University of Alberta

Modeling of Historic Ice Jams on the Athabasca River at Fort McMurray

by

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Report Summary

This report is an attempt at determining the validity of the suggestion that historical water levels recorded during an ice jam at MacEwan Bridge on the Athabasca River at Fort McMurray can be transposed downstream to the Clearwater confluence by simply subtracting 1 meter from the recorded water level. This report also investigates the importance of certain hydraulic properties on the difference in water levels between MacEwan Bridge and the Clearwater confluence. These parameters include discharge, ice jam roughness, ice jam location, and simple ice cover thickness.

This investigation was done using recorded data of ice jams on the Athabasca River at Fort McMurray and modeled with the United States Army Core of Engineers Software HEC RAS.

It was found that, based on simulations; the 1m suggestion was not valid as the difference in simulated water levels between the bridge and confluences varied from 0.04m to 4.61m. It was also determined that ice jam location, roughness, and discharge had a large effect on the water level difference whereas the simple ice cover thickness did not.

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Table of Contents

Appendices

List of Figures

List of Tables

List of Symbols

A_i = the flow area beneath the ice cover

B = the accumulation width

B_i = the width of the underside of the ice cover

C = expansion or contraction loss coefficient

e = the ice jam porosity

F = a shorthand expression of the force balance equation

g = gravitational acceleration

h_e = energy head loss

H = the total water depth

k_1 = the coefficient of lateral thrust

L = discharge weighted reach length

L_d = the distance between cross sections

n = Manning's roughness coefficient

n_b = the bed Manning's roughness value

n_c = the composite roughness

n_i = the ice Manning's roughness value

$n_{i(sim)}$ = simple ice cover roughness

$n_{i(jam)}$ = the Manning's roughness value for the ice jam

P_b = the wetted perimeter including the ice cover

Q = the discharge in the reach (cms) or flow between sections

R = hydraulic radius (flow area/wetted perimeter)

R_i = the hydraulic radius due to the ice cover

R_{ic} = the hydrostatic radius associated with the ice cover

List of Symbols

s = the specific gravity of ice

S_f = the friction slope of the flow

$\overline{S_f}$ = representative friction slope between two sections

S_w = the water surface slope

t = the accumulation thickness

t_i = the initial (minimum) accumulation thickness

t_{sim} = simple ice cover thickness (m)

t_{us} = the upstream cross section ice thickness

V_1, V_2 = average velocities (total discharge/total flow area)

V_{min} = the maximum velocity under the ice cover

Y_1, Y_2 = depth of water at cross sections

Z_1, Z_2 = elevation of the main channel inverts

α_1, α_2 = velocity weighting coefficients

φ = the angle of internal friction of the ice jam

ρ' = the ice density

$\overline{\sigma_x}$ = the longitudinal stress (along stream direction)

τ_b = the shear resistance of the banks

τ_i = the shear stress applied to the underside of the ice by the flowing water

1.0 Introduction

The formation of an ice jam and its subsequent release is both an exciting and dangerous event. While the awesome power an ice run exhibits as it mows down trees and other established vegetation with ease, gradually slowing its advance, and then jamming the river thus choking off the flow of water is awe-inspiring, it should be remembered that an ice jam has the potential to send ice and water over the banks of a river and into the surrounding flood plain. Severe flooding caused by ice jams can have extremely high costs with respect to property damage and, more importantly, loss of life. Therefore having an understanding of ice jam induced water levels is very important to engineers especially in situations where a city or town is in the vicinity of an area that is prone to ice jams. One such area that seems to be ideal for the formation of ice jams is confluence of the Clearwater and Athabasca rivers in Alberta Canada. This river junction is also the location of the town of Fort McMurray.

Many studies of ice jams at Fort McMurray have been performed in an effort to better understand and deal with the problems associated with the formation and behavior of ice jams and the flooding they cause. One of theses studies (Northwest Hydraulic Consultants Ltd., 1978) suggests that it is reasonable to assume that the measured water level at MacEwan Bridge less 1m would be an acceptable approximation of the water level at the Clearwater.

This study is an attempt at determining the validity of this suggestion and determining the effect of different hydraulic properties of the difference in water surface elevations at MacEwan Bridge and the Clearwater River. This will be done by performing an analysis of the Athabasca River at Fort McMurray using the HEC RAS (Hydraulic Engineering Center – River Analysis System) software.

2.0 Site Description

As mentioned previously the town of Fort McMurray is situated at the confluence of the north-flowing Athabasca and Clearwater rivers. The Athabasca River is a north-flowing river that originates in Alberta's Rocky Mountains. The hydraulic conditions presented by this reach, near Fort McMurray, are ideal for the formation of ice jams. Since the Athabasca River is north-flowing the tributaries and sections, upstream or Fort McMurray, all usually begin to break up before the downstream sections, this can, and usually does, cause ice runs to occur. Also there happens to be a significant decrease in the slope of the river and a significant widening of the river right at the town of Fort McMurray. These physical and hydraulic conditions make it easy for ice jams to occur in the vicinity of the town. When the toe of an ice jam stops at or downstream of the Clearwater it can cause water and ice to back up into the Clearwater and thereby flood Fort McMurray.

There have been numerous river cross section surveys done on the Athabasca River both upstream and, to a lesser extent, downstream of the Clearwater confluence. In conjunction with T. Kowalczyk a geometric data base was created using these cross sections for use in HEC RAS. Appendix A collects all of the available cross sections the justification for their removal or use in the functional data base.

3.0 Theory

3.1 Steady Flow With Out Ice Conditions

HEC RAS is a steady gradually varied flow model. The solution procedures used by HEC RAS can be found in detail in the HEC RAS manuals by Gary W. Brunner (2001). This section provides an outline of the formulas and approach that HEC RAS uses to model ice jams.

HEC-RAS models steady flow water surface profiles by utilizing an iterative procedure known as the standard step method to calculate the water surface profiles for one cross section to the next by solving the Energy equation (Brunner, 2001). For subcritical flow this iterative approach begins at the most down stream cross section and progresses up stream. The Energy equation takes the following form:

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^{\,2}}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^{\,2}}{2g} + h_e \qquad (3.1)$$

Where:

	Y_1, Y_2	= depth of water at cross sections
	Z_1, Z_2	= elevation of the main channel inverts
	V_1, V_2	= average velocities (total discharge/total flow area)
	α_1, α_2	= velocity weighting coefficients
	g	= gravitational acceleration
	h_e	= energy head loss

The energy head loss (h_e) is a representation of the friction and expansion or contraction losses between the two cross sections (Brunner, 2001). Energy head loss is equated in this manner:

$$h_e = L\overline{S}_f + C\left|\frac{\alpha_2 V_2^{\,2}}{2g} - \frac{\alpha_1 V_1^{\,2}}{2g}\right| \quad (3.2)$$

Where: L = discharge weighted reach length

$\overline{S_f}$ = representative friction slope between two sections

C = expansion or contraction loss coefficient

The determination of Manning's roughness coefficient, n, is done using Manning's Equation, which is found in this form:

$$Q = \frac{A}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad (3.3)$$

Where: Q = flow between sections

n = Manning's roughness coefficient

R = hydraulic radius (flow area/wetted perimeter)

In instances of divided flow, i.e. flow around an island, HEC RAS simply takes the two flow areas and the two wetted perimeters and sums them to create single values for hydraulic radius, flow area, and wetted perimeter.

3.2 Modeling a River with an Ice Cover

The presence of an ice cover on a river greatly affects its conveying capacity, substantially reducing the discharge for a given station when all other factors remain constant (Davar, 1996). The way the ice changes the hydraulic regime of the river is the cause of this decrease in flow. The ice cover decreases the flow area and increases the wetted perimeter, in fact, an ice cover completely frozen from bank to bank can virtually double the wetted perimeter of a station when compared to open water conditions. The changes in these two flow conditions when placed in Manning's Equation (shown above) reduce the hydraulic radius and therefore reduce the flow between sections.

HEC-RAS allows for the modeling of an ice covered river in two ways. The first is an ice cover with known geometry and the second being wide-river ice jams (Brunner, 2001).

3.2.1 Ice Cover with Known Geometry

The roughness characteristic of a channel due to an ice cover can vary significantly along a channel and even across the channel (Brunner, 2001). However this roughness can be estimated using the Belokon-Sabaneev composite roughness formula:

$$n_c = \left(\frac{n_b^{\frac{3}{2}} + n_i^{\frac{3}{2}}}{2} \right)^{\frac{2}{3}} \tag{3.4}$$

Where: n_c = the composite roughness

n_b = the bed Manning's roughness value

n_i = the ice Manning's roughness value

The hydraulic radius of an ice covered channel is found as:

$$R_i = \frac{A_i}{P_b + B_i} \tag{3.5}$$

Where: R_i = the hydraulic radius due to the ice cover

A_i = the flow area beneath the ice cover

P_b = the wetted perimeter including the ice cover

B_i = the width of the underside of the ice cover

The composite roughness (which for a single layer of ice typically ranges from 0.01 to 0.06) and the hydraulic radius modified to account for the ice cover can be substituted into equation 2.3 to estimate the flow in the ice covered channel (Brunner, 2001). The flow area beneath the ice cover is a function of the density of ice compared to that of water. Typically the density of ice is assumed to be approximately 90 % of the density of water. This means that approximately 90 % of the ice cover floats below the water surface.

3.2.2 One-Dimensional Ice Jam Modeling Theory:

The modeling capability of HEC RAS with respect to ice jams is limited to one type of ice jams. This type is referred to as a "wide" or "wide-river" ice jam (ref), a jam which is characterized by how they thicken through the consolidation or "shoving" of the ice cover. The accumulation is assumed to behave as a granular mass and the forces on the ice cover are assumed to be directly proportional to the channel width. These forces are the flow shear stress caused by both the water on the underside of the ice cover and banks of the river on the ice cover and the gravitational force from the down-slope component of the ice weight.

In order to model the wide ice jam these forces must be balanced. Therefore the stresses acting on the jam can be determined using the force balance equation:

$$\frac{d\left(\overline{\sigma_x} t\right)}{dx} + \frac{2\tau_b t}{B} = \rho' g S_w t + \tau_i \tag{3.6}$$

Where: $\overline{\sigma_x}$ = the longitudinal stress (along stream direction)

t = the accumulation thickness

τ_b = the shear resistance of the banks

B = the accumulation width

ρ' = the ice density

g = the gravitational acceleration

S_w = the water surface slope

τ_i = the shear stress applied to the underside of the ice by the flowing water

In order to evaluate the force balance equation estimations and assumptions of certain values and relationships must be made. The under ice shear, τ_i, is estimated as:

$$\tau_i = \rho g R_{ic} S_f \tag{3.7}$$

Where: R_{ic} = the hydrostatic radius associated with the ice cover

S_f = the friction slope of the flow

R_{ic} can be determined by:

$$R_{ic} = \left(\frac{n_i}{n_c}\right)^{1.5} R_i \tag{3.8}$$

Using the empirical relations developed from the data collected by Nezhikovsky (1964) the Manning's roughness for wide ice jams in HEC RAS is determined. In situations where the ice accumulation is less than 0.4572m (1.5 ft) thick

$$n_i = 0.0593 H^{-0.23} t^{\;0.77} \tag{3.9}$$

and when the accumulation is more than 0.4572m (1.5 ft) thick

$$n_i = 0.069 H^{-0.23} t^{\;0.40} \tag{3.10}$$

where:	H	= the total water depth
	t	= the accumulation thickness

In order to properly evaluate the force balance equation it must be assumed that the stresses $\overline{\sigma_x}$ and τ_i, as well as the accumulation's thickness, t, are constant across the width of the jam. It must also be assumed that the ice pieces are completely cohesionless and that the stresses on the jam and the mean vertical stress can be related to each other in a fashion analogous to passive pressure in soil mechanics. Therefore, if it is assumed that the mean vertical stress comes only from vertically acting hydrostatic forces then the vertical stress $\overline{\sigma_z}$ is

$$\overline{\sigma_z} = \gamma_e t \tag{3.11}$$

where: $$\gamma_e = 0.5 \rho' g (1-s)(1-e) \tag{3.12}$$

where: s = the specific gravity of ice

e = the ice jam porosity

Based on equation (vertical stress) the longitudinal stress, $\overline{\sigma_x}$, is therefore

$$\overline{\sigma_x} = k_x \overline{\sigma_z} \tag{3.13}$$

where:

$$k_x = \tan^2\left(45 + \frac{\varphi}{2}\right) \tag{3.14}$$

φ = the angle of internal friction of the ice jam

The longitudinal stress may then be used to express the lateral stress perpendicular to the banks so that

$$\overline{\sigma_y} = k_1 \overline{\sigma_x} \tag{3.15}$$

where: k_1 = the coefficient of lateral thrust

The lateral stress can then be used to equate the shear stress, τ_b,

$$\tau_b = k_0 \overline{\sigma_y} \tag{3.16}$$

where:

$$k_0 = \tan\varphi \tag{3.17}$$

Therefore, using the above estimations and relations, equation (force balance eqn) can be rewritten as:

$$\frac{dt}{dx} = \frac{1}{2k_x\gamma_e}\left[\rho' g S_w + \frac{\tau_i}{t}\right] - \frac{k_0 k_1 t}{B} = F \tag{3.18}$$

where: F = a shorthand expression of the force balance equation

Using a known ice jam thickness at the most upstream end of the jam the next downstream cross section ice jam thickness is then determined. This downstream cross section ice jam thickness, t_{ds}, is found using

$$t_{ds} = t_{us} + \left[\frac{F_{us} + F_{ds}}{2}\right] L_d \tag{3.19}$$

where: t_{us} = the upstream cross section ice thickness

L_d = the distance between cross sections

The solution procedure that has been adopted in HEC RAS involves a user defined minimum ice thickness profile used by the energy equation and, using the standard step method, is solved in the upstream direction. The depth profile created is then used in combination with the force balance equation to create a new ice thickness profile. The force balance equation and energy equation are solved alternately in an iterative fashion until a default or user specified tolerance is met.

3.3 Model Input requirements

HEC RAS requires that the user input values for certain physical and hydraulic parameters and the geometry of the reach being modeled. A detailed description of the necessary information and the methods of inputting them into HEC RAS can be found in the HEC RAS manuals by Gary W. Brunner (2001). This section provides a basic description of the required input parameters as well as the values decided upon by the author and the reasons for these decisions.

As can be seen from section 3.2.2 there are certain input parameters that must be entered into HEC RAS in order to solve the force balance equation (equation 3.6). These input parameters include

- t_i = the initial (minimum) accumulation thickness
- $n_{i(jam)}$ = the Manning's roughness value for the ice jam
- φ = the angle of internal friction of the ice jam
- k_1 = the coefficient of lateral thrust
- e = the ice jam porosity
- s = the specific gravity of ice

Other parameters that HEC RAS requires are:

- V_{min} = the maximum velocity under the ice cover
- Q = the discharge in the reach (cms)
- t_{sim} = simple ice cover thickness (m)
- $n_{i(sim)}$ = simple ice cover roughness

V_{min} is used to prevent the ice jam from becoming grounded at the toe of the jam by the thickening of the ice cover as HEC RAS solves the force balance equation. However, since the toe of an ice jam is not yet fully understood with regards to modeling the sensitivity of the model to the value selected is small. Therefore the default value of 1.524 m/s (5 ft/s) was selected and used for all runs of the model.

The default value used by HEC RAS for the specific gravity of ice is 0.916. As this is a commonly accepted value it was adopted for the purposes of modeling.

The value that was selected for the coefficient of lateral thrust, k1, was also the default value of 0.33 supplied by HEC RAS. Based on a sensitivity analysis it was determined that the value used for k1 was of little importance as it had little or no significant effect on the computed water level.

The angle of internal friction, φ, was set to 55^{o} and the porosity of the ice jam, e, was set to 0.4, based on the work of Healy and Hicks (1997).

4.0 Historical Ice Jam Modeling

Since 1977, thirteen ice jams have formed in the vicinity of Ft. McMurray (i.e. between Stations 327 km and 268.3km as defined by the University of Alberta). Each of these thirteen historic ice jams have been modeled and a possible ice jam scenario has been created, and in some instances, more than one based on the data collected or previous hydraulic analysis performed for the given ice jam event. For the purposes of modeling the two bridges crossing the river at 294.9km and 294.85km, collectively referred to as MacEwan Bridge, were not placed in the model as a sensitivity analysis showed that their presence did not have an appreciable effect on the results in both the open water and ice jam simulations. In instances where an ice jam occurred at or included the confluence of the Clearwater and Athabasca rivers and water began flowing back up the Clearwater (based on historical observation) the inflow was ignored as it could not be accurately determined nor would such a change in discharge have a large effect on the modeled water levels. However, in years where the inflow from the Clearwater did have an appreciable effect it was included in the model as a change in discharge.

The modeling procedure for each of the ice jams scenarios was very similar. For each year a geometry file and a flow file were created with these two files together creating a plan file. In instances where there were multiple possible ice jam scenarios multiple plans were created. As outlined in the previous section HEC RAS has many input parameters. For the geometry file the inputs that were required are: the minimum jam thickness (m), ice jam Manning's n (i.e. ice jam roughness), simple ice cover thickness, simple ice cover Manning's n (for all scenarios of this project $n_{i(sim)}$ = 0.0015), station for the toe location of the ice jam, and station for the head location of the ice jam. All of the other input ice jam geometry data, as discussed in the previous section, was either left at its default value or changed as outlined previously. It should be noted that for all ice jam runs HEC RAS demands that in the geometry file there can be no open water downstream of the toe of the ice jam and there must be open water upstream of the head of the jam. The flow file created to complement the geometry file consisted of entering the discharge at the most upstream station and then at any station where there was a change in discharge, which for this projects purposes was in certain modeled years was the station where the Clearwater River joins the Athabasca River, i.e. 293.2km. The other inputs needed were the observed water surface elevations for when the jam was in place and the boundary condition for which HEC RAS would use to perform its calculations. For the purposes of this project the boundary condition chosen was the downstream slope of the channel. The downstream slope was set at 0.0003 based on previous analysis performed by the University of Alberta. Also after a sensitivity analysis was done on the slope it was found to have no effect on the model output when varied significantly. After the plan of a particular ice jam event had been created the model was then run. At this point in the modeling procedure two issues became very important; the first being that, the model must finish running before reaching its maximum number of iterations, i.e. 101 iterations and second that obviously, the output or calculated water surface elevations must match the observed water surface elevation to within at least 10cm. Thus to ensure that the model reached a solution before it performed the maximum number of iterations the calculation tolerance were adjusted. After a sensitivity analysis was performed it was determined that the water surface calculation tolerance could be varied to adjust the number of iteration whereas the other parameters (critical depth calculation tolerance, maximum number of iterations, and maximum difference tolerance) had no effect on the number of iterations the model would perform for a given case and were set at the minimum possible tolerance. Therefore, for each scenario the water surface calculation tolerance was varied to four decimal places until the model closed within 101 iterations. Once this fact was secured for a given scenario the solution was checked to determine whether or not the computed water surface elevations matched the observed water surface elevations to within 10cm. If the calculated and observed water surface elevations did not match to within the desired limits the minimum ice jam thickness and ice jam roughness were changed and in some instances the discharge and the simple ice cover thickness was also varied. A given ice jam scenario was only deemed complete after it was determined that the computed water levels and the observed water level coincided to within ten centimeters and that the model finished running before reaching 101 iterations. Table 4.1 shows a summary of all of all of the relevant input values for each of the historical ice jam simulation scenarios. For each year, and in the cases of multiple scenarios, the inputted discharge, head and toe location stationing, minimum ice jam thickness, ice jam roughness, simple ice cover thickness, simple ice cover roughness, and the best water surface calculation tolerance can all be found in Table 4.1.

