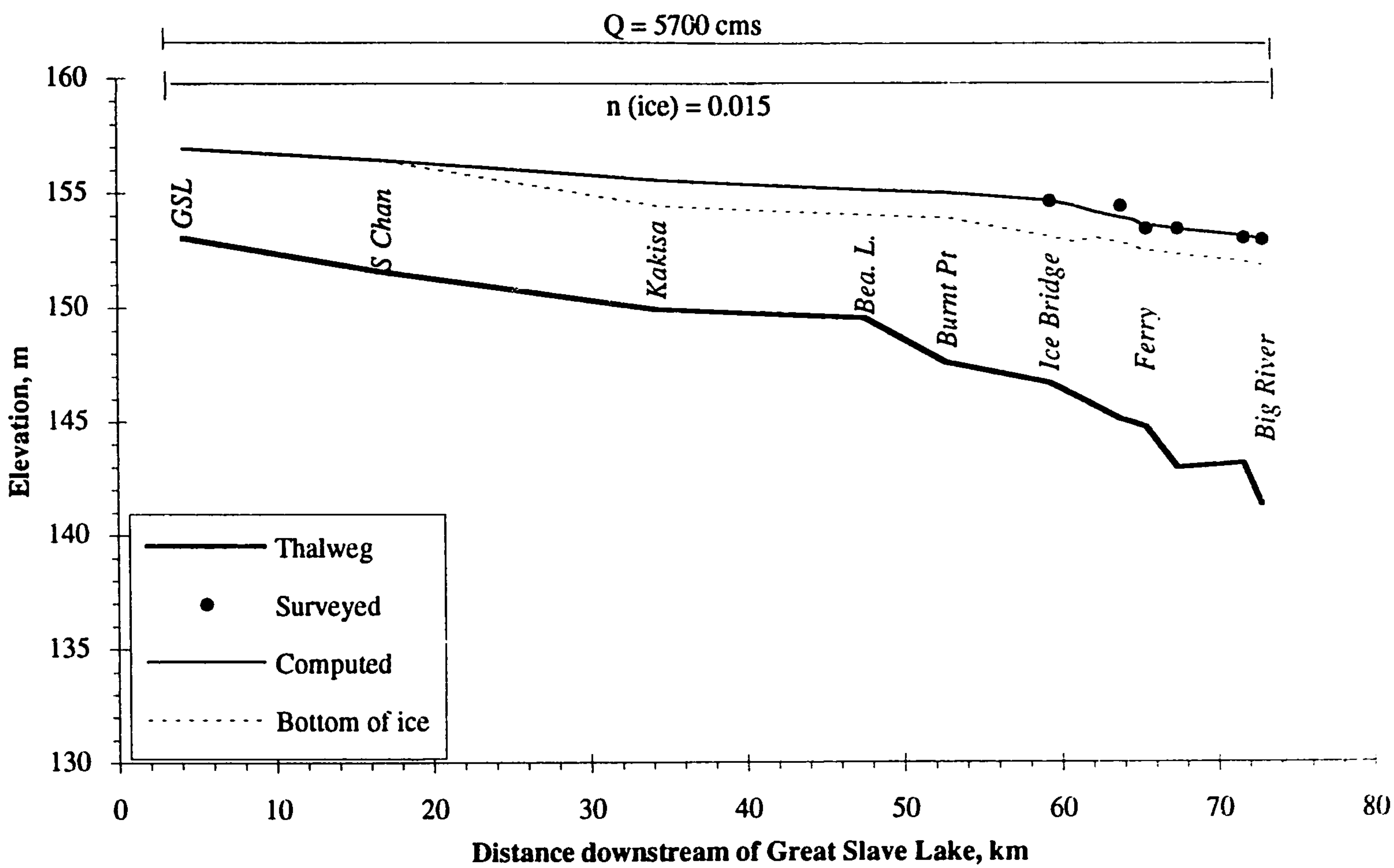


Figure 4.10 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 8, 1992.

Table 4.11 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 8, 1992.

Discharge =5700 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 8-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.94	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.44	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.57	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.16	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.03	
Ice Bridge	59.2	146.70	154.67	0.022		1.70	1.7	0.015	154.68	0.01
Dory Point	63.7	145.10	154.45	0.020	0.66		1.2	0.015	153.95	-0.50
Ferry	65.3	144.79	153.48	0.020	0.94	1.08	1.2	0.015	153.63	0.15
Coast Guard	67.3	142.97	153.48	0.020	0.70	1.30	1.2	0.015	153.45	-0.03
Blue Quonset	71.5	143.19	153.08	0.020			1.2	0.015	153.14	0.06
Big River	72.7	141.37	152.99	0.030			1.2	0.015	152.99	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

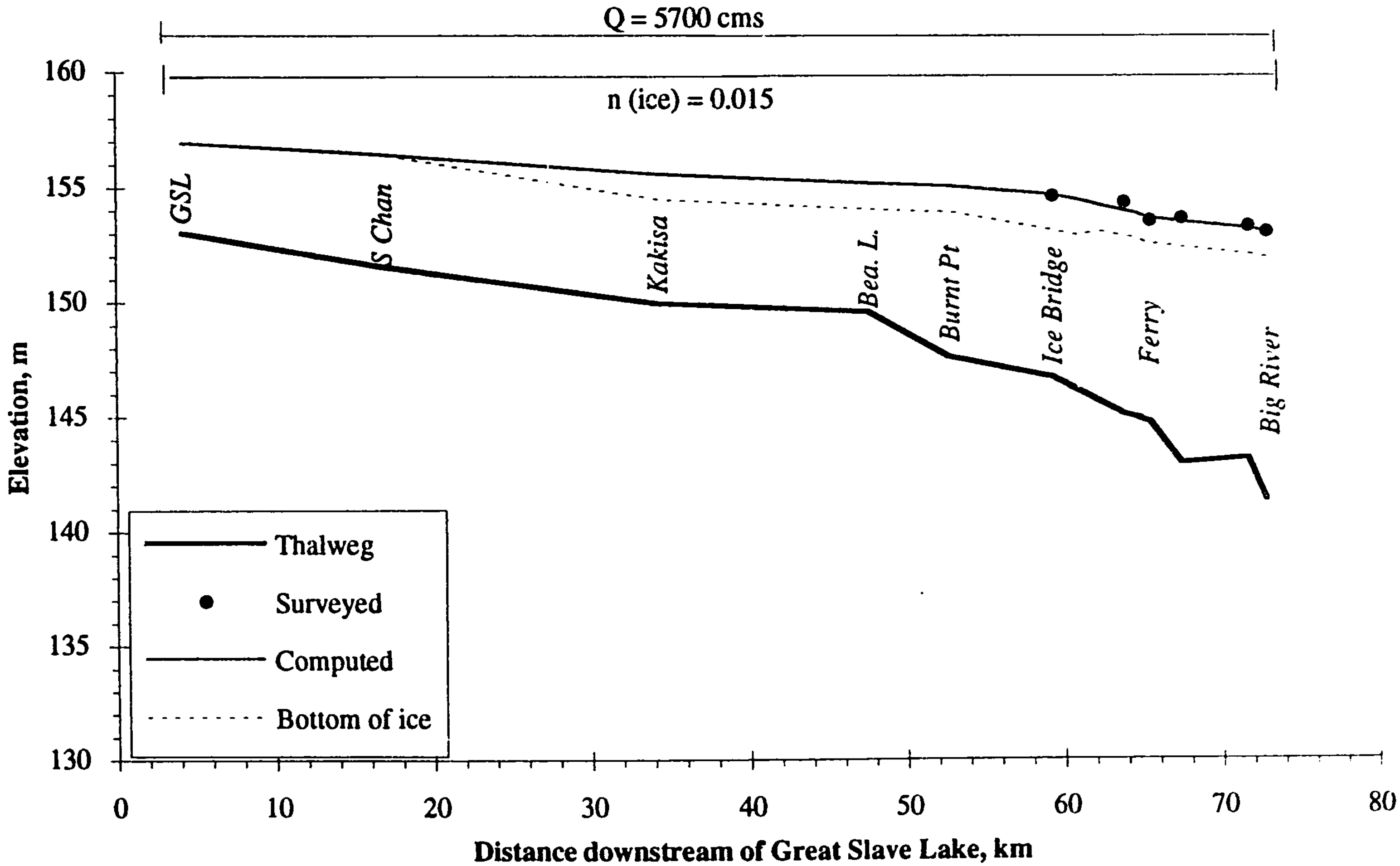


Figure 4.11 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 9, 1992.

Table 4.12 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 9, 1992.

Discharge =5700 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 9-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.94	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.44	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.58	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.17	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.04	
Ice Bridge	59.2	146.70	154.63	0.022		1.70	1.7	0.015	154.69	0.06
Dory Point	63.7	145.10	154.35	0.020	0.66		1.2	0.015	153.98	-0.37
Ferry	65.3	144.79	153.57	0.020	0.94	1.08	1.2	0.015	153.67	0.10
Coast Guard	67.3	142.97	153.67	0.020	0.70	1.30	1.2	0.015	153.50	-0.17
Blue Quonset	71.5	143.19	153.33	0.020			1.2	0.015	153.21	-0.12
Big River	72.7	141.37	153.06	0.030			1.2	0.015	153.06	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

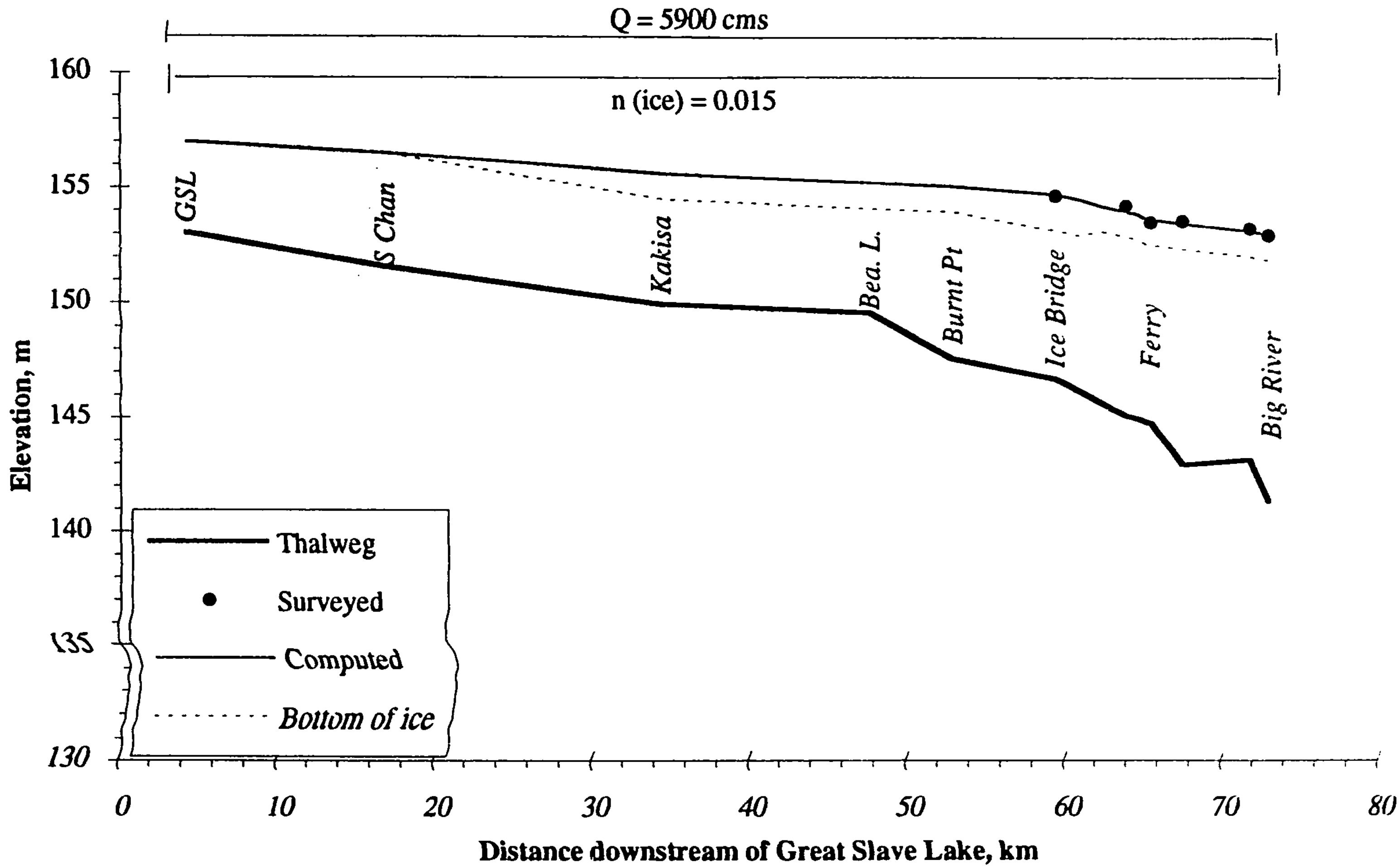


Figure 4.12 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 10, 1992.

Table 4.13 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 10, 1992.

Discharge =5900 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 10-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.99	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.50	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.63	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.22	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.09	
Ice Bridge	59.2	146.70	154.68	0.022		1.70	1.7	0.015	154.74	0.06
Dory Point	63.7	145.10	154.25	0.020	0.66		1.2	0.015	153.99	-0.26
Ferry	65.3	144.79	153.54	0.020	0.94	1.08	1.2	0.015	153.66	0.12
Coast Guard	67.3	142.97	153.59	0.020	0.70	1.30	1.2	0.015	153.47	-0.12
Blue Quonset	71.5	143.19	153.27	0.020			1.2	0.015	153.14	-0.13
Big River	72.7	141.37	152.98	0.030			1.2	0.015	152.98	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

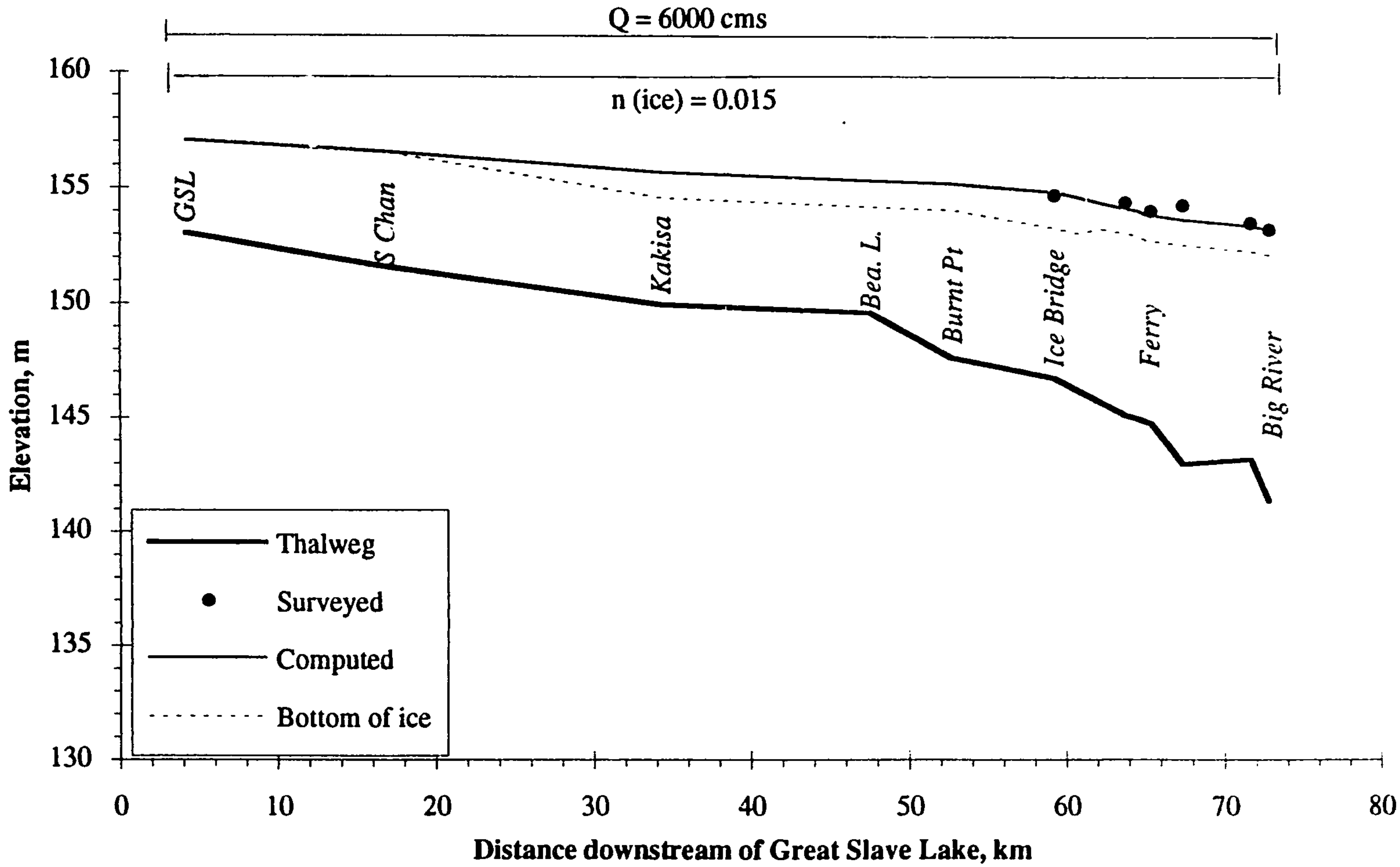


Figure 4.13 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 11, 1992.

Table 4.14 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 11, 1992.

Discharge =5700 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 11-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	157.02	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.53	
Kakisa River	34.2	149.92		0.022	1.04	1.26	1.2	0.015	155.58	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.29	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.17	
Ice Bridge	59.2	146.70	154.71	0.022		1.70	1.7	0.015	154.83	0.12
Dory Point	63.7	145.10	154.42	0.020	0.66		1.2	0.015	154.14	-0.28
Ferry	65.3	144.79	154.04	0.020	0.94	1.08	1.2	0.015	153.83	-0.21
Coast Guard	67.3	142.97	154.28	0.020	0.70	1.30	1.2	0.015	153.65	-0.63
Blue Quonset	71.5	143.19	153.52	0.020			1.2	0.015	153.37	-0.15
Big River	72.7	141.37	153.22	0.030			1.2	0.015	153.22	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

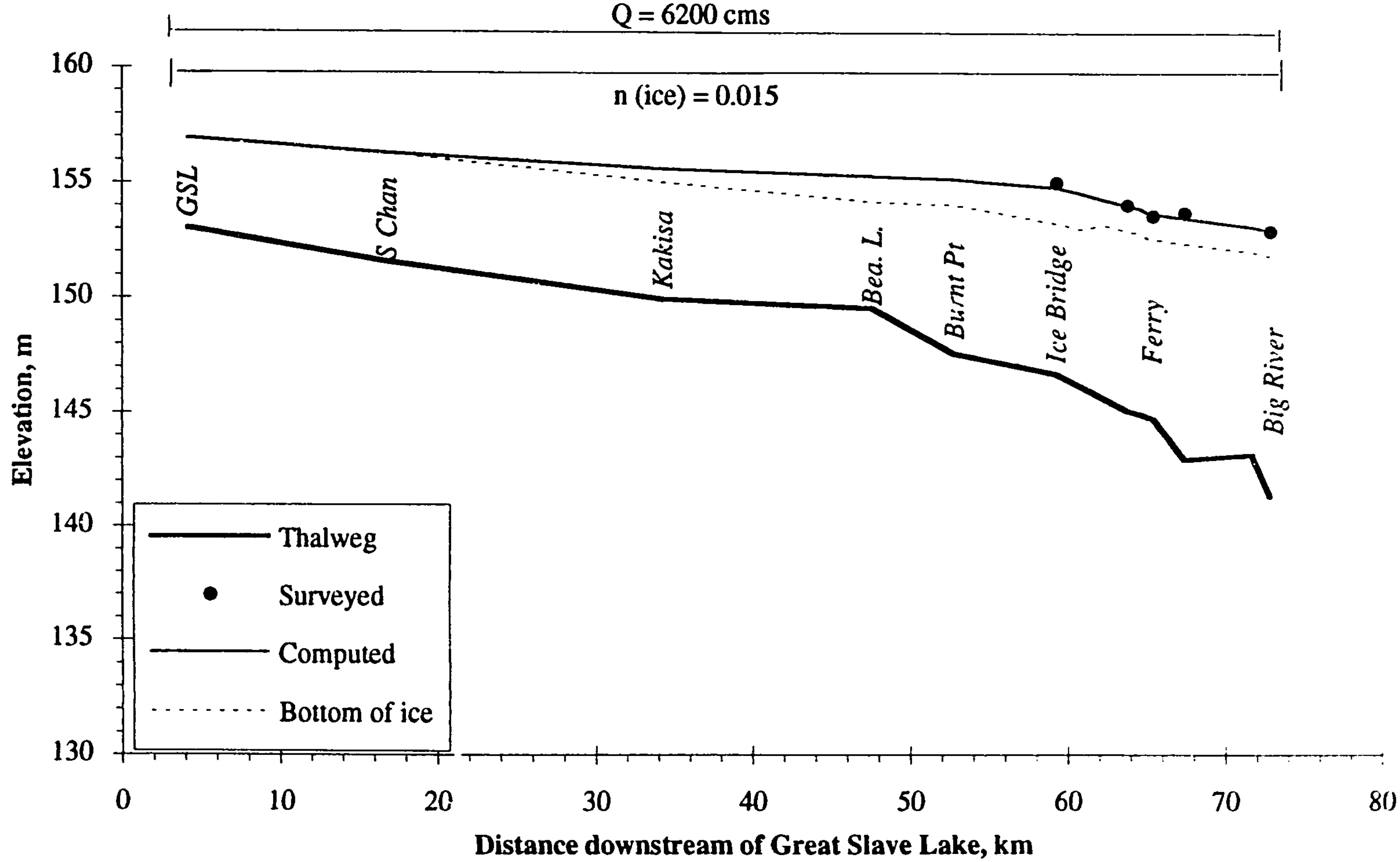


Figure 4.14 Water surface profile along upstream reach of Mackenzie River May 12, 1992.

Table 4.15 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 12, 1992.

Discharge =6200 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 12-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.93	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.29	
Kakisa River	34.2	149.92		0.022	1.04	1.26	0.6	0.015	155.61	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.31	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.18	
Ice Bridge	59.2	146.70	155.04	0.022		1.70	1.7	0.015	154.82	-0.22
Dory Point	63.7	145.10	154.10	0.020	0.66		1.2	0.015	154.05	-0.05
Ferry	65.3	144.79	153.61	0.020	0.94	1.08	1.2	0.015	153.70	0.09
Coast Guard	67.3	142.97	153.74	0.020	0.70	1.30	1.2	0.015	153.49	-0.25
Blue Quonset	71.5	143.19		0.020			1.2	0.015	153.13	
Big River	72.7	141.37	152.95	0.030			1.2	0.015	152.95	0.00

† Based on open water calibration.

Note: 'cms' means 'cubic meters per second'.

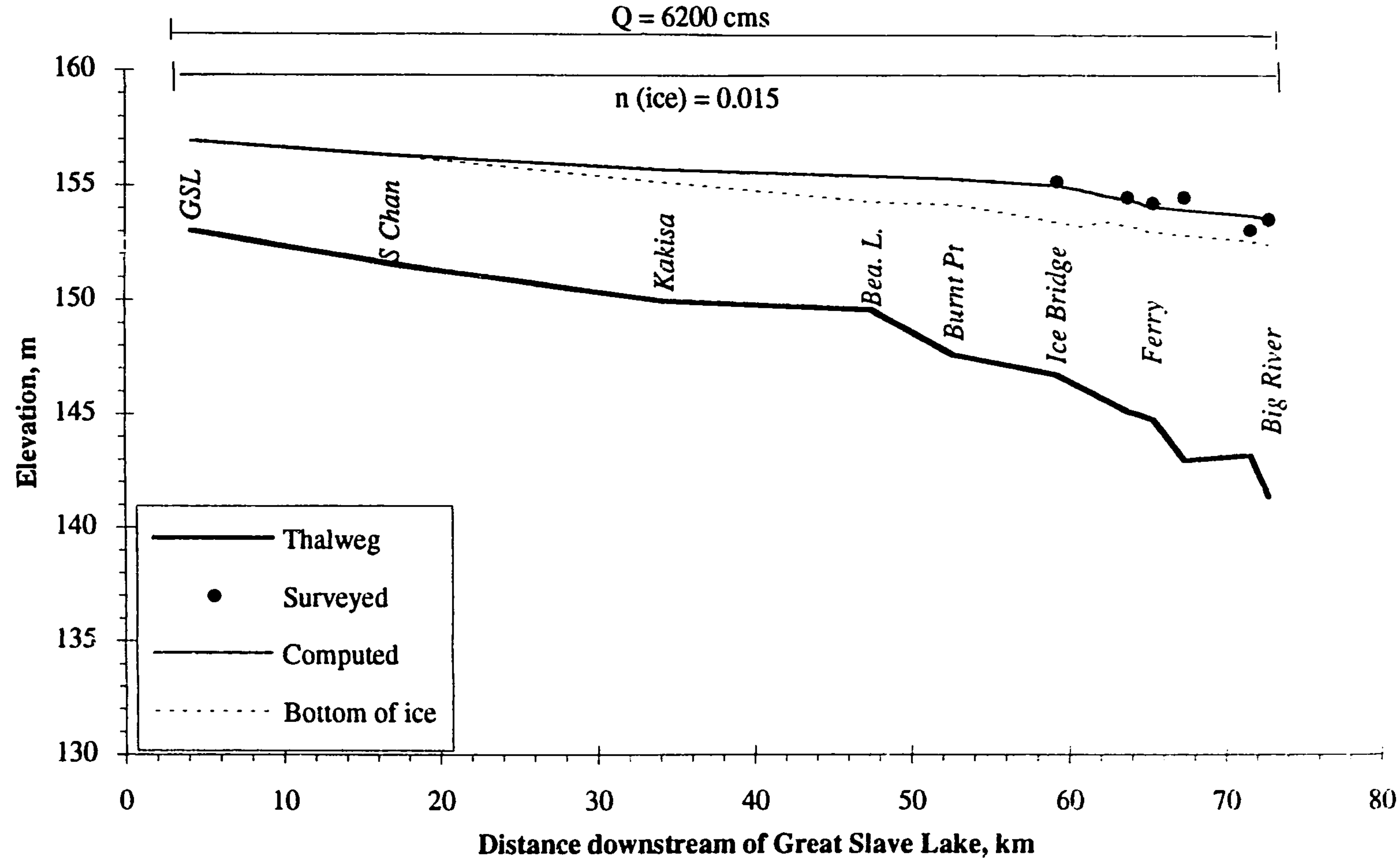


Figure 4.15 Water surface profile along the Mackenzie River between Great Slave Lake and Big River, May 13, 1992.

Table 4.16 Calculated water surface profiles on the Mackenzie River between Great Slave Lake and Big River, May 13, 1992.

Discharge =6200 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 13-May-92 (m)	Bed roughness n (bed) †	Measured border ice thickness (m)	Measured rough ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
G. S. Lake	4.2	153.03		0.022	0.62		0.0	0.000	156.94	
South Channel	16.7	151.57		0.022	0.78	0.45	0.0	0.000	156.31	
Kakisa River	34.2	149.92		0.022	1.04	1.26	0.6	0.015	155.69	
Beaver Lake	47.5	149.56		0.022	1.10	1.63	1.2	0.015	155.42	
Burnt Point	52.6	147.59		0.022	0.96	>1.7	1.2	0.015	155.31	
Ice Bridge	59.2	146.70	155.20	0.022		1.70	1.7	0.015	155.00	-0.20
Dory Point	63.7	145.10	154.50	0.020	0.66		1.2	0.015	154.37	-0.13
Ferry	65.3	144.79	154.25	0.020	0.94	1.08	1.2	0.015	154.09	-0.16
Coast Guard	67.3	142.97	154.52	0.020	0.70	1.30	1.2	0.015	153.94	-0.58
Blue Quonset	71.5	143.19	153.11	0.020			1.2	0.015	153.70	0.59
Big River	72.7	141.37	153.56	0.030			1.2	0.015	153.56	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

Table 4.17 Discharge estimation, Mackenzie River near Ft. Providence, 1992.

Date 1992	Time	Discharge cms GVF model calibration	Discharge cms Measured
27-Apr	15:00	4350††	4350
29-Apr	10:00	4400	
1-May	15:00		4780
3-May	11:00	5000	
4-May	11:00	5200	
6-May	20:00	5500	
6-May	15:00		5340
7-May	23:00	5700	
8-May	19:00	5700	
9-May	10:00	5700	
10-May	20:30	5900	
11-May	21:00	6000	
12-May	20:30	6200	
13-May	20:00	6200	

†† Measured discharge at April 27 is used to GVF model calibration.