Table 4.1 Summary of inputted HEC RAS parameters

Year	Discharge cms	Toe Location km	Head Location km	Minimum Ice Jam Thickness m	Ice Jam Roughness	Simple Ice Cover Thickness m	Simple Ice Cover Roughness	Water Surface Calculation Tolerance
1977	2000	292	312	1.5	0.09	0.8	0.015	0.0088
1978 Scenario 1	1200	294.85	316.45	2	0.07	0.9	0.015	0.0093
1978 Scenario 2	550/650*	294.85	316.45	2	0.07	0.9	0.015	0.0093
1979	1700	280	304.7	3.3/0.5a	0.08	0.6	0.015	0.0031
1982 Scenario 1	1300	293.2	296.55	3.1/1.5b	0.085	0.8	0.015	0.0005
1982 Scenario 2	100/200*	293.2	296.55	4/6.5c	0.1	0.8	0.015	0.0001
1984 Scenario 1	500/700*	295.7	306	1.5	0.08	0.8	0.015	0.013
1984 Scenario 2	500/700*	295.7	306	1.5	0.08	1.0 - 2.0	0.015	0.0123
1985 Scenario 1	1400/1500*	313.5	326.95	4	0.07	1	0.015	0.0016
1985 Scenatio 2	700/800*	313.5	326.95	4	0.07	1	0.015	0.0006
1986 Scenario 1	400/500*	288	304	1.5/3.5d	0.08	0.8	0.015	0.0329
1986 Scenario 2	400/500*	288	304	1.2	0.08	0.8	0.015	0.0329
1987 Scenario 1	500/600*	289	301	4.0/4.5e	0.08	0.8	0.015	0.0001
1987 Scenario 2	1000/1100*	289	301	2.5/3.1f	0.07	0.8	0.015	0.005
1988	250/300*	286	305.9	2.0/4.0g	0.1	0.8	0.015	0.0051
1996	870/1000*	279.3	293.2	1.9	0.09	0.8	0.015	0.0005
1997	1500	292	312	2.3	0.085	0.8	0.015	0.0071
2002	250/300*	300.4	308	1	0.07	0.9	0.015	0.0067
2003	700/800*	302	316	1	0.07	0.8	0.015	0.0067

* - #/# the former # refers to the inputted discharge above the Clearwater confluence, while the latter refers to the discharge below the Clearwater confluence.
a - from station 280km to 293.2 the minimum jam thickness was set to 3.3m and from station 293.3 to 304.7 it was set to 0.5m.
b - from station 293.2 to 293.5 the minimum ice jam thickness as set to 3.1m and from station 293.5 to 296.55 it was set to 1.5m.
c - from station 293.2 to 293.5 the minimum ice jam thickness as set to 4.0m and from station 293.5 to 296.55 it was set to 6.5m.
d - from station 288 to 293.2 the minimum ice jam thickness as set to 1.5m and from station 293.2 to 304 it was set to 3.5m.
e - from station 289 to 292.35 the minimum ice jam thickness as set to 4.0m and from station 292.35 to 301 it was set to 4.5m.
f - from station 289 to 292.35 the minimum ice jam thickness as set to 2.5m and from station 292.35 to 301 it was set to 3.1m.
g - from station 286 to 293.7 the minimum ice jam thickness as set to 4.0m and from station 293.7 to 305.9 it was set to 2.0m.

5.0 Historical Ice Jam Simulation Results

For every historical ice jam simulation scenario this section will feature a map of the Athabasca river detailing the head and toe locations of the ice jam for the given followed by a figure showing the water surface profile for the ice jam. In instances where there is considered to be more than one possible ice jam scenario, each water surface profile for all scenarios will be offered with commentary as to which is considered to be most plausible. Finally, the end of this section will feature a summarizing table reporting the calculated water surface elevations at MacEwan Bridge and Clearwater confluence as well as the difference between the two water levels.

5.1 1977 Simulation

Figure 5.1 shows a map of the Athabasca River with the toe of the 1977 ice jam at station 292 and with it's head at station 312. Figure 5.2 shows the water surface profile of the 1977 ice jam. Although the profile does not match the observed water surface elevation at the WSC gauge, this scenario is thought to be valid. This is due to the fact that the WSC gauge malfunctioned during the ice jam and the water level it did record is considered to be for the surge wave that was produced by the release of the ice jam and not the water level at that point for when the ice jam was in place. For the 1977 ice jam simulation the difference in water level between the Clearwater confluence and MacEwan Bridge is 1.14m.

5.2 1978 Simulation

Figure 5.3 shows a map of the Athabasca River with the toe of the 1978 ice jam at station 294.85 and with it's head at station 316.45. Figures 5.4 and 5.5 show the water surface profile for scenarios 1 and 2, respectively, of the 1978 ice jam. For 1978, scenario two is considered to be more accurate. This is due to the fact that it does utilize the WSC mean daily flow and although it does no match the observed water surface elevations at the Clearwater and WSC gauge it can be argued that those elevations are for a surge wave from when the jam released and not necessarily from when the jam was in place. It would seem that while booth scenarios are possible, scenario 2 is more likely as it uses more recorded data and, based on the above reasoning, is more logical. The difference in water surface elevations for the scenarios 1 and 2 are 1.67m and 1.91m, respectively.

5.3 1979 Simulation

Figure 5.6 shows a map of the Athabasca River with the toe of the 1979 ice jam at station 280 and with it's head at station 304.7. Figure 5.7 shows the water surface profile of the 1979 ice jam. This ice jam caused significant flooding along the Clearwater River due to its presence at the confluence. Thus the inflow from the Clearwater is considered to be of little consequence in this instance. As is shown by Figure 5.7 the observed water surface elevations are match very closely and the difference in water level between MacEwan Bridge and the Clearwater is 0.77m.

5.4 1982 Simulation

Figure 5.8 shows a map of the Athabasca River with the toe of the 1982 ice jam at station 293.2 and with it's head at station 296.55. Figures 5.9 and 5.10 show the water surface profile for scenarios 1 and 2, respectively, of the 1982 ice jam. Scenario 1 uses a much higher discharge, namely 1300 cms, while scenario 2 uses the mean daily flow recorded by WSC. However, scenario 1 calls for more realistic ice jam thicknesses than scenario

2, yet in the both cases the scenarios are equally possible and for the purposes of this report the two scenarios offer virtually the exact same water surface elevations at both MacEwan Bridge and at the Clearwater confluence. The difference in water levels for the two scenarios is 4.59m and 4.61m, respectively.

5.5 1984 Simulation

Figure 5.11 shows a map of the Athabasca River with the toe of the 1984 ice jam at station 295.7 and with it's head at station 306. Figures 5.12 and 5.13 show the water surface profile for scenarios 1 and 2, respectively, of the 1984 ice jam. The first scenario makes an attempt at matching the observed water level at the WSC gauge and requires a simple ice cover thickness of 2.0m which should be considered unlikely in reality. Thus with respect to the 1984 ice jam scenarios, scenario 2 is thought to be more plausible. This is because the recorded water surface elevations at the Clearwater and at the WSC gauge are considered to be surge wave water levels and do not reflect the water surface elevations for those areas for when the ice jam was in place. The difference in water levels for the two scenarios is 0.65m and 0.91m, respectively.

5.6 1985 Simulation

Figure 5.14 shows a map of the Athabasca River with the toe of the 1985 ice jam at station 313.5 and with it's head at station 326.95. Figures 5.15 and 5.16 show the water surface profile for scenarios 1 and 2, respectively, of the 1985 ice jam. It is believed that scenario 2 is more plausible than scenario 1. Due to the fact that the observed water surface elevations are very far downstream from the ice jam, the ice jam has little or no effect on the modeled water levels at those observed locations, thus they were considered to be surge wave water levels and were not matched. Scenario 1 utilizes the parameters that are suggested by the hydraulic analysis done on the equilibrium portion of the ice jam by Andres and Rickert (1985), while scenario 2 uses the same parameters except it uses the WSC recorded average daily flow. The difference in water levels for the two scenarios is 1.23m and 1.11m, respectively.

5.7 1986 Simulation

Figure 5.17 shows a map of the Athabasca River with the toe of the 1986 ice jam at station 288 and with it's head at station 304. Figures 5.18 and 5.19 show the water surface profile for scenarios 1 and 2, respectively, of the 1986 ice jam. With regards to the two 1986 ice jam scenarios, scenario 1 is the most plausible. Scenario 1 more closely represents the ice thicknesses from photographs taken of the ice jam and does create water levels that would lead to minor flooding along the Clearwater river, as was reported, where as scenario 2 does not. The difference in water levels for the two scenarios is 1.39m and 0.98m, respectively.

5.8 1987 Simulation

Figure 5.20 shows a map of the Athabasca River with the toe of the 1987 ice jam at station 289 and with it's head at station 301. Figures 5.21 and 5.22 show the water surface profile for scenarios 1 and 2, respectively, of the 1987 ice jam. The parameter values for scenario 1 are taken from an analysis performed previously by Andres (1988) on the equilibrium portion of the ice jam based on shear wall thicknesses. Scenario 2 uses the recorded WSC mean daily flow values. However, due to the fact that both scenarios produce very similar results, for the case of this report neither scenario is more plausible than the other. The difference in water levels for the two scenarios is 1.61m and 1.63m, respectively.

5.9 1988 Simulation

Figure 5.23 shows a map of the Athabasca River with the toe of the 1988 ice jam at station 286 and with it's head at station 305.9. Figure 5.24 shows the water surface profile of the 1988 ice jam. As shown by the figure the calculated water levels and the observed water level coincide to high degree. For the 1977 ice jam simulation the difference in water level between the Clearwater confluence and MacEwan Bridge is 0.38m.

5.10 1996 Simulation

Figure 5.25 shows a map of the Athabasca River with the toe of the 1996 ice jam at station 279.3 and with it's head at station 293.2. Figure 5.26 shows the water surface profile of the 1996 ice jam. The discharge for this simulation is, again, taken from the observed average daily flow for both the Athabasca and Clearwater Rivers. The difference in water levels is 0.04m. It should be noted that this difference in water levels is very robust in that greatly varying either the discharge, minimum ice jam thickness, or the ice jam roughness did not have any appreciable effect on the difference in water levels.

5.11 1997 Simulation

Figure 5.27 shows a map of the Athabasca River with the toe of the 1997 ice jam at station 292 and with it's head at station 312. Figure 5.28 shows the water surface profile of the 1997 ice jam. Although, as figure 5.28 shows, there was only one observed water surface elevation to compare to in this instance this scenario is thought to be a representative approximation. This scenario does use the discharge that is representative of the mean daily flow as reported by WSC. The difference in water level for this simulation is 1.02m.

5.12 2002 Simulation

Figure 5.29 shows a map of the Athabasca River with the toe of the 2002 ice jam at station 300.4 and with it's head at station 308. Figure 5.30 shows the water surface profile of the 2002 ice jam. This scenario uses the WSC recorded discharges and, as shown by figure 5.30, matches the observed water surface elevations very closely. The difference between the bridge and the Clearwater in this instance is 1.03m.

5.13 2003 Simulation

Figure 5.31 shows a map of the Athabasca River with the toe of the 2003 ice jam at station 302 and with it's head at station 316. Figure 5.32 shows the water surface profile of the 2003 ice jam. Figure 5.32 shows that this simulation very closely matches the observed water surface elevations for this event. The difference between the water surface elevations for the Clearwater confluence and MacEwan Bridge in this case is 1.11m.

A summary table of the water levels for MacEwan Bridge and the Clearwater, as well as the difference between the two can be found in Table 5.1. As can be seen from Table 5.1 the Delta H for each scenario ranges from 0.04m to 4.61m. Although in certain years, namely 1986 (scenario 2), 1997, and 2002, the difference in water levels is approximately 1m it is obvious that the suggestion of a one meter difference is not valid. Based on the historical ice jam simulations it would seem that the effects of discharge, ice jam location, ice jam thickness, and ice jam roughness are all rather significant, in fact too significant for the application of a simple 1m "rule-of-thumb".

Table 5.1 Delta H for all model scenarios

Year	Water Surface Elevation		Difference
	MacEwan Bridge	Clearwater	ΔH
	m	m	m
1977	248.76	247.62	1.14
1978 Scenario 1	243.64	241.97	1.67
1978 Scenario 2	243.12	241.21	1.91
1979	247.59	246.82	0.77
1982 Scenario 1	246.82	242.23	4.59
1982 Scenario 2	246.79	242.18	4.61
1984 Scenario 1	242.37	241.72	0.65
1984 Scenario 2	242.29	241.38	0.91
1985 Scenario 1	243.64	242.41	1.23
1985 Scenatio 2	242.64	241.53	1.11
1986 Scenario 1	245.32	243.93	1.39
1986 Scenario 2	243.59	242.61	0.98
1987 Scenario 1	246.49	244.88	1.61
1987 Scenario 2	246.46	244.83	1.63
1988	244.80	244.42	0.38
1996	244.62	244.58	0.04
1997	247.76	246.74	1.02
2002	241.57	240.54	1.03
2003	242.46	241.35	1.11

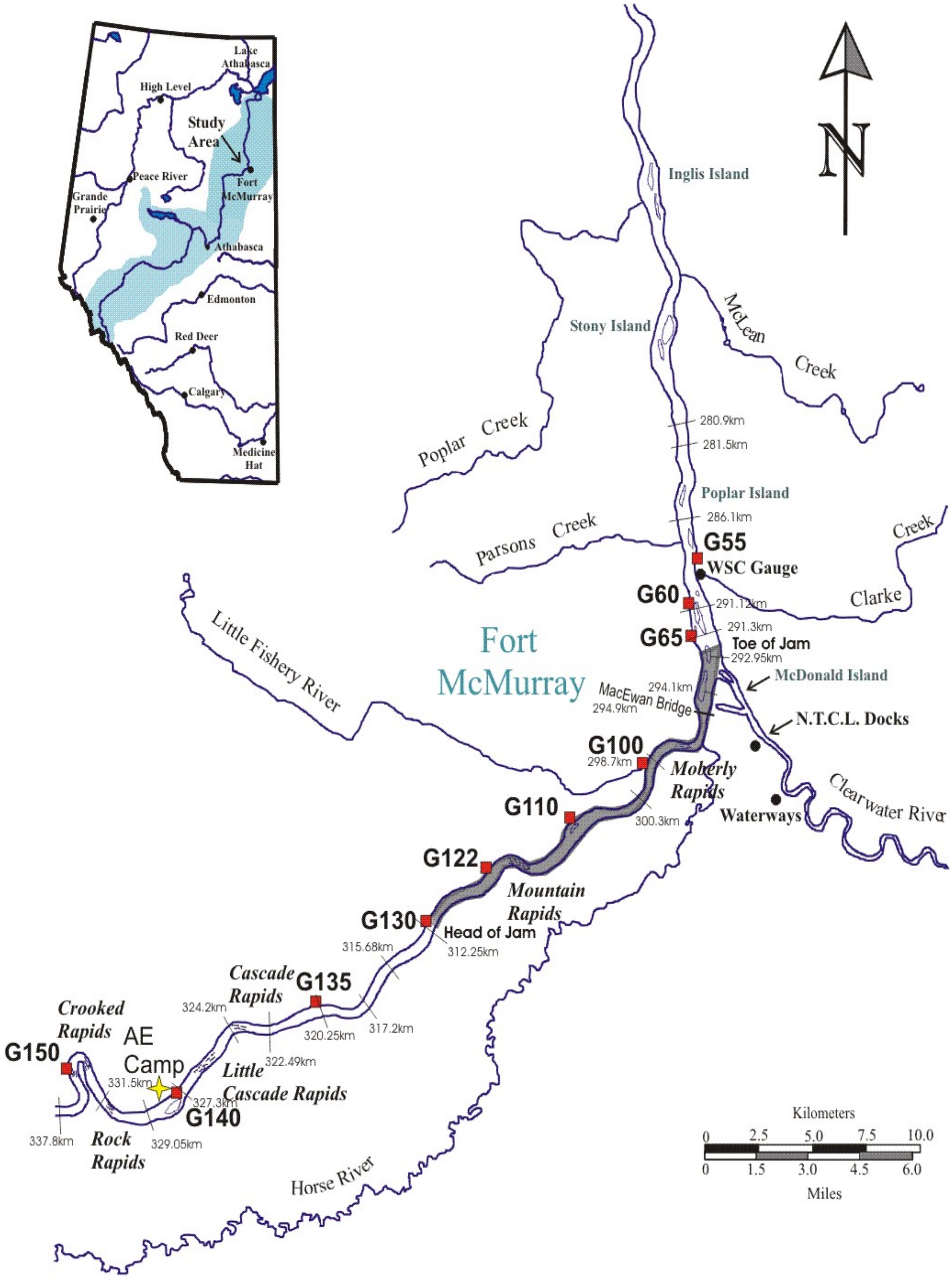

Figure 5.1 Location of 1977 ice jam (adapted from Robichaud, 2003)

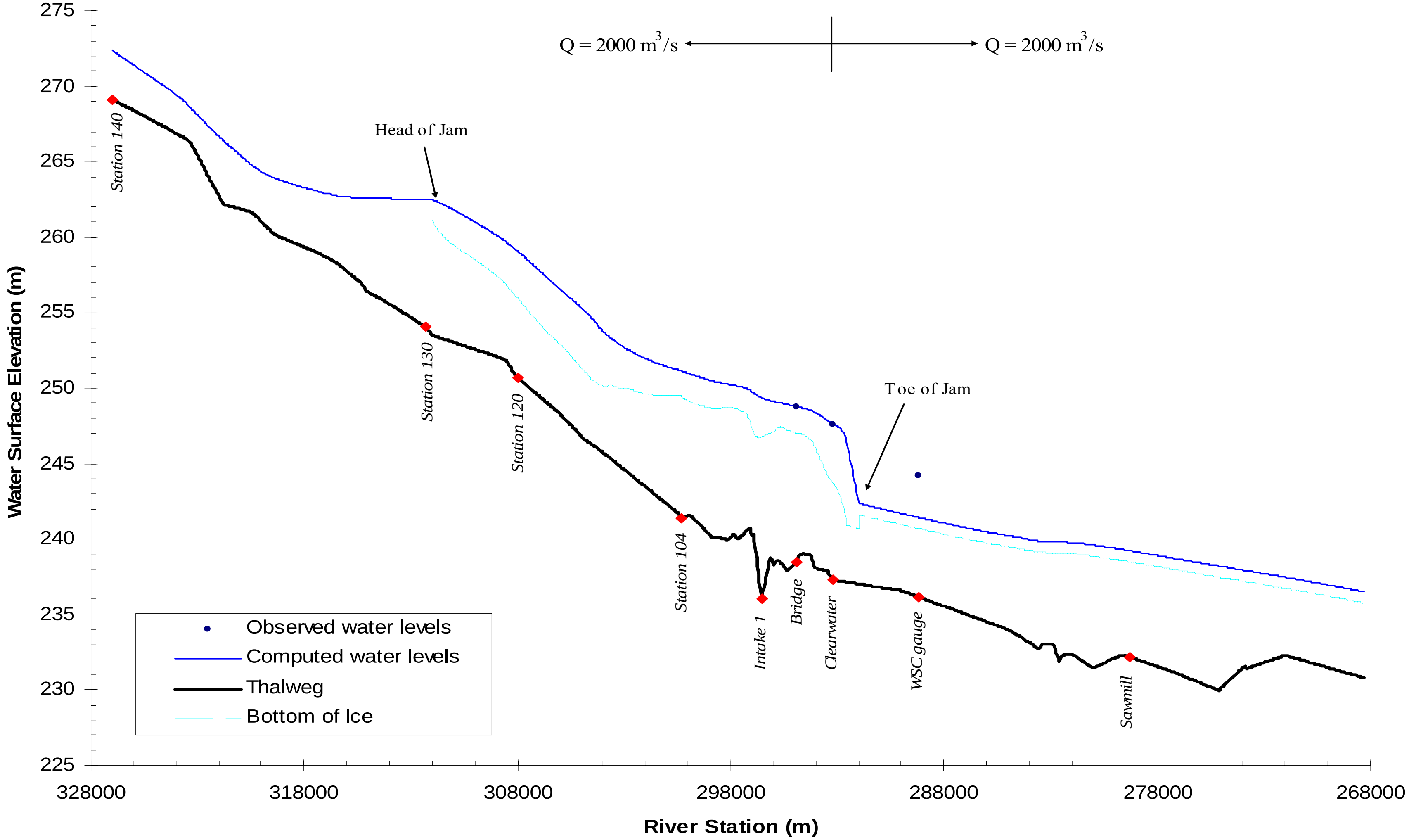

Figure 5.2 Simulated water surface profile for the 1977 ice jam

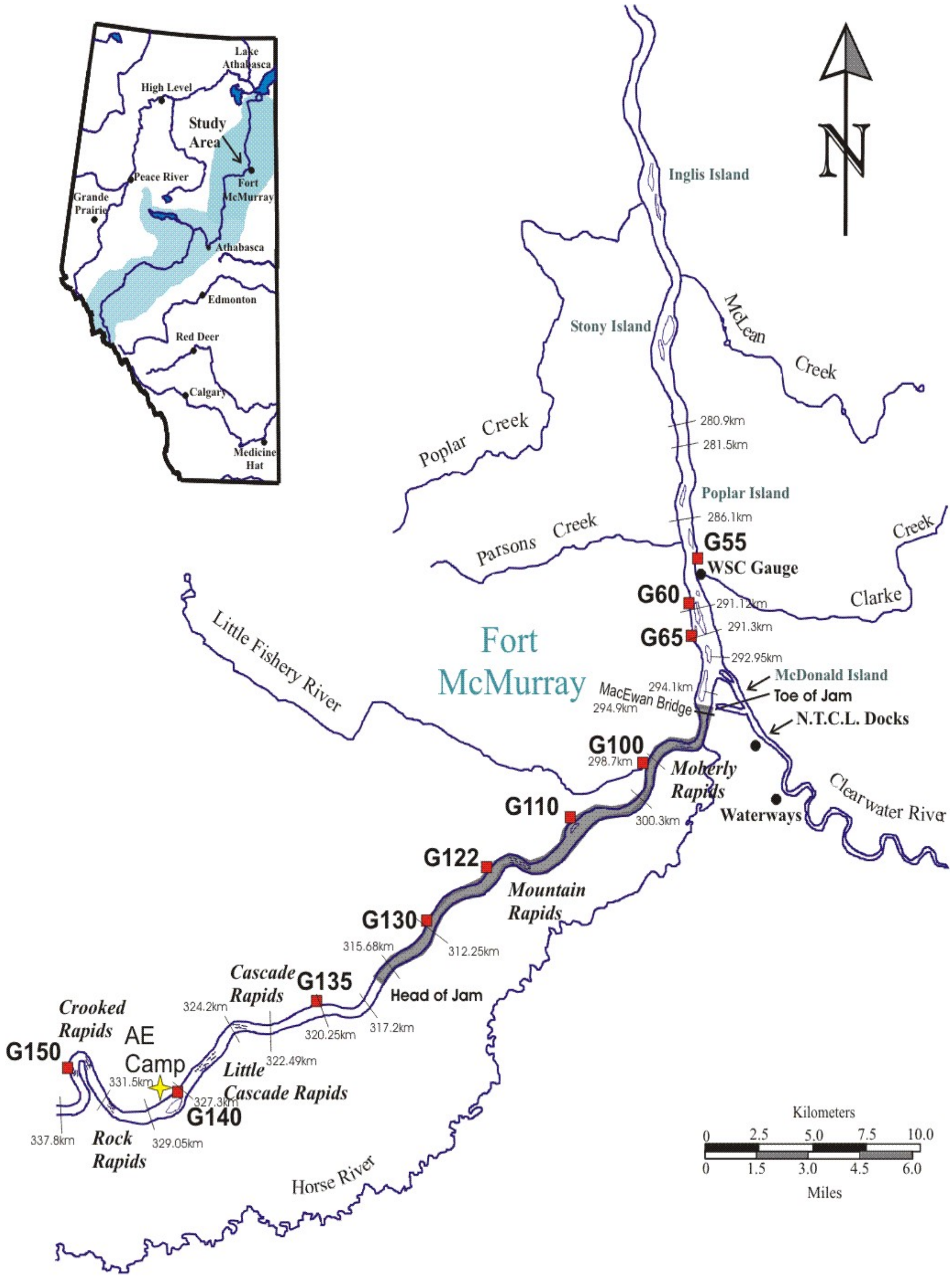

Figure 5.3 Location of 1978 ice jam (adapted from Robichaud, 2003)

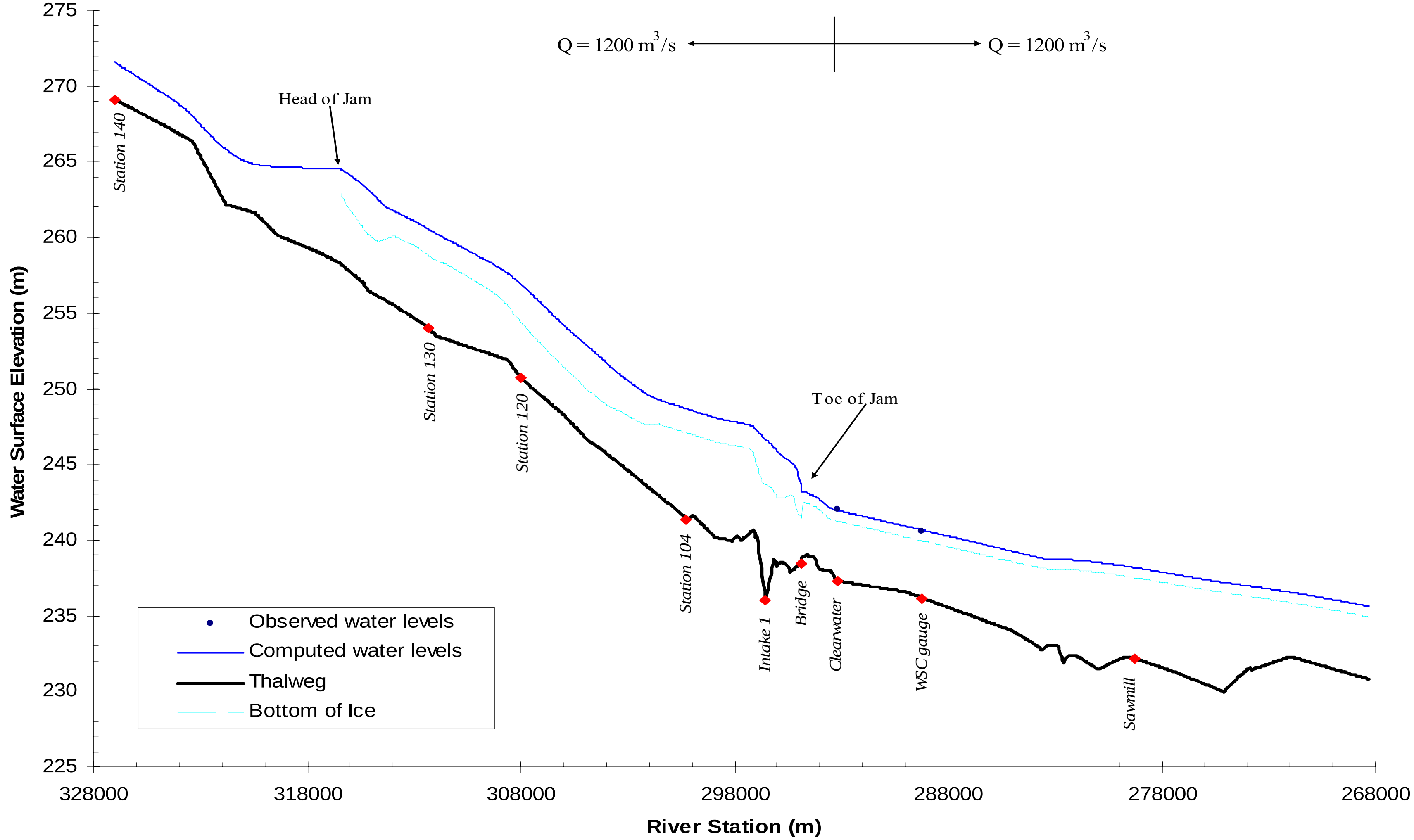

Figure 5.4 Simulated water surface profile for the 1978 ice jam (scenario 1)

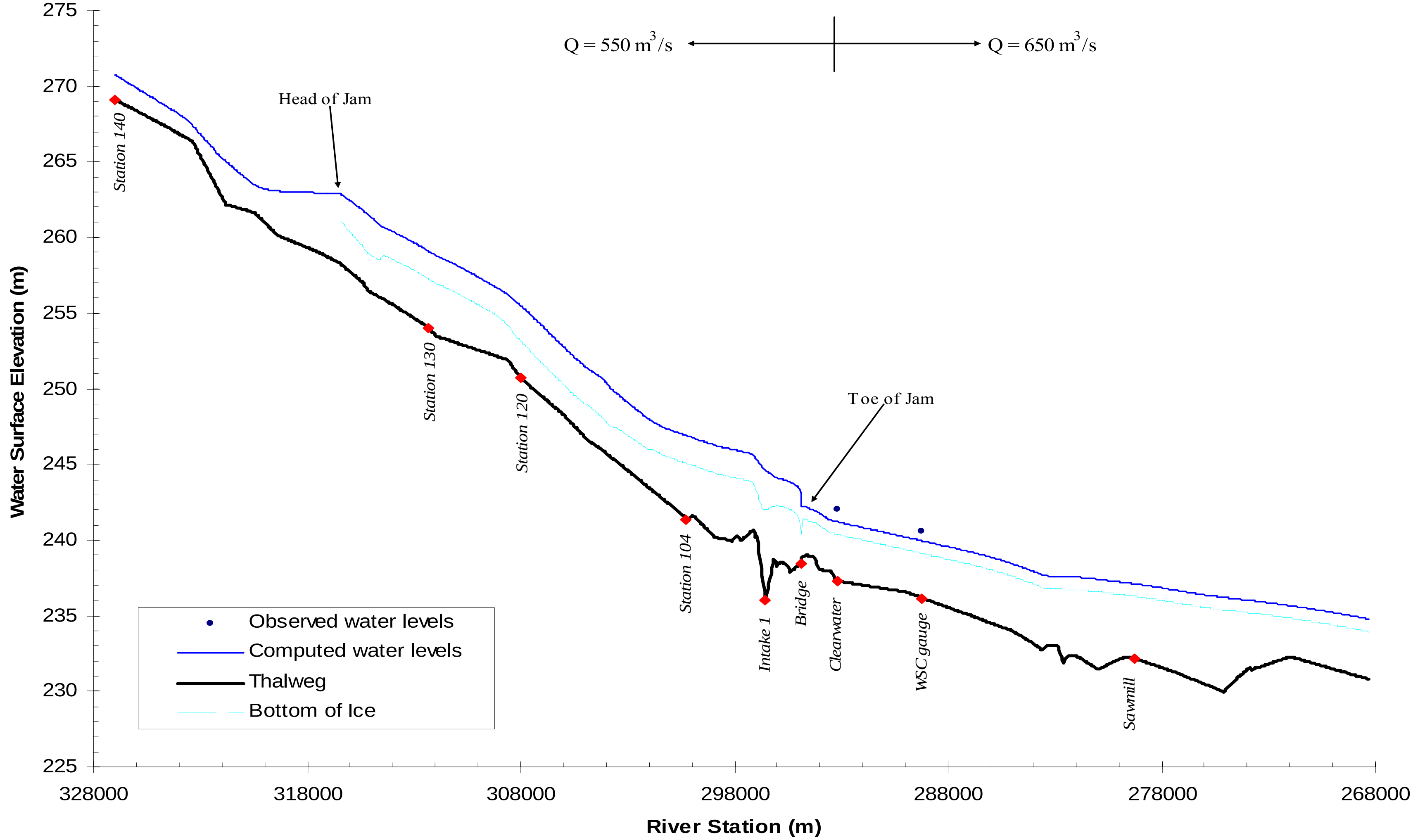

Figure 5.5 Simulated water surface profile for the 1978 ice jam (scenario 2)

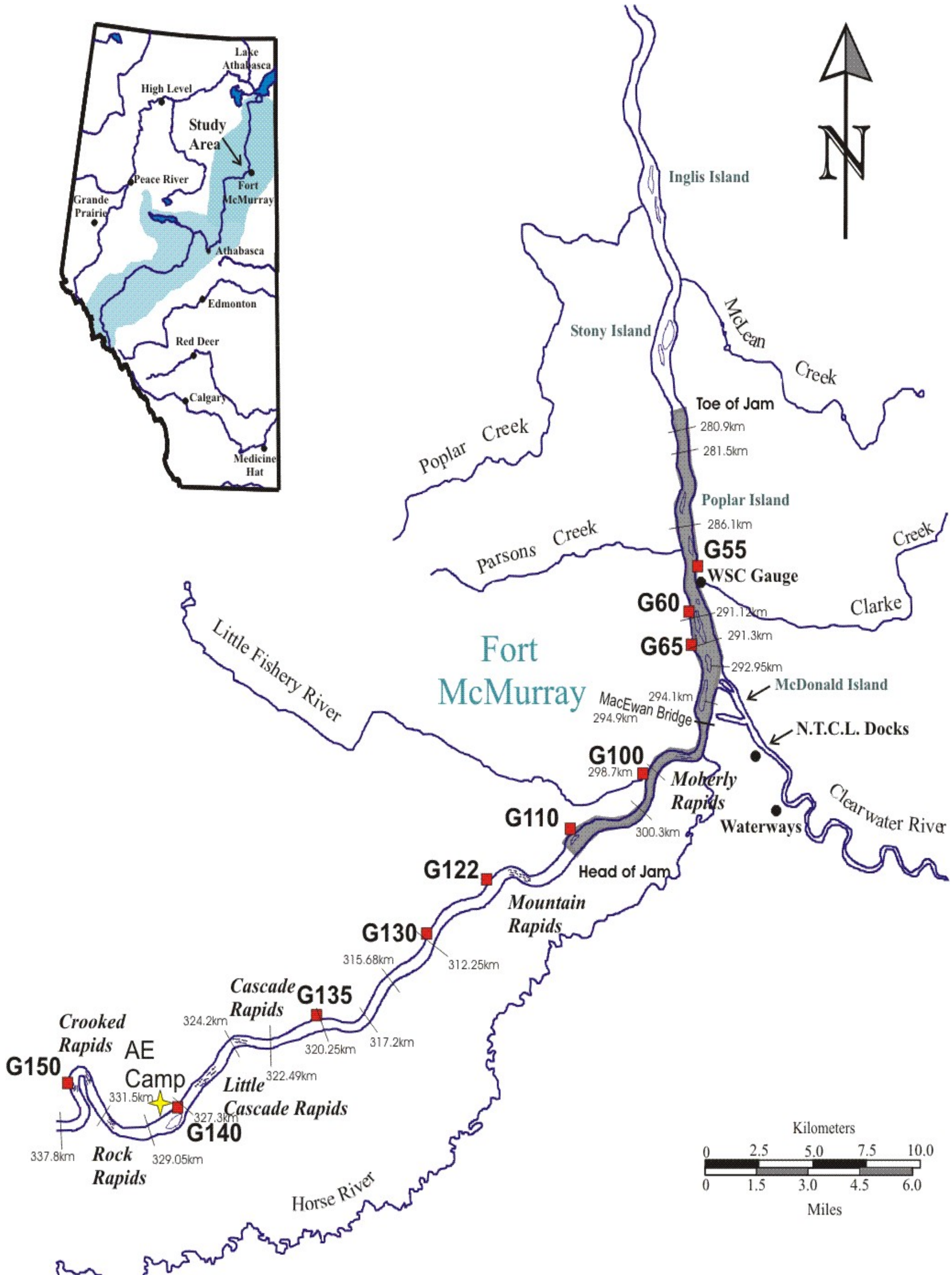

Figure 5.6 Location of 1979 ice jam (adapted from Robichaud, 2003)