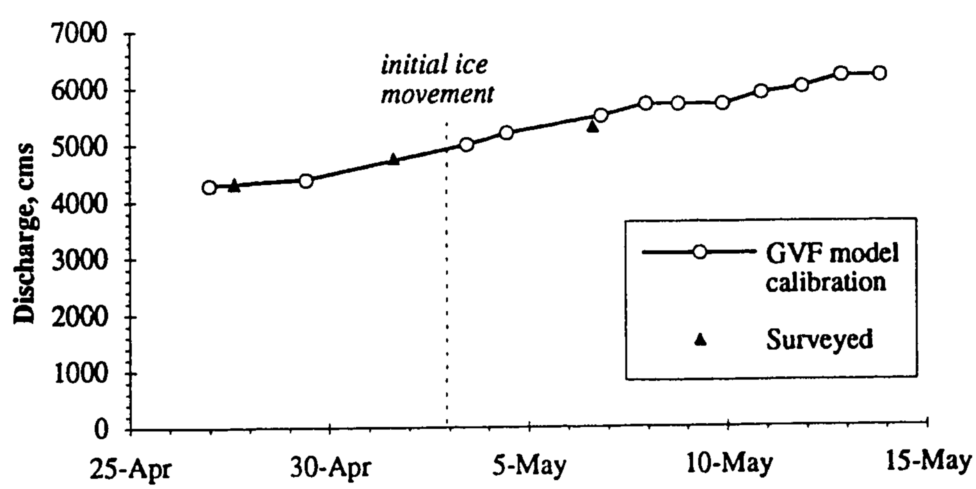


Figure 4.16 Discharge hydrograph before breakup, Mackenzie river near Ft. Providence, 1992.

Table 4.18 Ice roughness estimation from Big River to Ft. Providence Dock, April 27, 1992.

Discharge = 4350 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 27-Apr-92 (m)	Bed roughness n (bed) †	Measured border Ice thickness (m)	Measured rough Ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
Great Slave Lake	4.2	153.03	157.06	0.022	0.62		0.6	0.015	157.36	0.30
South Channel	16.7	151.57	156.59	0.022	0.78	0.45	0.8	0.015	156.58	-0.01
Kakisa River	34.2	149.92	155.03	0.022	1.04	1.26	1.2	0.015	155.10	0.07
Beaver Lake	47.5	149.56	154.44	0.022	1.10	1.63	1.2	0.015	154.58	0.14
Burnt Point	52.6	147.59	154.30	0.022	0.96	>1.7	1.2	0.015	154.45	0.15
Ice Bridge	59.2	146.70	154.10	0.022		1.70	1.7	0.015	154.09	-0.01
Dory Point	63.7	145.10	152.77	0.020	0.66	0.00	1.2	0.015	152.75	-0.02
Ferry	65.3	144.79	152.13	0.020	0.94	1.08	1.2	0.015	152.27	0.15
Coast Guard	67.3	142.97	151.80	0.020	0.70	1.30	1.2	0.015	151.93	0.13
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.07	
Big River	72.7	141.37	150.54	0.030			1.2	0.015	150.62	0.08
Campground	75.0	139.61		0.030			1.2	0.030	149.29	
Blue House	76.7	140.18	148.41	0.030		1.19	1.2	0.050	148.25	-0.16
Boat Launch	77.4	139.06		0.025		1.22	1.2	0.050	148.07	
RCMP	77.9	139.57	147.83	0.025		>1.7	1.9	0.050	147.88	0.05
Ft. Prov. Dock	79.5	137.50	147.34	0.025	0.75	1.50	1.5	0.050	147.34	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

Table 4.19 Ice roughness estimation from Big River to Ft. Providence Dock, April 29, 1992.

Discharge = 4400 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 29-Apr-92 (m)	Bed roughness n (bed) †	Measured border Ice thickness (m)	Measured rough Ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
Great Slave Lake	4.2	153.03	157.08	0.022	0.62		0.6	0.015	157.38	0.30
South Channel	16.7	151.57	156.87	0.022	0.78	0.45	0.8	0.015	156.59	-0.28
Kakisa River	34.2	149.92	155.14	0.022	1.04	1.26	1.2	0.015	155.11	-0.03
Beaver Lake	47.5	149.56	154.51	0.022	1.10	1.63	1.2	0.015	154.60	0.09
Burnt Point	52.6	147.59	154.47	0.022	0.96	>1.7	1.2	0.015	154.47	0.00
Ice Bridge	59.2	146.70	154.21	0.022		1.70	1.7	0.015	154.11	-0.10
Dory Point	63.7	145.10	152.85	0.020	0.66	0.00	1.2	0.015	152.77	-0.07
Ferry	65.3	144.79	152.15	0.020	0.94	1.08	1.2	0.015	152.30	0.15
Coast Guard	67.3	142.97		0.020	0.70	1.30	1.2	0.015	151.96	
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.10	
Big River	72.7	141.37	150.57	0.030			1.2	0.015	150.66	0.09
Campground	75.0	139.61		0.030			1.2	0.030	149.32	
Blue House	76.7	140.18	148.52	0.030		1.19	1.2	0.050	148.28	-0.24
Boat Launch	77.4	139.06		0.025		1.22	1.2	0.050	148.10	
RCMP	77.9	139.57	147.98	0.025		>1.7	1.9	0.050	147.91	-0.07
Ft. Prov. Dock	79.5	137.50	147.37	0.025	0.75	1.50	1.5	0.050	147.37	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

Table 4.20 Ice roughness estimation from Big River to Ft. Providence Dock, May 3, 1992.

Discharge = 5000 cms

Location of cross sections	Distance downstream of G S Lake (km)	Thalweg elevation (m)	Surveyed water level 3-May-92 (m)	Bed roughness n (bed) †	Measured border Ice thickness (m)	Measured rough Ice thickness (m)	Ice thickness used in computation (m)	Calibrated ice roughness n (ice)	Computed water level (m)	Calculated minus surveyed water level (m)
Great Slave Lake	4.2	153.03	157.03	0.022	0.62		0.6	0.015	157.56	0.53
South Channel	16.7	151.57	156.82	0.022	0.78	0.45	0.8	0.015	156.77	-0.05
Kakisa River	34.2	149.92	155.85	0.022	1.04	1.26	1.2	0.015	155.32	-0.53
Beaver Lake	47.5	149.56	154.81	0.022	1.10	1.63	1.2	0.015	154.84	0.03
Burnt Point	52.6	147.59	154.68	0.022	0.96	>1.7	1.2	0.015	154.70	0.02
Ice Bridge	59.2	146.70	154.45	0.022		1.70	1.7	0.015	154.33	-0.11
Dory Point	63.7	145.10	153.13	0.020	0.66	0.00	1.2	0.015	153.03	-0.10
Ferry	65.3	144.79	152.58	0.020	0.94	1.08	1.2	0.015	152.56	-0.02
Coast Guard	67.3	142.97	152.40	0.020	0.70	1.30	1.2	0.015	152.22	-0.18
Blue Quonset	71.5	143.19		0.020			1.2	0.015	151.41	
Big River	72.7	141.37	151.45	0.030			1.2	0.015	150.99	-0.46
Campground	75.0	139.61		0.030			1.2	0.030	149.63	
Blue House	76.7	140.18	148.80	0.030		1.19	1.2	0.050	148.49	-0.31
Boat Launch	77.4	139.06	148.39	0.025		1.22	1.2	0.050	148.29	-0.10
RCMP	77.9	139.57	147.87	0.025		>1.7	1.9	0.050	148.08	0.21
Ft. Prov. Dock	79.5	137.50	147.42	0.025	0.75	1.50	1.5	0.050	147.42	0.00

† Based on open water calibration.
Note: 'cms' means 'cubic meters per second'.

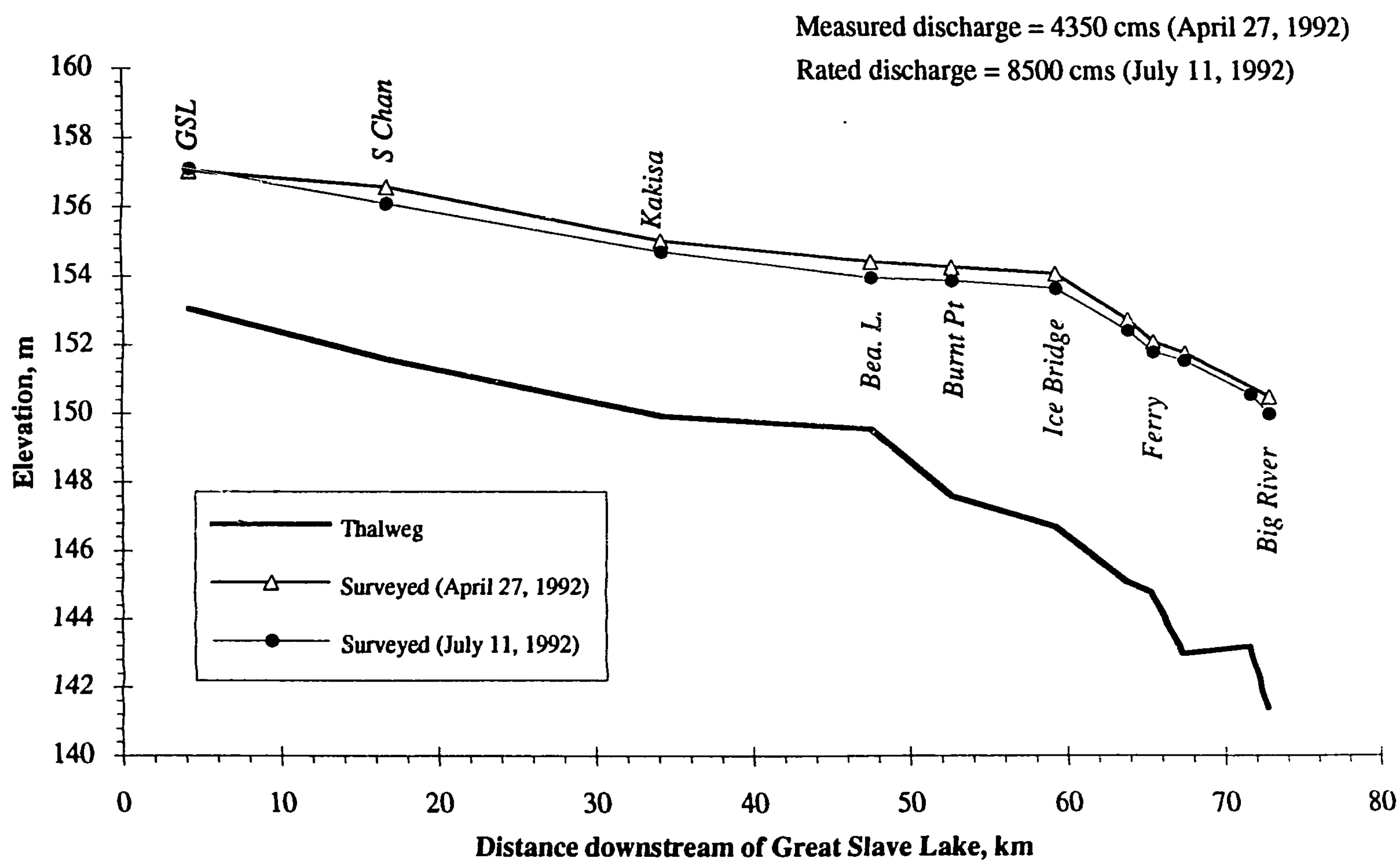


Figure 4.17 Water surface profiles along the Mackenzie River between Great Slave Lake and Big River.

Chapter 5
Interpretation of the outlet hydraulics

5.1 Introduction

The objective in this chapter is to examine the stage and discharge relation for every cross section for both the open water and ice covered cases. In order to do this, a brief theoretical background of lake outlet hydraulics is first reviewed. In section 5.2, the calculation of gradually varied flow (GVF) and uniform flow (UF) in open water conditions at each cross section is presented and the results are discussed. A comparison of uniform flow rating curves and measured data under 1992 late winter ice conditions is presented in section 5.3. In section 5.4, a discussion of the rating curve at Dory Point both for the open water and ice covered cases is presented.

Before the discussion begins, a brief theoretical description of lake outlet hydraulics is presented here. The outlet of the Mackenzie River represents a classic lake outflow to a mild sloping channel (a channel in which uniform flow is subcritical). In such a case, lake outflow is controlled from downstream. If the channel is sufficiently long and the cross section relatively uniform, then the outflow from the lake can be defined based on a simple uniform flow relation, such as Chezy's or Manning's equation (Henderson, 1966). However, if some downstream control imposes a water level in excess of the uniform flow depth, and the resulting M1 or "backwater" curve extends all the way upstream to the lake outlet, then outflow will be somewhat less than that described by the uniform flow relation (all other things being equal). Conversely, if some downstream control imposes a water level below the uniform flow depth, and the resulting M2 or "drawdown" curve extends all the way upstream to the lake outlet, then outflow will be increased beyond that described by the uniform flow relation.

In this particular study reach there are two questions of interest. Is the flow out of the lake relatively uniform (and therefore a relatively simple hydraulic relationship exists between lake level and outflow) or is outflow from Great Slave Lake influenced by backwater or drawdown? Also, what is the effect of ice on this lake outflow relation?

5.2 Rating curves for open water

5.2.1 Development of GVF rating curves

After calibration of the GVF model, a group of rating curves of GVF at each of the eighteen cross sections from Great Slave Lake and Mills Lake was developed. The procedure for developing the GVF rating curve was as follows: first, the discharges were calculated by the GVF model based on a group of measured water surface profiles; secondly, at each cross section, a rating curve was developed using the group of water elevations and corresponding discharges. Since the starting water elevation for the GVF model was unknown, the calibrated energy slope at the starting cross section was used to calculate water surface profiles for different discharges (Hydraulic Engineering Center, 1982). This analysis was based on the assumption that bed roughness was not a strong function of discharge (which was one of the assumptions used in the calibration, as well).

5.2.2 Development of UF rating curves

The purpose of the uniform flow calculation was to compare UF rating curves with GVF rating curves at each cross section for open water conditions to determine if the lake outflow was affected by backwater or drawdown conditions. The calculation of the uniform flow rating curves for open water conditions was conducted for each of the eighteen cross sections from Great Slave Lake to Mills Lake. These uniform flow rating curves were developed based on Manning's equation (Henderson, 1966). The

Manning's *n* used in the uniform flow calculation at each section was the same as the one calibrated in the GVF model.

As the uniform flow calculation requires an estimate of the bed slope, four sub-reaches were identified along the study reach. The calculation of average bed slope was based on the slope of the thalweg along each sub-reach. Figure 5.1 shows these four sub-reaches. The first sub-reach extends from the Great Slave Lake section to the Beaver Lake section. From the Beaver Lake section to the Ferry Crossing, the bed slope steepens slightly, though it is still a mild slope. Between the Ferry Crossing and the Dock in Ft. Providence, which includes the reach known as Providence Rapids, the bed slope increases further (though it still remains a mild slope). Downstream of Ft. Providence to Mills Lake, the bed slope decreases again. The average bed slope was calculated by connecting the thalweg at the above four cross sections. Since the average bed slope calculated by this method agreed well with the bed slopes observed along the study reach, no further calculations were carried out. Table 5.1 presents the bed slope values at different cross sections.

Table 5.1 Average bed slope calculation.

Location of cross sections	Distance downstream of G. S. Lake (km)	Thalweg elevation (m)	Surveyed water level 11-July-92 (m)	Average bed slope
G. S. Lake	4.2	153.03	157.11	0.00008
Beaver Lake	47.5	149.56	153.98	0.00027
Ferry Crossing	65.3	144.79	151.80	0.00051
Ft. Prov. Dock	79.5	137.50	145.19	0.00014
Mills Lake	103.9	134.15	142.54	

One problem encountered was which bed slope should be used for the uniform flow calculation at the sections joining two different bed slopes (such as at the Beaver

Lake, Ferry Crossing, and Dock cross sections). For this analysis, the bed slope of the downstream channel was adopted at these sections since the flow along the study reach is subcritical flow. When water flows from a milder bed slope to a mild bed slope, the shape of the M2 curve appears at the end of upstream reach. It can be assumed that the water surface profile in the downstream reach is parallel with the downstream bed slope even at the joining sections (K. Subramanya, 1982). Therefore the water elevation at a joining bed slope section is controlled by the downstream bed slope.

5.2.3 Comparison of rating curve of UF and GVF

The open water rating curves obtained from the calibrated GVF model and UF calculation can be used to identify the flow conditions at different cross sections. If the rating curve of the GVF model calibration is close to the rating curve of uniform flow at a cross section, then the stage-discharge can be considered to be well approximated by uniform flow equations. If the rating curve of the GVF model calibration is higher than the rating curve of uniform flow, then the stage-discharge relationship at that cross section is influenced by backwater. If the rating curve of the GVF model calibration is lower than the rating curve of uniform flow, then drawdown conditions exist. Figure 5.2 presents the UF and GVF rating curves in open water at every cross section from Great Slave Lake to Dock section. The measured water level and its rated discharge (based on the power law regression of the measured data: Equation (3-1)) at Dory Point were also plotted in the figure for comparison.

From Figure 5.2, the trend of flow variation along the study reach can be seen. Since subcritical flow is controlled from downstream, the discussion of the effect of backwater and water drawdown is also presented from downstream to upstream. From the Dock section to Boat Launch section, the GVF rating curve is higher than UF rating curve, indicating that the flow is affected by backwater (Figure 5.2 n, p). The reason is because downstream of Dock section, the bed slope is milder than that in upstream and a backwater profile extends upstream. By the RCMP section, the backwater effect is negligible, so the GVF and UF rating curves are very close each other (Figure 5.2 o) and the flow is near uniform. From the Blue House to the Big River section, drawdown effects are clearly evident (Figure 5.2 i, m). This is because the river is narrow, the bed slope is steep (though it is still a mild slope) and the downstream backwater does not extend up to these sections. From the Blue Quonset to the Ferry Crossing section, the flow is again affected by backwater (Figure 5.2 j, i, h). This is because of the flow contraction at the Big River section. At the Dory Point cross section, the backwater effect is diminished so the flow is close to uniform again (Figure 5.2 g). From the Ice Bridge to Beaver Lake section, the flow is affected by backwater (Figure 5.2 d, e and f). This is because of the flow contraction at Ice Bridge section. The flow is blocked when it passes through the Ice Bridge and the backwater effect extends up to the Beaver Lake section even though the average bed slope increases in this reach compared with that in upstream. Upstream of Beaver Lake, the flow is close to uniform (Figure 5.2 a, b and c).This is because the backwater effects from downstream are diminished by the wide nature of the channel in Beaver Lake.

Combining the above scenarios with Figure 3.2 (map), one can see the backwater effect is associated not only with changes in the bed slope, but also with the planform geometry. There are two major contractions along the study reach, one is at the Ice Bridge section and another is at the Big River section. These two contractions have pronounced effects on the flow, which results in the flow along the study reach being affected by backwater. Comparing the flow variation with the river's geometry, the interpretation of the rating curves along the study reach is reasonable.

5.3 Rating curves for 1992 ice conditions

5.3.1 Development of UF rating curves based on 1992 late winter ice conditions

Manning's equation was also used to develop UF rating curves based on 1992 late winter ice conditions. The ice and bed roughness were obtained from the calibrated GVF model. The bed slopes were again based on the 4 sub-reach average bed slopes (Table 5.1). To be consistent with the GVF analysis, the Belokon-Sabaneev equation was used to compute the composite roughness. The hydraulic radius was recomputed by considering the ice cover and effective flow area. Due to the complications associated with the ice accumulation downstream of the Big River cross section, the rating curves were developed in ten cross sections from the Great Slave Lake to Big River (Figure 5.3). Rating curves produced for ice conditions varied with changing ice roughness and thickness. Since these factors change with time, the ice rating curves presented are specific to late winter 1992, and in particular to the calibration period (April 25-27, 1992).

5.3.2 Comparison of rating curves of UF and measured data

After the UF ice rating curves were developed, the measured data were plotted on the same figure for comparison. Figure 5.3 presents this comparison, in which "measured data" refers to the measured water level versus the discharge calculated by the GVF model (as discussed in Section 4.5.2).

From Figure 5.3, the trend of flow variation along the study reach in late winter, 1992 can be seen. The flow had backwater effects from the Big River to the Ferry Crossing section, (Figure 5.3 h, i and j). This is because the flow was obstructed at the Big River section due to the change of the river width and due to the ice accumulation downstream of Big River. At Dory Point, the flow had both backwater and drawdown effects (Figure 5.3 g), reflecting the increasing water level (and corresponding backwater effects) downstream as breakup progressed. From the Ice

Bridge cross section to the Beaver Lake section, the flow had backwater effects (Figure 5.3 d, e, f). This can be explained by river contraction at Ice Bridge section. As in the open water case, the flow was close to uniform between the Great Slave Lake and Kakisa cross sections (Figure 5.3 a, b, c).

The reason for backwater dominating the study reach can also be explained by the effects of ice thickness and roughness. If the ice thickness and roughness are large in downstream, as the situation in Ft. Providence Rapids, pre-breakup in 1992, the water level tends to increase, that results in backwater effects upstream. Furthermore, if the ice from upstream accumulates in the downstream reach, it causes the water level to increase and leads to a significant increase in backwater effects. Therefore, the backwater probably has more chance to occur when the river has an ice cover than in open water conditions.

It should be mentioned that the water level increased quickly from the Ferry section to the Big River section (Figure 5.3 h, i and j) when the discharge exceeded 5000 m^3/s. This was due to the varying backwater effect of an ice jam which formed downstream of the Big River section in Providence Rapids. Note that, the flow was close to uniform at Big River when the discharge was less than 5000 m^3/s (Figure 5.3 j). As the discharge increased, the ice downstream of Big River shoved repeatedly, resulting in water level increases and severe backwater effects.

The UF rating curves at some cross sections in ice conditions (Figure 5.3 i and e) are not smooth. This can be explained by the irregularity of cross section shape. For example, at the Coast Guard cross section, the channel has a shallow flat area along the north bank (Figure A.10). When flow inundates this shallow zone, the wetted perimeter increases suddenly, which decreases the hydraulic radius. Consequently, the discharge decreases and the slope of UF rating curve becomes flatter.

5.4 Interpretation of the rating curve at Dory Point

After comparing the rating curves of UF with the results of GVF model in open water and ice conditions, a further analysis for the rating curve at Dory Point is presented in this section. As mentioned before, WSC operated the gauging station at Dory Point from 1961 to 1978. A group of measured discharge data is available both for open water and ice cover cases.

Figure 5.4 demonstrates the rating curves and measured data for open water conditions. The best fit curve, GVF rating curve and UF rating curve are plotted. The development of the best fit curve was discussed in Chapter 3. The best fit curve represents the flow average situation from 1961 to 1978. It can be used to find the discharge using measured water levels. However, the scatter in the measured data is indicative of the varied backwater conditions occurring due to the downstream constriction.

The development of the GVF rating curve was discussed in Section 5.2.1. The GVF rating curve for open water conditions represents a lower envelope to the measured points, which indicates that for most of the measured points, the actual depth would be larger than that obtained from GVF rating curve. This is because the rating curve was based on the calibration of the water surface profile measured on July 11, 1992 with the discharge based on the power law regression (note that the two curve cross at this point). At smaller discharges (i.e. as hydraulic radius decreases), the relative roughness effect would be increased. Therefore, use of the Manning's n values obtained in the calibration would not reflect the increase in the effect of roughness values expected at lower discharges and consequently lower depths are computed for a given discharge, compared with the measured data.

The development of the UF rating curve was discussed in Section 5.2.2. The UF rating curve clearly indicates that the stage-discharge relationship at Dory Point is affected by backwater, an effect which increases with increasing discharge.

Figure 5.4 also shows the measured data for ice conditions. A single rating curve for ice covered conditions is not appropriate. This is because there are more factors affecting the rating curve, such as, ice thickness and ice roughness. Besides, the ice scenario changes with time. Due to these effects, the measured points are scattered and a single curve cannot not be used to represent this group of data. Thus, multiple parameters have to be used to describe the ice situation. To identify the dominant parameters, a number of comparisons were conducted.

Figure 5.5 shows ice thickness as a parameter in the stage-discharge relation. However, no trend in ice thickness variation is seen in the figure. One reason might be that ice thickness is not an important parameter for the stage-discharge relation. Another possible explanation is that there is not enough ice thickness data to find the trend of variation.

It has already been shown that due to the existence of the ice cover, a backwater effect usually occurs. Since the magnitude of this effect would be expected to increase as a function of ice roughness and thickness (which vary throughout the winter), an attempt was made to identify a pattern as a function of time. Figure 5.6 illustrates the measured winter data in this form and although a rough pattern may be evident, there is still considerable scatter which requires consideration of the varying effect of backwater on the stage discharge relations.

In an attempt to account for this effect, Figure 5.6 show a family of ice rating curves with downstream water level as a parameter, based on a nominal ice thickness of 0.8 m, obtained from the calibrated GVF model (ice roughness n = 0.015). Curves for ice thicknesses of 1.2 and 1.6 m, are presented in Figures 5.7 and 5.8, respectively. The procedure to develop these rating curves was as follows: first, given the ice thickness and water level at Big River, the water surface profile can be calculated using the GVF model based on different discharges; secondly, the water level and corresponding discharge at Dory Point are plotted as a rating curve with a downstream elevation as a parameter. Figures 5.6 to 5.8 indicate that the backwater effect becomes less important than thickness as ice thickness increases.

These figures provide a method to find winter discharge in different conditions. Through the family curves, the discharge can be roughly estimated by knowing the water elevation, ice thickness and ice roughness at Dory Point and the water surface elevation at the Big River section.

5.5 Discussion

Based upon the open water calibration and verification, gradually varied flow (GVF) rating curves were calculated and compared with uniform flow (UF) rating curves (based on the mean bed slope and the calibrated bed roughness) for all cross sections. The comparison showed that the flow is essentially uniform at the sections between Great Slave Lake and Kakisa River under open water conditions. A backwater (or M1) profile extends between the Big River and Beaver Lake cross sections. Downstream, through Ft. Providence Rapids to the RCMP section (just upstream of Ft. Providence), a drawdown (M2) curve is observed. Backwater from Mills Lake extends upstream to the dock in Ft. Providence. In a comparison between GVF and UF rating curves computed for the ice conditions which prevailed in 1992, backwater effects were evident between the Big River and Kakisa River sections.