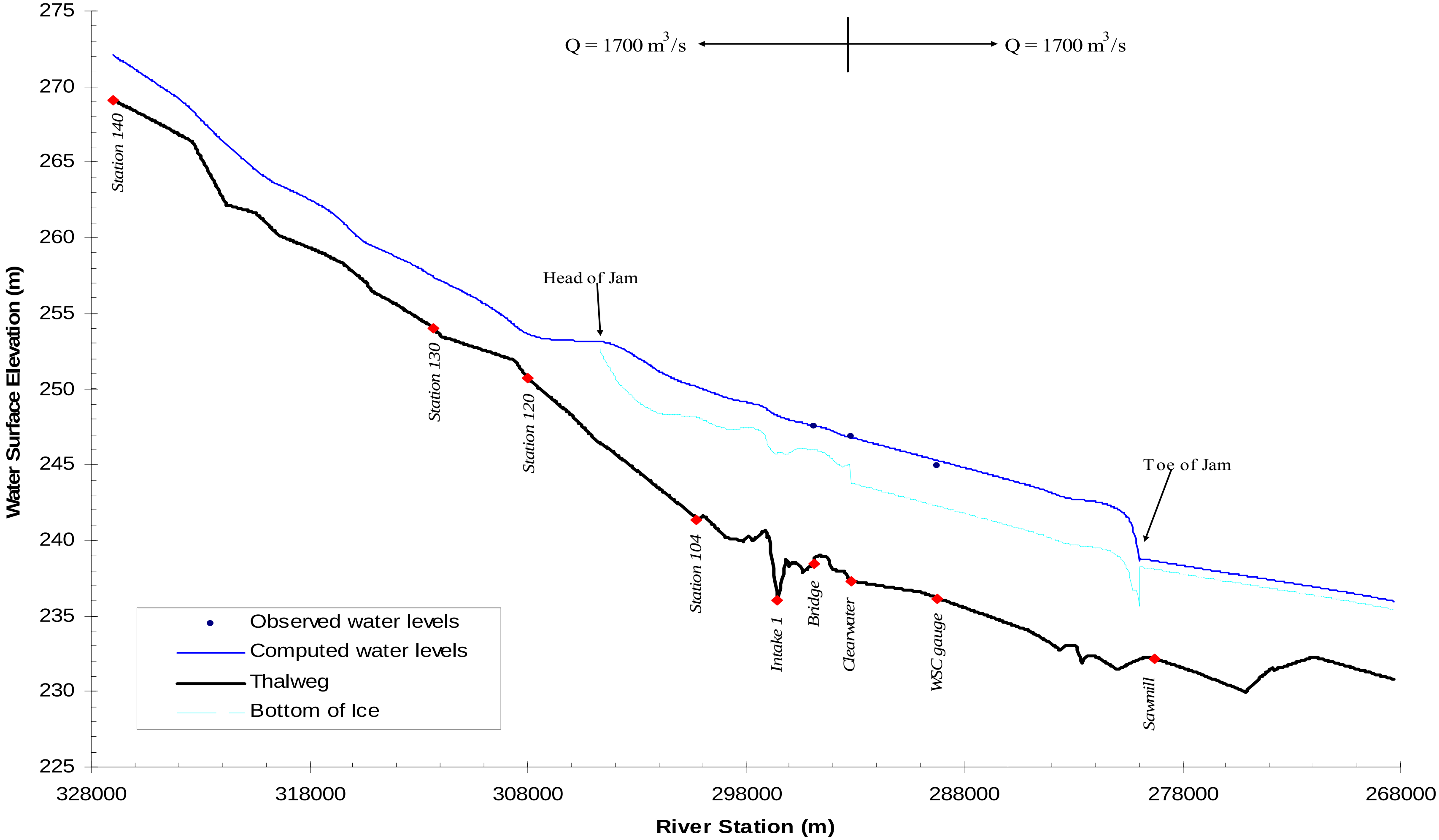

Figure 5.7 Simulated water surface profile for the 1979 ice jam

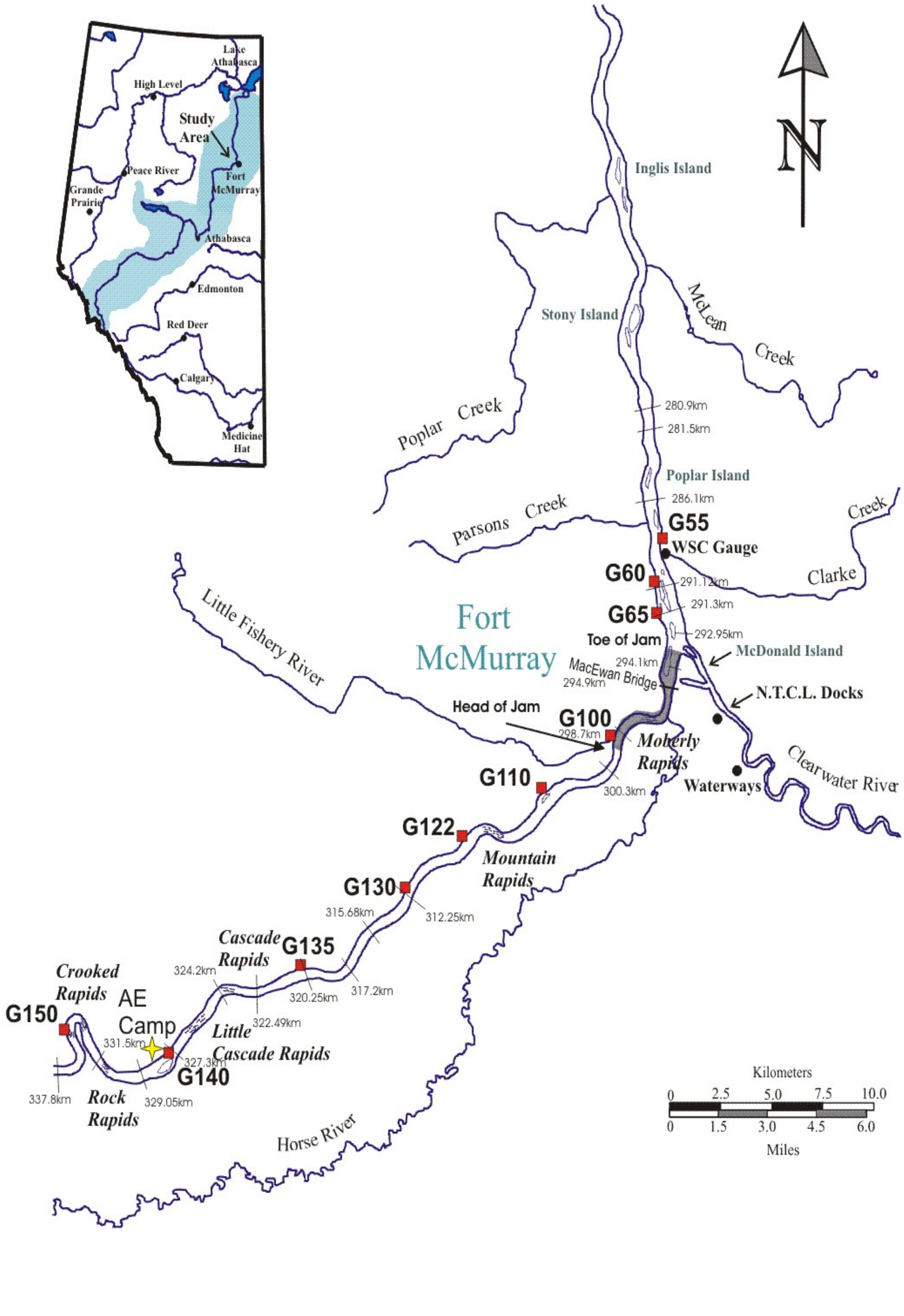

Figure 5.8 Location of 1982 ice jam (adapted from Robichaud, 2003)

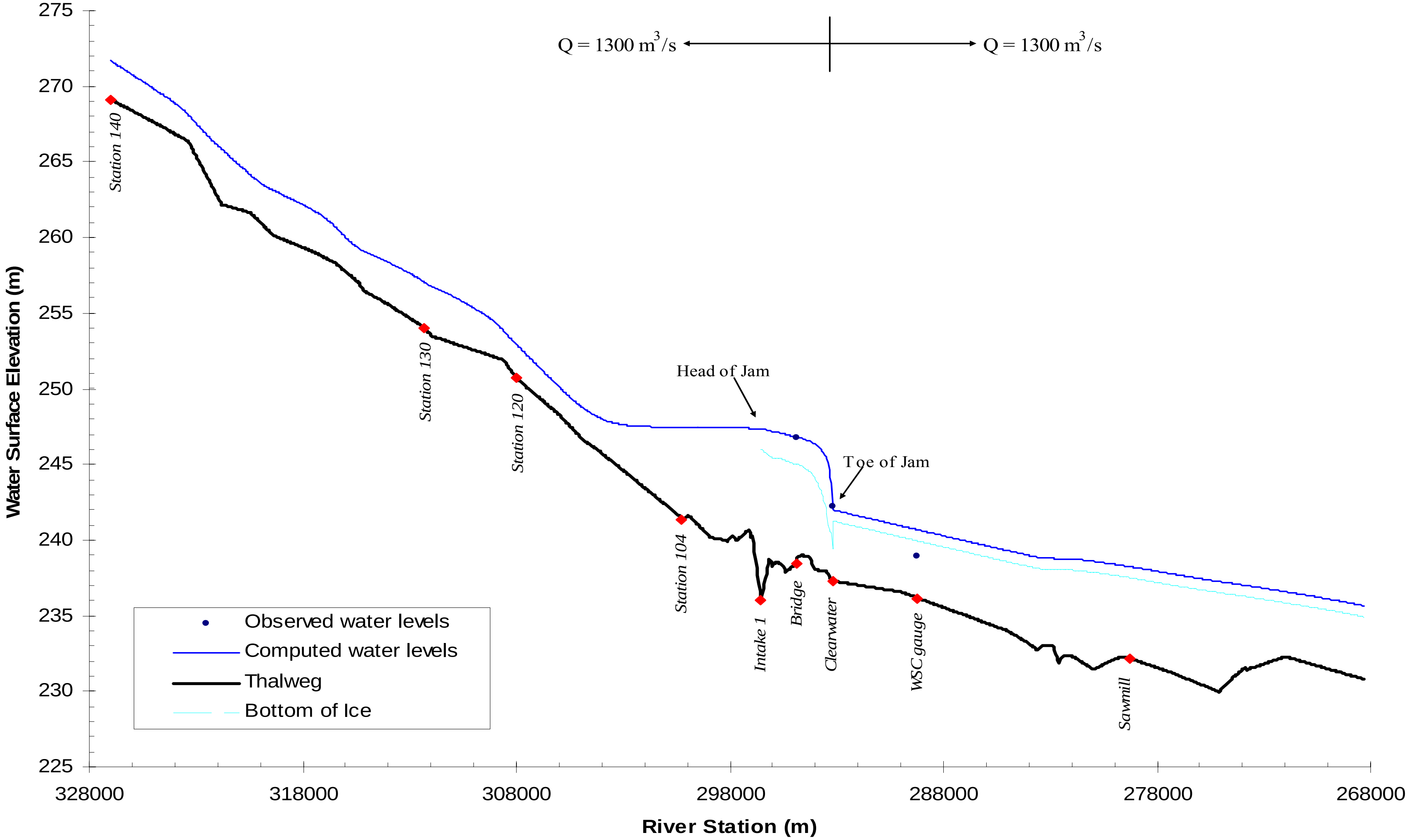

Figure 5.9 Simulated water surface profile for the 1982 ice jam (scenario 1)

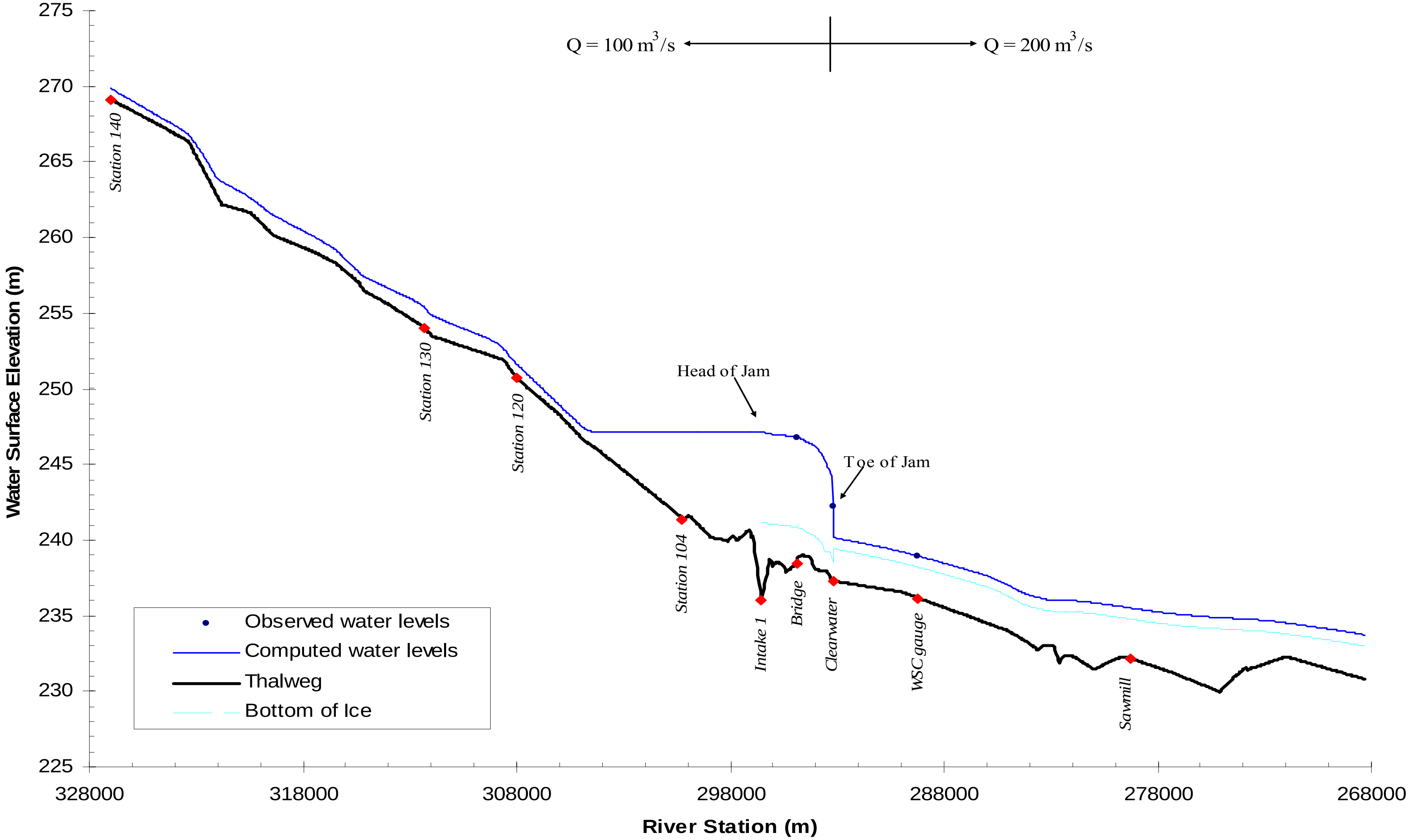

Figure 5.10 Simulated water surface profile for the 1982 ice jam (scenario 2)

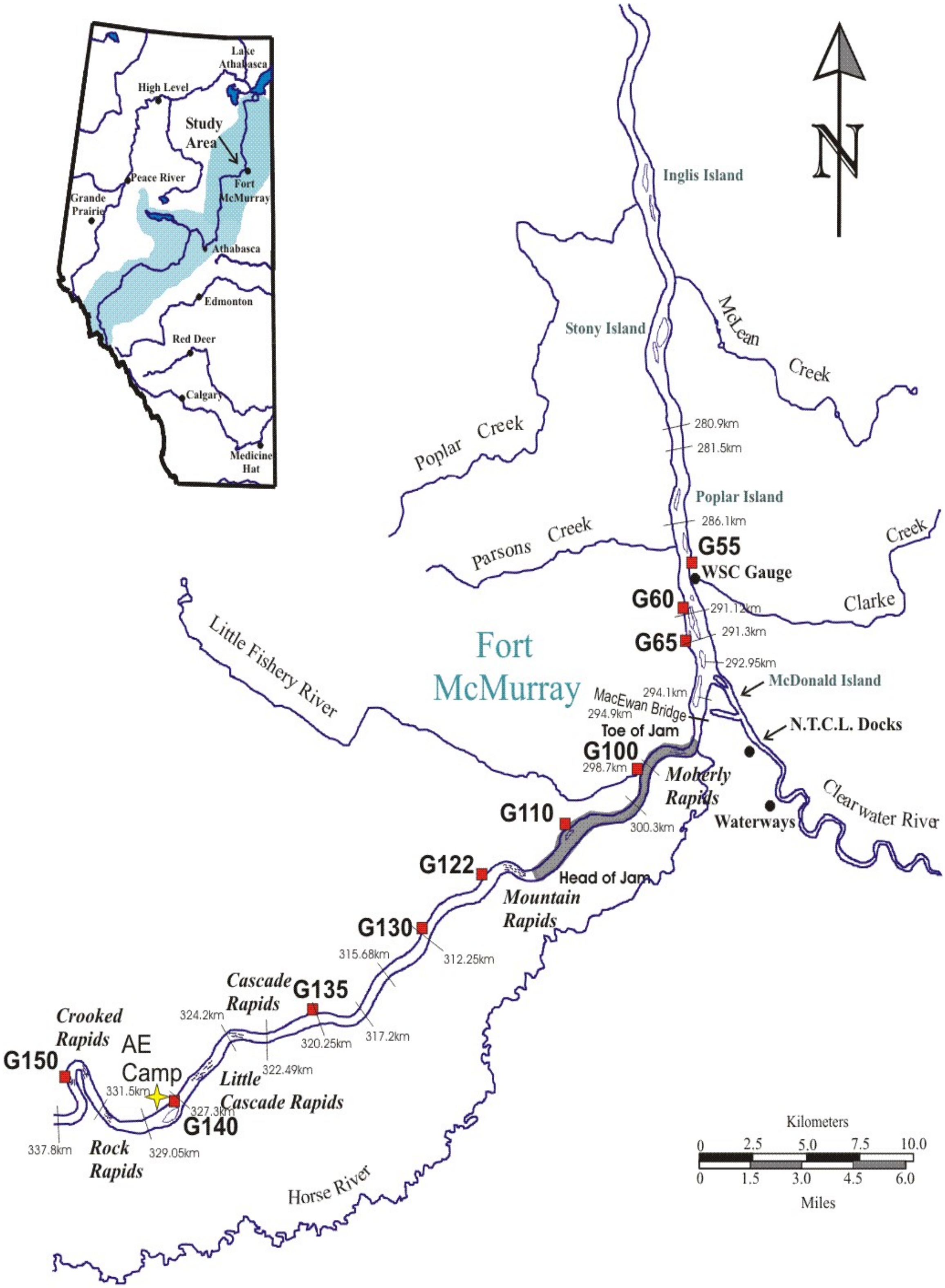

Figure 5.11 Location of 1984 ice jam (adapted from Robichaud, 2003)

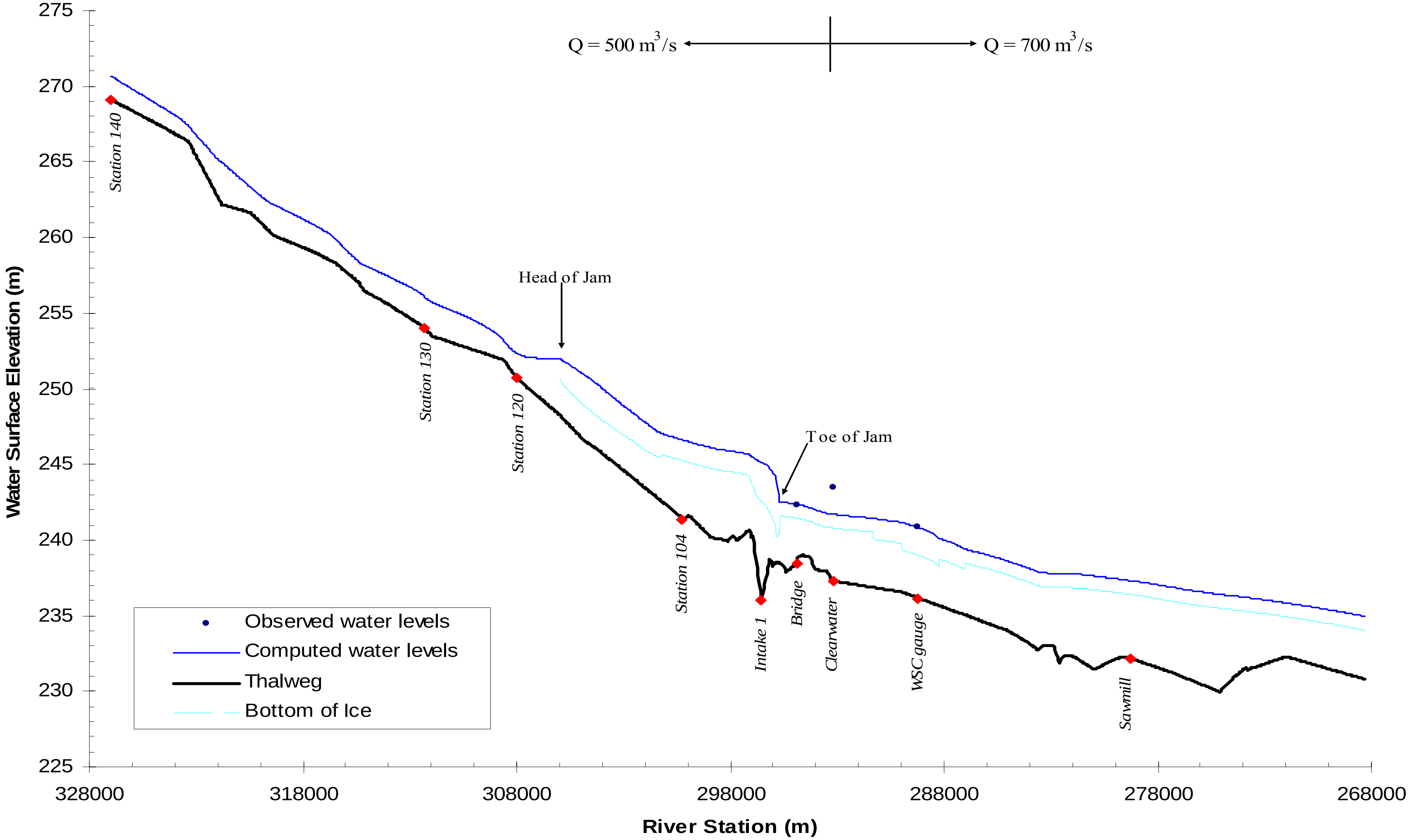

Figure 5.12 Simulated water surface profile for the 1984 ice jam (scenario 1)

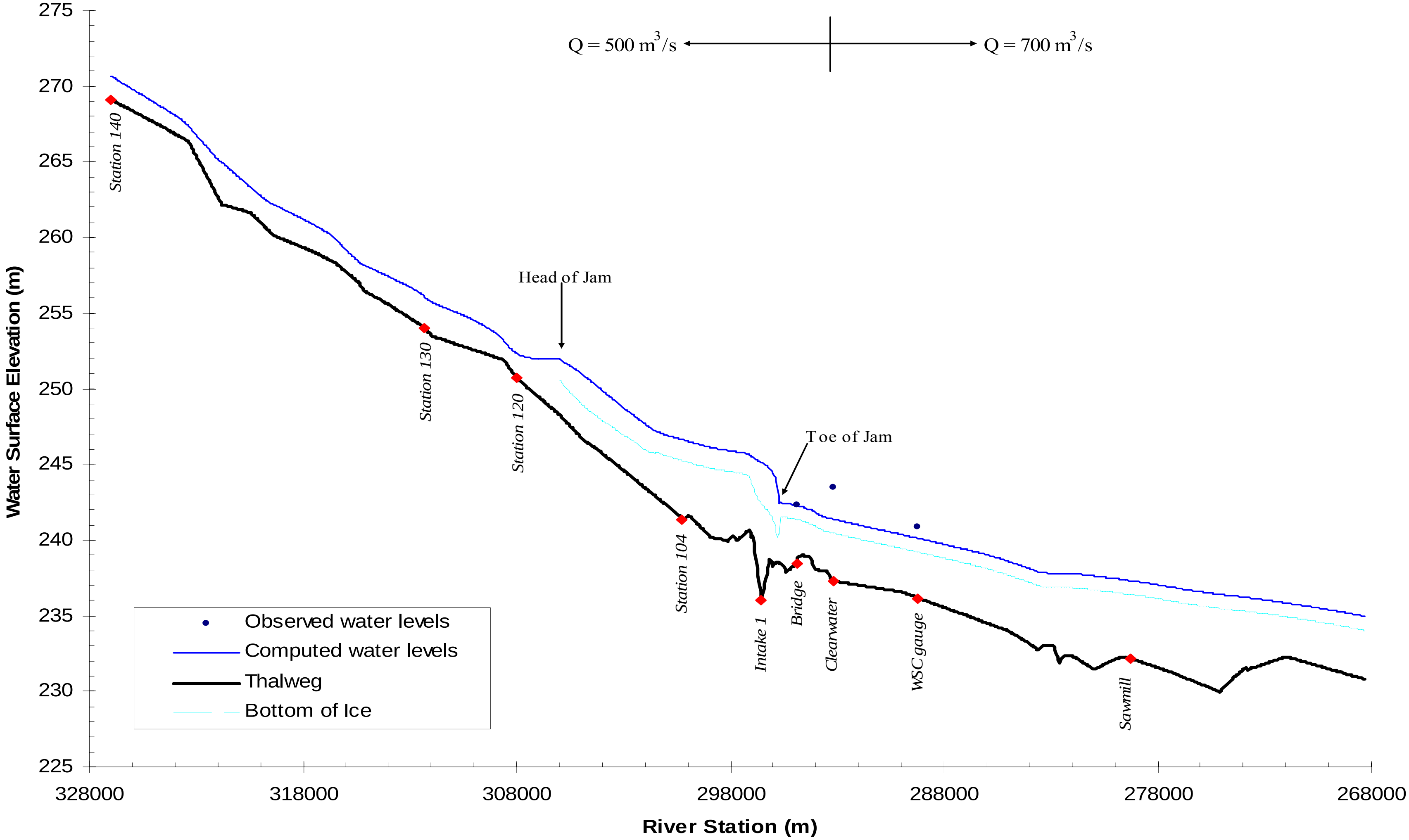

Figure 5.13 Simulated water surface profile for the 1984 ice jam (scenario 2)

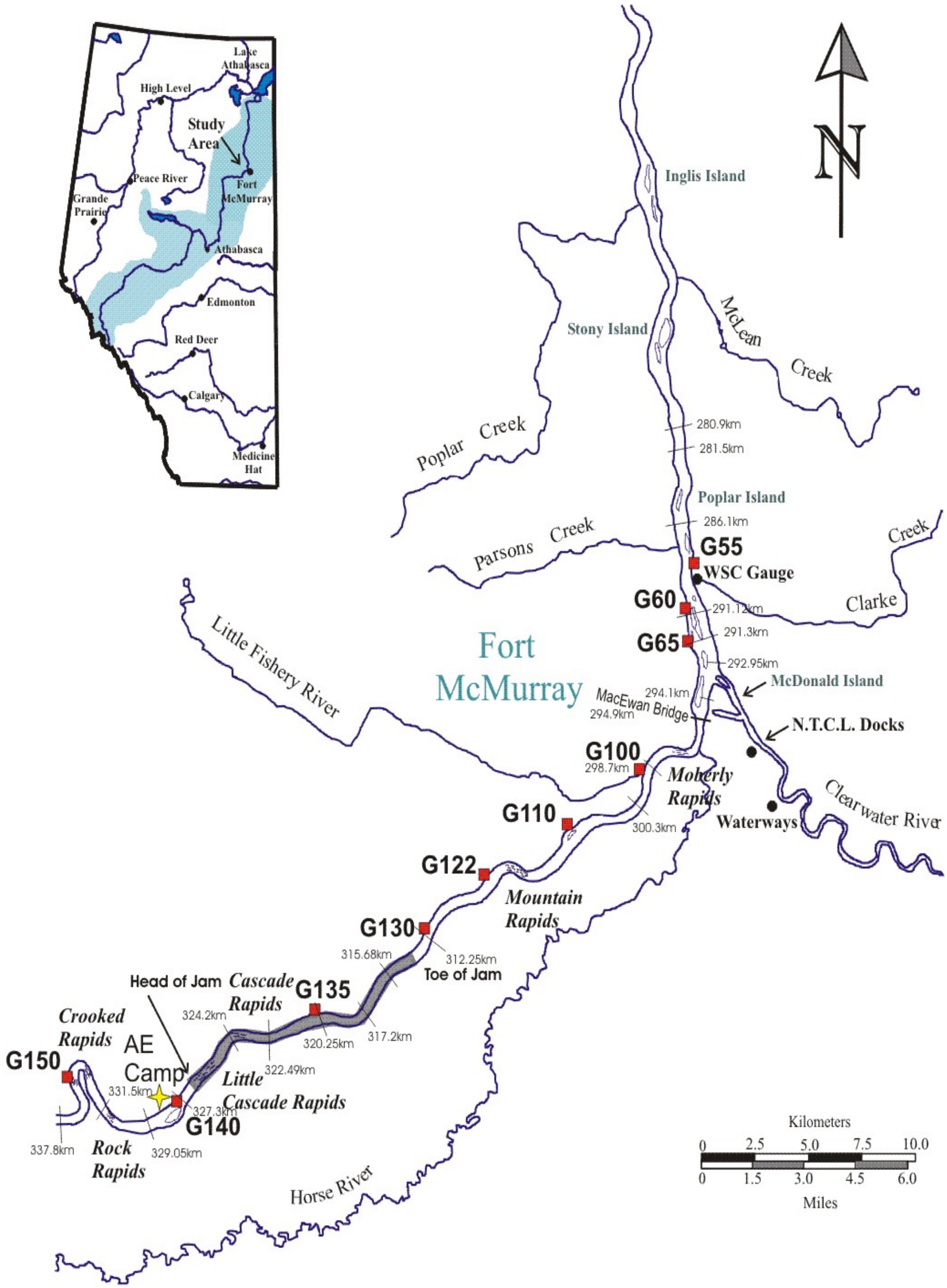

Figure 5.14 Location of 1985 ice jam (adapted from Robichaud, 2003)

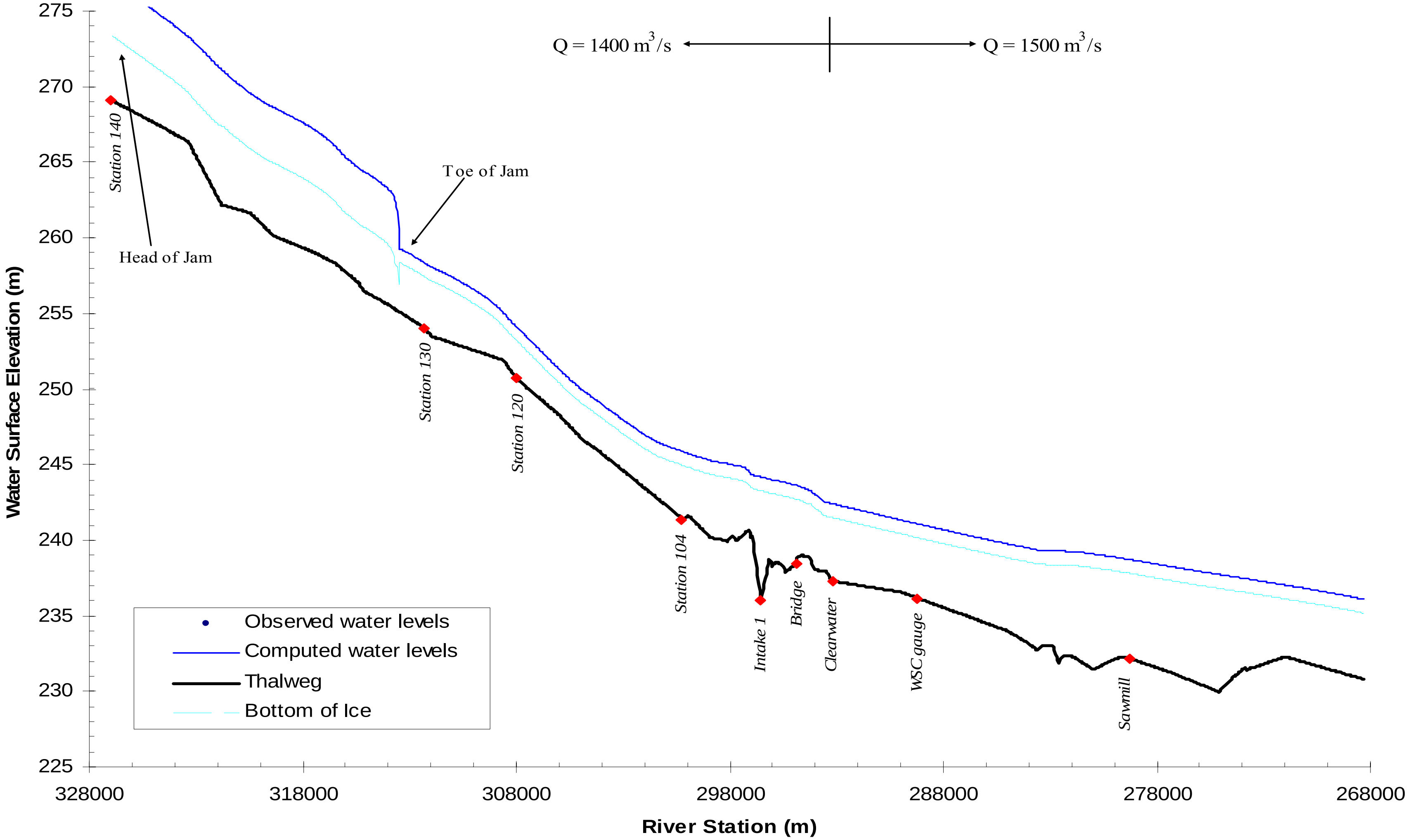

Figure 5.15 Simulated water surface profile for the 1985 ice jam (scenario 1)

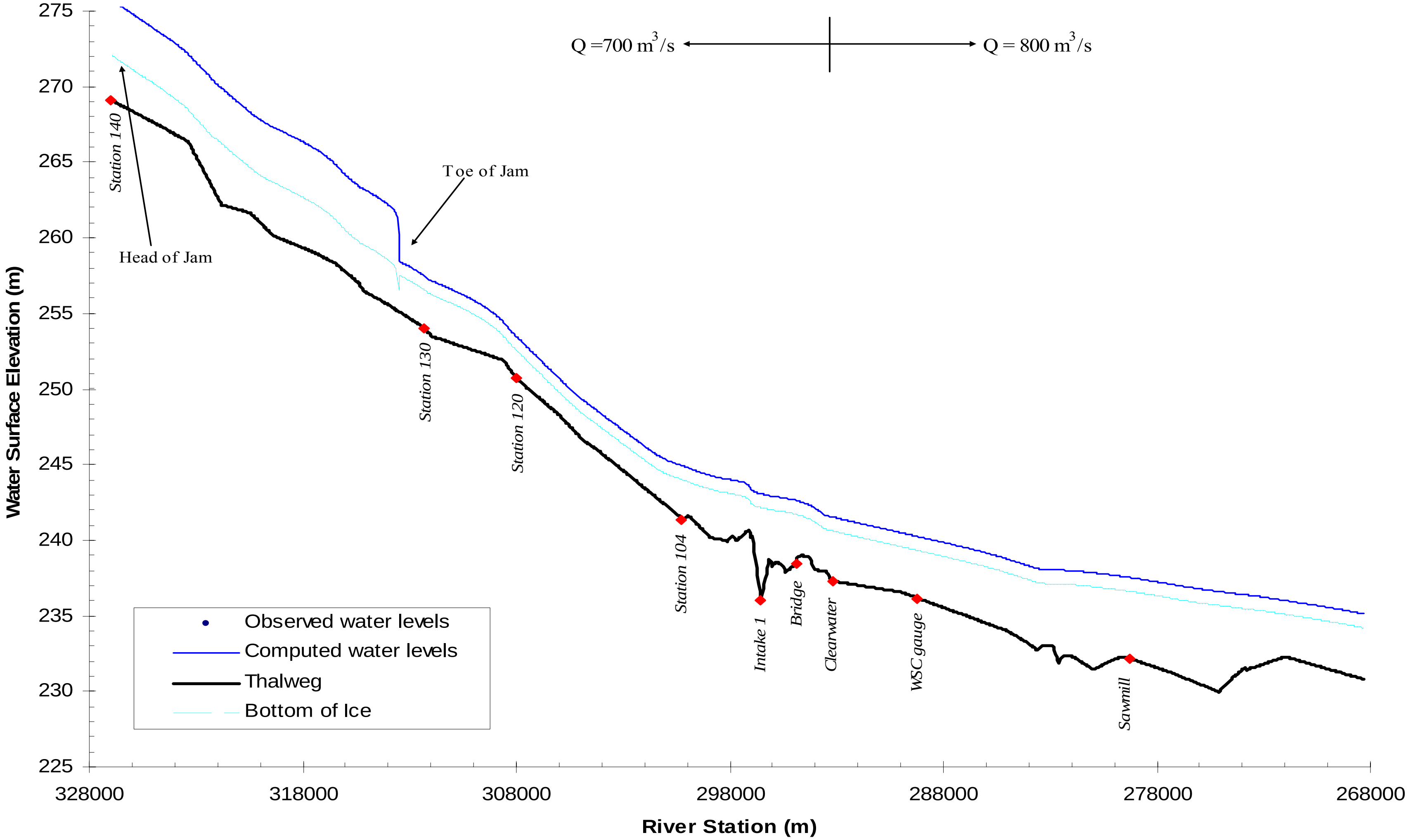

Figure 5.16 Simulated water surface profile for the 1985 ice jam (scenario 2)

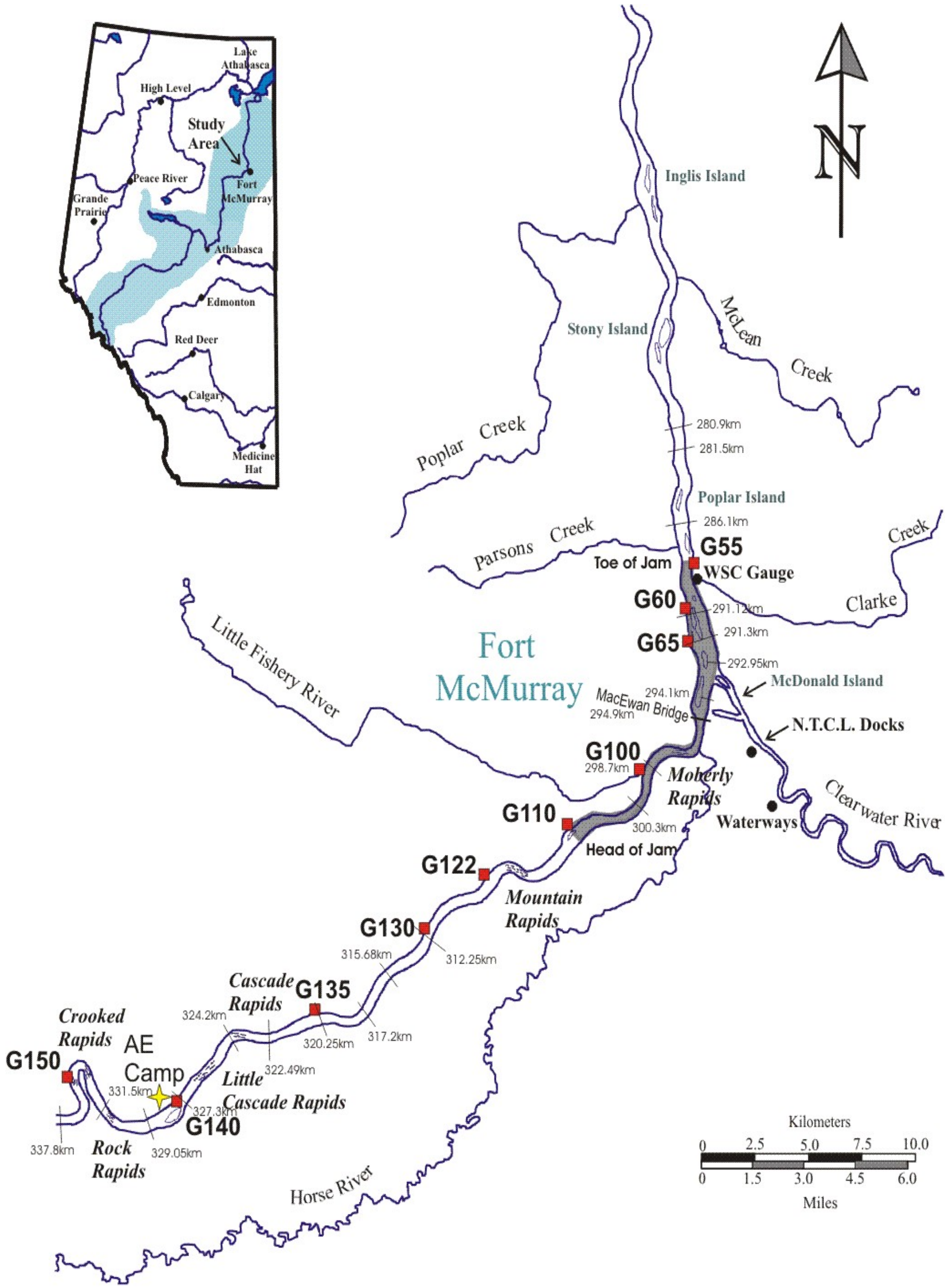

Figure 5.17 Location of 1986 ice jam (adapted from Robichaud, 2003)