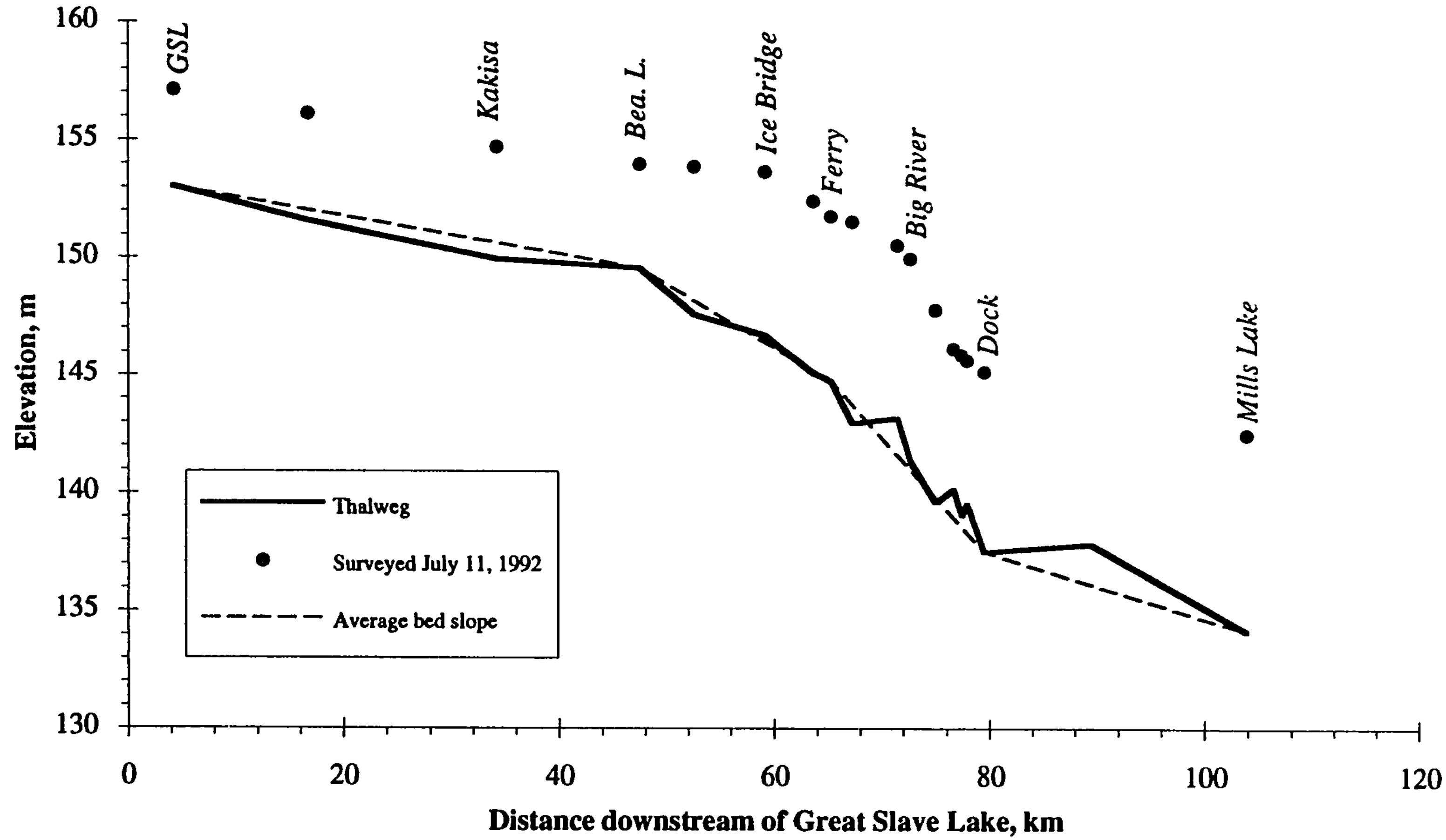
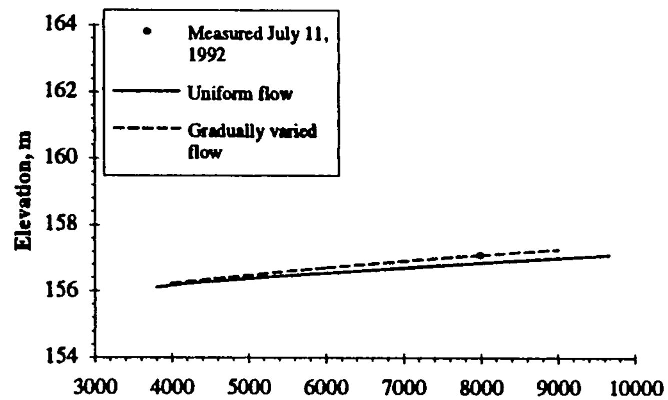
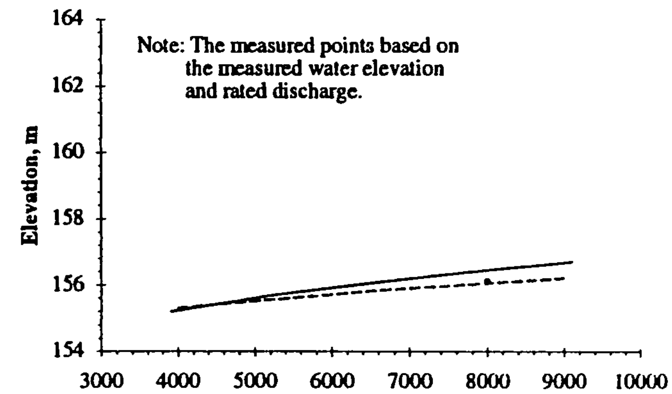


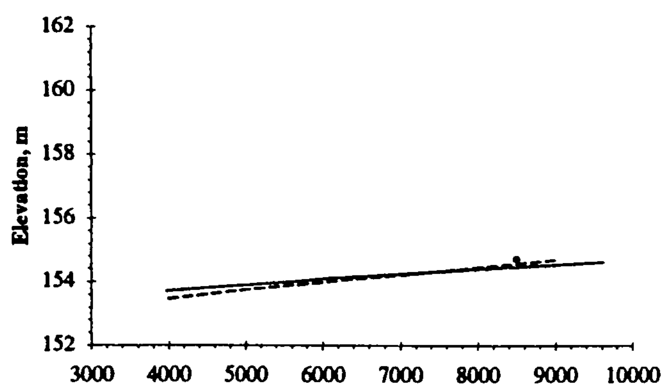
Figure 5.1 Bed slope and measured water level in the study reach of Mackenzie River.



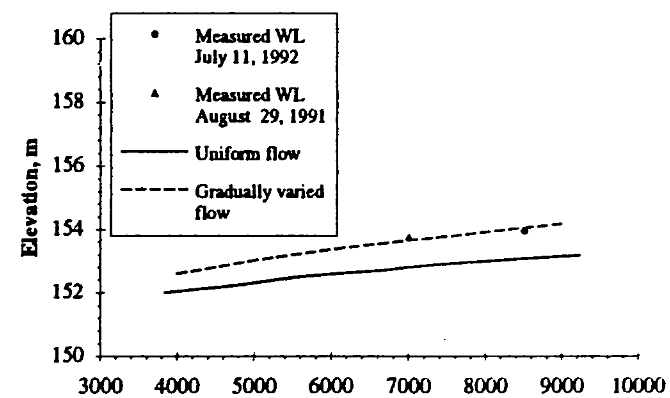
Discharge, cms
(a) Great Slave Lake cross section rating curve, 4.2 km downstream of Great Slave Lake.



Discharge, cms
(b) South Channel cross section rating curve, 16.7 km downstream of Great Slave Lake.

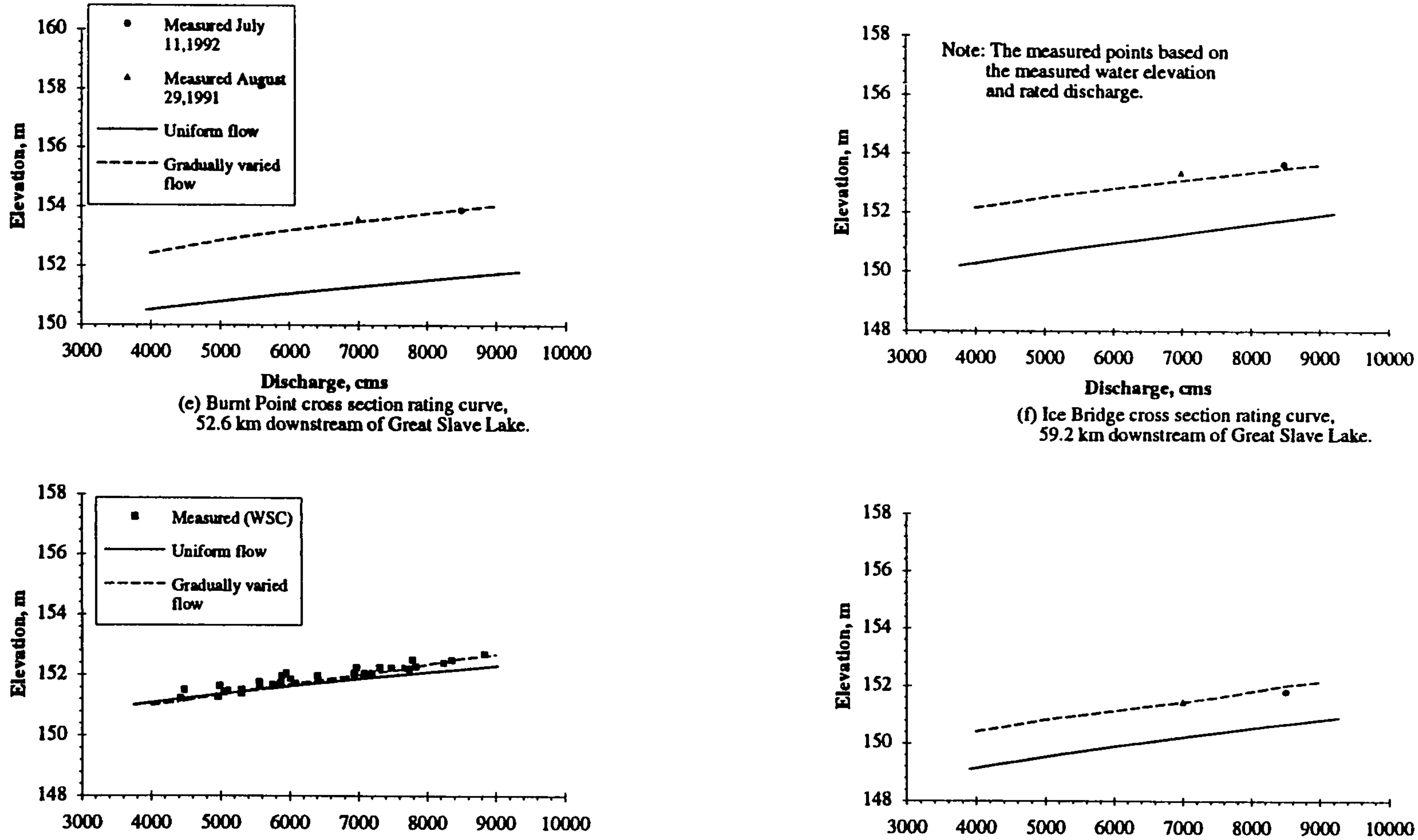


Discharge, cms
(c) Kakisa River cross section rating curve, 34.2 km downstream of Great Slave Lake.



Discharge, cms
(d) Beaver Lake cross section rating curve, 47.5 km downstream of Great Slave Lake.

Figure 5.2 UF and GVF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Dock.



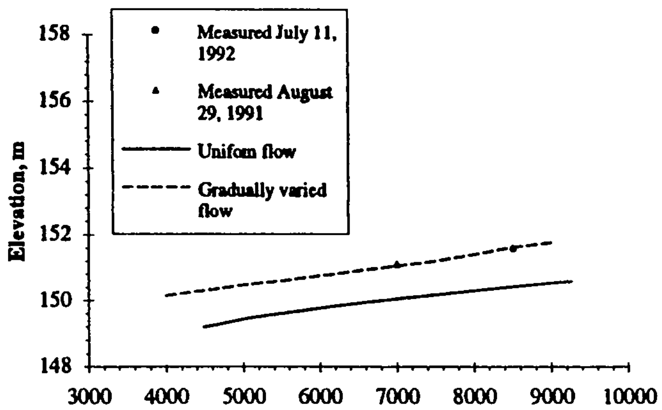
(e) Burnt Point cross section rating curve, 52.6 km downstream of Great Slave Lake.

(f) Ice Bridge cross section rating curve, 59.2 km downstream of Great Slave Lake.

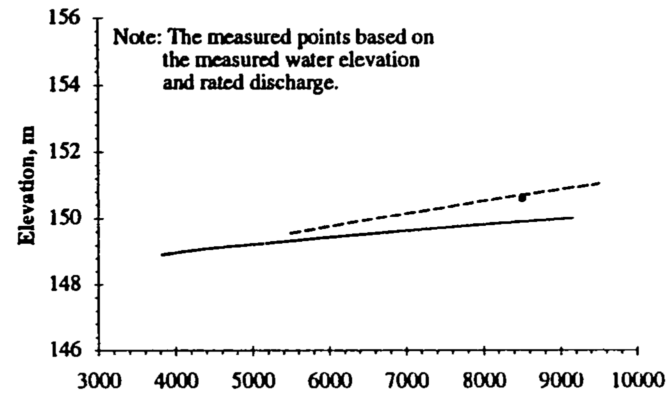
(g) Dory Point cross section rating curve, 63.7 km downstream of Great Slave Lake.

(h) Ferry cross section rating curve, 65.3 km downstream of Great Slave Lake.

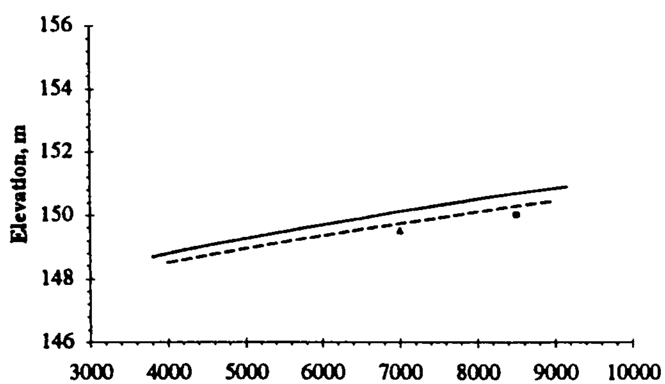
Figure 5.2 UF and GVF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Dock.



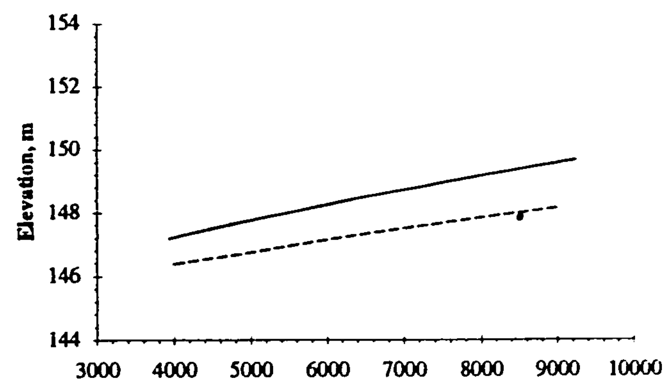
(i) Coast Guard cross section rating curve,
67.3 km downstream of Great Slave Lake.



(j) Blue Quonset cross section rating curve,
71.5 km downstream of Great Slave Lake.

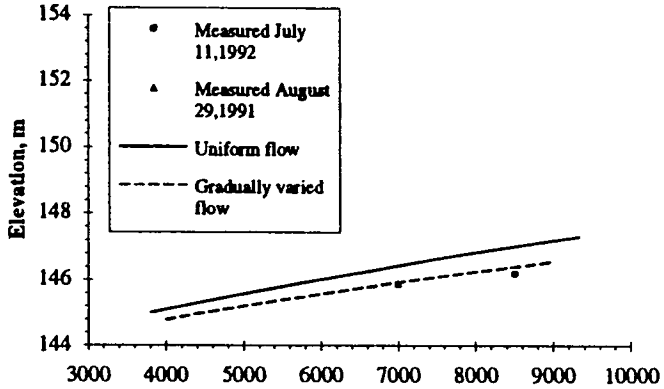


(k) Big River cross section rating curve,
72.7 km downstream of Great Slave Lake.

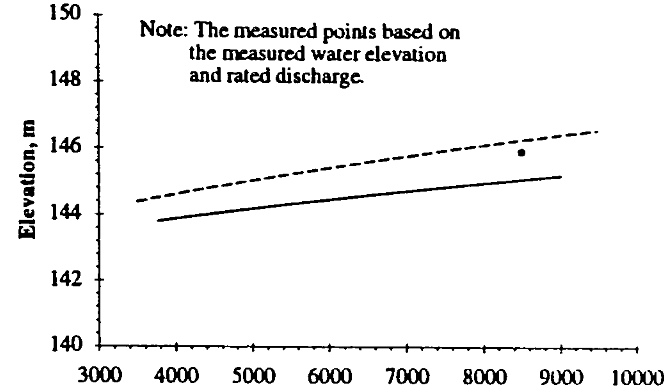


(l) Campground cross section rating curve,
75.0 km downstream of Great Slave Lake.

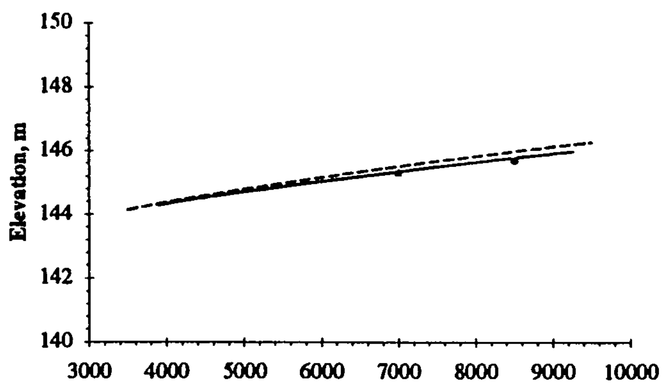
Figure 5.2 UF and GVF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Dock.



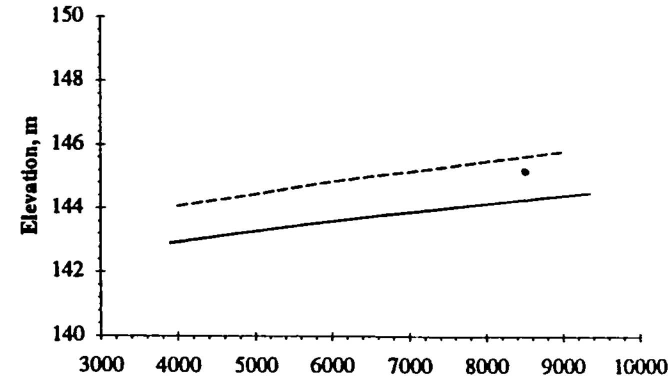
(m) Blue House cross section rating curve, 76.7 km downstream of Great Slave Lake.



(n) Boat Launch cross section rating curve, 77.4 km downstream of Great Slave Lake.

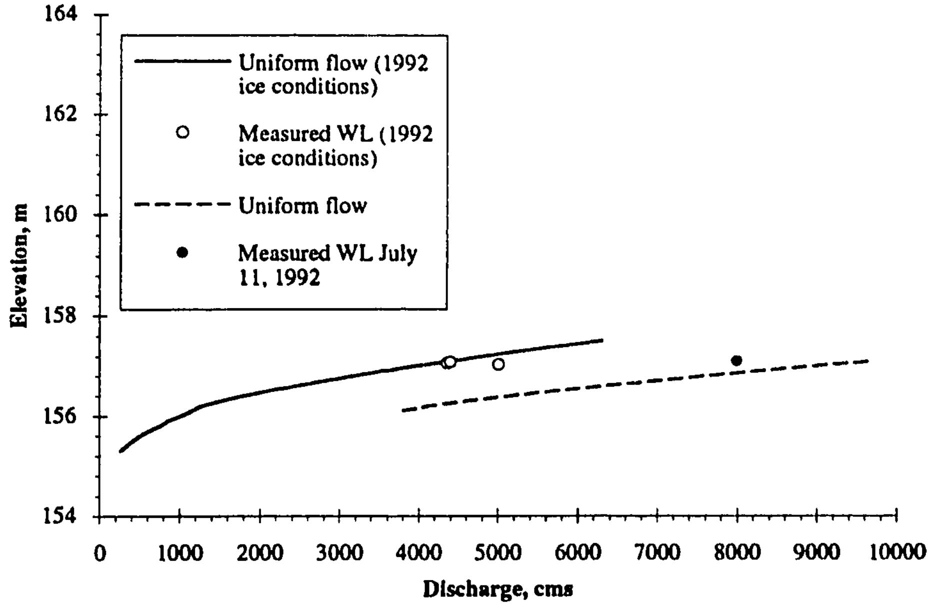


(o) RCMP cross section rating curve, 77.9 km downstream of Great Slave Lake.

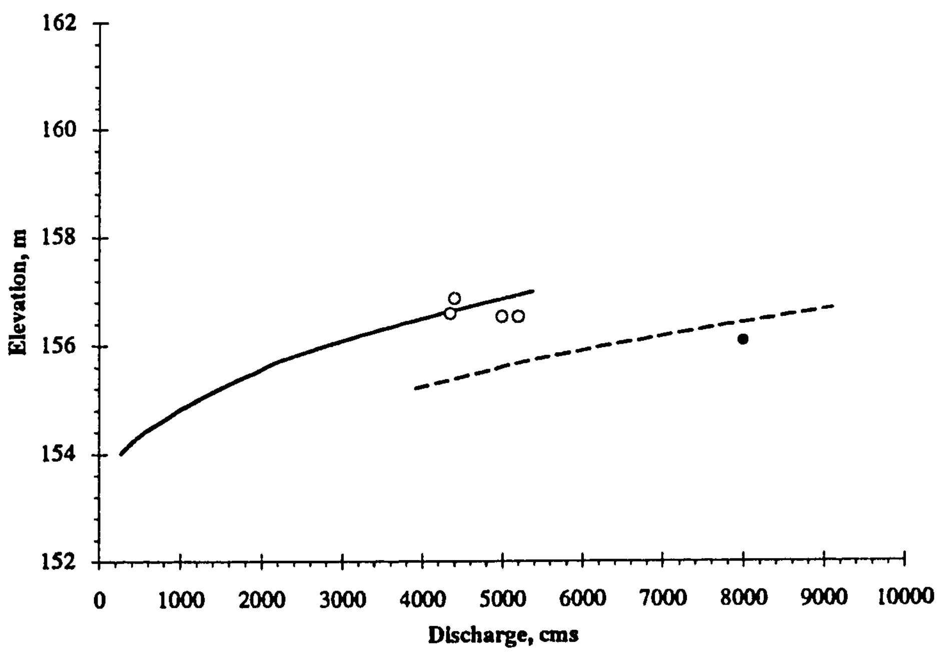


(p) Dock cross section rating curve, 79.5 km downstream of Great Slave Lake.

Figure 5.2 UF and GVF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Dock.

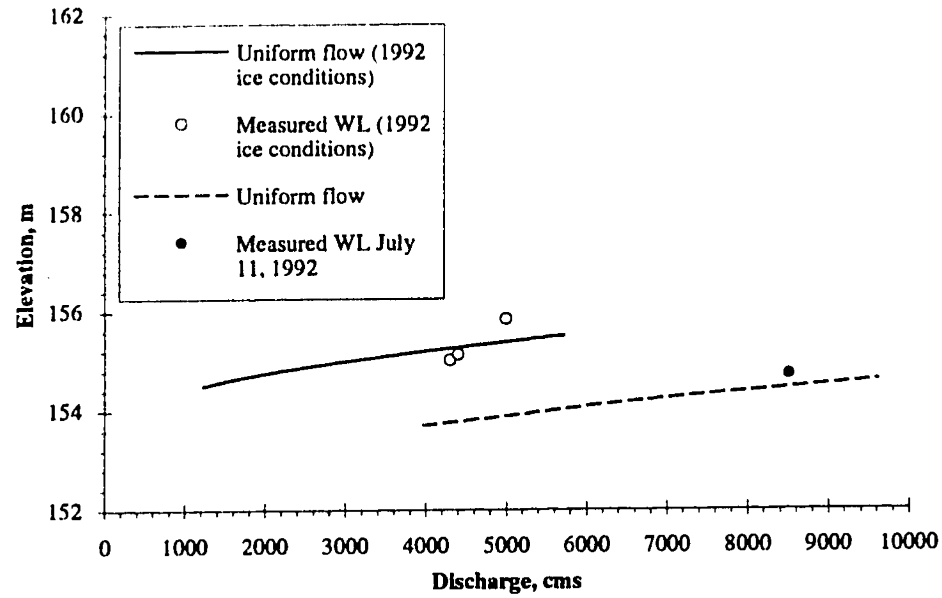


(a) Great Slave Lake cross section rating curve,
4.2 km downstream of Great Slave Lake.

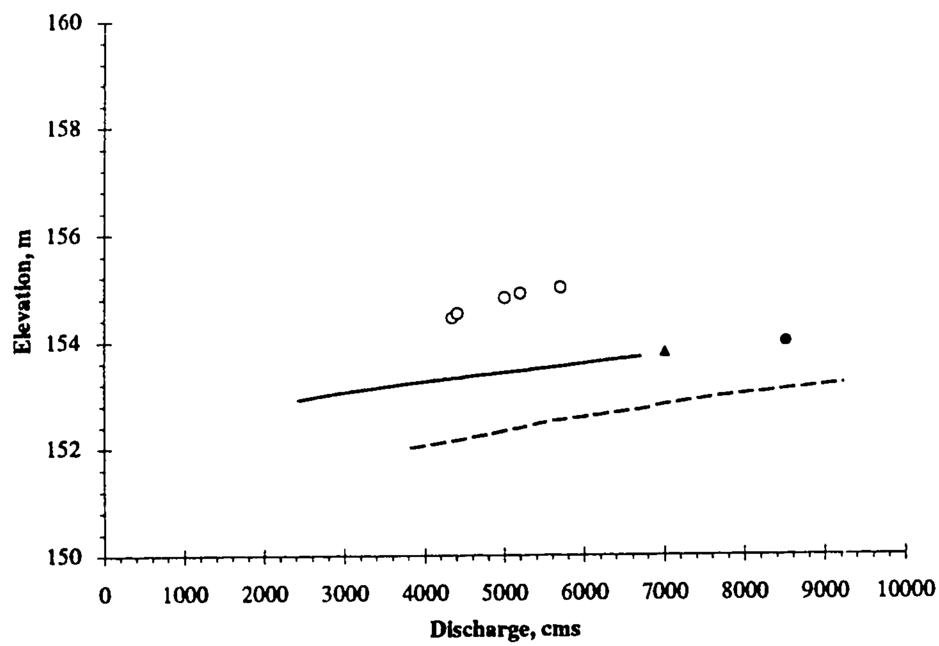


(b) South Channel cross section rating curve,
16.7 km downstream of Great Slave Lake.

Figure 5.3 A comparison of UF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Big River under open water and 1992 spring ice conditions.

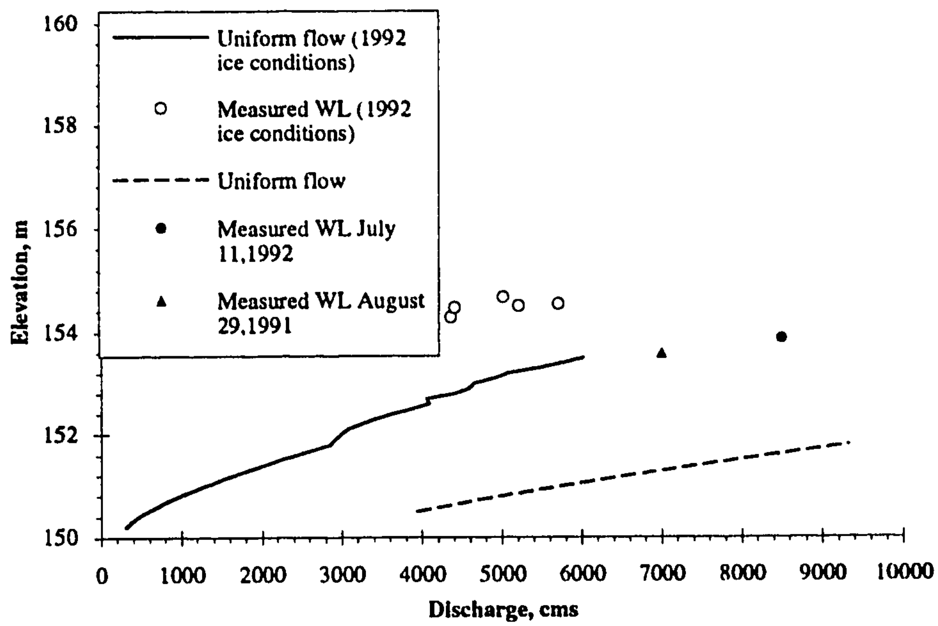


(c) Kakisa River cross section rating curve,
34.2 km downstream of Great Slave Lake.

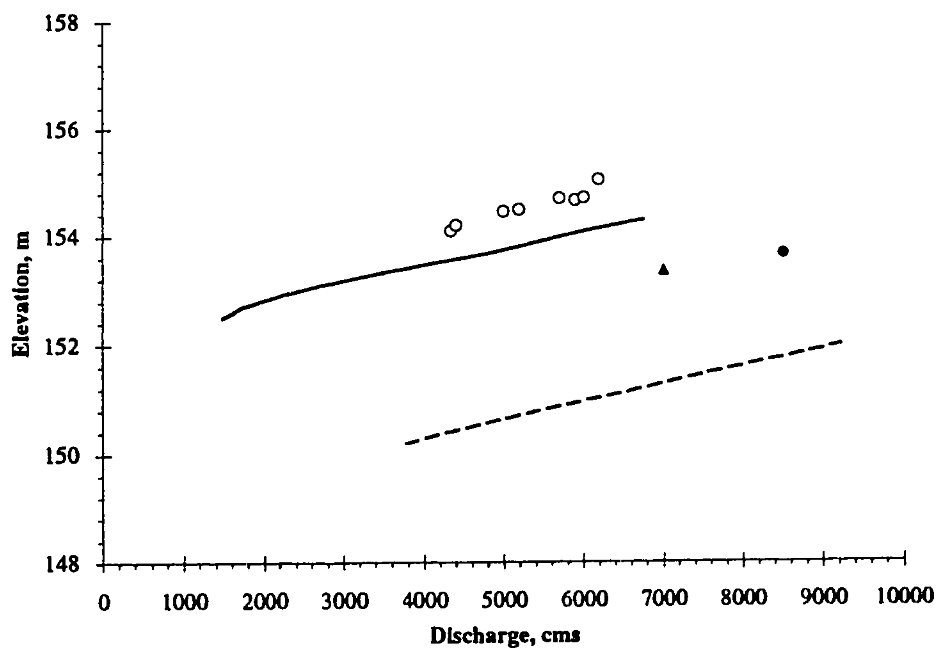


(d) Beaver Lake cross section rating curve,
47.5 km downstream of Great Slave Lake.

Figure 5.3 A comparison of UF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Big River under open water and 1992 spring ice conditions.

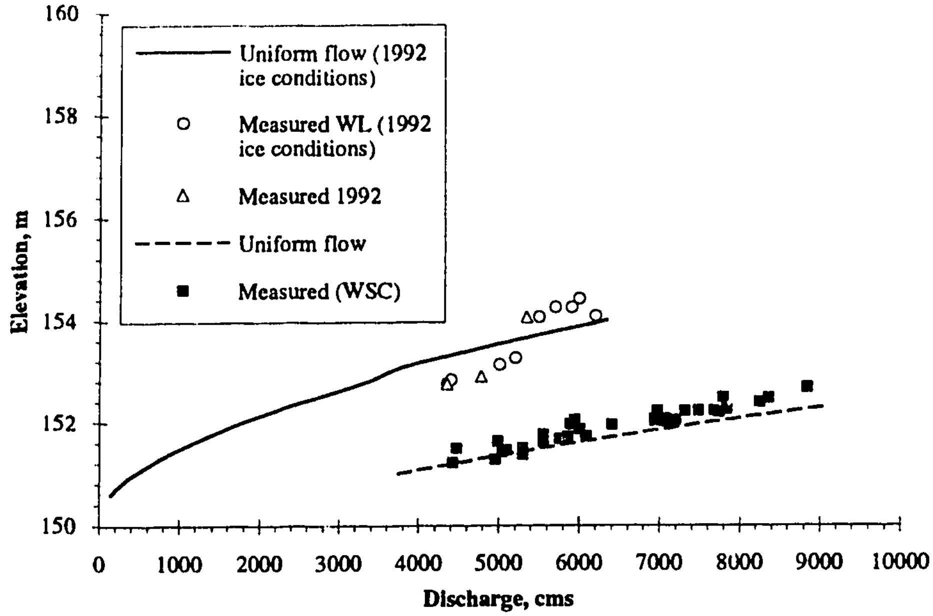


(e) Burnt Point cross section rating curve,
52.6 km downstream of Great Slave Lake.

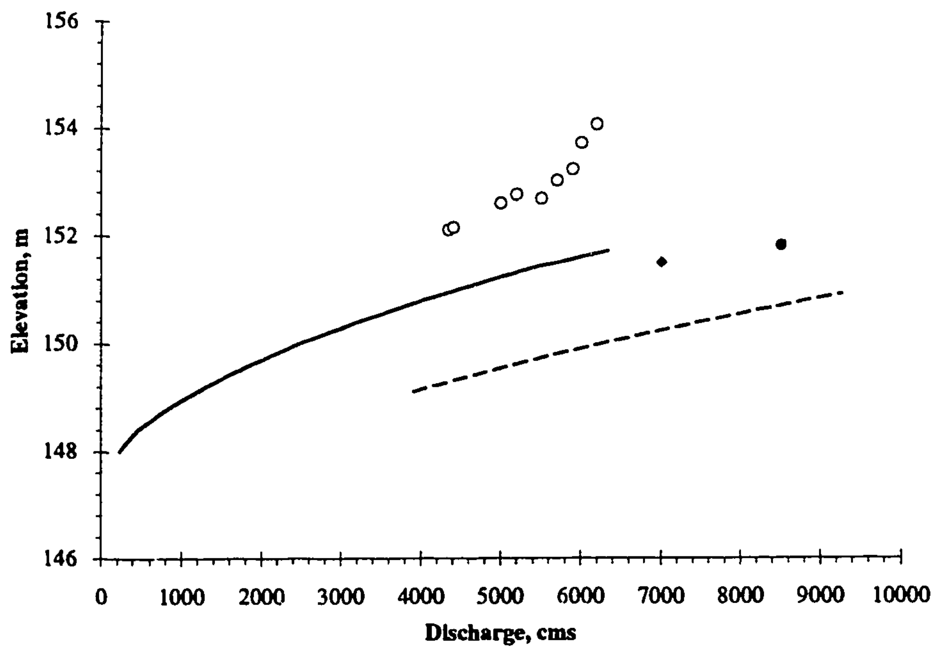


(f) Ice Bridge cross section rating curve,
59.2 km downstream of Great Slave Lake.

Figure 5.3 A comparison of UF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Big River under open water and 1992 spring ice conditions.

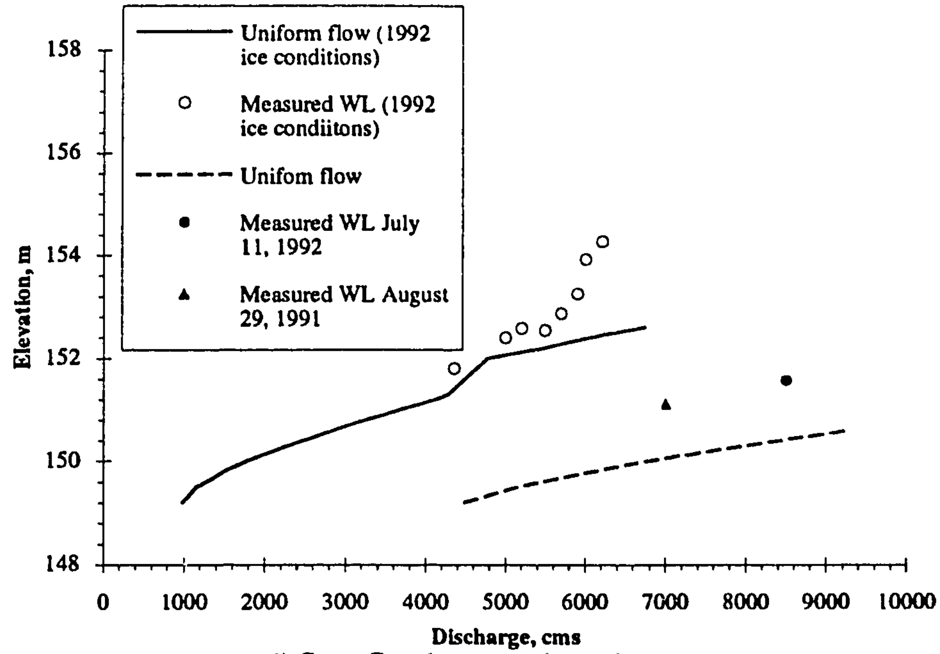


(g) Dory Point cross section rating curve,
63.7 km downstream of Great Slave Lake.

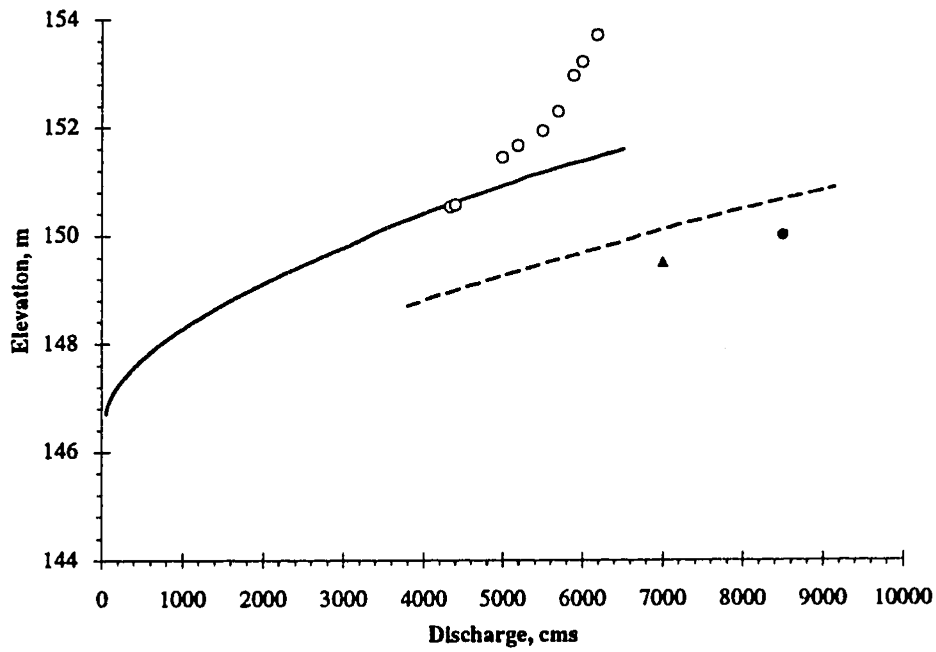


(h) Ferry cross section rating curve,
65.3 km downstream of Great Slave Lake.

Figure 5.3 A comparison of UF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Big River under open water and 1992 spring ice conditions.

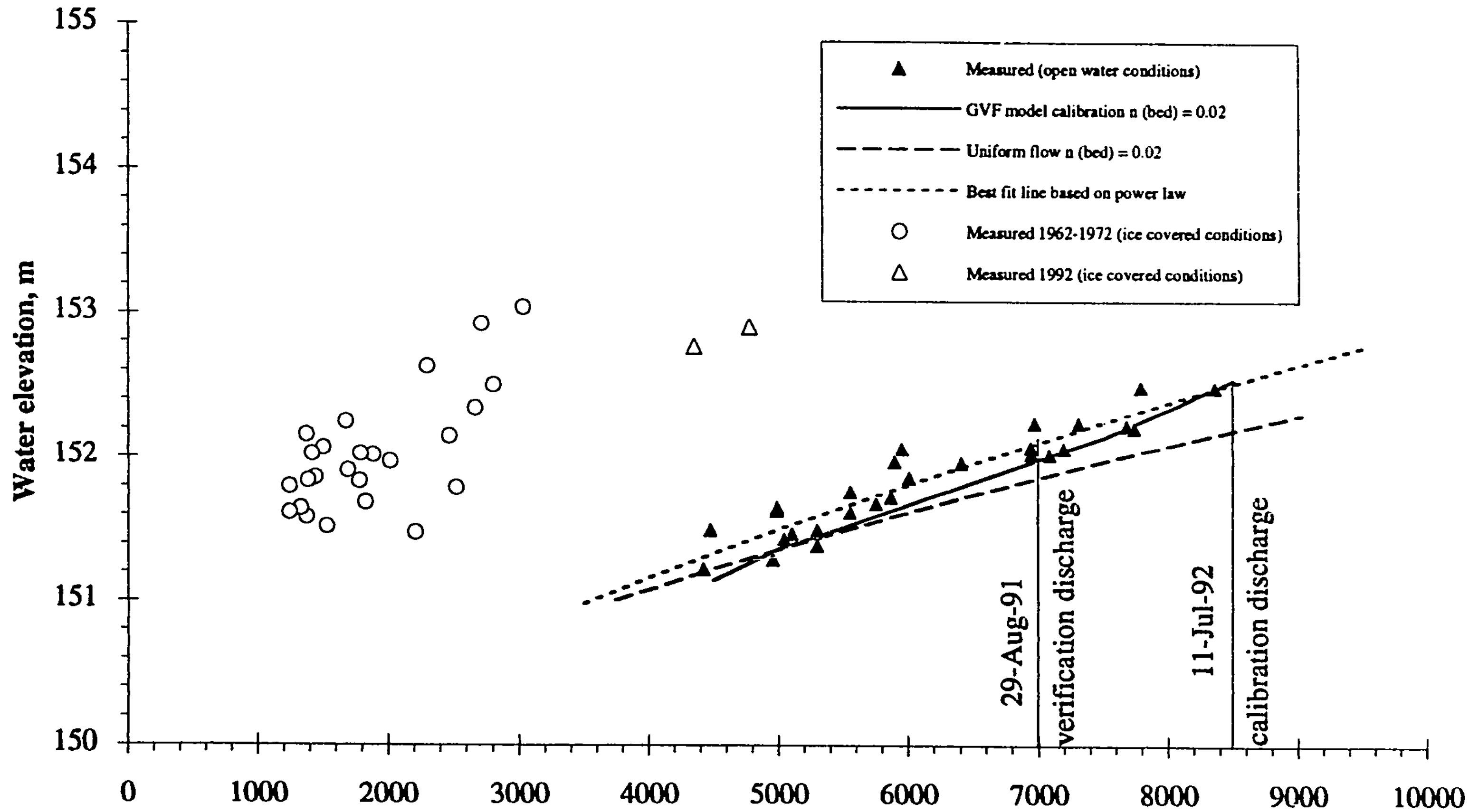


(i) Coast Guard cross section rating curve,
67.3 km downstream of Great Slave Lake.



(j) Big River cross section rating curve,
72.7 km downstream of Great Slave Lake.

Figure 5.3 A comparison of UF rating curves for surveyed cross sections on the Mackenzie River from Great Slave Lake to Big River under open water and 1992 spring ice conditions.



Discharge, cms

Figure 5.4 Water level and discharge relation for ice covered and open water conditions, Mackenzie River at Dory Point.

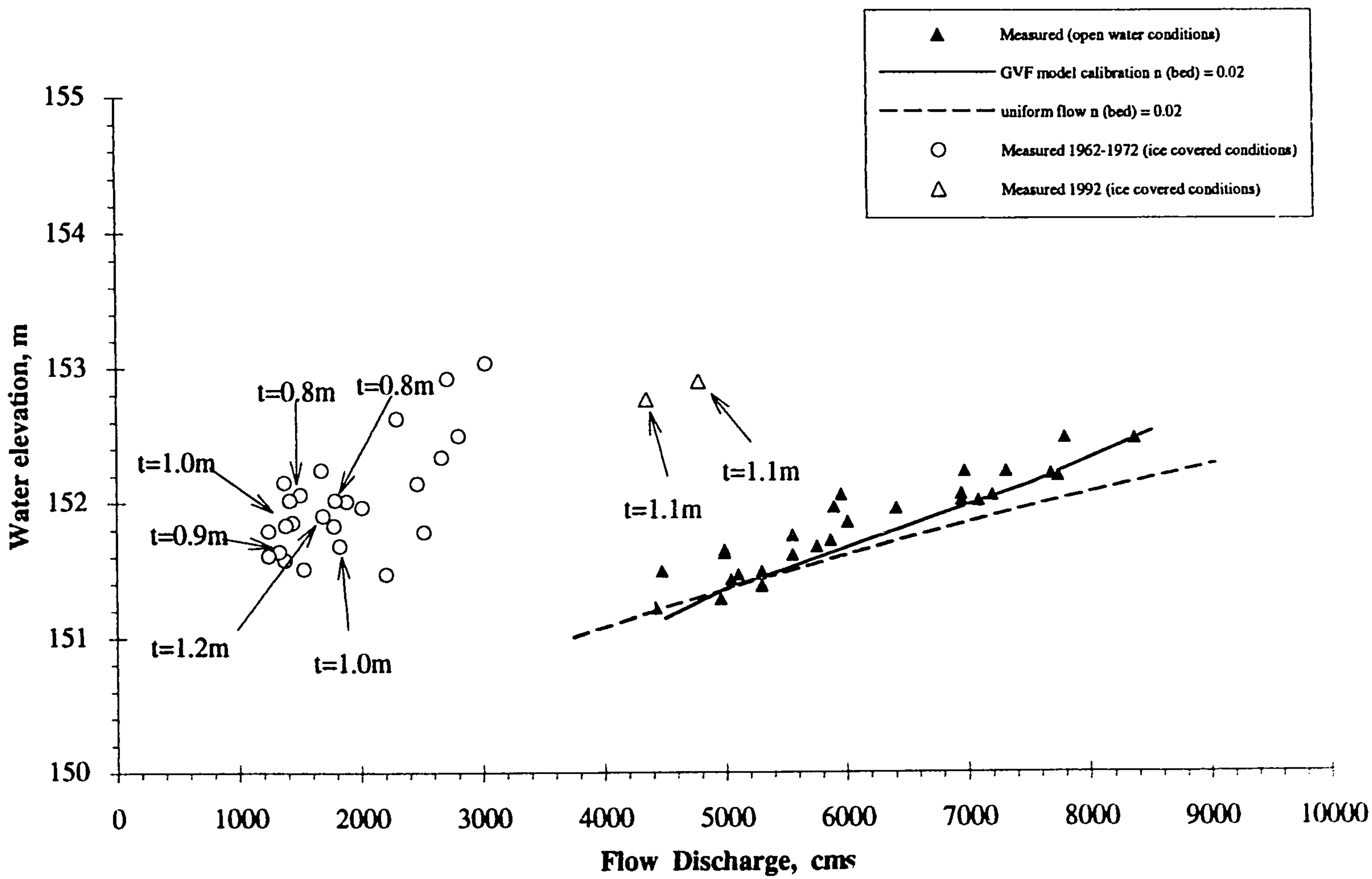


Figure 5.5 Measured water level and discharge with ice thickness t, Mackenzie River at Dory Point.

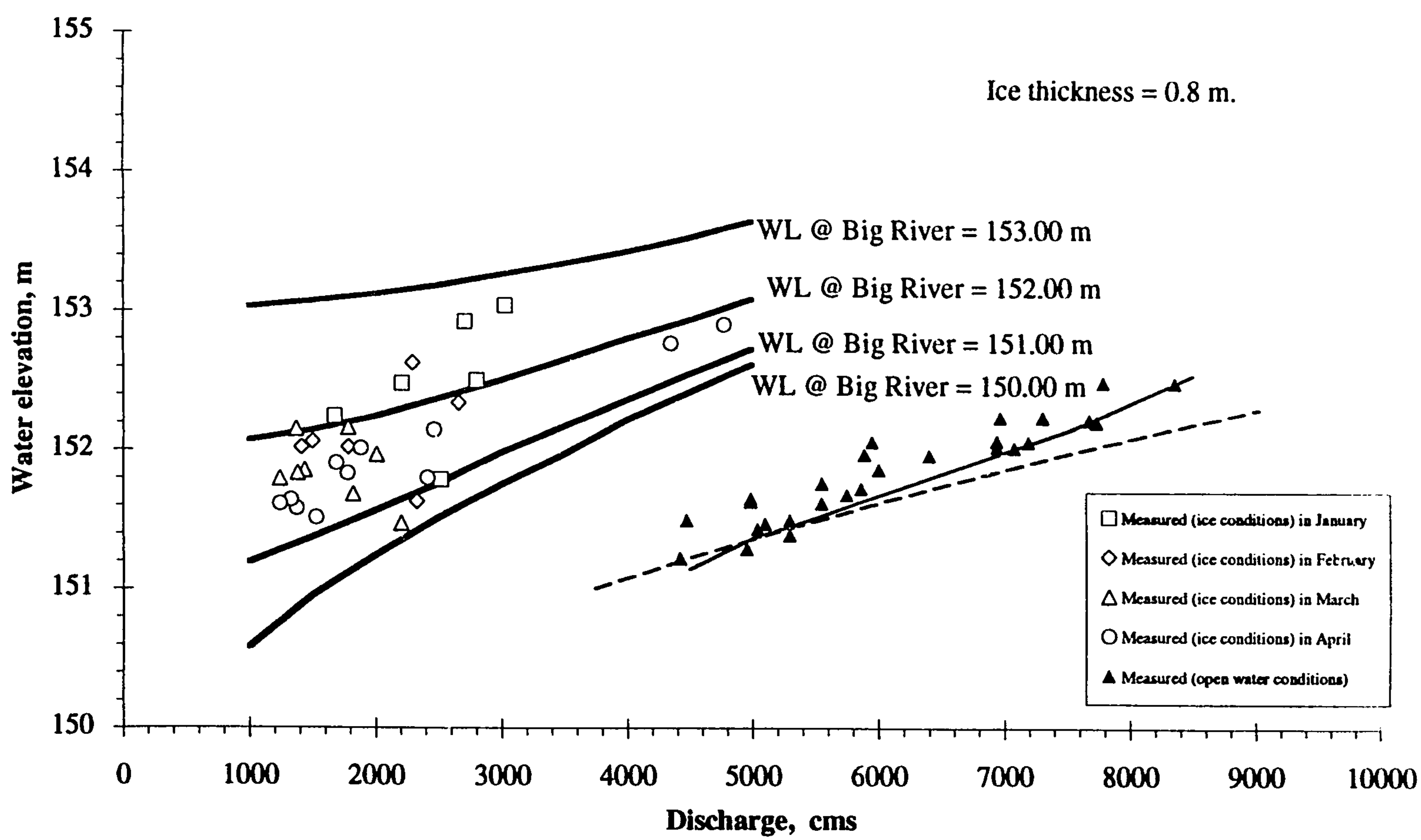


Figure 5.6 Rating curves for ice covered and open water conditions, Mackenzie River at Dory Point.

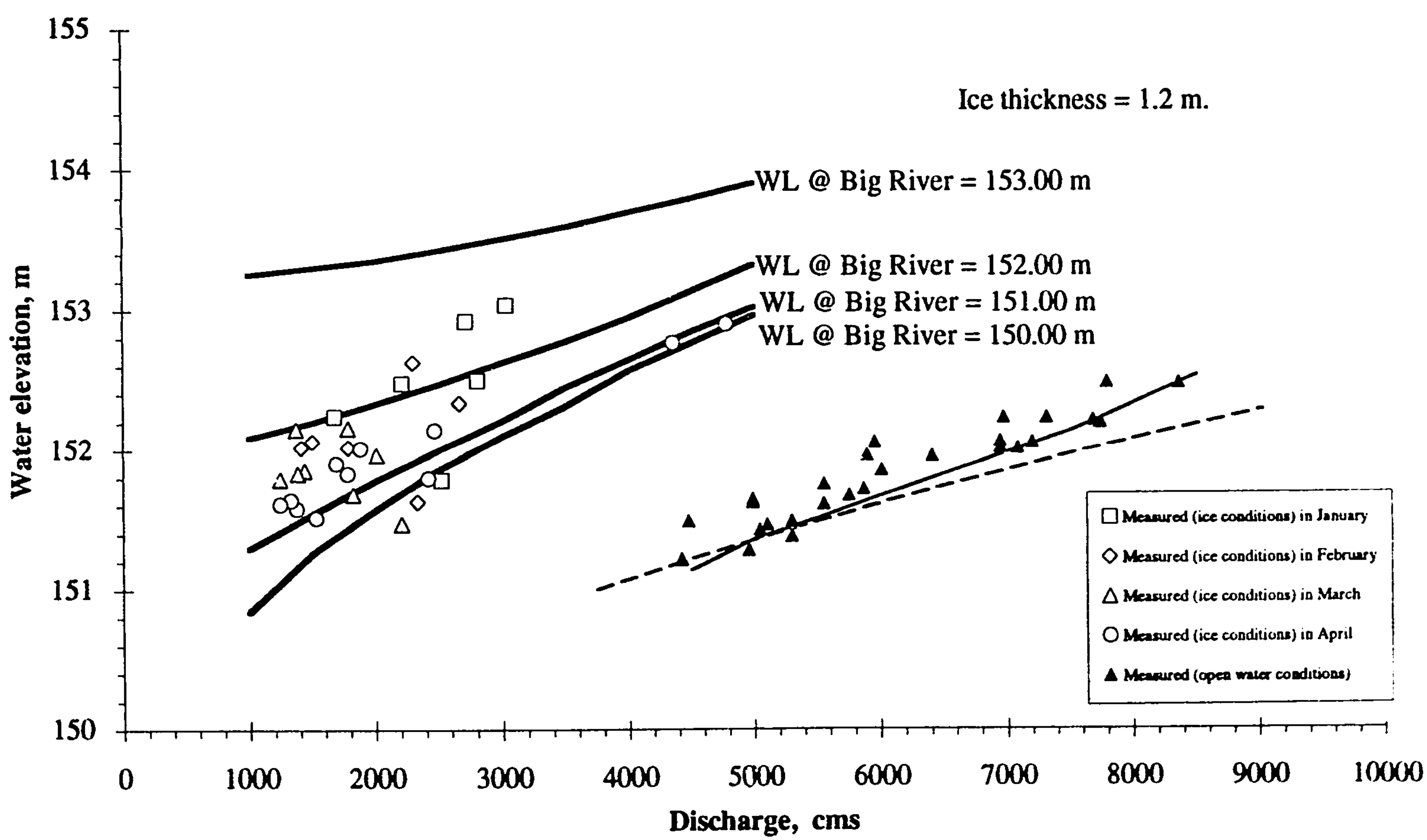


Figure 5.7 Rating curves for ice covered and open water conditions, Mackenzie River at Dory Point.

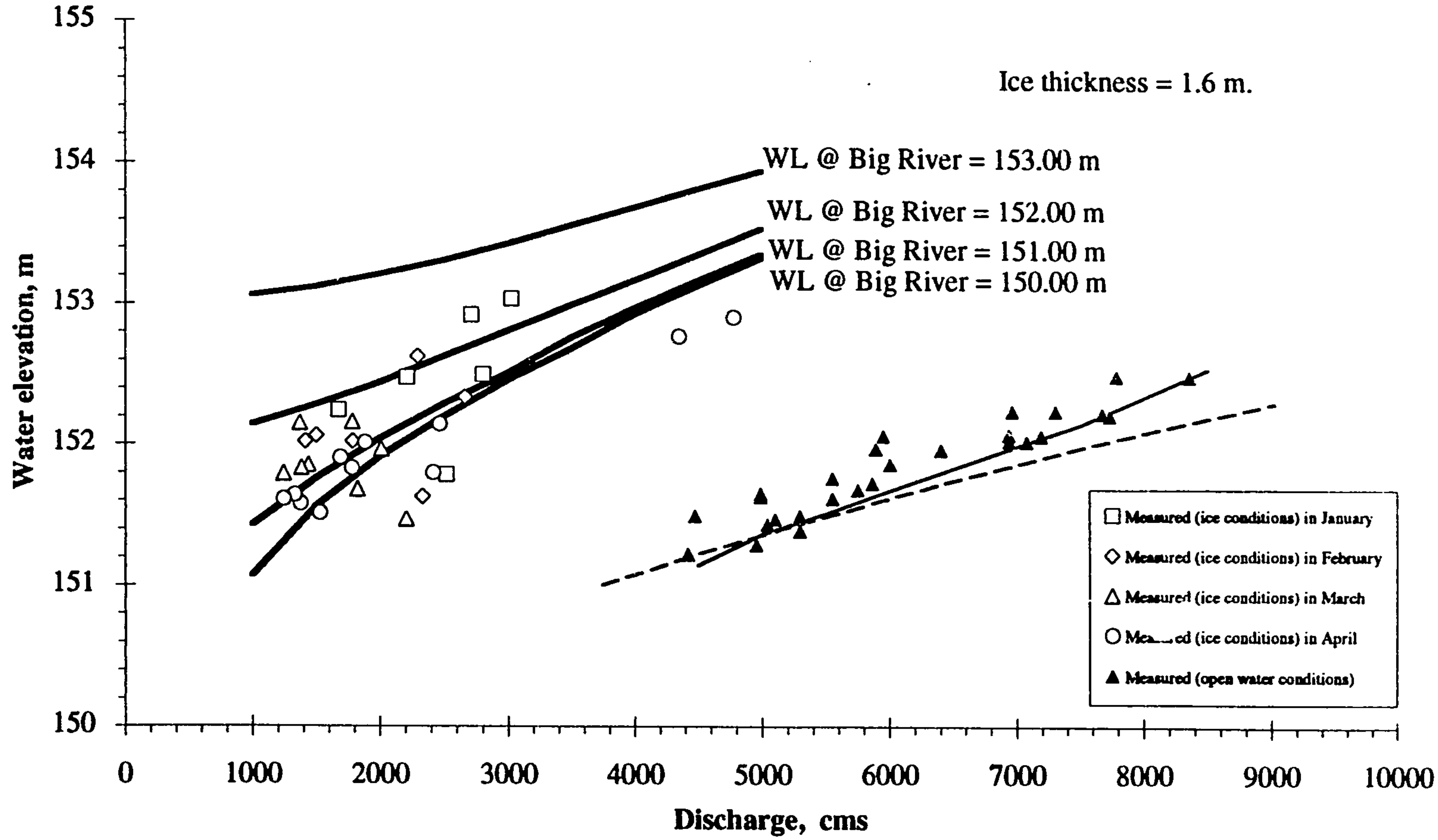


Figure 5.8 Rating curves for ice covered and open water conditions, Mackenzie River at Dory Point.

Chapter 6

Conclusions and recommendations

The purpose of this study was to develop an understanding of the effects of ice on the hydraulics of the Mackenzie River at the outlet of Great Slave Lake, NWT. The reach of the Mackenzie River considered extends from the outlet of the Great Slave Lake downstream to Mills Lake, a distance of about 100 kilometers (km). Based on detailed field surveys establishing the hydraulic geometry of this reach of the Mackenzie River, it can be divided into four distinct sub-reaches. The first sub-reach extends from the Great Slave Lake section to the Beaver Lake section. Here, the channel is wide, typically about 6000 meters, and the average bed slope is 0.00008. From the Beaver Lake section to the Ferry Crossing, the average bed slope steepens slightly and has a value of 0.00027. The river width varies from 6000 m at the Beaver Lake section, to 1000 meters at the Ferry Crossing. From the Ferry Crossing to the dock in Ft. Providence, the average bed slope increases further to a value of 0.00051 and the river becomes narrows to a width of about 800 meters. Downstream of the Dock to the Mills Lake section, the bed slope decreases again to an average value of 0.00014 gradually increasing in width to 3700 meters just upstream of Mills Lake.