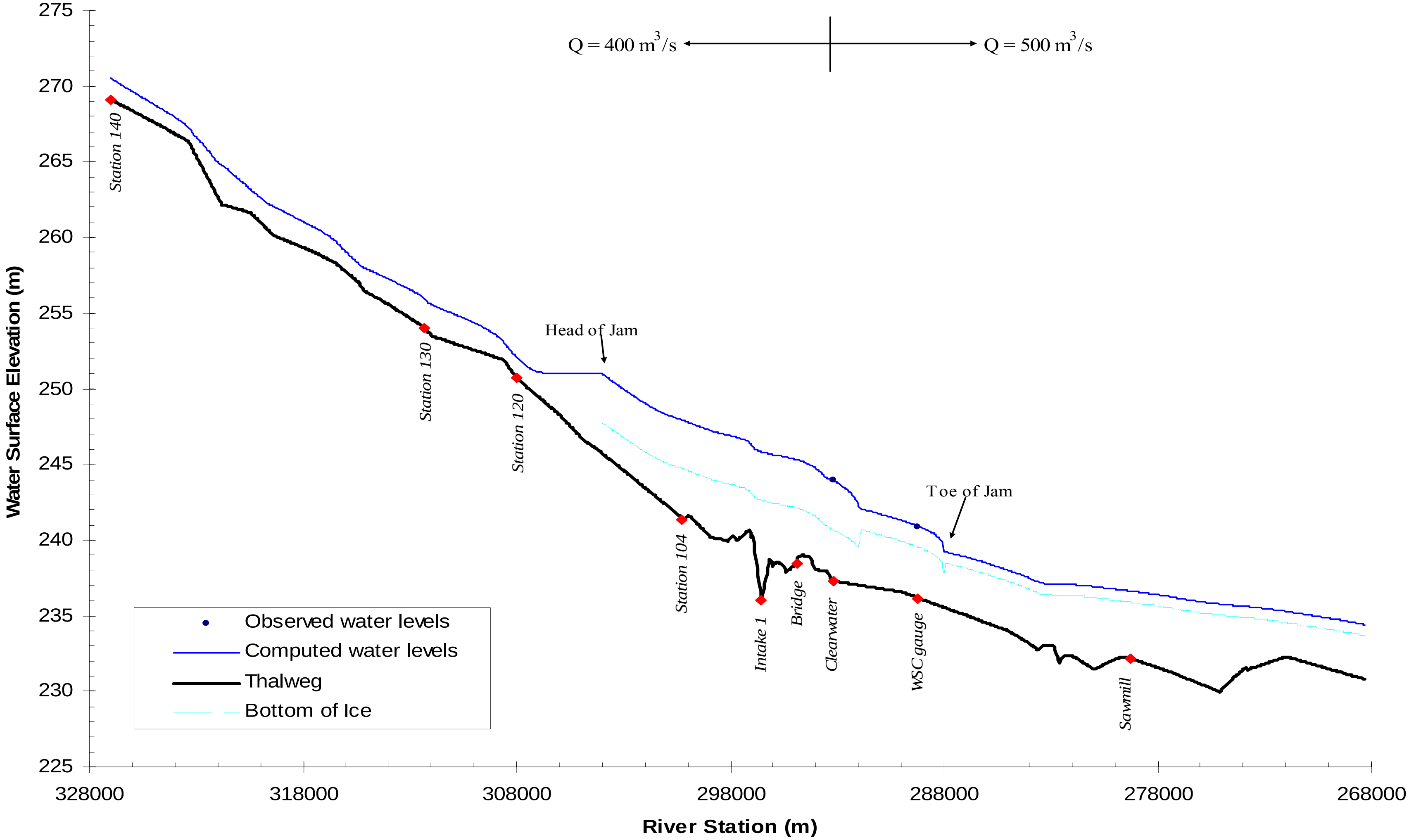

Figure 5.18 Simulated water surface profile for the 1986 ice jam (scenario 1)

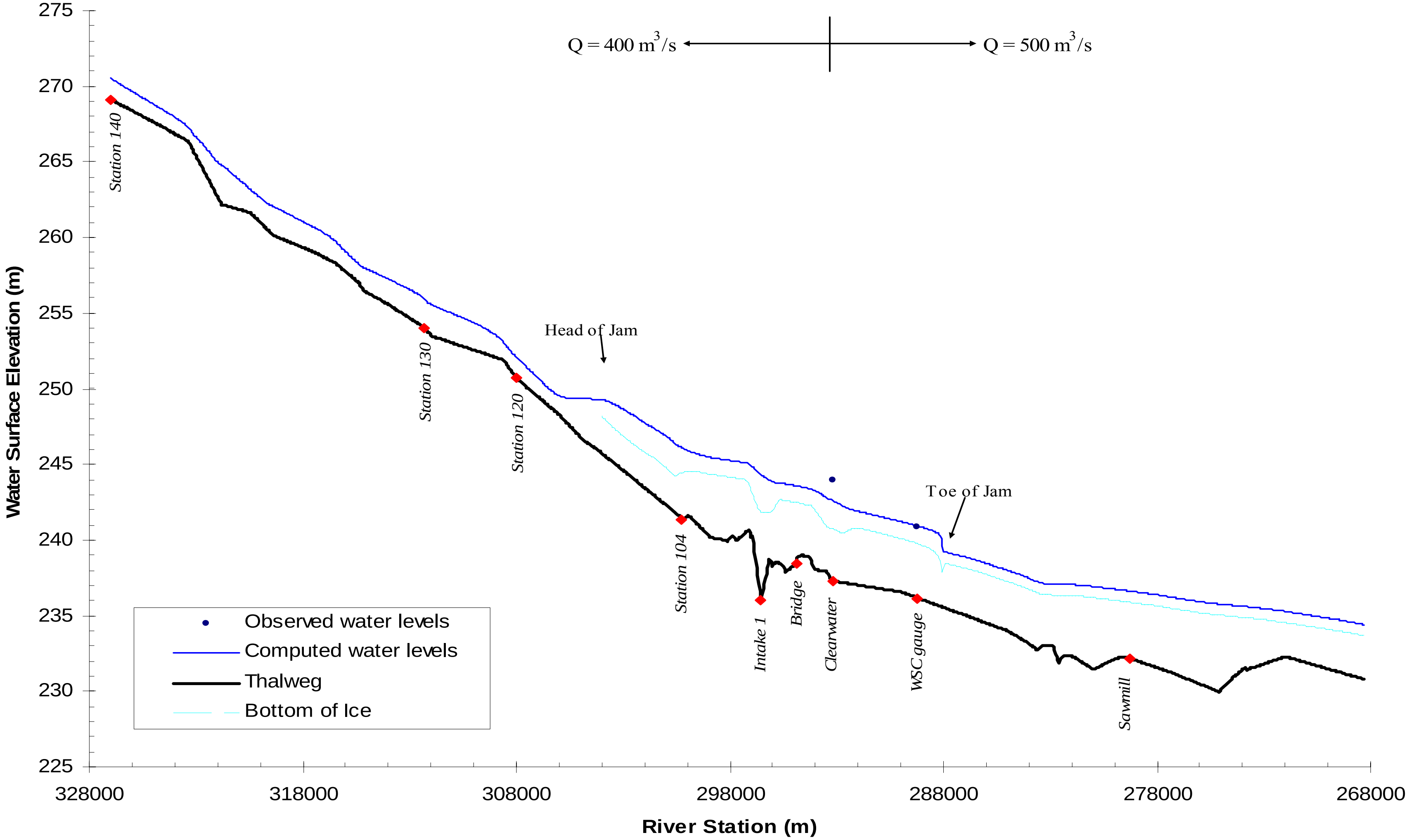

Figure 5.19 Simulated water surface profile for the 1986 ice jam (scenario 2)

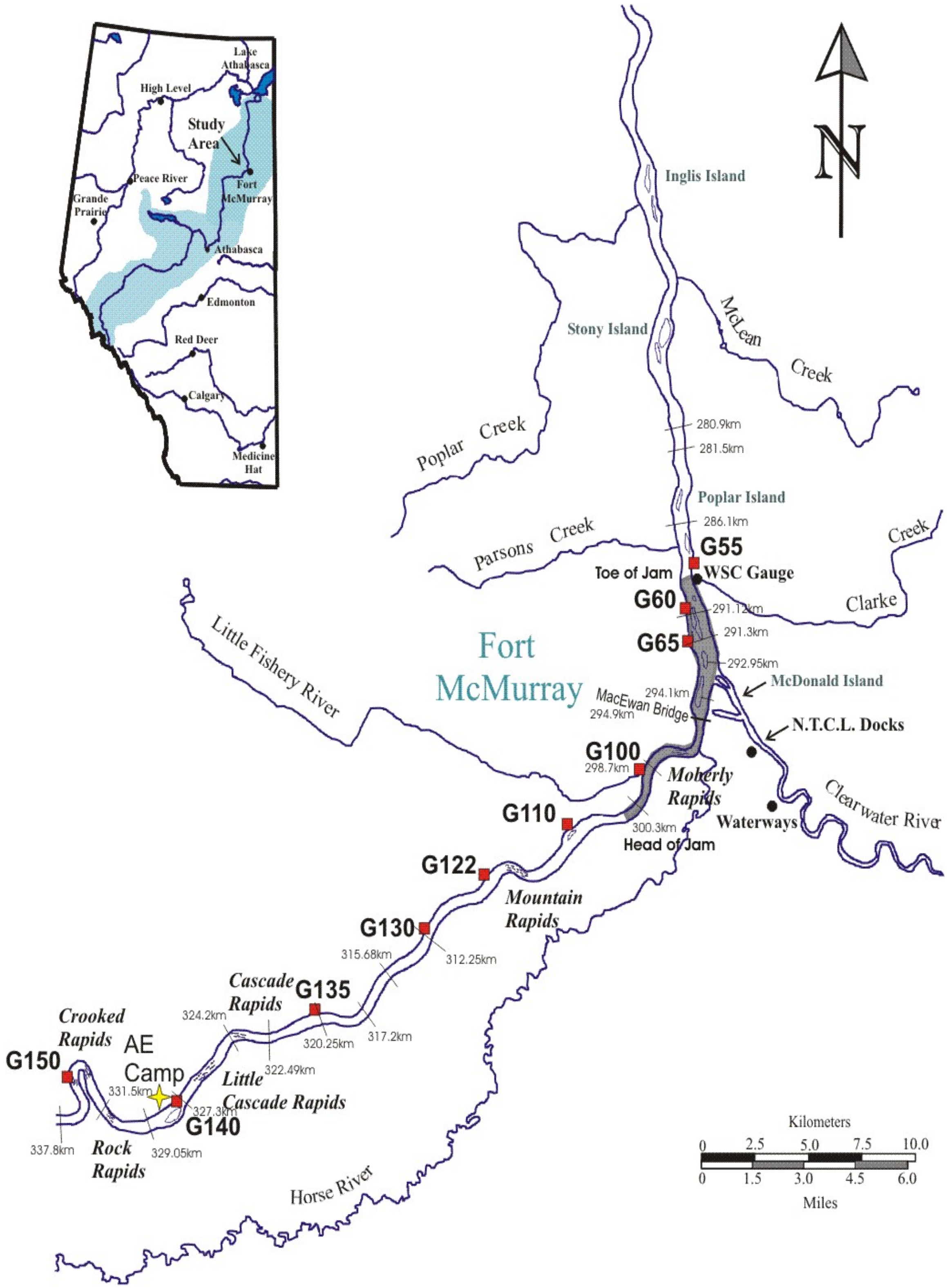

Figure 5.20 Location of 1987 ice jam (adapted from Robichaud, 2003)

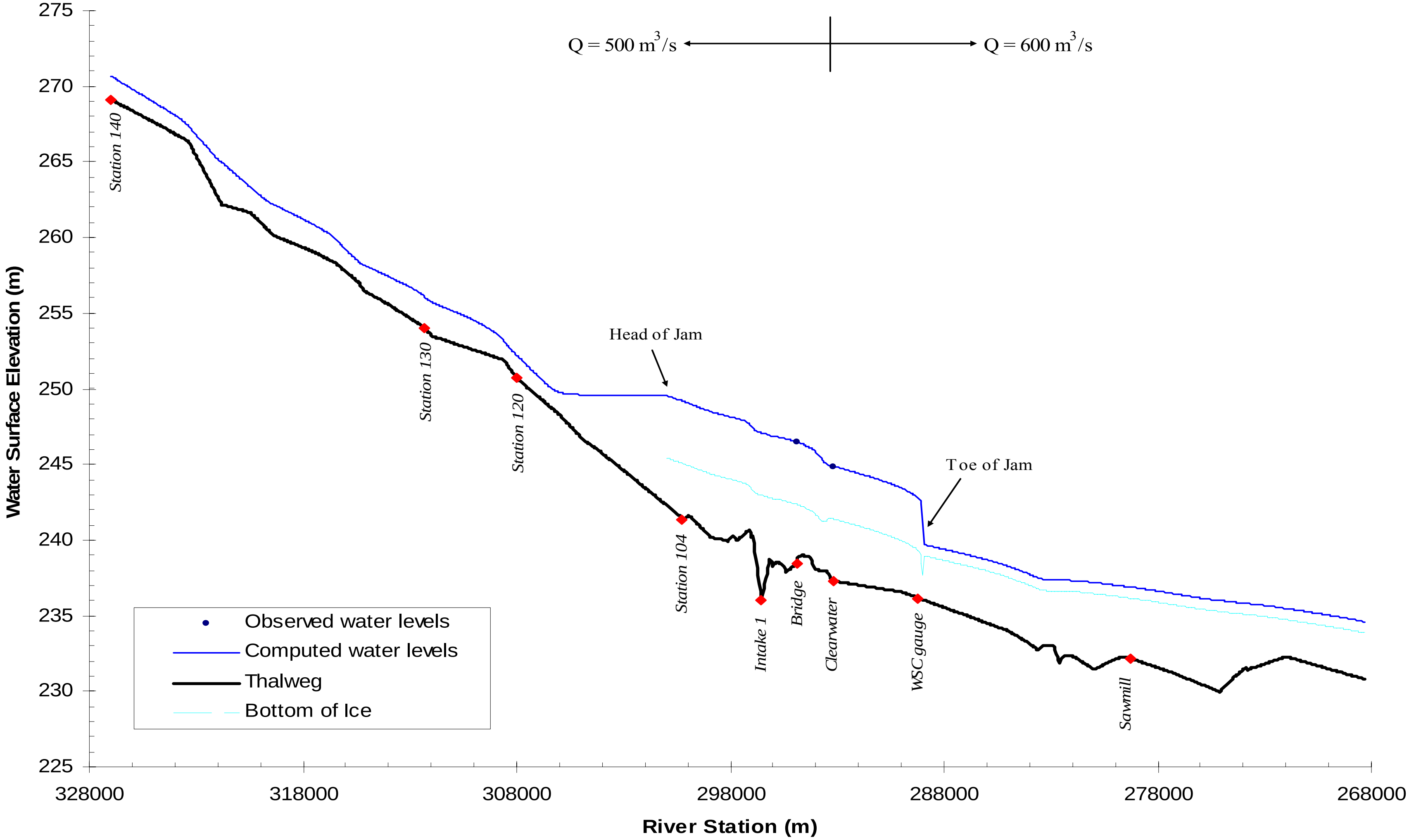

Figure 5.21 Simulated water surface profile for the 1987 ice jam (scenario 1)

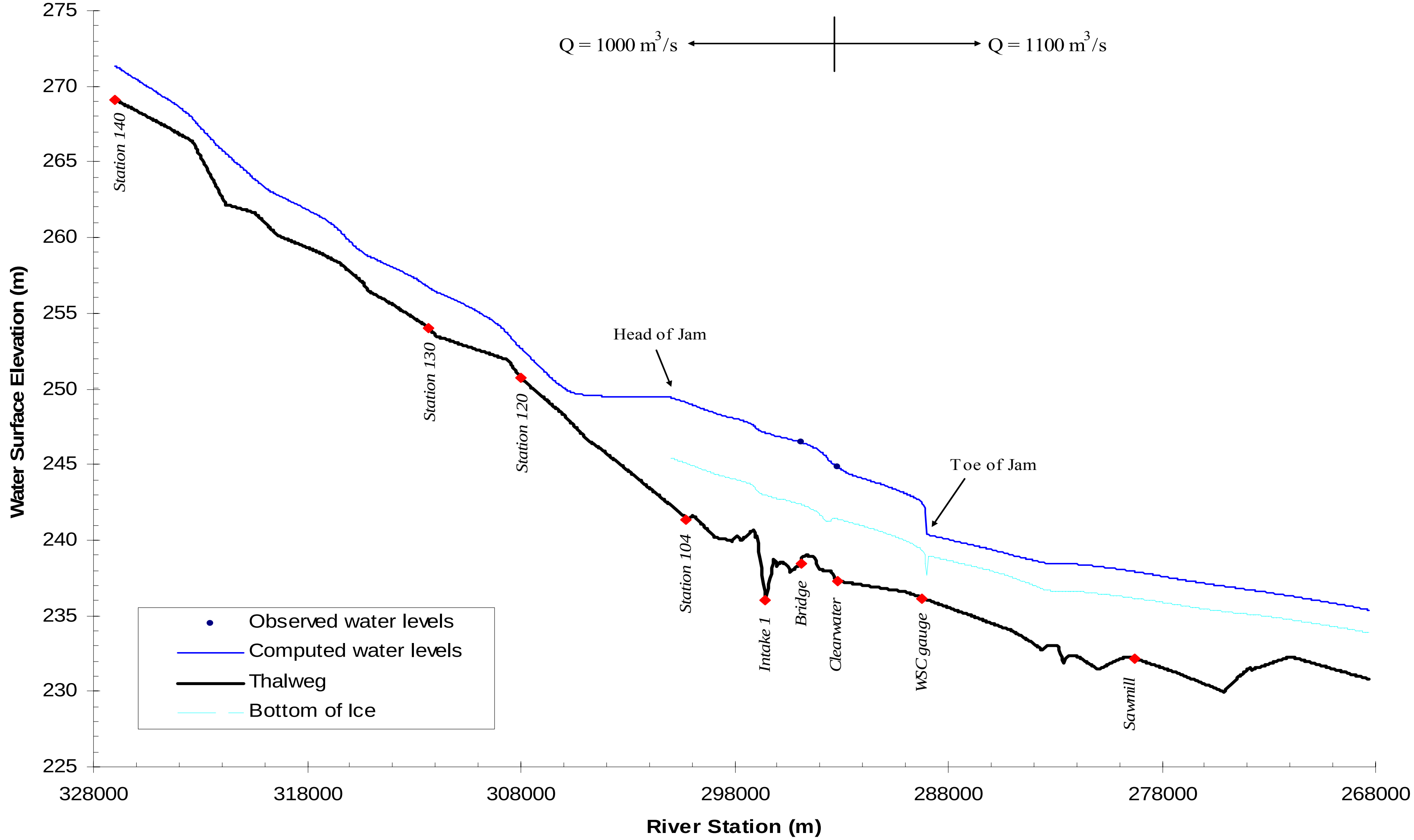

Figure 5.22 Simulated water surface profile for the 1987 ice jam (scenario 2)