Two water surface profiles, measured on July 11, 1992 and August 29 to September 1, 1991, were used to calibrate and verify bed roughness values during open water conditions, respectively. This gradually varied flow analysis was conducted with the steady, one-dimensional model, HEC-2, developed by the U.S. Corps of Engineers. Based on a rating curve established from data collected by Water Survey of Canada staff at the Dory Point gauging station, the discharges for these two water surface profiles were estimated to be 8500 and 7000 m^3/s, respectively. The calibrated Manning's n for the bed under open water conditions was found to vary in the range of 0.02 to 0.03. The values of Manning's n for each cross section are as follows: from the Great Slave Lake section to the Ice Bridge section, it was 0.022; from the Ice Bridge section to the Big River section, it was 0.020; from the Big River section to the dock in Ft. Providence, it was in the range of 0.025 to 0.030; and downstream of the dock, it was 0.020. It is proposed that the reason for the Manning's n being larger between the Big River section and the dock was that the bed slope increases significantly in this reach and this would be expected to lead to a larger median size of bed material thus presenting a rougher bed surface.

A gradually varied flow open water rating curve, developed for the Dory Point gauging section, based on this calibration and verification was found to represent a lower envelope to the data measured by Water Survey of Canada at the gauging station. Although the bed is known to consist of a hard glacial till (and therefore not subject to varying bed forms) the effective resistance of the bed roughness features would be increased as flow depth decreased. As the use of the Manning's n values obtained in this calibration would not reflect the increase in Manning's n value expected at lower discharges, the validity of using these calibrated bed roughness values at low discharges remains to be confirmed. Verification tests at lower discharges could be used to assess the sensitivity of the resistance values to depth.

Calibration of the GVF model with a water surface profile measured under late winter ice conditions between April 25 and 27, 1992 and a measured discharge of 4350 m^3/s produced an ice cover roughness of $n_i = 0.015$ upstream of the Big River section and $n_i = 0.050$ in the accumulation through Providence Rapids (prior to ice movement). These ice resistance values were deduced from the total composite resistance calibrated based on the Belokon-Sabaneev equation, assuming that the calibrated open water bed resistance values were applicable under late winter ice conditions and at this low discharge. An attempt to verify or disprove this assumption was made by measuring velocity profiles at the Ferry cross section on the day of the discharge measurement and two days later. These velocity distributions, when fit to the Karman-Prandtl log law produced inconsistent and unreasonably large values for the roughness height for both the bed and the ice (values greater than the depth in some cases). Conversion of these roughness heights to Manning's *n* values yielded results which were not in agreement with the calibration values. It was concluded that the gradually varied flow analysis results, though likely inaccurate given the use of the results of the open water calibration and the Belokon-Sabaneev equation, were more reliable than those of the measured velocity profiles. Further justification for this opinion is provided by the fact that the gradually varied flow analysis was based on reach averaged rather than point values and in recognition of the problems encountered in measuring the velocity profiles. It is recommended that further measurements of velocity profiles under the ice cover be conducted in future to resolve this question.

The calibrated, late winter 1992, gradually varied flow model was used to determine discharge through the early breakup period, beyond the point which discharge measurements could be safely obtained. The discharges estimated by GVF model for April 27 to May 13, 1992 are in the range of 4350 to 6200 m^3/s. Comparing the results with two other discharge measurements: 4780 m^3/s on May 1, 1992 and 5340 m^3/s on May 6, 1992, lend credibility to the results obtained.

The GVF ice model was also used to develop a family of ice rating curves for the Dory Point section based on ice thickness and roughness as well as backwater conditions from downstream as reflected in a representative water level at the Big River section. Generally, the measurements of water surface profile are easier than the measurements of discharge. Therefore the method by using GVF model to estimate discharges is significant and practical.

A number of conclusions may be drawn regarding the effects of ice on the outflow from Great Slave Lake. First of all, the lake exits to a mild sloping channel which has an irregular geometry. Despite this, the channel displays near uniform flow from the lake outlet to Kakisa River both for the open water case and for the ice conditions which prevailed in late winter of 1992. This occurs despite the fact the constrictions in the downstream channel result in backwater effects which are enhanced in the presence of an ice cover. The reason is likely due to the fact that the channel is quite wide upstream of the Burnt Point cross section and, therefore, downstream backwater has only a marginal effect on increasing water levels upstream in Beaver Lake.

The reason for the increase in discharge observed during the breakup period remains a question, given that the lateral inflows downstream of Great Slave Lake are considered negligible and that recorded water levels on Great Slave Lake did not vary substantially. However, it is noted that, based on the late winter ice condition of 1992, the rating curve at Great Slave Lake displays significantly reduced outflows for a given water level compared to that predicted under open water conditions. Therefore, it is possible that increased outflows from the lake occur as warm water issuing from the lake increases the open water area in the South Channel (thus increasing the efficiency of the outlet).

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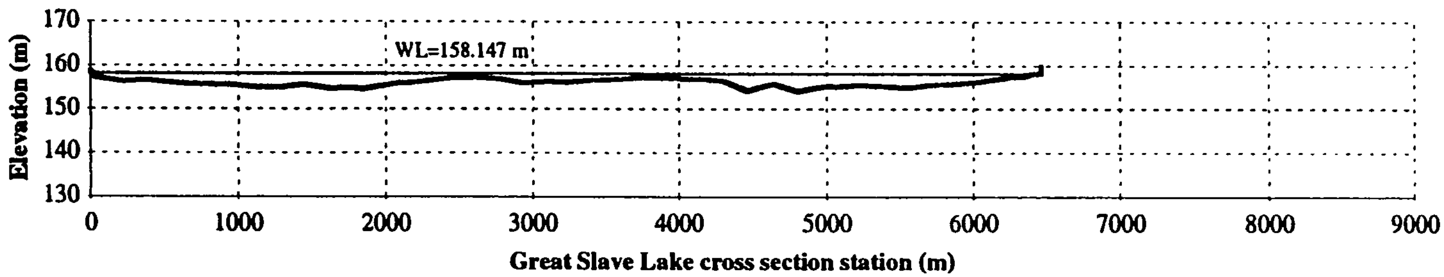
Appendix A

Cross Section Surveys



Description: This cross section is located 4.2 km downstream of Great Slave Lake. Surveying and depth soundings were performed on July 9, 1992. The survey was started on the south bank, 1.7 m from the edge of the water. The depth sounding was begun 3 m from the edge of the water and stopped 5 m short of the north bank of the large island immediately upstream of Lobstick Island, which was then surveyed for a distance of 61.5 m from the edge of the water. This large island immediately upstream of Lobstick Island was mistaken for Big Island, so the soun[illegible]d cross section does not actually cross the entire Mackenzie River. However, the remaining portion of the Mackenzie is mostly shallow mud flats. The sounding data was evenly distributed across the sounded channel (no horizontal control available due to GPS system battery failure). The water surface elevation was estimated as 157.11 m on July 10, 1992.

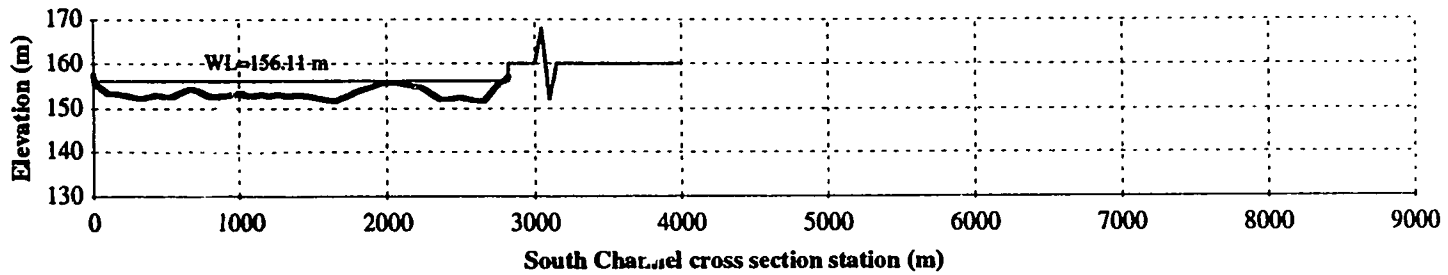
TBM: Spike in a flagged 30 cm diameter spruce tree on the south bank. *Elevation 158.43 m was estimated by using water levels measured at Hay River in Great Slave Lake during April and May of 1992.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	158.61	2436.35	157.13	4712.13	154.98
35.88	157.24	2623.40	157.21	4805.66	154.07
222.93	156.32	2779.28	156.85	4930.36	154.87
378.80	156.63	2935.15	155.97	5023.88	155.21
503.50	156.20	2997.50	156.00	5055.06	155.16
659.38	155.65	3122.20	156.26	5242.11	155.46
784.08	155.54	3184.55	156.10	5335.63	155.19
815.25	155.71	3309.25	156.32	5460.33	155.11
846.43	155.52	3402.78	156.57	5491.51	155.00
939.95	155.56	3465.13	156.67	5553.86	154.83
1002.30	155.36	3652.18	156.95	5740.91	155.60
1127.00	155.04	3745.70	157.23	5803.26	155.59
1282.88	154.92	3901.58	157.07	6021.48	156.12
1438.75	155.58	3932.75	157.16	6208.53	157.12
1625.80	154.65	4088.63	156.84	6239.71	157.26
1750.50	154.88	4182.15	156.85	6270.88	157.32
1844.03	154.57	4306.86	156.38	6333.23	157.35
2093.43	155.90	4462.73	154.24	6403.70	158.17
2155.78	155.91	4618.61	155.57	6463.70	158.20
2218.13	156.13	4649.78	155.65	6465.20	159.70

Figure A.1 Great Slave Lake cross section (south channel only), 4.2 km downstream of Great Slave Lake.

Table A.1 Hydraulic components at Great Slave Lake cross section (south channel only), 4.2 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
153.5	0.47	37	178	178	0.2
153.6	0.57	58	257	257	0.2
153.7	0.67	92	418	418	0.2
153.8	0.77	142	592	592	0.2
153.9	0.87	212	810	810	0.3
154.0	0.97	308	1116	1116	0.3
154.1	1.07	431	1365	1365	0.3
154.2	1.17	586	1714	1714	0.3
154.3	1.27	770	1965	1965	0.4
154.4	1.37	979	2210	2210	0.4
154.5	1.47	1210	2426	2426	0.5
154.6	1.57	1473	2808	2808	0.5
154.7	1.67	1762	2941	2941	0.6
154.8	1.77	2060	3036	3036	0.7
154.9	1.87	2371	3195	3195	0.7
155.0	1.97	2700	3394	3395	0.8
155.1	2.07	3049	3598	3598	0.9
155.2	2.17	3421	3836	3836	0.9
155.3	2.27	3813	4014	4014	1.0
155.4	2.37	4225	4229	4229	1.0
155.5	2.47	4659	4451	4451	1.1
155.6	2.57	5116	4683	4683	1.1
155.7	2.67	5593	4853	4853	1.2
155.8	2.77	6087	5027	5027	1.2
155.9	2.87	6609	5338	5338	1.2
156.0	2.97	7153	5528	5528	1.3
156.1	3.07	7718	5829	5829	1.3
156.2	3.17	8324	6200	6200	1.3
156.3	3.27	8946	6279	6279	1.4
156.4	3.37	9577	6310	6310	1.5
156.5	3.47	10208	6321	6321	1.6
156.6	3.57	10841	6333	6333	1.7
156.7	3.67	11475	6344	6344	1.8
156.8	3.77	12110	6355	6355	1.9
156.9	3.87	12746	6367	6367	2.0
157.0	3.97	13383	6378	6378	2.1
157.1	4.07	14022	6389	6389	2.2
157.2	4.17	14664	6454	6454	2.3
157.3	4.27	15310	6457	6457	2.4
157.4	4.37	15956	6460	6460	2.5
157.5	4.47	16602	6462	6463	2.6
157.6	4.57	17248	6464	6465	2.7
157.7	4.67	17895	6464	6465	2.8
157.8	4.77	18541	6464	6465	2.9
157.9	4.87	19188	6464	6465	3.0
158.0	4.97	19834	6465	6465	3.1



Description: This cross section is located 16.7 km downstream of Great Slave Lake, passing between the Grassy Islands. Surveying and depth soundings were performed on July 9, 1992. The survey was started on the south bank, 6.9 m from the edge of the water. The depth sounding was started 3 m from the waterline and stopped 30 m short of the north bank, which was then surveyed for a distance of 30 m from the edge of the water. The sounding data was evenly distributed across the channel (no horizontal control available due to GPS system battery failure). The water surface elevation was estimated as 156.11 m by using water elevations at Kakisa and Hay River on July 11, 1992.

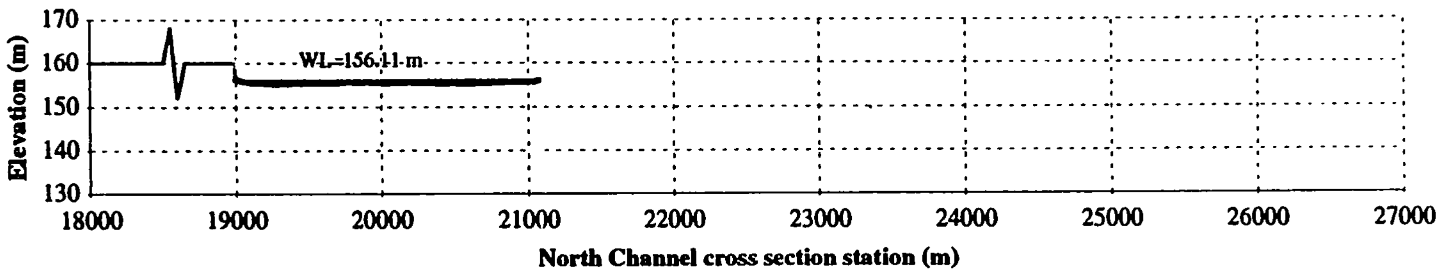
TBM: Spike in a flagged 20 cm diameter spruce tree with a gnarled top, on the south bank. *Elevation 158.58 m estimated by tying into Kakisa River TBM on April 8, 1992.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	157.63	872.25	152.73	1734.59	152.73
9.90	155.41	927.29	152.85	1807.98	153.86
101.64	153.28	945.64	153.08	1881.37	154.55
138.33	153.23	963.98	152.96	1973.11	155.51
211.73	152.89	982.33	153.24	2064.85	155.68
285.12	152.37	1019.03	153.25	2156.59	155.02
321.81	152.26	1037.38	152.90	2229.98	154.68
358.51	152.37	1074.07	152.75	2358.41	151.90
376.86	152.65	1110.77	152.84	2431.81	152.06
395.20	152.59	1147.46	153.07	2486.85	152.32
413.55	152.82	1202.50	152.65	2560.24	151.84
450.25	152.86	1257.55	152.98	2578.59	151.73
505.29	152.50	1294.24	152.95	2596.94	151.71
541.99	152.54	1312.59	152.75	2651.98	151.61
560.33	152.89	1349.29	152.73	2763.90	155.77
652.07	154.15	1367.63	152.86	2793.90	156.11
670.42	154.32	1404.33	152.88	2823.90	157.11
725.46	153.75	1477.72	152.58		
780.51	152.78	1569.46	152.00		
835.55	152.43	1642.85	151.57		

Figure A.2 South Channel cross section, 16.7 km downstream of Great Slave Lake.

Table A.2 Hydraulic components at South Channel cross section, 16.7 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
152.5	0.93	302	692	692	0.4
152.6	1.03	379	832	832	0.5
152.7	1.13	469	975	976	0.5
152.8	1.23	578	1220	1220	0.5
152.9	1.33	715	1488	1489	0.5
153.0	1.43	871	1642	1642	0.5
153.1	1.53	1040	1741	1741	0.6
153.2	1.63	1217	1801	1801	0.7
153.3	1.73	1404	1914	1914	0.7
153.4	1.83	1596	1945	1945	0.8
153.5	1.93	1792	1976	1976	0.9
153.6	2.03	1992	2007	2007	1.0
153.7	2.13	2194	2038	2038	1.1
153.8	2.23	2399	2071	2071	1.2
153.9	2.33	2608	2108	2108	1.2
154.0	2.43	2821	2147	2147	1.3
154.1	2.53	3038	2186	2186	1.4
154.2	2.63	3258	2227	2227	1.5
154.3	2.73	3483	2270	2270	1.5
154.4	2.83	3712	2296	2296	1.6
154.5	2.93	3942	2318	2318	1.7
154.6	3.03	4175	2340	2340	1.8
154.7	3.13	4410	2364	2364	1.9
154.8	3.23	4649	2402	2403	1.9
154.9	3.33	4891	2440	2441	2.0
155.0	3.43	5137	2478	2479	2.1
155.1	3.53	5386	2510	2511	2.2
155.2	3.63	5639	2541	2541	2.2
155.3	3.73	5895	2572	2572	2.3
155.4	3.83	6153	2602	2602	2.4
155.5	3.93	6415	2629	2629	2.4
155.6	4.03	6681	2696	2696	2.5
155.7	4.13	6954	2753	2754	2.5
155.8	4.23	7230	2758	2759	2.6
155.9	4.33	7506	2768	2768	2.7
156.0	4.43	7783	2777	2777	2.8
156.1	4.53	8061	2786	2787	2.9
156.2	4.63	8340	2790	2791	3.0
156.3	4.73	8619	2794	2794	3.1
156.4	4.83	8899	2797	2798	3.2
156.5	4.93	9179	2801	2801	3.3
156.6	5.03	9459	2804	2804	3.4
156.7	5.13	9740	2808	2808	3.5
156.8	5.23	10021	2811	2811	3.6
156.9	5.33	10302	2814	2815	3.7
157.0	5.43	10584	2818	2818	3.8



Description: This cross section is located on the North Channel of the Mackenzie River, approximately 19.2 km downstream of Great Slave Lake. The cross section is about half way between the start of the north channel at Deep Bay and Birch Island. It is a continuation of the South Channel cross section, on the north side of Big Island. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south bank, 37 m from the edge of the water. The depth sounding was started 20 m from the edge of the water and stopped 40 m short of the north bank. The north bank was not surveyed since access by boat was impossible. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation was assumed to be the same as that at the South Channel cross section, which was 156.11 m.

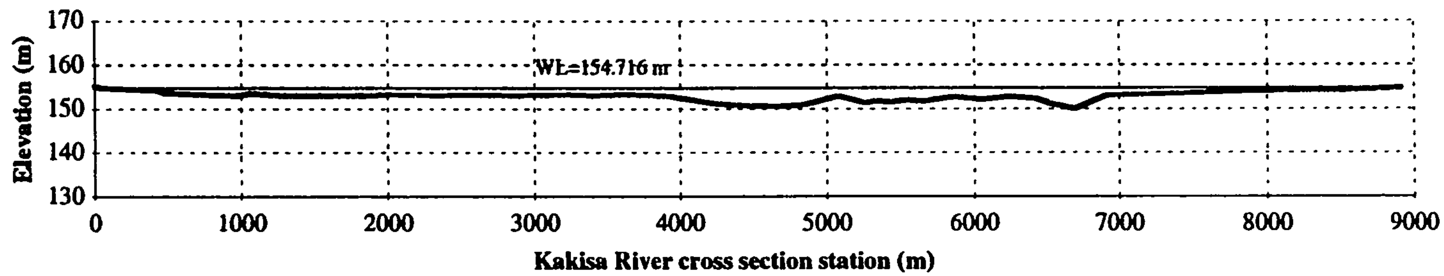
TBM: *This cross section is not tied into GSC.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
19000.00	156.47	19725.51	155.46	20484.35	155.27
19037.00	155.99	19761.64	155.57	20520.49	155.29
19075.07	155.67	19797.78	155.56	20556.62	155.14
19111.20	155.50	19833.91	155.49	20592.76	155.15
19147.34	155.45	19942.32	155.48	20610.83	155.12
19183.47	155.39	19978.46	155.31	20628.90	155.22
19219.61	155.38	20014.59	155.23	20665.03	155.34
19255.75	155.31	20032.66	155.14	20701.17	155.40
19309.95	155.13	20050.73	155.20	20737.30	155.39
19364.15	155.24	20086.86	155.32	20773.44	155.44
19400.29	155.30	20123.00	155.40	20809.57	155.50
19472.56	155.21	20159.13	155.42	20845.71	155.55
19508.69	155.25	20195.27	155.42	20881.84	155.57
19580.97	155.36	20231.40	155.35	20917.98	155.58
19599.03	155.39	20267.54	155.33	20954.12	155.60
19617.10	155.36	20303.68	155.32	20990.25	155.59
19635.17	155.40	20339.81	155.28	21008.32	155.59
19653.24	155.36	20375.95	155.21	21026.39	155.68
19671.30	155.36	20412.08	155.19	21030.00	155.62
19689.37	155.37	20448.22	155.23	21070.00	156.11

Figure A.3 North Channel cross section, 19.2 km downstream of Great Slave Lake.

Table A.3 Hydraulic components at North Channel cross section, 19.2 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
155.25	0.13	23	444	444	0.1
155.30	0.18	52	712	712	0.1
155.35	0.23	92	909	909	0.1
155.40	0.28	145	1227	1227	0.1
155.45	0.33	211	1405	1405	0.2
155.50	0.38	285	1608	1608	0.2
155.55	0.43	368	1697	1697	0.2
155.60	0.48	458	1920	1920	0.2
155.65	0.53	555	1945	1945	0.3
155.70	0.58	653	1965	1965	0.3
155.75	0.63	751	1975	1975	0.4
155.80	0.68	850	1985	1985	0.4
155.85	0.73	950	1995	1995	0.5
155.90	0.78	1050	2005	2005	0.5
155.95	0.83	1150	2015	2015	0.6
156.00	0.88	1251	2025	2025	0.6
156.05	0.93	1353	2033	2033	0.7
156.[illegible]	0.98	1454	2041	2041	0.7
156.15	1.03	1557	2045	2045	0.8
156.20	1.08	1659	2049	2049	0.8
156.25	1.13	1762	2053	2053	0.9
156.30	1.18	1864	2057	2057	0.9
156.35	1.23	1967	2061	2061	1.0
156.40	1.28	2070	2065	2065	1.0
156.45	1.33	2174	2068	2068	1.1
156.50	1.38	2277	2070	2070	1.1
156.55	1.43	2381	2070	2070	1.2
156.60	1.48	2484	2070	2070	1.2
156.65	1.53	2588	2070	2070	1.3
156.70	1.58	2691	2070	2070	1.3
156.75	1.63	2795	2070	2070	1.4
156.80	1.68	2898	2070	2070	1.4
156.85	1.73	3002	2070	2070	1.5
156.90	1.78	3105	2070	2070	1.5
156.95	1.83	3209	2070	2070	1.6
157.00	1.88	3312	2070	2070	1.6



Description: This cross section is located 34.2 km downstream of Great Slave Lake, on Beaver Lake upstream of the Kakisa River outlet. The section's north bank is close to Willow Point. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south shore, 44 m from the edge of the water. The depth sounding was begun 400 m from the edge of the water and stopped 400 m short of the north shore. The north shore was not surveyed since access by boat was impossible. The sounding data was evenly distributed across the channel (no horizontal control available due to GPS system battery failure). The water surface elevation, measured at 11:45 PM on July 10, 1992 was 154.716 m.

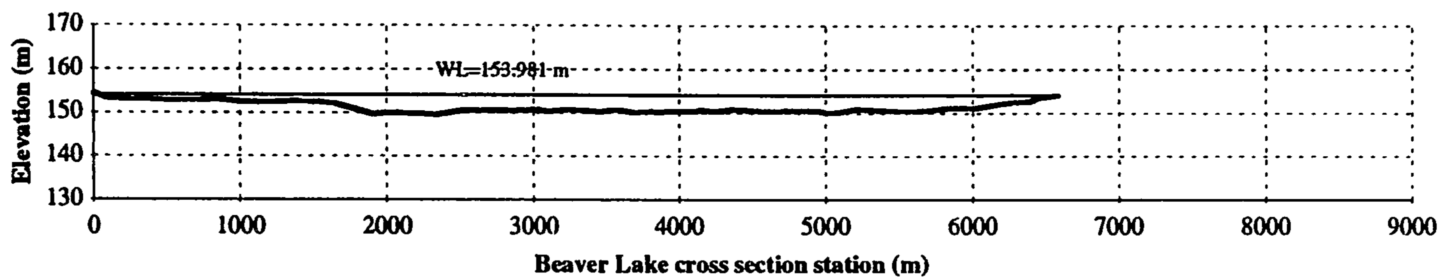
TBM: Spike in a flagged 30 cm diameter spruce tree, approximately 150 m into the bush on the south bank. Elevation 155.881 m determined by tying into Beaver Lake TBM on April 7, 1992.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	155.15	3560.93	153.23	6249.28	152.66
44.00	154.72	3677.81	153.19	6424.61	152.28
444.00	154.06	3775.22	153.03	6522.01	151.08
463.48	153.72	3931.06	152.84	6697.34	149.92
482.96	153.47	4008.99	152.43	6911.63	152.92
833.62	153.10	4223.28	151.26	7223.32	153.18
969.98	153.01	4379.12	150.73	7535.01	153.49
1067.39	153.36	4496.01	150.66	7846.70	153.88
1281.67	152.98	4671.33	150.51	8041.51	154.02
1320.64	152.97	4846.66	150.82	8294.76	154.08
1632.33	152.96	5080.43	152.86	8314.24	154.08
1905.06	152.99	5236.28	151.50	8511.00	154.11
2002.46	153.20	5275.24	151.32	8911.00	154.72
2333.64	153.01	5333.68	151.69		
2450.52	153.10	5431.09	151.44		
2723.25	153.09	5547.97	151.91		
2879.10	152.97	5645.37	151.53		
2995.99	153.06	5820.70	152.51		
3229.75	153.22	5879.14	152.56		
3405.08	152.94	6054.47	151.99		

Figure A.4 Kakisa River cross section, 34.2 km downstream of Great Slave Lake.

Table A.4 Hydraulic components at Kakisa River cross section, 34.2 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
151.0	1.08	310	808	808	0.4
151.1	1.18	394	870	870	0.5
151.2	1.28	483	926	926	0.5
151.3	1.38	579	978	978	0.6
151.4	1.48	680	1053	1053	0.7
151.5	1.58	791	1174	1174	0.7
151.6	1.68	916	1340	1340	0.7
151.7	1.78	1059	1514	1514	0.7
151.8	1.88	1217	1639	1639	0.7
151.9	1.98	1387	1764	1764	0.8
152.0	2.08	1567	1849	1850	0.9
152.1	2.18	1759	1984	1984	0.9
152.2	2.28	1964	2118	2118	0.9
152.3	2.38	2183	2260	2260	1.0
152.4	2.48	2417	2432	2432	1.0
152.5	2.58	2669	2605	2605	1.0
152.6	2.68	2941	2808	2808	1.1
152.7	2.78	3228	2902	2902	1.1
152.8	2.88	3520	2951	2951	1.2
152.9	2.98	3819	3029	3029	1.3
153.0	3.08	4152	3996	3996	1.0
153.1	3.18	4606	5363	5363	0.9
153.2	3.28	5185	6225	6225	0.8
153.3	3.38	5834	6649	6650	0.9
153.4	3.48	6512	6895	6895	0.9
153.5	3.58	7211	7063	7063	1.0
153.6	3.68	7922	7151	7151	1.1
153.7	3.78	8641	7239	7239	1.2
153.8	3.88	9370	7325	7325	1.3
153.9	3.98	10107	7422	7422	1.4
154.0	4.08	10856	7567	7567	1.4
154.1	4.18	11631	8027	8027	1.5
154.2	4.28	12445	8211	8211	1.5
154.3	4.38	13273	8337	8337	1.6
154.4	4.48	14113	8464	8464	1.7
154.5	4.58	14965	8590	8590	1.7
154.6	4.68	15831	8716	8716	1.8
154.7	4.78	16709	8842	8842	1.9
154.8	4.88	17596	8875	8875	2.0
154.9	4.98	18484	8885	8886	2.1
155.0	5.08	19373	8896	8896	2.2
155.1	5.18	20263	8906	8906	2.3
155.2	5.28	21154	8911	8911	2.4
155.3	5.38	22045	8911	8911	2.5
155.4	5.48	22936	8911	8911	2.6
155.5	5.58	23827	8911	8911	2.7



Description: This cross section is located 47.5 km downstream of Great Slave Lake, at Beaver Lake near Point Sarristo. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south shore, 27 m from the edge of the water. The depth sounding was begun 20 m from the edge of the waterand stopped 150 m short of the north shore. The north shore was not surveyed, due to problems accessing the shore by boat. The sounding data was evenly distributed across the channel (no horizontal control available due to GPS system battery failure). The water surface elevation, measured at 4:35 PM on July 10, 1992 was 153.981 m.

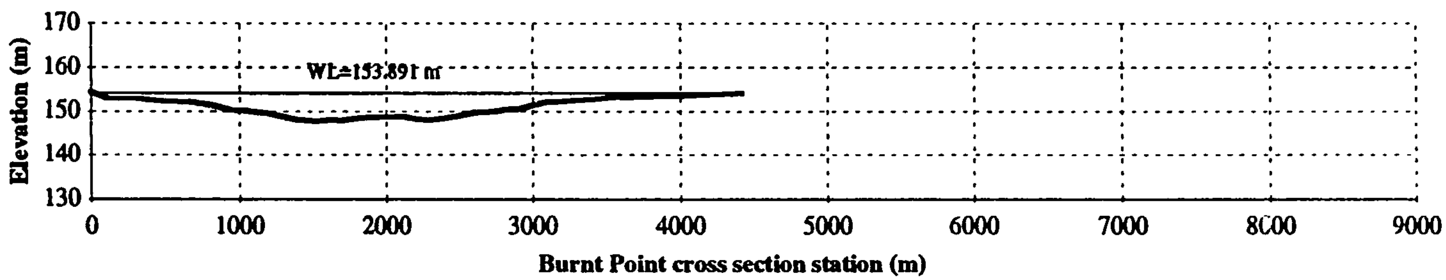
TBM: The TBM used to tie in Beaver Lake is located 1.7 km downstream of this cross section sounding, and 47.3 km downstream of Great Slave Lake. Spike in 13 cm diameter spruce farthest out on point. Elevation 155.351 m determined by tying into the original Burnt Point TBM on Dec 10, 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	154.49	2692.68	150.58	4766.32	150.53
94.67	153.22	2859.52	150.37	4813.99	150.40
261.51	152.88	3026.37	150.69	4933.17	150.50
333.02	152.94	3097.87	150.23	4957.00	150.38
476.03	152.76	3217.05	150.66	4980.83	150.18
738.21	152.76	3336.22	150.54	5052.34	149.94
833.55	152.90	3455.40	150.19	5219.18	150.87
881.22	152.82	3526.90	150.47	5433.70	150.52
1000.40	152.37	3598.41	150.47	5481.37	150.40
1214.91	152.23	3693.75	150.13	5648.21	150.43
1357.92	152.45	3812.92	150.32	5862.73	151.07
1524.77	152.41	3860.59	150.19	6005.74	150.94
1643.94	152.02	3979.77	150.40	6077.24	151.33
1906.13	149.56	4027.44	150.24	6196.42	151.96
2001.47	149.98	4098.94	150.32	6291.76	152.37
2120.64	149.79	4146.61	150.63	6387.10	152.47
2239.82	149.76	4241.95	150.32	6410.93	152.77
2335.16	149.46	4361.13	150.76	6430.00	153.13
2525.83	150.54	4551.81	150.45	6580.00	153.98
2645.01	150.44	4647.15	150.28		

Figure A.5 Beaver Lake cross section, 47.5 km downstream of Great Slave Lake.

Table A.5 Hydraulic components at Beaver Lake cross section, 47.5 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
150.0	0.54	136	600	600	0.2
150.1	0.64	200	676	676	0.3
150.2	0.74	274	827	827	0.3
150.3	0.84	375	1252	1252	0.3
150.4	0.94	526	1769	1769	0.3
150.5	1.04	757	2810	2810	0.3
150.6	1.14	1071	3403	3403	0.3
150.7	1.24	1431	3766	3766	0.4
150.8	1.34	1818	3943	3943	0.5
150.9	1.44	2218	4043	4043	0.6
151.0	1.54	2627	4164	4164	0.6
151.1	1.64	3051	4293	4293	0.7
151.2	1.74	3482	4322	4322	0.8
151.3	1.84	3916	4351	4351	0.9
151.4	1.94	4352	4380	4380	1.0
151.5	2.04	4792	4410	4410	1.1
151.6	2.14	5234	4439	4439	1.2
151.7	2.24	5680	4469	4469	1.3
151.8	2.34	6128	4498	4498	1.4
151.9	2.44	6579	4528	4528	1.5
152.0	2.54	7034	4559	4559	1.5
152.1	2.64	7492	4609	4609	1.6
152.2	2.74	7956	4663	4663	1.7
152.3	2.84	8430	4870	4870	1.7
152.4	2.94	8931	5126	5126	1.7
152.5	3.04	9463	5424	5424	1.7
152.6	3.14	10007	5458	5458	1.8
152.7	3.24	10555	5493	5493	1.9
152.8	3.34	11118	5848	5848	1.9
152.9	3.44	11713	6087	6087	1.9
153.0	3.54	12331	6220	6220	2.0
153.1	3.64	12955	6275	6275	2.1
153.2	3.74	13586	6338	6338	2.1
153.3	3.84	14222	6371	6371	2.2
153.4	3.94	14860	6396	6396	2.3
153.5	4.04	15501	6421	6421	2.4
153.6	4.14	16145	6446	6446	2.5
153.7	4.24	16790	6472	6472	2.6
153.8	4.34	17439	6497	6497	2.7
153.9	4.44	18090	6522	6522	2.8
154.0	4.54	18743	6543	6543	2.9
154.1	4.64	19398	6551	6551	3.0
154.2	4.74	20054	6558	6558	3.1
154.3	4.84	20710	6566	6566	3.2
154.4	4.94	21367	6573	6573	3.3
154.5	5.04	22025	6580	6580	3.4



Description: This cross section is located 52.6 km downstream of Great Slave Lake, by Burnt Point. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south bank, 19 m from the edge of the water. The depth sounding was begun 50 m from the edge of the water and stopped 400 m short of the north bank. The north bank could not be surveyed, due to problems accessing the bank by boat. The sounding data was evenly distributed across the channel (horizontal control provided by GPS). The water surface elevation, measured at 5:45 PM on July 10, 1992 was 153.891 m.

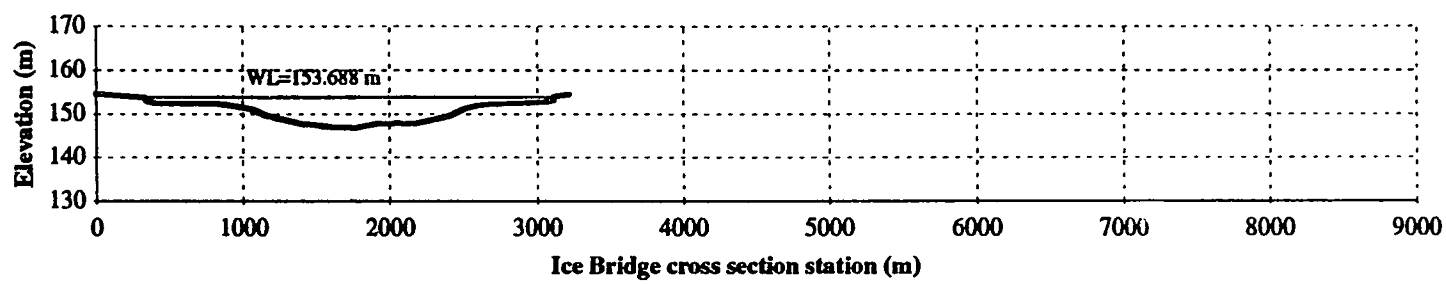
TBM: The orginal TBM for Burnt Point was located 1.8 km downstream of this cross section sounding, and 52.8 km downstream of Great Slave Lake. It was lost during the ice run from Great Slave Lake in June 1992. The new TBM, a spike in 6" birch tree in the bush, was set up on July 11,1992 by tying into a large rock. Elevation 154.426 m determined based on this rock, which was tied into Ice Bridge TBM #1 on Dec 10, 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	154.35	1625.65	148.06	3271.25	152.33
19.00	154.11	1692.37	147.90	3360.21	152.54
69.00	153.42	1781.32	148.29	3426.92	152.73
91.24	153.13	1870.27	148.51	3515.87	153.07
113.48	152.89	1959.22	148.66	3582.59	153.20
313.62	152.81	2048.17	148.64	3627.06	153.03
402.57	152.51	2114.89	148.79	3716.01	153.17
491.52	152.31	2203.84	148.28	3827.20	153.24
580.47	152.20	2292.79	148.03	3916.15	153.40
669.42	152.04	2381.74	148.37	3982.87	153.35
758.37	151.62	2470.69	148.83	4014.00	153.43
847.33	151.09	2559.64	149.36	4414.00	154.11
936.28	150.29	2604.12	149.65		
1025.23	150.15	2670.83	149.67		
1114.18	149.78	2737.55	149.92		
1203.13	149.49	2826.50	150.43		
1292.08	148.77	2915.45	150.58		
1381.03	148.04	3004.40	151.37		
1514.46	147.81	3093.35	152.00		
1581.18	147.88	3182.30	152.14		

Figure A.6 Burnt Point cross section, 52.6 km downstream of Great Slave Lake.

Table A.6 Hydraulic components at Burnt Point cross section, 52.6 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
150.0	2.41	[illegible]	1806	1806	1.5
150.1	2.51		1873	1873	1.5
150.2	2.61		1902	1902	1.6
150.3	2.71		1965	1965	1.6
150.4	2.81		2019	2019	1.7
150.5	2.91		2041	2041	1.8
150.6	3.01	[illegible]	2064	2064	1.9
150.7	3.11	[illegible]	2087	2087	1.9
150.8	3.21	4229	2109	2109	2.0
150.9	3.31	4441	2134	2134	2.1
151.0	3.41	4656	2161	2161	2.2
151.1	3.51	4874	2189	2189	2.2
151.2	3.61	5094	2218	2218	2.3
151.3	3.71	5317	2249	2249	2.4
151.4	3.81	5544	2279	2279	2.4
151.5	3.91	5773	2314	2314	2.5
151.6	4.01	6007	2349	2349	2.6
151.7	4.11	6243	2384	2384	2.6
151.8	4.21	6483	2425	2425	2.7
151.9	4.31	6731	2541	2541	2.7
152.0	4.41	6991	2653	2653	2.6
152.1	4.51	7262	2771	2771	2.6
152.2	4.61	7544	2858	2858	2.6
152.3	4.71	7834	2945	2945	2.7
152.4	4.81	8132	3014	3014	2.7
152.5	4.91	8437	3082	3082	2.7
152.6	5.01	8748	3163	3163	2.8
152.7	5.11	9077	3366	3366	2.7
152.8	5.21	9415	3401	3401	2.8
152.9	5.31	9761	3522	3522	2.8
153.0	5.41	10121	3695	3695	2.7
153.1	5.51	10496	3791	3792	2.8
153.2	5.61	10883	3937	3937	2.8
153.3	5.71	11279	4000	4000	2.8
153.4	5.81	11683	4067	4067	2.9
153.5	5.91	12093	4134	4134	2.9
153.6	6.01	12509	4201	4201	3.0
153.7	6.11	12933	4268	4268	3.0
153.8	6.21	13363	4335	4335	3.1
153.9	6.31	13800	4396	4396	3.1
154.0	6.41	14240	4403	4403	3.2
154.1	6.51	14681	4411	4411	3.3
154.2	6.61	15122	4414	4414	3.4
154.3	6.71	15563	4414	4414	3.5
154.4	6.81	16005	4414	4414	3.6
154.5	6.91	16446	4414	4414	3.7



Description: This cross section is located 59.2 km downstream of Great Slave Lake, near the ice bridge approach roads. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south bank, 326 m from the edge of the water. The depth sounding was begun 15 m from the edge of the water and stopped 2 m short of the north bank, which was then surveyed for a distance of 101 m from the edge of the water. The sounding data was evenly distributed across the channel (no horizontal control available due to GPS system battery failure). The water surface elevation, measured at 6:40 PM on July 10, 1992 was 153.688 m.

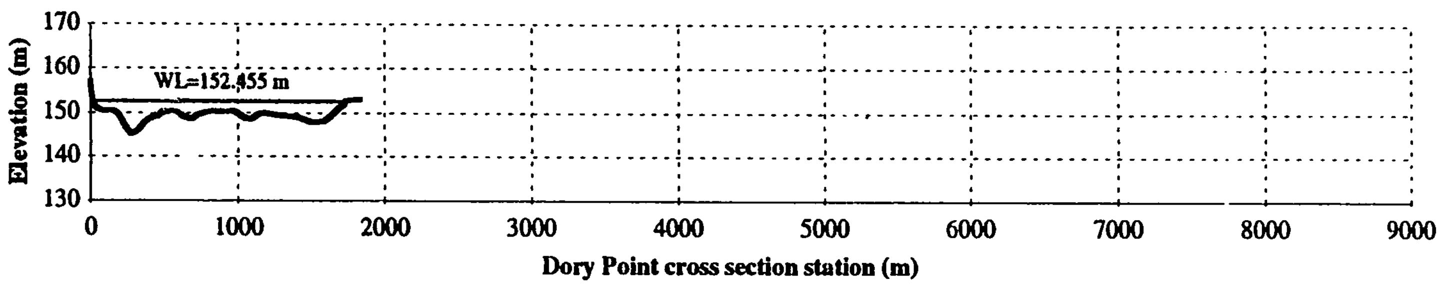
SOUTH TBM #1: Spike in an 18 cm diameter birch tree on the east side of the road on the south bank Elevation 154.605 m determined by tying into GSC Bench Mark No. 86T037 on May 8, 1991.
SOUTH TBM #2: Spike in 15 cm diameter tree on west side of road. Elevation 154.710 m determined by tying into TBM #1 on May 8,1991.
NORTH TBM: Spike in a flagged 10 cm diameter poplar tree approximately 10 m north of the road. Elevation 155.884 m determined by tying into Dory Point North TBM on May 15, 1992. *Elevation to be confirmed - spring 1993.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	154.60	1805.03	147.04
326.00	153.69	1915.94	147.74
341.00	153.09	1982.49	147.82
363.18	152.66	2004.67	147.73
407.55	152.33	2049.03	147.86
496.28	152.44	2159.94	147.68
740.28	152.44	2315.22	148.79
806.83	152.33	2403.95	149.47
939.92	151.77	2514.86	151.27
1050.83	151.15	2603.59	151.94
1073.01	150.83	2670.14	152.16
1161.74	149.62	2736.68	152.29
1294.84	148.54	2869.78	152.35
1405.75	147.61	3002.87	152.63
1472.29	147.53	3047.24	152.63
1494.48	147.35	3113.78	153.02
1605.39	146.89	3118.00	153.71
1694.12	146.87	3119.00	153.99
1738.48	146.78	3219.00	154.41
1760.66	146.70		

Figure A.7 Ice Bridge cross section, 59.2 km downstream of Great Slave Lake.

Table A.7 Hydraulic components at Ice Bridge cross section, 59.2 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
149.5	2.8	2066	1229	1229	1.7
149.6	2.9	2189	1248	1248	1.8
149.7	3	2315	1262	1262	1.8
149.8	3.1	2442	1276	1276	1.9
149.9	3.2	2570	1289	1289	2.0
150.0	3.3	2700	1303	1303	2.1
150.1	3.4	2831	1316	1316	2.2
150.2	3.5	2963	1330	1330	2.2
150.3	3.6	3097	1343	1343	2.3
150.4	3.7	3232	1357	1357	2.4
150.5	3.8	3368	1370	1370	2.5
150.6	3.9	3506	1384	1384	2.5
150.7	4	3645	1397	1397	2.6
150.8	4.1	3785	1411	1411	2.7
150.9	4.2	3927	1424	1424	2.8
151.0	4.3	4070	1437	1437	2.8
151.1	4.4	4214	1450	1450	2.9
151.2	4.5	4360	1469	1469	3.0
151.3	4.6	4508	1495	1495	3.0
151.4	4.7	4659	1526	1526	3.1
151.5	4.8	4813	1557	1557	3.1
151.6	4.9	4971	1588	1589	3.1
151.7	5	5131	1620	1620	3.2
151.8	5.1	5295	1653	1653	3.2
151.9	5.2	5462	1690	1690	3.2
152.0	5.3	5633	1737	1737	3.2
152.1	5.4	5809	1791	1791	3.2
152.2	5.5	5991	1853	1853	3.2
152.3	5.6	6181	1946	1946	3.2
152.4	5.7	6388	2196	2196	2.9
152.5	5.8	6630	2557	2557	2.6
152.6	5.9	6889	2618	2618	2.6
152.7	6	7156	2698	2698	2.7
152.8	6.1	7427	2720	2721	2.7
152.9	6.2	7700	2743	2743	2.8
153.0	6.3	7976	2765	2765	2.9
153.1	6.4	8253	2774	2774	3.0
153.2	6.5	8530	2777	2777	3.1
153.3	6.6	8808	2780	2780	3.2
153.4	6.7	9086	2783	2783	3.3
153.5	6.8	9365	2786	2786	3.4
153.6	6.9	9644	2789	2789	3.5
153.7	7	9923	2796	2796	3.6
153.8	7.1	10204	2832	2832	3.6
153.9	7.2	10489	2868	2868	3.7
154.0	7.3	10778	2907	2907	3.7



Description: This cross section is located 63.7 km downstream of Great Slave Lake at Dory Point. Surveying and depth soundings were performed on July 10, 1992. The survey was started on the south bank, 12 m from the edge of the water. The depth sounding was begun 5 m from the edge of the water and stopped 5 m short of the north bank, which was then surveyed for a distance of 101 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal contrc) was provided by using GPS). The water surface elevation, measured at 8:20 PM on July 10, 1992 was 152.455 m.

SOUTH TBM: Spike in a 22 cm diameter spruce tree at the east side of the footpath. Elevation of 155.900 m determined by tying into GSC Bench Mark No. 86T038 on April 22, 1991. This elevation was confirmed by WSC on June 3, 1992.

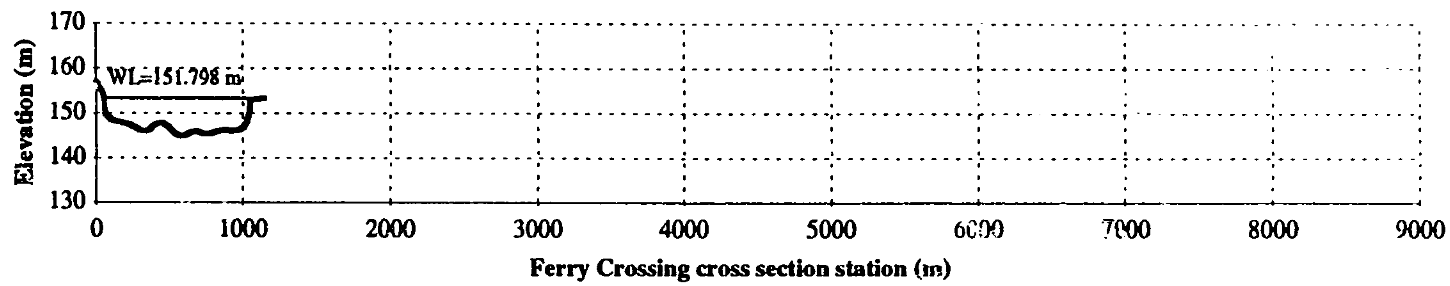
NORTH TBM: Top of northeast bolt in the base of a navigational beacon on the north bank, adjacent to a cabin south of the road. Elevat· a 155.752 m determined by tying into GSC Bench Mark No. 66T132 on May 16, 1992. *Elevation to be confirmed - spring 1993.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	157.03	446.40	149.24	1090.49	148.60
2.00	155.20	489.34	149.75	1111.96	149.03
7.00	154.25	532.28	150.15	1133.43	149.58
12.00	152.97	575.22	150.30	1154.90	149.82
17.00	152.00	596.69	149.91	1176.37	149.97
38.47	150.95	618.16	149.41	1305.19	149.31
59.94	150.58	639.63	148.96	1369.60	149.17
81.41	150.38	682.57	148.56	1412.54	148.91
145.82	150.44	704.04	149.02	1476.95	148.14
167.29	150.16	725.51	149.46	1498.42	147.78
188.76	149.45	746.97	149.71	1584.30	148.00
210.23	148.31	789.91	150.19	1627.24	149.19
231.70	147.14	832.85	150.31	1648.71	149.85
253.17	145.94	940.20	150.25	1670.18	150.52
274.64	145.10	961.67	150.46	1691.65	151.24
317.58	145.87	983.14	150.21	1713.12	151.65
339.05	146.67	1004.61	149.74	1726.00	151.99
360.52	147.58	1026.08	149.19	1731.00	152.34
381.99	148.37	1047.55	148.78	1732.00	152.76
424.93	148.99	1069.02	148.42	1832.00	153.06

Figure A.8 Dory Point cross section, 63.7 km downstream of Great Slave Lake.

Table A.8 Hydraulic components at Dory Point cross section, 63.7 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
148.5	3.4	417	354	354	1.2
148.6	3.5	454	398	398	1.1
148.7	3.6	496	445	445	1.1
148.8	3.7	543	492	492	1.1
148.9	3.8	595	538	538	1.1
149.0	3.9	651	590	590	1.1
149.1	4	713	640	640	1.1
149.2	4.1	779	698	698	1.1
149.3	4.2	853	776	776	1.1
149.4	4.3	933	829	829	1.1
149.5	4.4	1019	881	881	1.2
149.6	4.5	1110	937	937	1.2
149.7	4.6	1206	997	997	1.2
149.8	4.7	1309	1059	1059	1.2
149.9	4.8	1418	1126	1127	1.3
150.0	4.9	1534	1186	1186	1.3
150.1	5	1655	1222	1223	1.4
150.2	5.1	1779	1272	1272	1.4
150.3	5.2	1913	1456	1456	1.3
150.4	5.3	2062	1530	1530	1.4
150.5	5.4	2220	1601	1601	1.4
150.6	5.5	2381	1614	1614	1.5
150.7	5.6	2543	1623	1623	1.6
150.8	5.7	2706	1632	1632	1.7
150.9	5.8	2869	1641	1641	1.8
151.0	5.9	3034	1648	1648	1.8
151.1	6	3199	1653	1653	1.9
151.2	6.1	3364	1658	1658	2.0
151.3	6.2	3530	1664	1664	2.1
151.4	6.3	3697	1671	1672	2.2
151.5	6.4	3865	1678	1679	2.3
151.6	6.5	4033	1685	1686	2.4
151.7	6.6	4202	1692	1692	2.5
151.8	6.7	4371	1698	1698	2.6
151.9	6.8	4541	1704	1704	2.7
152.0	6.9	4712	1709	1710	2.8
152.1	7	4883	1711	1711	2.9
152.2	7.1	5054	1713	1713	3.0
152.3	7.2	5226	1715	1715	3.1
152.4	7.3	5397	1716	1717	3.1
152.5	7.4	5569	1717	1717	3.2
152.6	7.5	5741	1718	1718	3.3
152.7	7.6	5913	1718	1719	3.4
152.8	7.7	6085	1733	1733	3.5
152.9	7.8	6260	1766	1767	3.5
153.0	7.9	6438	1800	1801	3.6



Description: This cross section is located 65.3 km downstream of Great Slave Lake, at the ferry crossing, adjacent to the relocated WSC gauge station 10FB001. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the south bank, 5.02 m from the edge of the sheet pile wall. The depth sounding was begun 5 m from the sheet piling and stopped 5 m short of the north bank, which was then surveyed for a distance of 36 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 10:30 AM on July 11, 1992 was 151.798 m.

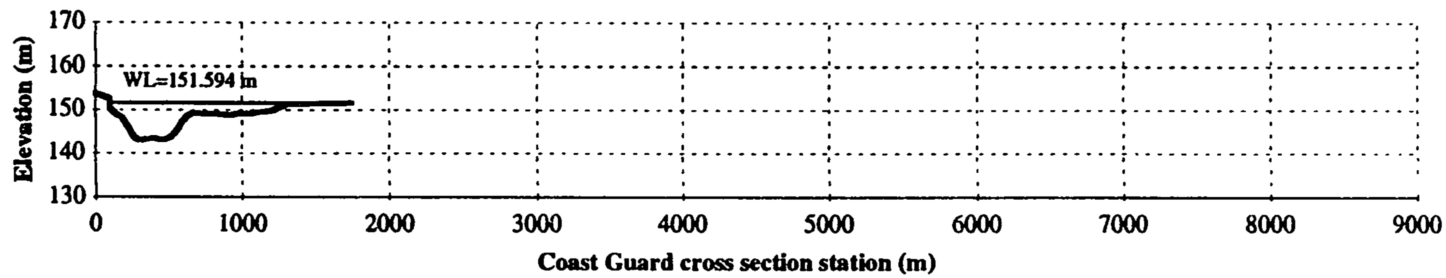
TBM #1: Top of the southwest end of the sheet piling at the south bank ferry landing. Elevation 153.358 m determined by tying into GSC Bench Mark No. 86T0.? on April 29, 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	156.85	320.73	146.03	751.93	145.40
12.00	156.40	342.29	145.93	773.49	145.34
18.00	155.65	363.85	146.39	795.05	145.58
42.00	154.87	385.41	147.06	816.62	145.76
44.00	154.26	406.97	147.49	838.18	146.03
55.00	153.51	428.53	147.70	859.74	146.14
56.80	152.17	450.09	147.81	881.30	146.26
57.00	151.06	471.65	147.52	902.36	146.09
62.00	150.01	493.21	146.90	924.42	146.07
83.56	149.20	514.77	146.28	945.98	146.10
105.12	148.37	536.33	145.61	967.54	146.28
126.68	148.28	557.89	145.18	989.10	146.34
148.24	148.09	579.45	144.81	1010.66	147.06
169.80	147.90	601.01	144.95	1032.22	148.24
191.36	147.68	622.57	145.36	1043.00	149.59
212.92	147.55	644.13	145.63	1048.00	150.80
234.48	147.34	665.69	145.87	1048.20	153.08
256.04	146.92	687.25	145.97	1148.00	153.36
277.60	146.66	708.81	145.72		
299.16	146.17	730.37	145.31		

Figure A.9 Ferry Crossing cross section, 65.3 km downstream of Great Slave Lake.

Table A.9 Hydraulic components at Ferry Crossing cross section, 65.3 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
148.0	3.21	1482	872	872	1.7
148.1	3.31	1570	886	886	1.8
148.2	3.41	1659	899	900	1.8
148.3	3.51	1750	917	917	1.9
148.4	3.61	1843	930	930	2.0
148.5	3.71	1936	933	934	2.1
148.6	3.81	2029	937	937	2.2
148.7	3.91	2123	940	940	2.3
148.8	4.01	2217	944	944	2.4
148.9	4.11	2312	947	947	2.4
149.0	4.21	2407	951	951	2.5
149.1	4.31	25[illegible]	954	954	2.6
149.2	4.41	25[illegible]	957	958	2.7
149.3	4.51	2694	961	961	2.8
149.4	4.61	2790	964	965	2.9
149.5	4.71	2886	968	968	3.0
149.6	4.81	2983	971	971	3.1
149.7	4.91	3081	974	974	3.2
149.8	5.01	3178	977	977	3.3
149.9	5.11	3276	980	981	3.3
150.0	5.21	3374	983	983	3.4
150.1	5.31	3473	984	984	3.5
150.2	5.41	3571	985	985	3.6
150.3	5.51	3670	986	986	3.7
150.4	5.61	3768	986	987	3.8
150.5	5.71	3867	987	988	3.9
150.6	5.81	3966	988	989	4.0
150.7	5.91	4065	989	990	4.1
150.8	6.01	4164	990	990	4.2
150.9	6.11	4263	990	991	4.3
151.0	6.21	4362	991	992	4.4
151.1	6.31	4461	991	992	4.5
151.2	6.41	4560	991	992	4.6
151.3	6.51	4659	991	992	4.7
151.4	6.61	4758	991	993	4.8
151.5	6.71	4857	991	993	4.9
151.6	6.81	4956	992	993	5.0
151.7	6.91	5056	992	993	5.1
151.8	7.01	5155	992	994	5.2
151.9	7.11	5254	992	994	5.3
152.0	7.21	5353	992	994	5.4
152.1	7.31	5452	992	994	5.5
152.2	7.41	5552	992	994	5.6
152.3	7.51	5651	992	995	5.7
152.4	7.61	5750	992	995	5.8
152.5	7.71	5849	992	995	5.9



Description: This cross section is located 67.3 km downstream of Great Slave Lake, next to the Coast Guard road. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the south bank, 100 m from the wharf edge. The depth sounding was started 0.2 m from the wharf edge and stopped 400 m short of the north bank. The north bank was not surveyed because large rocks prevented access by boat. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 11:20 AM on July 11, 1992 was 151.594 m.