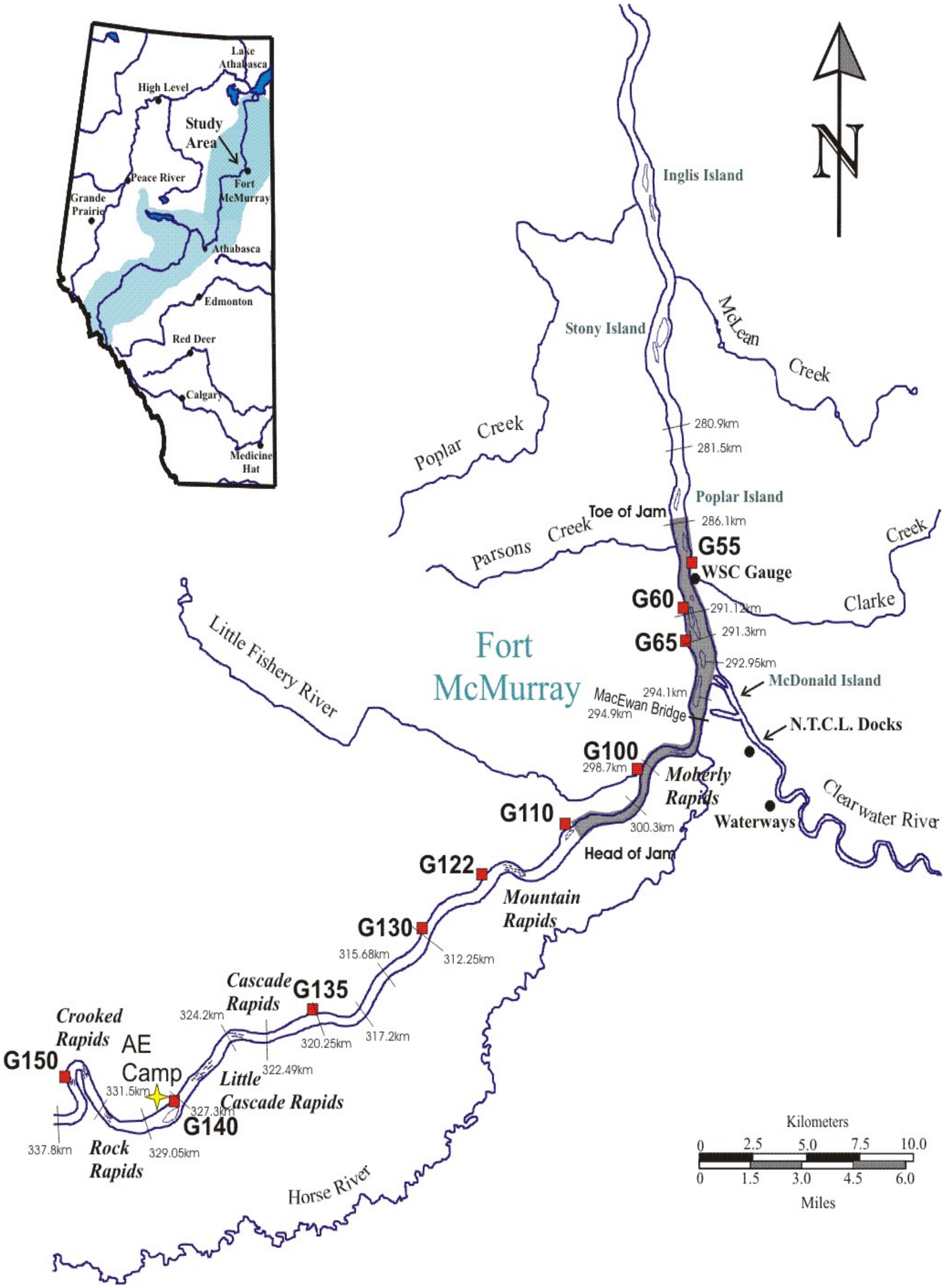

Figure 5.23 Location of 1988 ice jam (adapted from Robichaud, 2003)

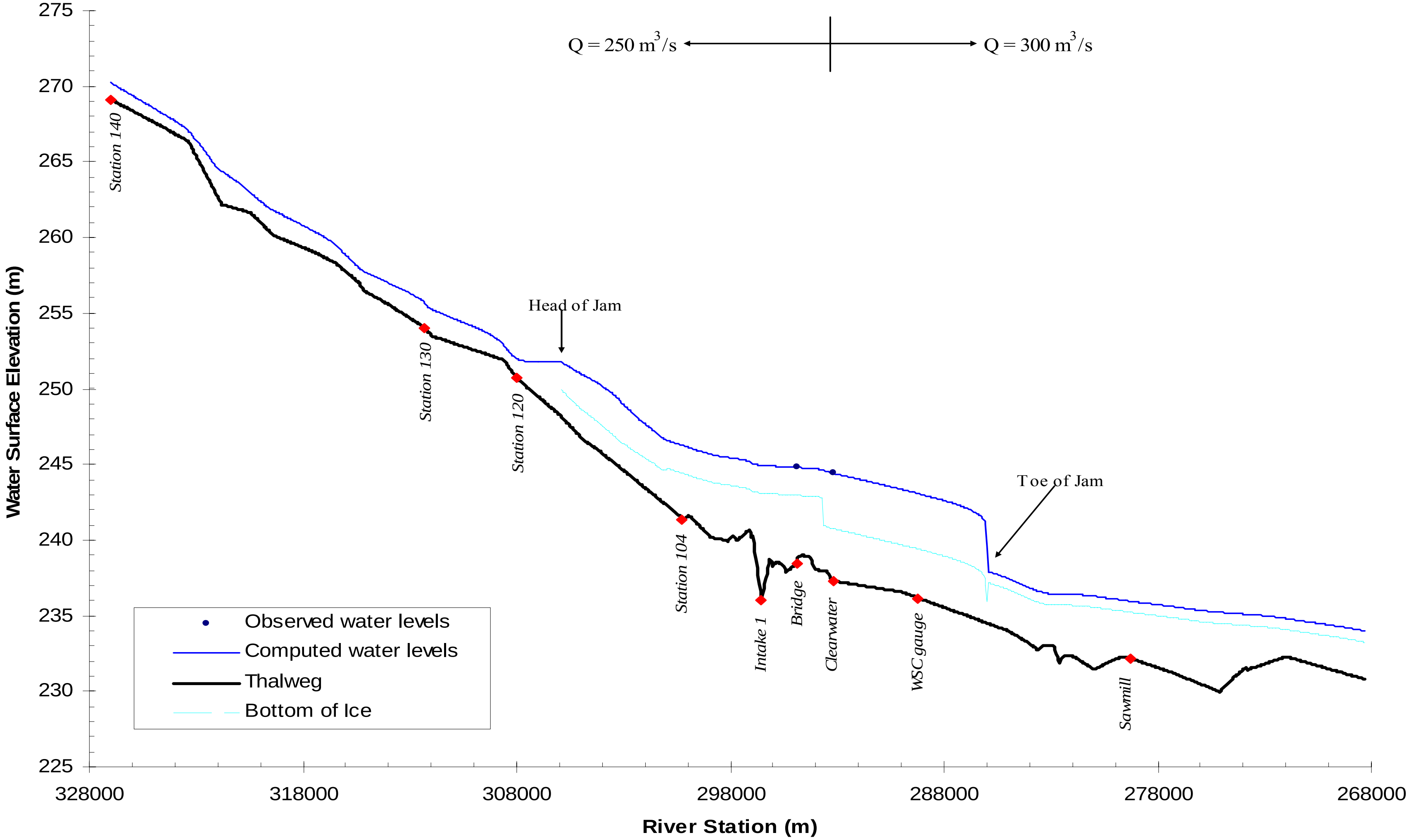

Figure 5.24 Simulated water surface profile for the 1988 ice jam

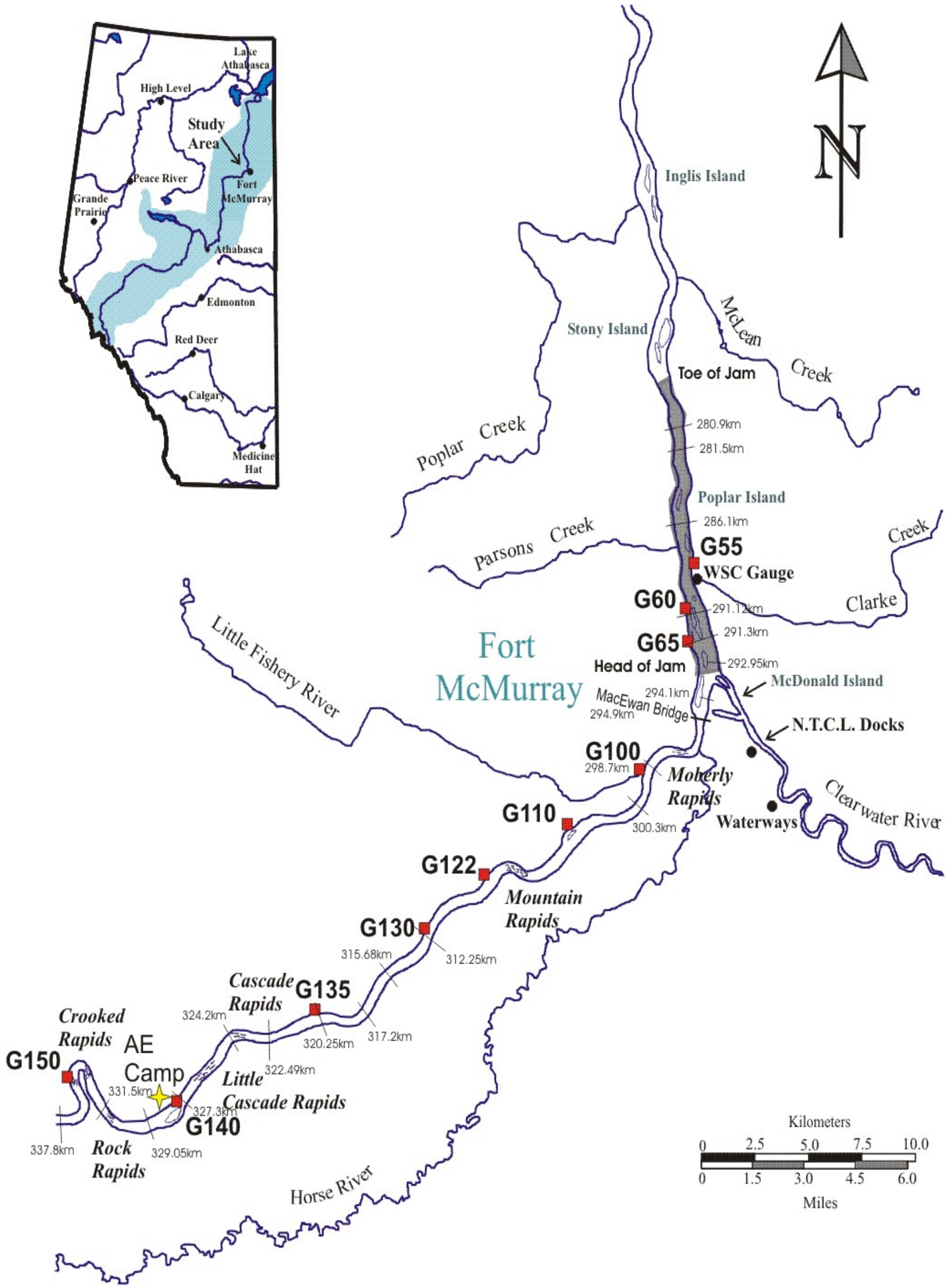

Figure 5.25 Location of 1996 ice jam (adapted from Robichaud, 2003)

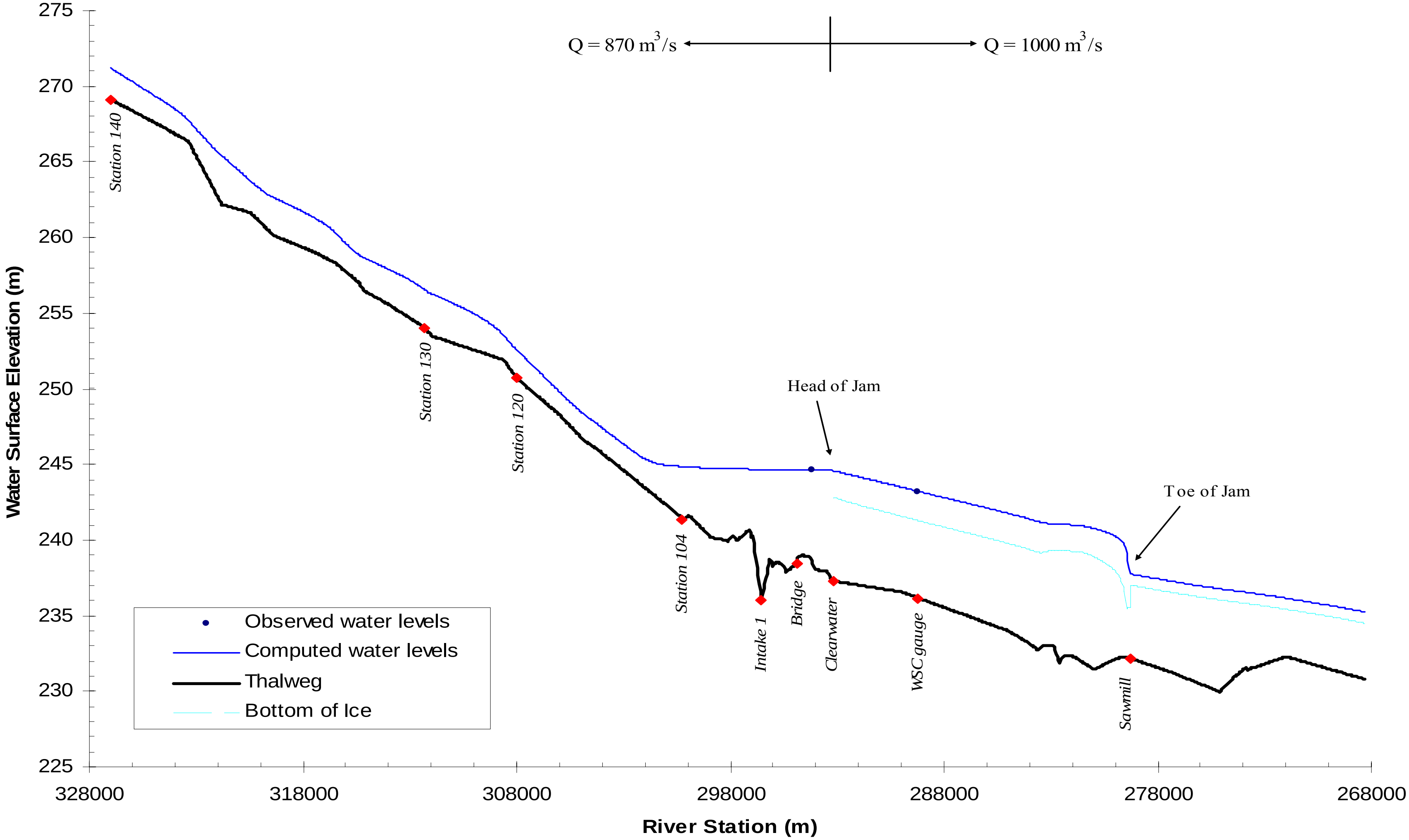

Figure 5.26 Simulated water surface profile for the 1996 ice jam

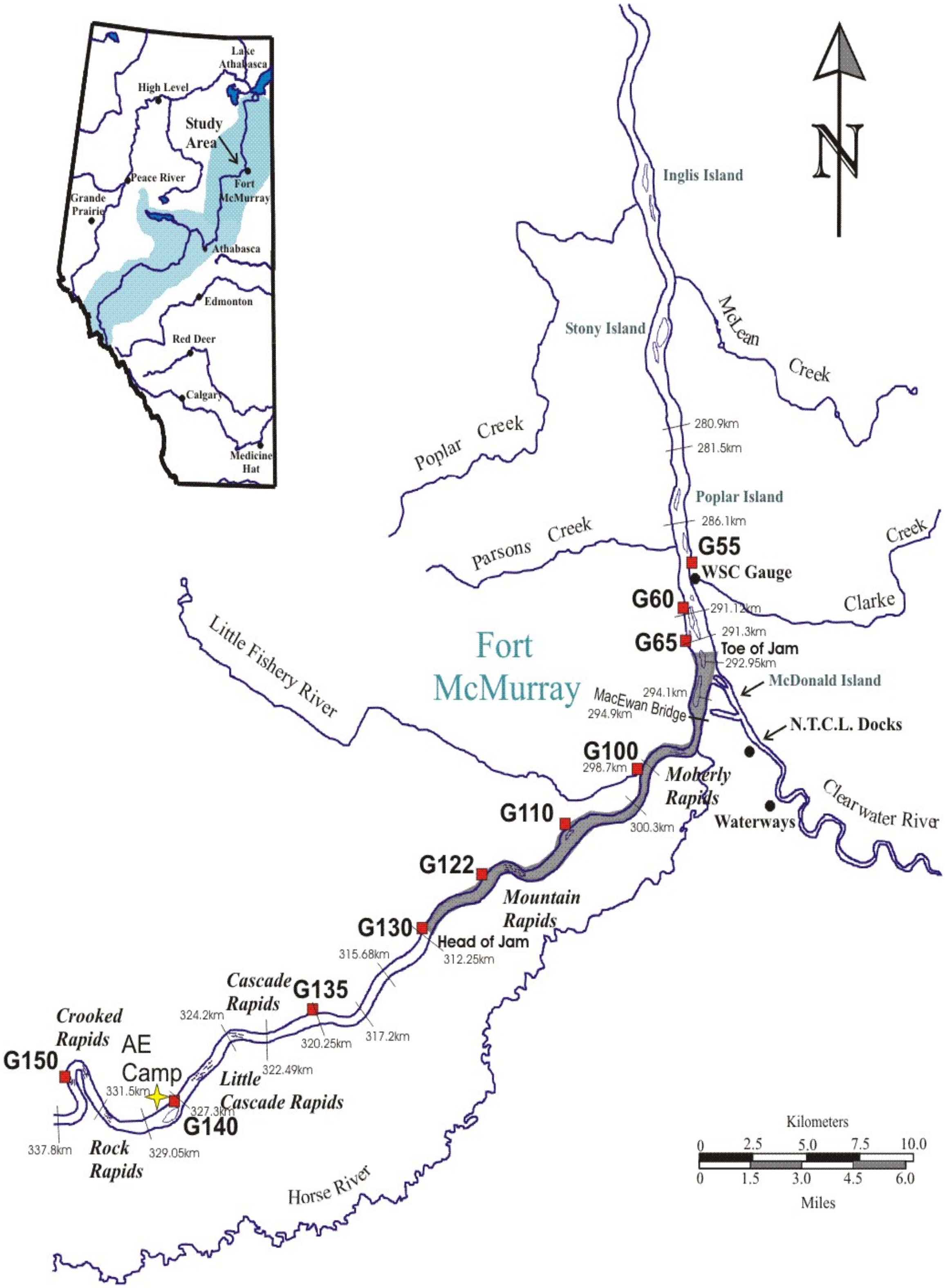

Figure 5.27 Location of 1997 ice jam (adapted from Robichaud, 2003)