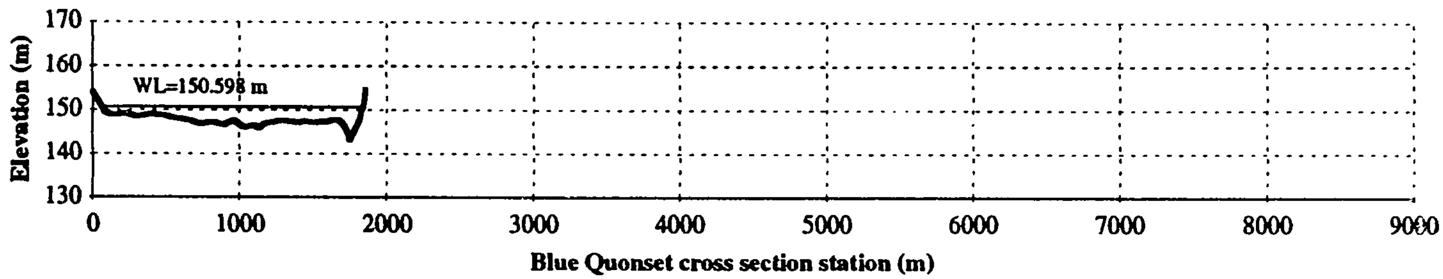
SOUTH TBM: Western most bolt on the west mooring post of the Coast Guard dock on the south bank. Elevation 152.492 m determined by tying into GSC Bench Mark No. 86T039 on May 9, 1991.
NORTH TBM: Spike in a flagged 8 cm diameter poplar tree approximately 30 m south of the road, adjacent to a culvert. Elevation 155.522 m determined by tying into the green plate on top of GSC Bench Mark No. 86T040 on May 12, 1992. *Elevation to be confirmed - spring 1993.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	153.62	435.18	143.18	1012.08	149.02
100.00	152.47	472.40	143.16	1030.69	149.12
100.00	151.21	509.62	143.72	1049.30	149.06
100.20	150.32	546.84	145.01	1067.91	149.19
118.81	149.65	565.45	145.97	1086.52	149.27
137.42	148.98	584.06	146.92	1105.13	149.42
156.03	148.59	602.67	147.68	1123.74	149.34
174.64	148.29	621.28	148.33	1142.35	149.45
193.25	147.47	658.50	149.13	1160.96	149.46
211.86	146.37	677.11	149.21	1179.57	149.68
230.47	145.44	714.33	149.10	1198.18	149.74
249.08	144.45	751.55	148.99	1216.79	149.87
267.69	143.59	788.77	149.06	1235.40	150.24
286.30	143.20	825.98	149.05	1254.01	150.54
304.91	142.97	863.20	148.87	1272.62	150.71
323.52	142.98	900.42	148.72	1291.23	151.01
342.13	143.29	937.64	148.81	1309.84	151.29
360.74	143.27	956.25	148.99	1328.45	151.35
379.35	143.32	974.86	149.11	1345.00	151.29
397.96	143.44	993.47	149.11	1745.00	151.59

Figure A.10 Coast Guard cross section, 67.3 km downstream of Great Slave Lake.

Table A.10 Hydraulic components at Coast Guard cross section, 67.3 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
148.0	5.03	1566	431	431	3.6
148.1	5.13	1609	435	436	3.7
148.2	5.23	1653	440	441	3.8
148.3	5.33	1697	446	446	3.8
148.4	5.43	1743	456	456	3.8
148.5	5.53	1789	467	467	3.8
148.6	5.63	1836	478	478	3.8
148.7	5.73	1884	488	488	3.9
148.8	5.83	1936	551	551	3.5
148.9	5.93	1993	597	597	3.3
149.0	6.03	2055	646	646	3.2
149.1	6.13	2129	833	833	2.6
149.2	6.23	2218	934	934	2.4
149.3	6.33	2313	962	963	2.4
149.4	6.43	2411	1001	1001	2.4
149.5	6.53	2513	1041	1042	2.4
149.6	6.63	2618	1053	1053	2.5
149.7	6.73	2724	1069	1069	2.6
149.8	6.83	2832	1092	1092	2.6
149.9	6.93	2942	1107	1107	2.7
150.0	7.03	3053	1114	1115	2.7
150.1	7.13	3165	1122	1122	2.8
150.2	7.23	3278	1130	1130	2.9
150.3	7.33	3391	1138	1139	3.0
150.4	7.43	3505	1145	1146	3.1
150.5	7.53	3620	1152	1152	3.1
150.6	7.63	3736	1161	1161	3.2
150.7	7.73	3852	1172	1173	3.3
150.8	7.83	3970	1178	1179	3.4
150.9	7.93	4088	1184	1185	3.5
151.0	8.03	4207	1190	1191	3.5
151.1	8.13	4326	1197	1198	3.6
151.2	8.23	4446	1204	1205	3.7
151.3	8.33	4567	1230	1231	3.7
151.4	8.43	4699	1392	1394	3.4
151.5	8.53	4845	1526	1527	3.2
151.6	8.63	5004	1645	1647	3.0
151.7	8.73	5169	1645	1647	3.1
151.8	8.83	5333	1645	1647	3.2
151.9	8.93	5498	1645	1647	3.3
152.0	9.03	5662	1645	1647	3.4
152.1	9.13	5827	1645	1647	3.5
152.2	9.23	5991	1645	1647	3.6
152.3	9.33	6156	1645	1647	3.7
152.4	9.43	6320	1645	1647	3.8
152.5	9.53	6485	1648	1650	3.9



Description: This cross section is located 71.5 km downstream of Great Slave Lake, adjacent to a blue-green quonset on the north bank. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 16.529 m from the edge of the water. The depth sounding was begun 10 m from the edge of the water and stopped 3 m short of the south bank, which was then surveyed for a distance of 60 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 11:55 PM on July 11, 1992 was 150.598 m.

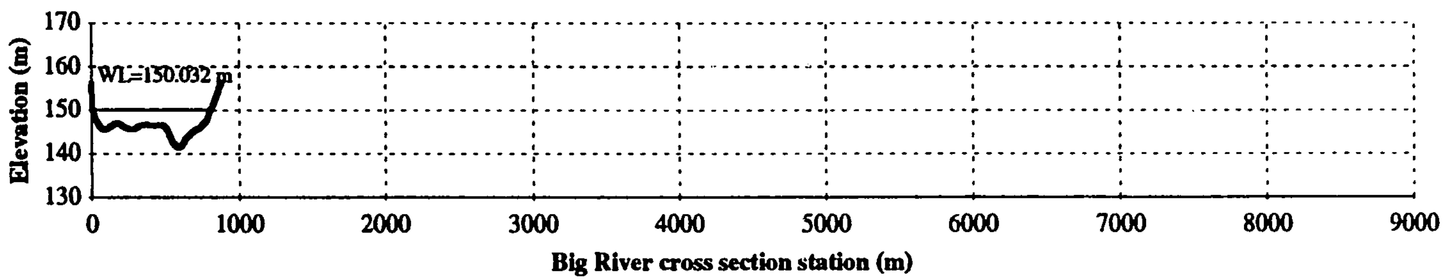
TBM: Spike in a flagged 12 cm diameter poplar tree approximately 200 m southwest of the road. Elevation 155.383 m determined by tying into GSC Bench Mark No. 86T042 on May 3, 1992.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	153.93	631.92	147.82	1301.24	147.55
60.00	150.60	665.39	147.62	1334.70	147.49
63.00	150.55	698.85	147.17	1368.17	147.29
79.73	149.60	732.32	146.84	1401.64	147.07
96.47	149.27	765.78	146.85	1435.10	147.38
129.93	148.76	799.25	147.21	1468.57	147.28
163.40	148.82	832.72	147.15	1502.03	147.18
196.86	149.01	866.18	146.73	1535.50	147.04
230.33	149.13	899.65	146.61	1568.97	147.37
263.80	148.83	933.11	147.16	1602.43	147.32
297.26	148.48	966.58	147.60	1635.90	147.74
330.73	148.61	1000.05	146.72	1669.36	147.77
364.19	148.83	1033.51	146.08	1702.83	146.92
397.66	149.01	1066.98	146.30	1736.30	145.19
431.13	148.88	1100.44	146.45	1753.03	143.19
464.59	148.77	1133.91	145.82	1803.23	146.67
498.06	148.62	1167.38	146.73	1819.96	148.01
531.52	148.34	1200.84	147.06	1830.00	149.90
564.99	148.14	1234.31	147.17	1840.00	150.60
598.45	148.03	1267.77	147.52	1856.53	154.57

Figure A.11 Blue Quonset cross section, 71.5 km downstream of Great Slave Lake.

Table A.11 Hydraulic components at Blue Quonset cross section, 71.5 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
147.0	3.81	336	455	456	0.7
147.1	3.91	385	544	544	0.7
147.2	4.01	447	697	697	0.6
147.3	4.11	522	806	807	0.7
147.4	4.21	610	939	939	0.7
147.5	4.31	707	1002	1002	0.7
147.6	4.41	813	1097	1098	0.7
147.7	4.51	924	1125	1126	0.8
147.8	4.61	1039	1182	1182	0.9
147.9	4.71	1158	1200	1200	1.0
148.0	4.81	1279	1217	1217	1.1
148.1	4.91	1402	1244	1244	1.1
148.2	5.01	1528	1266	1266	1.2
148.3	5.11	1655	1283	1283	1.3
148.4	5.21	1784	1297	1298	1.4
148.5	5.31	1915	1317	1318	1.5
148.6	5.41	2049	1366	1366	1.5
148.7	5.51	2188	1412	1412	1.6
148.8	5.61	2332	1486	1487	1.6
148.9	5.71	2485	1577	1577	1.6
149.0	5.81	2647	1658	1658	1.6
149.1	5.91	2815	1707	1707	1.7
149.2	6.01	2987	1726	1726	1.7
149.3	6.11	3160	1732	1733	1.8
149.4	6.21	3334	1738	1738	1.9
149.5	6.31	3508	1743	1744	2.0
149.6	6.41	3683	1748	1749	2.1
149.7	6.51	3857	1751	1751	2.2
149.8	6.61	4033	1753	1754	2.3
149.9	6.71	4208	1755	1756	2.4
150.0	6.81	4384	1759	1759	2.5
150.1	6.91	4560	1762	1762	2.6
150.2	7.01	4736	1765	1766	2.7
150.3	7.11	4913	1768	1769	2.8
150.4	7.21	5090	1771	1772	2.9
150.5	7.31	5267	1775	1775	3.0
150.6	7.41	5445	1780	1781	3.1
150.7	7.51	5623	1782	1783	3.2
150.8	7.61	5801	1784	1785	3.3
150.9	7.71	5980	1787	1787	3.4
151.0	7.81	6159	1789	1790	3.4
151.1	7.91	6338	1791	1792	3.5
151.2	8.01	6517	1793	1794	3.6
151.3	8.11	6696	1796	1796	3.7
151.4	8.21	6876	1798	1799	3.8
151.5	8.31	7056	1800	1801	3.9



Description: This cross section is located 72.7 km downstream of Great Slave Lake, adjacent to the Big River Restaurant and across the Providence Narrows to Meridian Island. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 71.7 m from the edge of the water. The depth sounding was started 12 m from the edge of the water and stopped 2 m short of the south bank, which was then surveyed for a distance of 6 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 2:00 PM on July 11, 1992 was 150.032 m.

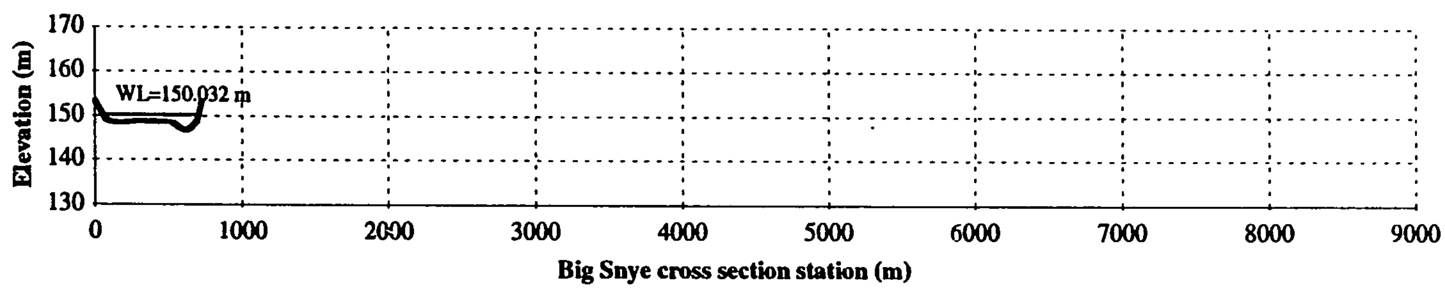
TBM #1: Southwest corner of Big River Restaurant at ground elevation. Elevation 157.178 m determined by tying into GSC Bench Mark No. 86T043 on Aug. 27, 1991. TBM #1 was lost during building renovations, fall 1992.
TBM #2: Spike in power pole located between restaurant and river. Elevation 157.477 m determined by tying into TBM #1 on Aug. 27, 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	156.03	332.99	146.49	694.09	145.33
6.00	150.03	351.04	146.62	712.14	145.69
8.00	150.16	369.10	146.74	730.20	145.93
26.05	147.94	387.15	146.65	748.25	146.56
44.11	146.88	405.21	146.48	766.31	147.17
62.16	145.99	423.26	146.43	784.36	148.02
80.22	145.50	441.32	146.51	797.00	149.96
98.27	145.53	459.37	146.56	809.00	150.03
116.33	146.00	477.43	146.55	880.70	156.33
134.38	146.36	495.48	146.30		
152.44	146.83	513.54	145.33		
170.49	147.07	531.59	143.97		
188.55	146.88	549.65	142.68		
206.60	146.48	567.70	141.82		
224.66	146.08	585.76	141.37		
242.71	145.82	603.81	141.54		
260.77	145.58	621.87	142.45		
278.82	145.57	639.92	143.63		
296.88	145.85	657.98	144.07		
314.93	146.25	676.03	144.75		

Figure A.12 Big River Restaurant cross section, 72.7 km downstream of Great Slave Lake.

Table A.12 Hydraulic components at Big River cross section, 72.7 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
146.5	5.13	775	518	518	1.5
146.6	5.23	831	597	597	1.4
146.7	5.33	893	641	641	1.4
146.8	5.43	958	668	668	1.4
146.9	5.53	1026	685	685	1.5
147.0	5.63	1096	707	707	1.6
147.1	5.73	1167	724	724	1.6
147.2	5.83	1240	728	728	1.7
147.3	5.93	1313	732	732	1.8
147.4	6.03	1386	736	736	1.9
147.5	6.13	1460	740	740	2.0
147.6	6.23	1534	743	744	2.1
147.7	6.33	1609	747	748	2.2
147.8	6.43	1684	751	751	2.2
147.9	6.53	1759	755	755	2.3
148.0	6.63	1835	758	758	2.4
148.1	6.73	1911	760	760	2.5
148.2	6.83	1987	761	762	2.6
148.3	6.93	2063	763	763	2.7
148.4	7.03	2139	764	765	2.8
148.5	7.13	2216	766	766	2.9
148.6	7.23	2292	767	768	3.0
148.7	7.33	2369	769	769	3.1
148.8	7.43	2446	770	771	3.2
148.9	7.53	2523	772	772	3.3
149.0	7.63	2600	773	774	3.4
149.1	7.73	2678	775	775	3.5
149.2	7.83	2755	776	777	3.6
149.3	7.93	2833	778	778	3.6
149.4	8.03	2911	779	780	3.7
149.5	8.13	2989	781	781	3.8
149.6	8.23	3067	782	783	3.9
149.7	8.33	3145	784	784	4.0
149.8	8.43	3224	785	786	4.1
149.9	8.53	3302	787	787	4.2
150.0	8.63	3381	795	795	4.3
150.1	8.73	3461	802	803	4.3
150.2	8.83	3542	805	806	4.4
150.3	8.93	3622	806	807	4.5
150.4	9.03	3703	808	808	4.6
150.5	9.13	3784	809	810	4.7
150.6	9.23	3865	810	811	4.8
150.7	9.33	3946	811	812	4.9
150.8	9.43	4027	813	814	5.0
150.9	9.53	4108	814	815	5.0
151.0	9.63	4190	815	816	5.1



Description: This cross section is located approximately 73.6 km downstream of Great Slave Lake in the Big Snye. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 21.76 m from the edge of the water. The depth sounding was started 4 m from the edge of the water and stopped 3 m short of the south bank, which was then surveyed for a distance of 52.9 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation was assumed to be the same as that measured at the Big River cross section, which was 150.032 m.

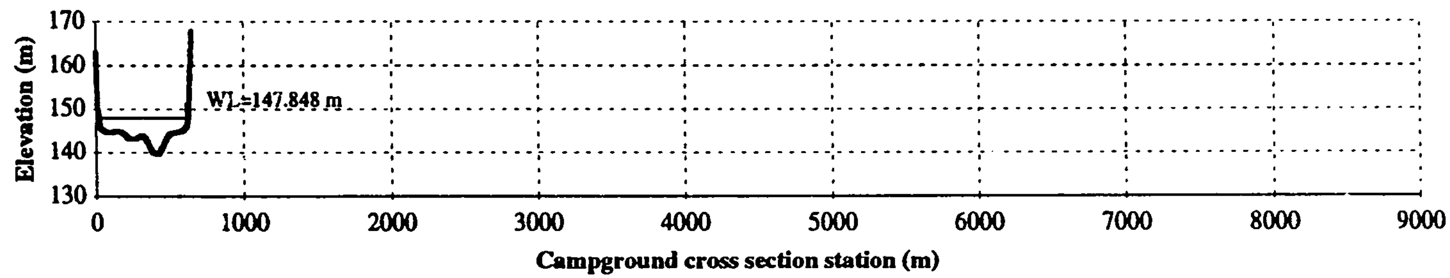
TBM: *This cross section is not yet tied into GSC.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	153.33	393.40	148.67
52.90	150.03	412.15	148.65
55.90	150.05	430.90	148.64
74.65	149.09	449.65	148.60
93.40	148.70	468.40	148.56
112.15	148.45	487.15	148.48
130.90	148.46	505.90	148.47
149.65	148.38	524.65	148.43
168.40	148.37	543.40	148.04
187.15	148.40	562.15	147.65
205.90	148.41	580.90	147.07
224.65	148.43	599.65	146.87
243.40	148.48	618.40	146.69
262.15	148.59	637.15	146.91
280.90	148.67	655.90	147.44
299.65	148.68	674.65	148.15
318.40	148.70	693.40	148.67
337.15	148.70	700.90	149.83
355.90	148.64	704.90	150.03
374.65	148.61	726.66	153.27

Figure A.13 Big Snye cross section, 73.6 km downstream of Great Slave Lake.

Table A.13 Hydraulic components at Big Snye cross section, 73.6 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
148.50	1.81	184	343	343	0.5
148.55	1.86	202	369	369	0.6
148.60	1.91	221	405	405	0.6
148.65	1.96	243	494	494	0.5
148.70	2.01	271	600	600	0.5
148.75	2.06	301	603	603	0.5
148.80	2.11	331	606	606	0.6
148.85	2.16	361	608	608	0.6
148.90	2.21	392	611	611	0.6
148.95	2.26	422	614	614	0.7
149.00	2.31	453	617	617	0.7
149.05	2.36	484	619	619	0.8
149.10	2.41	515	622	622	0.8
149.15	2.46	546	623	623	0.9
149.20	2.51	577	624	624	0.9
149.25	2.56	609	626	626	1.0
149.30	2.61	640	627	627	1.0
149.35	2.66	671	628	628	1.1
149.40	2.71	703	630	630	1.1
149.45	2.76	734	631	631	1.2
149.50	2.81	766	632	632	1.2
149.55	2.86	797	633	634	1.3
149.60	2.91	829	635	635	1.3
149.65	2.96	861	636	636	1.4
149.70	3.01	893	637	637	1.4
149.75	3.06	925	639	639	1.5
149.80	3.11	957	640	640	1.5
149.85	3.16	989	642	642	1.5
149.90	3.21	1021	643	644	1.6
149.95	3.26	1053	645	646	1.6
150.00	3.31	1085	647	648	1.7
150.05	3.36	1118	652	653	1.7
150.10	3.41	1150	654	654	1.8
150.15	3.46	1183	655	655	1.8
150.20	3.51	1216	656	656	1.9
150.25	3.56	1249	657	657	1.9
150.30	3.61	1282	658	658	2.0
150.35	3.66	1315	659	659	2.0
150.40	3.71	1348	660	661	2.0
150.45	3.76	1381	662	662	2.1
150.50	3.81	1414	663	663	2.1



Description: This cross section is located 75.0 km downstream of Great Slave Lake, near the Ft. Providence Campground located on the north bank of the river just west of the airport. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 20 m from the edge of the water. The depth sounding was started 6 m from the edge of the water and stopped 3 m short of the south bank, which was then surveyed for a distance of 15 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 2:55 PM on July 11, 1992 was 147.848 m.

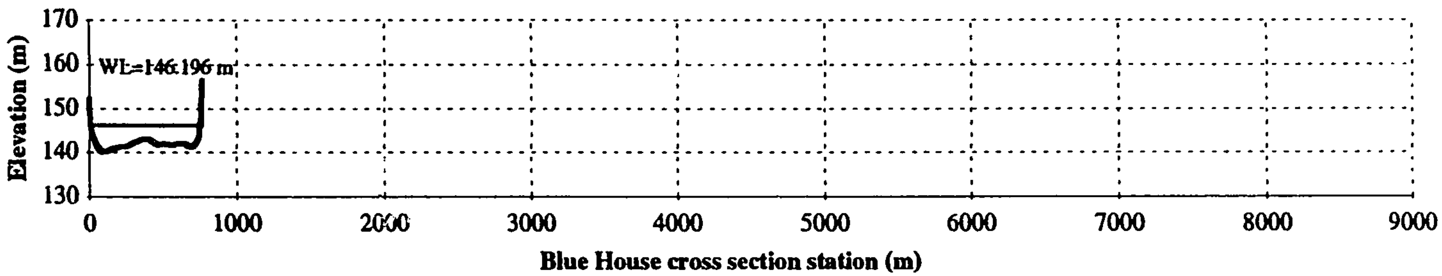
TBM: Spike in a flagged 15 cm spruce tree approximately 300 m southwest of the Ft. Providence road along the access between the campground and the airport on the east side of the ravine. Elevation 157.791 m determined by tying into GSC Bench Mark No. 86T046 on May 5, 1992.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	162.85	226.97	143.17	459.15	141.61
15.00	147.85	238.57	143.06	470.76	142.57
18.00	149.43	250.18	143.03	482.37	143.37
29.61	145.80	261.79	143.06	493.98	143.93
41.22	145.19	273.40	143.20	505.59	144.28
52.83	144.99	285.01	143.45	517.20	144.38
64.44	144.74	296.62	143.49	528.80	144.44
76.05	144.56	308.23	143.81	540.41	144.54
87.66	144.59	319.84	143.88	552.02	144.59
99.26	144.57	331.45	143.65	563.63	144.62
110.87	144.56	343.06	143.04	575.24	144.74
122.48	144.65	354.67	142.38	586.85	144.84
134.09	144.85	366.28	141.39	598.46	145.19
145.70	144.83	377.89	140.58	610.07	145.61
157.31	144.80	389.49	139.99	621.68	146.22
168.92	144.71	401.10	139.80	624.00	150.83
180.53	144.52	412.71	139.61	630.00	147.85
192.14	144.16	424.32	139.71	650.00	167.85
203.75	143.83	435.93	140.15		
215.36	143.47	447.54	140.84		

Figure A.14 Campground cross section, 75.0 km downstream of Great Slave Lake.

Table A.14 Hydraulic components at Campground cross section, 75.0 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
145.5	5.89	1184	571	572	2.1
145.6	5.99	1242	576	576	2.2
145.7	6.09	1299	580	580	2.2
145.8	6.19	1358	584	584	2.3
145.9	6.29	1416	586	586	2.4
146.0	6.39	1475	588	589	2.5
146.1	6.49	1534	591	591	2.6
146.2	6.59	1593	593	593	2.7
146.3	6.69	1652	594	594	2.8
146.4	6.79	1712	594	595	2.9
146.5	6.89	1771	594	595	3.0
146.6	6.99	1831	595	596	3.1
146.7	7.09	1890	595	596	3.2
146.8	7.19	1950	596	596	3.3
146.9	7.29	2009	596	597	3.4
147.0	7.39	2069	596	597	3.5
147.1	7.49	2129	597	598	3.6
147.2	7.59	2188	597	598	3.7
147.3	7.69	2248	597	599	3.8
147.4	7.79	2308	598	599	3.9
147.5	7.89	2368	598	600	4.0
147.6	7.99	2427	599	600	4.1
147.7	8.09	2487	599	601	4.1
147.8	8.19	2547	599	601	4.2
147.9	8.29	2607	600	602	4.3
148.0	8.39	2667	601	603	4.4
148.1	8.49	2727	602	604	4.5
148.2	8.59	2788	603	605	4.6
148.3	8.69	2848	604	607	4.7
148.4	8.79	2908	605	608	4.8
148.5	8.89	2969	606	609	4.9
148.6	8.99	3029	607	610	5.0
148.7	9.09	3090	608	611	5.1
148.8	9.19	3151	609	612	5.2
148.9	9.29	3212	610	614	5.2
149.0	9.39	3273	611	615	5.3
149.1	9.49	3334	612	616	5.4
149.2	9.59	3395	613	617	5.5
149.3	9.69	3457	613	618	5.6
149.4	9.79	3518	614	619	5.7
149.5	9.89	3579	615	620	5.8
149.6	9.99	3641	615	621	5.9
149.7	10.09	3703	616	621	6.0
149.8	10.19	3764	616	622	6.1
149.9	10.29	3826	617	623	6.1
150.0	10.39	3888	617	623	6.2



Description: This cross section is located 76.7 km downstream of Great Slave Lake, adjacent to the small blue building at the water intake site. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 10 m from the edge of the water. The depth sounding was begun 10 m from the edge of the water and stopped 3 m short of the south bank, which was then surveyed for a distance of 6 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 3:45 PM on July 11, 1992 was 146.196 m.

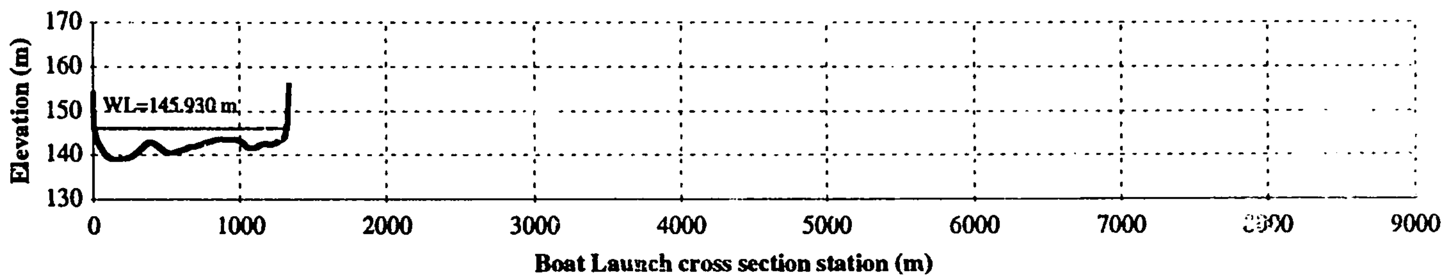
TBM: Canada Lands Bench Mark No. C2 1982 located 15 m towards the river from the blue building, on a concrete pad with a manhole cover. Elevation 153.817 m determined by tying into GSC Bench Mark No. 86T046 on Aug. 27, 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	152.20	253.85	141.45	525.91	141.89
6.00	146.20	267.46	141.56	539.51	141.81
9.00	145.83	281.06	141.81	553.12	141.76
22.60	143.71	294.66	142.05	566.72	141.73
36.21	142.62	308.26	142.27	580.32	141.78
49.81	141.60	321.87	142.45	593.93	141.86
63.41	140.90	335.47	142.63	607.53	141.94
77.01	140.49	349.07	142.87	621.13	142.03
90.62	140.18	362.68	142.99	634.74	142.10
104.22	140.19	376.28	143.09	648.34	142.04
117.82	140.27	389.88	143.20	661.94	141.78
131.43	140.40	403.49	143.17	675.54	141.44
145.03	140.60	417.09	142.81	689.15	141.27
158.63	140.83	430.69	142.48	702.75	141.24
172.24	140.98	444.29	142.20	716.35	141.78
185.84	141.09	457.90	141.92	729.96	142.56
199.44	141.22	471.50	141.81	743.56	143.71
213.04	141.28	485.10	141.87	749.00	146.69
226.65	141.31	498.71	141.97	759.00	146.20
240.25	141.34	512.31	141.95	769.00	156.20

Figure A.15 Blue House cross section, 76.7 km downstream of Great Slave Lake.

Table A.15 Hydraulic components at Blue House cross section, 76.7 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
143.5	3.32	1238	716	716	1.7
143.6	3.42	1309	718	719	1.8
143.7	3.52	1381	721	721	1.9
143.8	3.62	1453	722	722	2.0
143.9	3.72	1526	723	723	2.1
144.0	3.82	1598	723	724	2.2
144.1	3.92	1670	724	725	2.3
144.2	4.02	1743	725	725	2.4
144.3	4.12	1815	726	726	2.5
144.4	4.22	1888	727	727	2.6
144.5	4.32	1961	72[illegible]	728	2.7
144.6	4.42	2033	728	729	2.8
144.7	4.52	2106	729	730	2.9
144.8	4.62	2179	730	731	3.0
144.9	4.72	2252	731	732	3.1
145.0	4.82	2325	732	732	3.2
145.1	4.92	2399	733	733	3.3
145.2	5.02	2472	733	734	3.4
145.3	5.12	2545	734	735	3.5
145.4	5.22	2619	735	736	3.6
145.5	5.32	2692	736	737	3.7
145.6	5.42	2766	737	738	3.8
145.7	5.52	2840	737	738	3.9
145.8	5.62	2914	738	739	3.9
145.9	5.72	2987	739	740	4.0
146.0	5.82	3061	740	741	4.1
146.1	5.92	3135	741	742	4.2
146.2	6.02	3210	742	743	4.3
146.3	6.12	3284	745	746	4.4
146.4	6.22	3359	747	748	4.5
146.5	6.32	3433	749	751	4.6
146.6	6.42	3508	752	753	4.7
146.7	6.52	3584	754	756	4.7
146.8	6.62	3659	754	756	4.8
146.9	6.72	3735	754	756	4.9
147.0	6.82	3810	755	757	5.0
147.1	6.92	3886	755	757	5.1
147.2	7.02	3961	755	757	5.2
147.3	7.12	4037	755	757	5.3
147.4	7.22	4112	755	758	5.4
147.5	7.32	4188	756	758	5.5
147.6	7.42	4263	756	758	5.6
147.7	7.52	4339	756	758	5.7
147.8	7.62	4414	756	759	5.8
147.9	7.72	4490	756	759	5.9
148.0	7.82	4566	757	759	6.0



Description: This cross section is located 77.4 km downstream of Great Slave Lake, adjacent to a boat launch on the north bank. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 10 m from the edge of the water. The depth sounding was begun 10 m from the edge of the water and stopped 2 m short of the south bank, which was then surveyed for a distance of 8 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 4:25 PM on July 11, 1992 was 145.930 m.

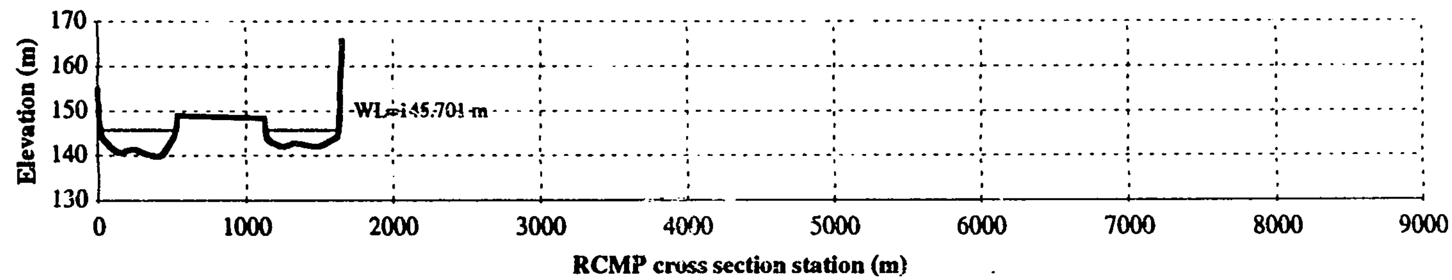
TBM: Spike in a flagged power pole east of the culvert and ravine leading down to the boat launch. Elevation 153.762 m determined by tying into GSC Bench Mark No. 86T046 on May 1, 1992.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	153.93	438.52	142.05	1050.70	[illegible].78
8.00	145.93	469.13	141.13	1081.31	[illegible].50
10.00	146.13	499.74	140.58	1111.92	141.63
25.30	143.49	530.35	140.47	1142.53	142.34
40.61	142.36	560.96	140.69	1173.14	142.62
55.91	141.37	591.57	141.01	1203.75	142.37
71.22	140.62	622.18	141.36	1219.05	142.33
86.52	139.91	652.79	141.83	1234.36	142.52
101.83	139.55	683.40	141.93	1249.66	142.83
117.13	139.25	714.00	142.17	1264.96	143.15
132.44	139.07	744.61	142.58	1280.27	143.45
163.04	139.06	775.22	142.88	1295.57	143.67
193.65	139.13	805.83	143.10	1310.88	144.16
224.26	139.23	836.44	143.47	1317.00	146.66
254.87	139.61	867.05	143.53	1327.00	145.93
285.48	140.28	897.66	14[illegible].52	1337.00	155.93
316.09	141.14	928.27	143.52		
346.70	142.06	958.88	143.56		
377.31	142.89	989.48	143.40		
407.92	142.83	1020.09	142.72		

Figure A.16 Boat Launch cross section, 77.4 km downstream of Great Slave Lake.

Table A.16 Hydraulic components at Boat Launch cross section, 77.4 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
142.5	3.44	1218	819	819	1.5
142.6	3.54	1303	868	869	1.5
142.7	3.64	1392	900	901	1.5
142.8	3.74	1483	929	929	1.6
142.9	3.84	1578	986	986	1.6
143.0	3.94	1678	1011	1011	1.7
143.1	4.04	1781	1036	1036	1.7
143.2	4.14	1885	1054	1055	1.8
143.3	4.24	1992	1074	1074	1.9
143.4	4.34	2100	1093	1093	1.9
143.5	4.44	2211	1140	1140	1.9
143.6	4.54	2324	1267	1267	1.8
143.7	4.64	2461	1273	1273	1.9
143.8	4.74	2589	1277	1277	2.0
143.9	4.84	2717	1280	1281	2.1
144.0	4.94	2845	1284	1284	2.2
144.1	5.04	2973	1288	1288	2.3
144.2	5.14	3102	1290	1290	2.4
144.3	5.24	3231	1291	1291	2.5
144.4	5.34	3360	1292	1292	2.6
144.5	5.44	3490	1293	1293	2.7
144.6	5.54	3619	1293	1294	2.8
144.7	5.64	3748	1294	1295	2.9
144.8	5.74	3878	1295	1295	3.0
144.9	5.84	4007	1296	1296	3.1
145.0	5.94	4137	1297	1297	3.2
145.1	6.04	4267	1297	1298	3.3
145.2	6.14	4397	1298	1299	3.4
145.3	6.24	4526	1299	1300	3.5
145.4	6.34	4656	1300	1301	3.6
145.5	6.44	4786	1301	1301	3.7
145.6	6.54	4916	1301	1302	3.8
145.7	6.64	5047	1302	1303	3.9
145.8	6.74	5177	1303	1304	4.0
145.9	6.84	5307	1304	1305	4.1
146.0	6.94	5438	1306	1307	4.2
146.1	7.04	5569	1310	1311	4.3
146.2	7.14	5700	1312	1313	4.3
146.3	7.24	5831	1314	1315	4.4
146.4	7.34	5963	1316	1317	4.5
146.5	7.44	6094	1318	1319	4.6
156.6	5.03	9459	2804	2804	3.4
156.7	5.13	9740	2808	2808	3.5
156.8	5.23	10021	2811	2811	3.6
156.9	5.33	10302	2814	2815	3.7
157.0	5.43	10584	2818	2818	3.8



Description: This cross section is located 77.9 km downstream of Great Slave Lake, adjacent to the RCMP office and across the channels on both sides of Providence Island. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank of the south channel, 8 m from the waterline. The depth sounding was started 2 m from waterline and stopped 4 m short of the south bank, which was then surveyed for a distance of 9 m from the edge of the water. The north channel was then surveyed and sounded. The survey was started on the north bank of the north channel, 20 m from the edge of the water. The depth sounding was begun 5 m from the edge of the water and stopped 5 m short of the south bank. The south bank was then surveyed for a distance of 9 m from the edge of the water. The sounding data was evenly distributed across the channels (horizontal control was provided by using GPS). The water surface elevation of the north channel, measured at 5:00 PM on July 11, 1992 was 145.701 m. The south channel was assumed to have the same water surface elevation as the north channel.

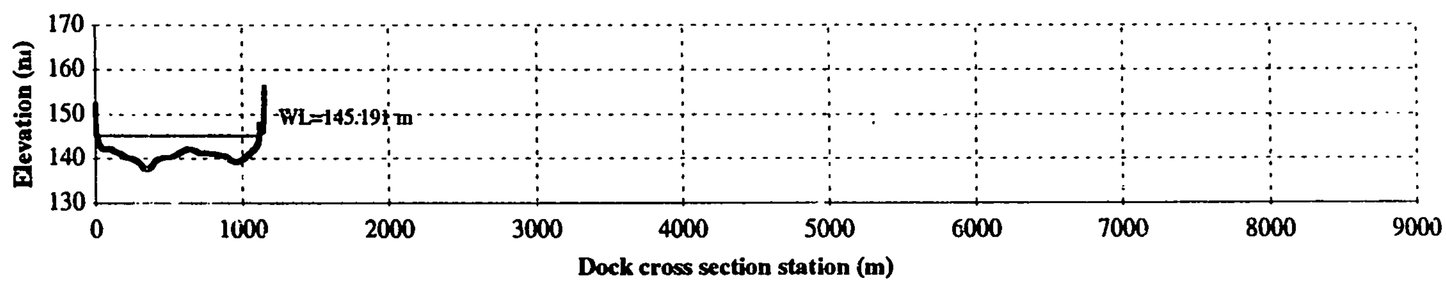
TBM: Spike in wooden power pole located between the road and the RCMP storage house. Elevation 154.171 m determined by tying into GSC Bench Mark No. 72T002 on Aug. 27, 1991. ***The south channel TBM is not yet tied into GSC.***

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	154.70	348.55	140.02	1263.05	141.88
9.00	145.70	363.80	140.06	1279.61	142.09
13.00	146.57	379.05	139.86	1296.16	142.30
28.25	144.18	394.31	139.57	1312.72	142.55
43.50	143.48	424.81	139.88	1329.28	142.74
58.76	142.93	440.06	140.16	1362.39	142.62
74.01	142.38	455.31	140.84	1378.94	142.51
89.26	141.82	470.57	141.78	1412.06	142.32
104.51	141.43	485.82	142.57	1494.84	141.89
119.77	141.10	501.07	143.43	1511.39	142.16
135.02	140.7[illegible]	516.32	144.22	1527.95	142.39
150.27	140.54	527.00	146.45	1544.51	142.67
180.77	140.76	5[illegible]7.00	148.98	1561.06	142.9[illegible]
196.03	141.01	1125.60	148.41	1577.62	143.[illegible]
211.28	141.22	1130.60	146.23	1594.18	143.[illegible]
241.78	141.40	1147.16	143.85	1610.73	143.83
257.04	141.30	1163.[illegible]	143.29	1627.29	144.35
272.29	141.05	11[illegible].2[illegible]	142.90	1630.60	148.87
287.54	140.83	1213.38	142.39	1635.60	145.70
302.79	140.61	1246.49	141.94	1655.60	165.70

Figure A.17 RCMP cross section, 77.9 km downstream of Great Slave Lake.

Table A.17 Hydraulic components at RCMP cross section, 77.9 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
142.0	2.43	516	450	450	1.2
142.1	2.53	563	495	495	1.1
142.2	2.63	615	540	541	1.1
142.3	2.73	671	587	587	1.1
142.4	2.83	732	630	630	1.2
142.5	2.93	797	672	672	1.2
142.6	3.03	866	712	712	1.2
142.7	3.13	940	762	762	1.2
142.8	3.23	1018	793	793	1.3
142.9	3.33	1098	809	809	1.4
143.0	3.43	1180	822	823	1.4
143.1	3.53	1263	836	836	1.5
143.2	3.63	1347	849	849	1.6
143.3	3.73	1432	862	862	1.7
143.4	3.83	1519	876	876	1.7
143.5	3.93	1608	890	891	1.8
143.6	4.03	1697	904	905	1.9
143.7	4.13	1788	918	918	2.0
143.8	4.23	1881	932	932	2.0
143.9	4.33	1975	942	942	2.1
144.0	4.43	2069	950	950	2.2
144.1	4.53	2165	958	958	2.3
144.2	4.63	2261	966	966	2.3
144.3	4.73	2358	971	971	2.4
144.4	4.83	2455	974	974	2.5
144.5	4.93	2552	976	976	2.6
144.6	5.03	2650	978	978	2.7
144.7	5.13	2748	980	980	2.8
144.8	5.23	2846	982	982	2.9
144.9	5.33	2944	983	984	3.0
145.0	5.43	3043	985	986	3.1
145.1	5.53	3141	987	988	3.2
145.2	5.63	3240	989	990	3.3
145.3	5.73	3339	991	992	3.4
145.4	5.83	3438	993	994	3.5
145.5	5.93	3538	995	996	3.6
145.6	6.03	3637	997	998	3.7
145.7	6.13	3737	998	1000	3.7
145.8	6.23	3837	1001	1003	3.8
145.9	6.33	3937	1004	1006	3.9
146.0	6.43	4038	1007	1008	4.0
146.1	6.53	4139	1009	1011	4.1
146.2	6.63	4240	1012	1014	4.2
146.3	6.73	4341	1014	1017	4.3
146.4	6.83	4443	1017	1019	4.4
146.5	6.93	4544	1019	1022	4.5



Description: This cross section is located 79.5 km downstream of Great Slave Lake, at the Fort Providence dock which is on the north bank at the west end of town. Surveying and depth soundings were performed on July 11, 1992. The survey was started on the north bank, 36 m from the edge of the water. The depth sounding was started 3 m from the edge of the water and stopped 5 m short of the south bank, which was then surveyed for a distance of 7 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 5:15 PM on July 11, 1992 was 145.191 m.

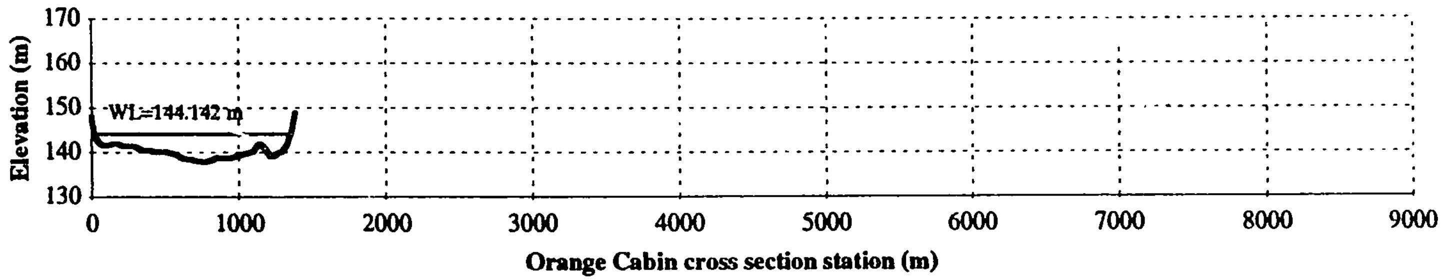
TBM: Southwest corner of the Fort Providence dock sheet piling. Elevation 146.021 m determined by tying into RCMP TBM on October 29 1991.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	152.19	355.71	137.50	823.16	140.97
7.00	145.19	369.46	137.84	878.15	140.61
12.00	145.18	383.21	138.38	891.90	140.39
25.75	142.98	396.96	138.97	905.65	140.09
39.50	142.46	410.70	139.54	919.40	139.72
53.25	[illegible]	424.45	139.86	960.64	139.14
66.99	141.97	438.20	140.03	1001.89	[illegible]
80.74	142.19	465.70	140.27	1015.64	140.18
94.49	142.28	520.69	140.40	1029.38	140.58
108.24	142.06	548.19	140.79	1043.13	140.98
121.99	141.75	575.69	141.37	1056.88	141.45
135.74	141.54	589.43	141.61	1070.63	141.81
163.23	141.14	603.18	141.87	1084.38	142.17
176.98	140.95	630.68	142.20	1098.13	142.92
204.48	140.41	671.93	141.86	1111.88	143.59
218.23	140.15	685.67	141.62	1116.00	144.33
245.72	140.00	699.42	141.39	1119.00	145.04
273.22	139.64	713.17	141.22	1119.00	147.69
300.72	138.93	740.67	141.25	1145.00	146.02
328.21	137.82	781.91	141.05	1155.00	156.02

Figure A.18 Dock cross section, 79.5 km downstream of Great Slave Lake.

Table A.18 Hydraulic components at Dock cross section, 79.5 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
142.0	4.5	1529	931	931	1.6
142.1	4.6	1625	977	977	1.7
142.2	4.7	1724	1019	1019	1.7
142.3	4.8	1828	1043	1043	1.8
142.4	4.9	1932	1049	1049	1.8
142.5	5	2037	1053	1054	1.9
142.6	5.1	2143	1058	1058	2.0
142.7	5.2	2249	1062	1062	2.1
142.8	5.3	2355	1066	1066	2.2
142.9	5.4	2462	1070	1070	2.3
143.0	5.5	2569	1074	1074	2.4
143.1	5.6	2677	1077	1077	2.5
143.2	5.7	2785	1080	1080	2.6
143.3	5.8	2893	1082	1082	2.7
143.4	5.9	3001	1085	1085	2.8
143.5	6	3110	1088	1088	2.9
143.6	6.1	3219	1090	1090	3.0
143.7	6.2	3328	1091	1092	3.1
143.8	6.3	3437	1092	1093	3.2
143.9	6.4	3546	1094	1094	3.2
144.0	6.5	3656	1095	1095	3.3
144.1	6.6	3765	1096	1096	3.4
144.2	6.7	3875	1097	1098	3.5
144.3	6.8	3985	1098	1099	3.6
144.4	6.9	4095	1099	1100	3.7
144.5	7	4205	1100	1101	3.8
144.6	7.1	4315	1102	1102	3.9
144.7	7.2	4425	1103	1103	4.0
144.8	7.3	4535	1104	1104	4.1
144.9	7.4	4646	1105	1105	4.2
145.0	7.5	4756	1106	1106	4.3
145.1	7.6	4867	1107	1107	4.4
145.2	7.7	4978	1112	1113	4.5
145.3	7.8	5089	1112	1113	4.6
145.4	7.9	5200	1112	1113	4.7
145.5	8	5311	1112	1113	4.8
145.6	8.1	5422	1112	1114	4.9
145.7	8.2	5534	1113	1114	5.0
145.8	8.3	5645	1113	1114	5.1
145.9	8.4	5756	1113	1114	5.2
146.0	8.5	5868	1113	1115	5.3
146.1	8.6	5979	1114	1116	5.4
146.2	8.7	6090	1116	1118	5.5
146.3	8.8	6202	1118	1120	5.5
146.4	8.9	6314	1120	1122	5.6
146.5	9	6426	1121	1124	5.7



Description: This cross section is located on the Mackenzie River, 89.5 km downstream of Great Slave Lake. Surveying and depth soundings were performed on July 12, 1992. The survey was started on the north bank, 31.6 m from the edge of the water. The depth sounding was started 5 m from the edge of the water and stopped 4 m short of the south bank, which was then surveyed for a distance of 17.6 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation was estimated by interpolation using the water surface elevations at Mills Lake and the Fort Providence Dock. The interpolated elevation was 144.14 m.

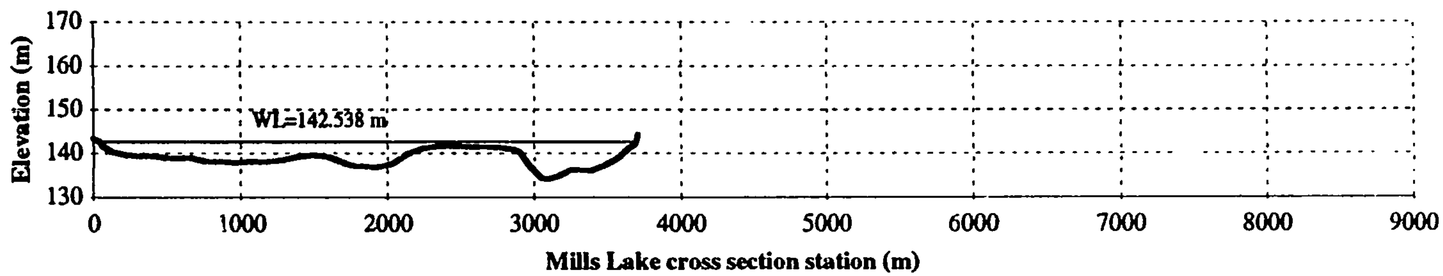
TBM: *This cross section is not tied into GSC.*

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	147.95	375.05	140.23	934.70	138.57
17.59	144.14	404.51	140.33	949.42	138.75
21.59	144.03	419.23	140.17	1096.70	140.14
36.32	142.73	433.96	140.06	1111.43	140.80
51.05	142.16	448.69	140.00	1126.15	141.42
65.77	[illegible]	507.60	140.07	1140.88	141.91
80.50	[illegible]	522.33	[illegible]	1170.34	141.15
95.23	[illegible]	537.05	139.86	1185.06	140.42
124.68	141.67	551.78	139.75	1199.79	139.73
154.14	141.97	566.51	139.56	1214.52	139.15
183.59	141.82	595.96	139.13	1229.24	139.06
213.05	141.44	610.69	138.79	1258.70	139.68
227.78	141.30	625.42	138.62	1273.43	139.93
242.50	141.43	669.60	138.40	1288.15	140.07
271.96	141.34	684.33	138.31	1302.88	140.52
301.41	141.22	699.06	138.07	1317.61	141.25
316.14	140.92	772.69	137.84	1332.34	141.93
330.87	140.57	802.15	138.09	1345.59	143.72
345.60	140.48	831.60	138.50	1350.59	144.14
360.32	140.36	846.33	138.77	1382.25	148.82

Figure A.19 Orange Cabin cross section, 89.5 km downstream of Great Slave Lake.

Table A.19 Hydraulic components at Orange Cabin cross section, 89.5 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
141.5	3.66	2083	1096	1096	1.9
141.6	3.76	2195	1139	1139	1.9
141.7	3.86	2311	1173	1174	2.0
141.8	3.96	2430	1204	1205	2.0
141.9	4.06	2552	1245	1246	2.1
142.0	4.16	2679	1273	1273	2.1
142.1	4.26	2806	1278	1279	2.2
142.2	4.36	2934	1284	1284	2.3
142.3	4.46	3063	1287	1287	2.4
142.4	4.56	3192	1291	1291	2.5
142.5	4.66	3321	1294	1294	2.6
142.6	4.76	3451	1298	1298	2.7
142.7	4.86	3581	1301	1301	2.8
142.8	4.96	3711	1304	1304	2.9
142.9	5.06	3841	1305	1306	2.9
143.0	5.16	3972	1307	1308	3.0
143.1	5.26	4103	1309	1309	3.1
143.2	5.36	4234	1311	1311	3.2
143.3	5.46	4365	1313	1313	3.3
143.4	5.56	4496	1315	1315	3.4
143.5	5.66	4628	1317	1317	3.5
143.6	5.76	4760	1318	1319	3.6
143.7	5.86	4892	1320	1321	3.7
143.8	5.96	5024	1322	1323	3.8
143.9	6.06	5156	1325	1325	3.9
144.0	6.16	5289	1327	1327	4.0
144.1	6.26	5422	1331	1331	4.1
144.2	6.36	5555	1334	1334	4.2
144.3	6.46	5688	1335	1335	4.3
144.4	6.56	5822	1336	1336	4.4
144.5	6.66	5956	1337	1338	4.5
144.6	6.76	6089	1338	1339	4.6
144.7	6.86	6223	1339	1340	4.6
144.8	6.96	6357	1340	1341	4.7
144.9	7.06	6491	1342	1342	4.8
145.0	7.16	6626	1343	1343	4.9
156.1	4.53	8061	2786	2787	2.9
156.2	4.63	8340	2790	2791	3.0
156.3	4.73	8619	2794	2794	3.1
156.4	4.83	8899	2797	2798	3.2
156.5	4.93	9179	2801	2801	3.3
156.6	5.03	9459	2804	2804	3.4
156.7	5.13	9740	2808	2808	3.5
156.8	5.23	10021	2811	2811	3.6
156.9	5.33	10302	2814	2815	3.7
157.0	5.43	10584	2818	2818	3.8



Description: This cross section is located on the Mackenzie River, 103.9 km downstream of Great Slave Lake, passing just downstream of the last island before Mills Lake. Surveying and depth soundings were performed on July 12, 1992. The survey was started on the north shore, 3.9 m from the edge of the water. The depth sounding was started 5 m from the edge of the water and stopped 5 m short of the south shore, which was then surveyed for a distance of 50 m from the edge of the water. The sounding data was evenly distributed across the channel (horizontal control was provided by using GPS). The water surface elevation, measured at 11:50 AM on July 12, 1992 was 142.538 m.

TBM: Public Works of Canada benchmark P11B-5, elevation 144.343 m located on the south bank near a navigational aid. A second, Hydrographic Services of Canada, benchmark was found (#86C99865) on the southwest leg of the navigational aid.

Station (m)	Elevation (m)	Station (m)	Elevation (m)	Station (m)	Elevation (m)
0.00	143.34	1382.63	139.21	3159.95	134.71
40.00	142.70	1489.70	139.61	3224.19	135.79
50.00	142.34	1596.77	139.20	3245.60	136.06
55.00	141.78	1725.25	137.51	3267.01	136.23
76.41	141.29	1768.07	137.17	3395.49	136.15
97.83	140.78	1853.73	137.01	3481.15	137.31
119.24	140.37	1917.97	136.82	3566.80	138.85
226.31	139.53	2025.04	137.50	3588.22	139.48
354.79	139.34	2132.10	139.77	3609.63	140.11
397.61	[illegible]	2239.17	141.09	3631.04	140.67
504.68	[illegible]	2346.24	141.51	3652.46	141.36
568.92	138.81	2410.48	141.62	3673.87	141.61
654.58	138.98	2496.13	141.51	3691.00	142.26
761.64	138.19	2581.78	141.37	3696.00	142.54
890.12	138.07	2753.09	141.26	3709.88	144.33
954.36	137.84	2860.16	140.88		
997.19	[illegible]	2902.99	140.25		
1040.02	[illegible]	2967.23	137.25		
1147.08	138.09	3052.88	134.32		
1275.57	138.46	3095.71	134.15		

Figure A.20 Mills Lake cross section, 103.9 km downstream of Great Slave Lake.

Table A.20 Hydraulic components at Mills Lake cross section, 103.9 km downstream of Great Slave Lake.

Water elevation (m)	Maximum water depth (m)	Cross section area (m^2)	Top width (m)	Wetted perimeter (m)	Hydraulic radius (m)
137.0	2.85	681	573	573	1.2
137.1	2.95	742	651	651	1.1
137.2	3.05	811	718	718	1.1
137.3	3.15	885	756	756	1.2
137.4	3.25	962	793	793	1.2
137.5	3.35	1043	829	829	1.3
137.6	3.45	1127	849	849	1.3
137.7	3.55	1213	869	869	1.4
137.8	3.65	1301	889	889	1.5
137.9	3.75	1392	952	952	1.5
138.0	3.85	1492	1033	1033	1.4
138.1	3.95	1600	1242	1242	1.3
138.2	4.05	1732	1394	1394	1.2
138.3	4.15	1875	1463	1463	1.3
138.4	4.25	2024	1531	1531	1.3
138.5	4.35	2181	1591	1591	1.4
138.6	4.45	2342	1639	1639	1.4
138.7	4.55	2509	1687	1687	1.5
138.8	4.65	2680	1735	1735	1.5
138.9	4.75	2862	1899	1899	1.5
139.0	4.85	3057	2002	2003	1.5
139.1	4.95	3260	2055	2055	1.6
139.2	5.05	3468	2107	2107	1.7
139.3	5.15	3683	2189	2189	1.7
139.4	5.25	3909	2354	2354	1.7
139.5	5.35	4151	2485	2485	1.7
139.6	5.45	4405	2577	2577	1.7
139.7	5.55	4664	2505	2606	1.8
139.8	5.65	4926	2629	2630	1.9
139.9	5.75	5190	2656	2656	2.0
140.0	5.85	5457	2682	2683	2.0
140.1	5.95	5726	2709	2709	2.1
140.2	6.05	5999	2736	2736	2.2
140.3	6.15	6274	2765	2765	2.3
140.4	6.25	6552	2794	2794	2.3
140.5	6.35	6832	2818	2818	2.4
140.6	6.45	7115	2841	2842	2.5
140.7	6.55	7401	2865	2865	2.6
140.8	6.65	7688	2888	2888	2.7
140.9	6.75	7978	2915	2915	2.7
141.0	6.85	8272	2958	2958	2.8
141.1	6.95	8570	3004	3004	2.9
141.2	7.05	8873	3065	3065	2.9
141.3	7.15	9184	3177	3177	2.9
141.4	7.25	9511	3339	3339	2.9
141.5	7.35	9850	3439	3439	2.9