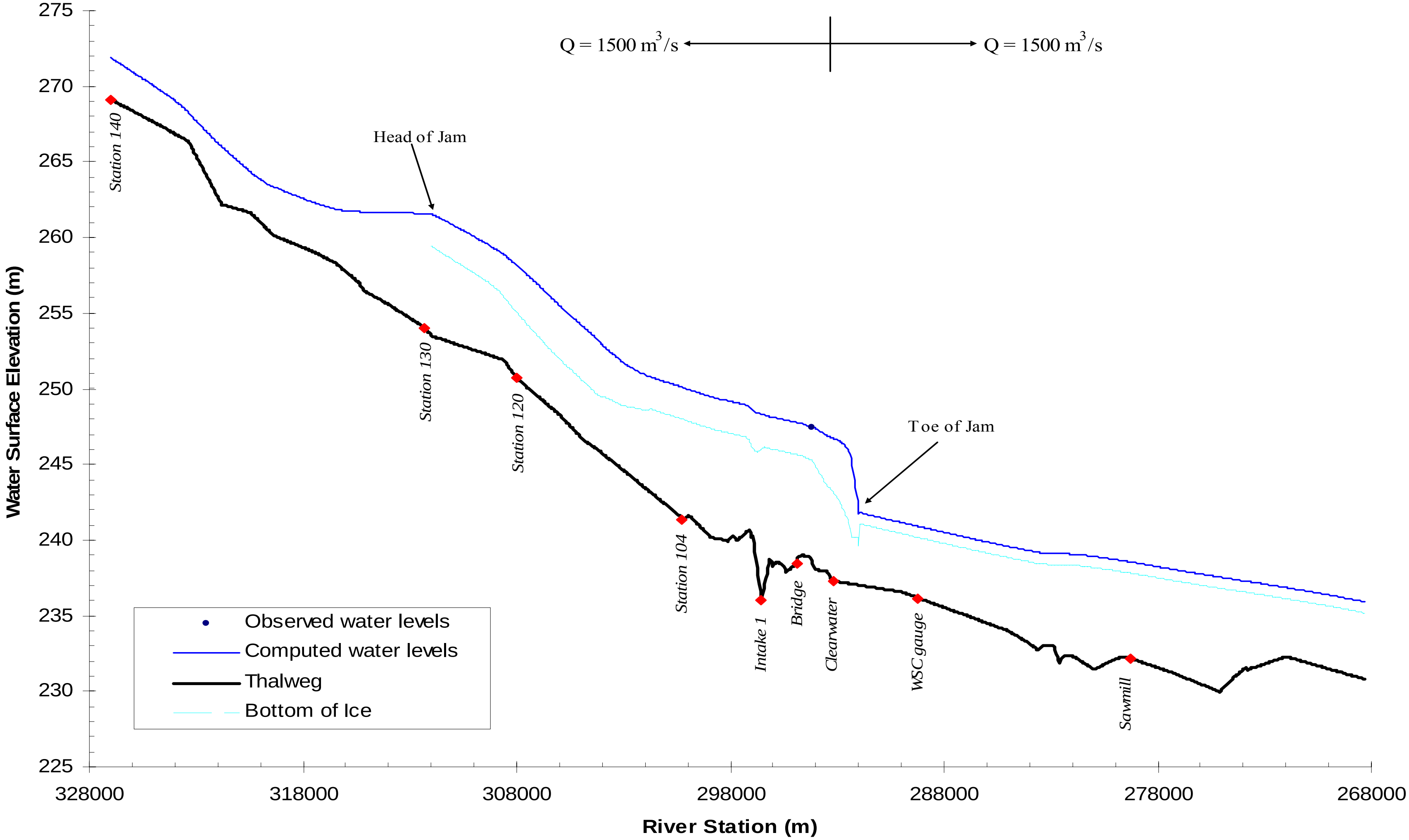

Figure 5.28 Simulated water surface profile for the 1997 ice jam

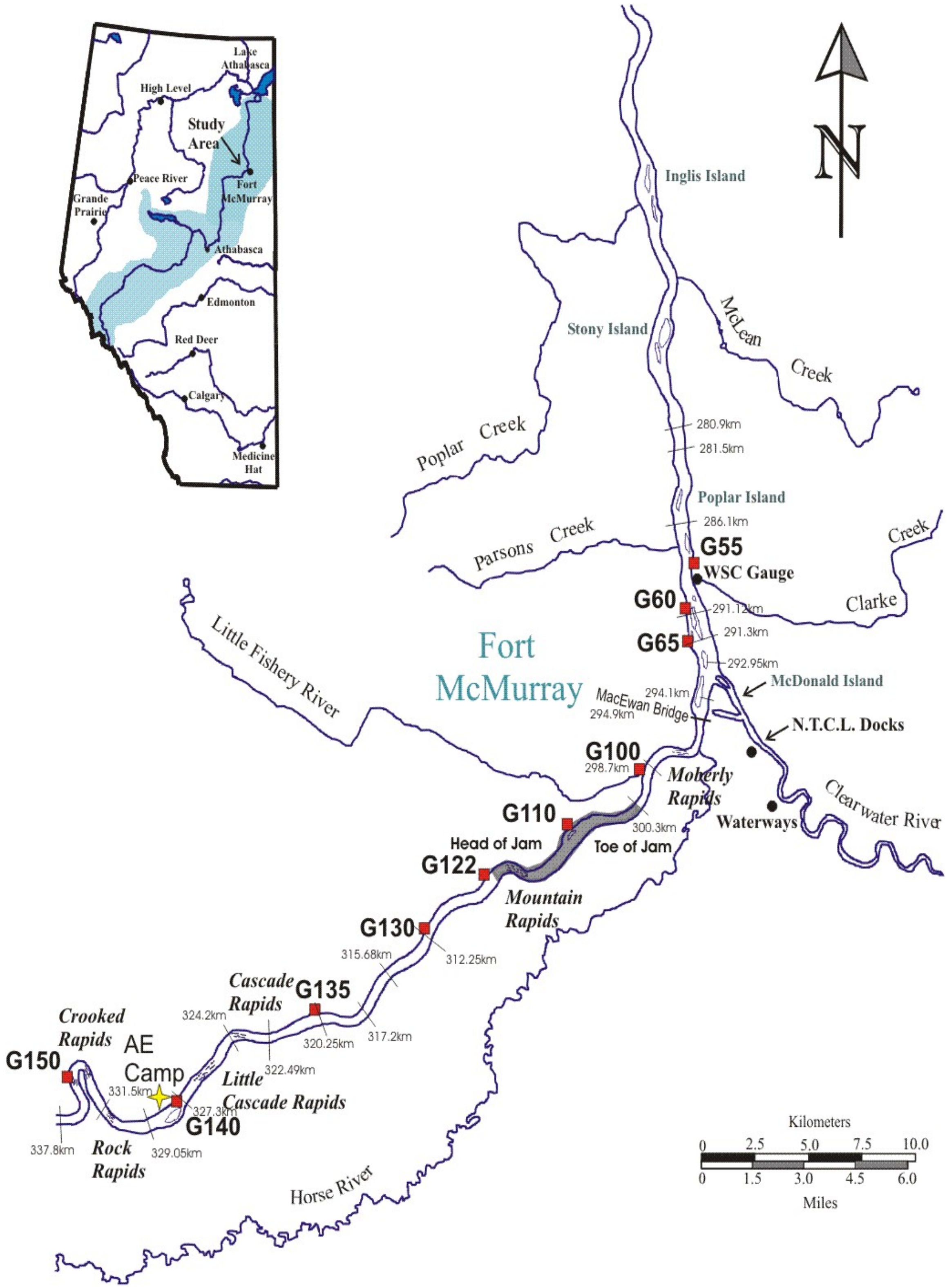

Figure 5.29 Location of 2002 ice jam (adapted from Robichaud, 2003)

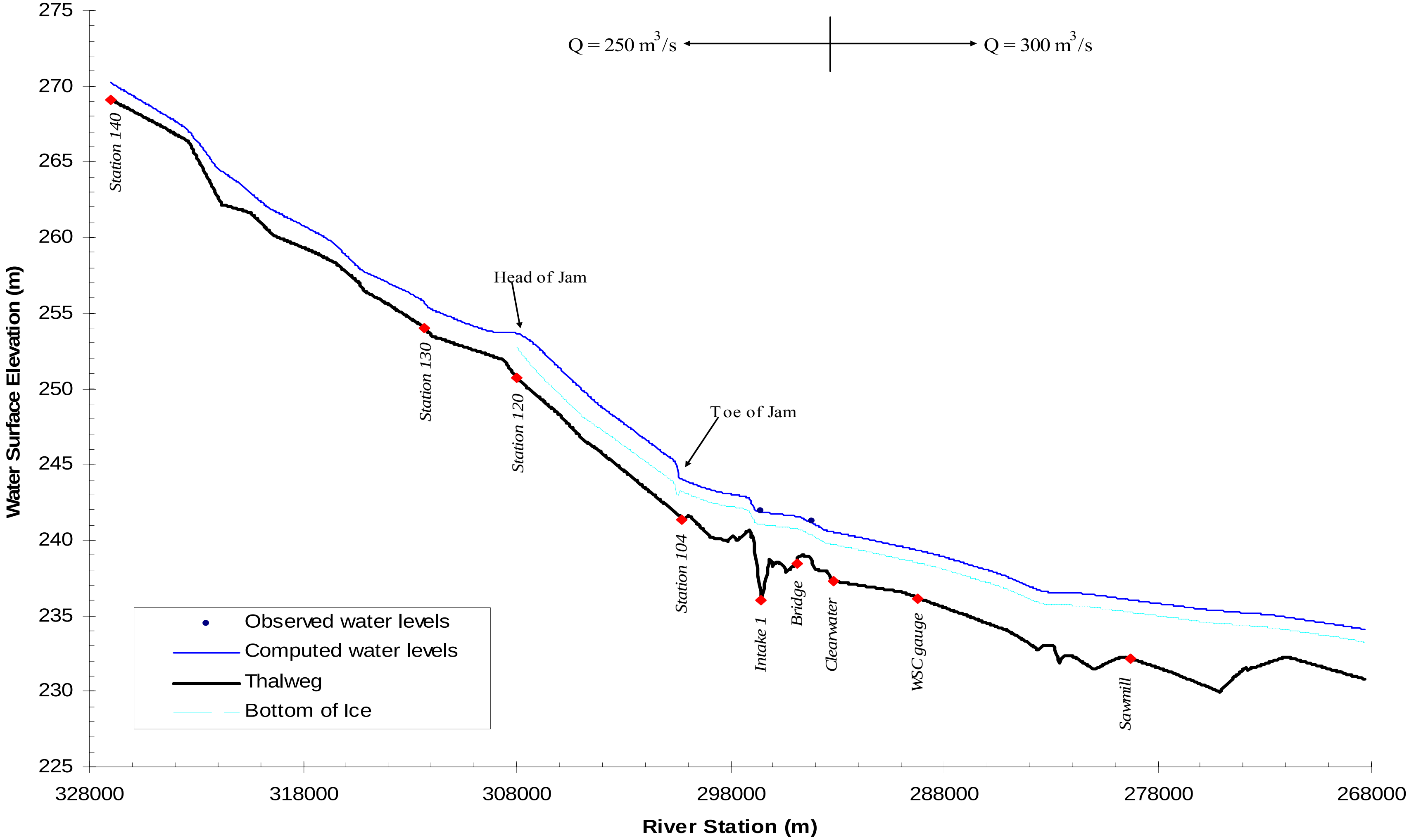

Figure 5.30 Simulated water surface profile for the 2002 ice jam

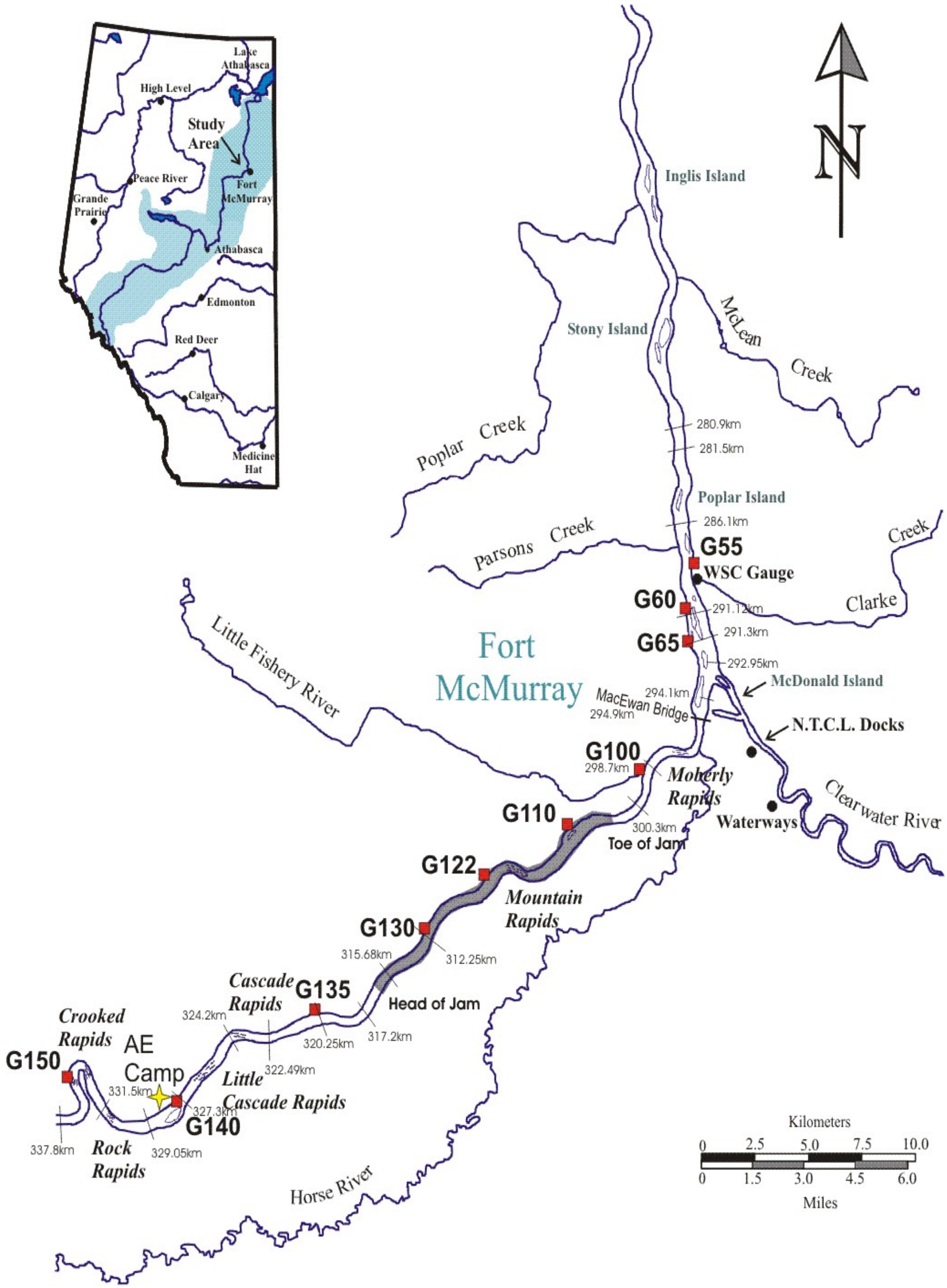

Figure 5.31 Location of 2003 ice jam (adapted from Robichaud, 2003)

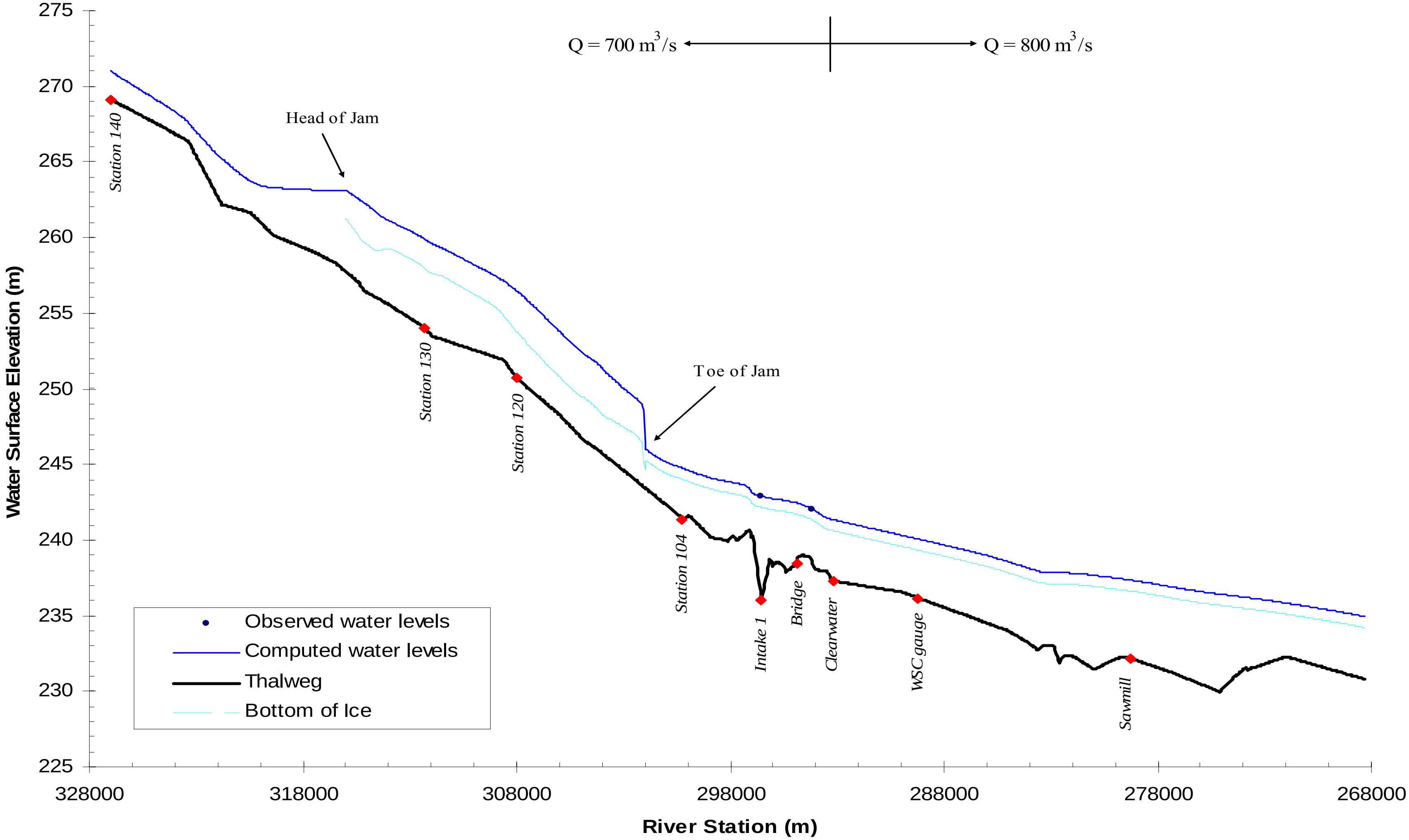

Figure 5.32 Simulated water surface profile for the 2003 ice jam

6.0 General Analysis of the Effects of Certain Parameters on Delta H

In addition to the historical ice jam simulations, a general analysis was done to determine the effects that discharge and the ice jam roughness coefficient have on the difference between the water levels at MacEwan Bridge and the Clearwater. Two generic ice jam scenarios were created in HEC RAS to perform this analysis. One of the ice jams had its toe set at the Clearwater and its head placed at 326.55 while the other ice jam had its toe placed at the Sewage Lagoons (station 290.2km) with its head at the same location. For both of these ice jams the discharge and ice jam roughness were varied to determine the effects they had on delta H. Also, the simple ice cover thickness for the scenario where the toe was placed at the Clearwater was also changed to determine if it had any effect on the water levels. For this analysis a change in discharge at the Clearwater was not included based on the assumption that the ice jam would block up the Clearwater and the outflow from it would be insignificant in comparison to the flow in the Athabasca River. Figures 6.1, 6.2, and 6.3 show the plots of the effect various ice jam Manning's n and discharge on water level difference between the bridge and Clearwater for the toe at the sewage lagoons, the toe at the Clearwater with a simple ice cover thickness equal to 0.6m, and the toe at the Clearwater with a simple ice cover thickness equal to 0.8m, respectively. Figure 6.1 suggests that as both ice jam roughness and discharge increases the difference between the two water levels increase as well. However, due to the irregular pattern of the data especially with regards to the larger discharges with n_{jam} = 0.11 it would seem that the lack of cross sectional data for the portion of the reach downstream of the Clearwater is having an effect. In reality, there are many islands in this portion of the channel and as of yet there are no river bed profiles of these locations. Thus, it would be unreasonable to attempt to make any conclusions from this plot other than to say that in comparison with Figure 6.2 it would seem that the Delta H is much smaller when the toe is at the sewage lagoons. This is a reasonable observation as it is logical that the effects of the ice jam on Delta H would be smaller the farther the toe was from the Clearwater and Bridge locations. Figure 6.2 shows there is a steady, almost linear relationship between the difference in water level and discharge. It also shows that an increase in ice jam roughness for the same discharge causes the water level to be larger comparatively, which is very logical. It is interesting to note that the general shape of each of the curve is very similar between the three roughness values this suggests a definite relationship between the parameters. Finally, Figure 6.3 shows roughly the exact same plot as Figure 6.2 including the same general curve shape and almost linear trends, and while there is a slight differences between the two plots it can be reasonably suggested that the effect of the simple ice cover thickness on delta H is small. It should also be noted that the one meter "rule-of-thumb" does hold true for this analysis. In all three figures the minimum difference in water levels is greater than one meter.

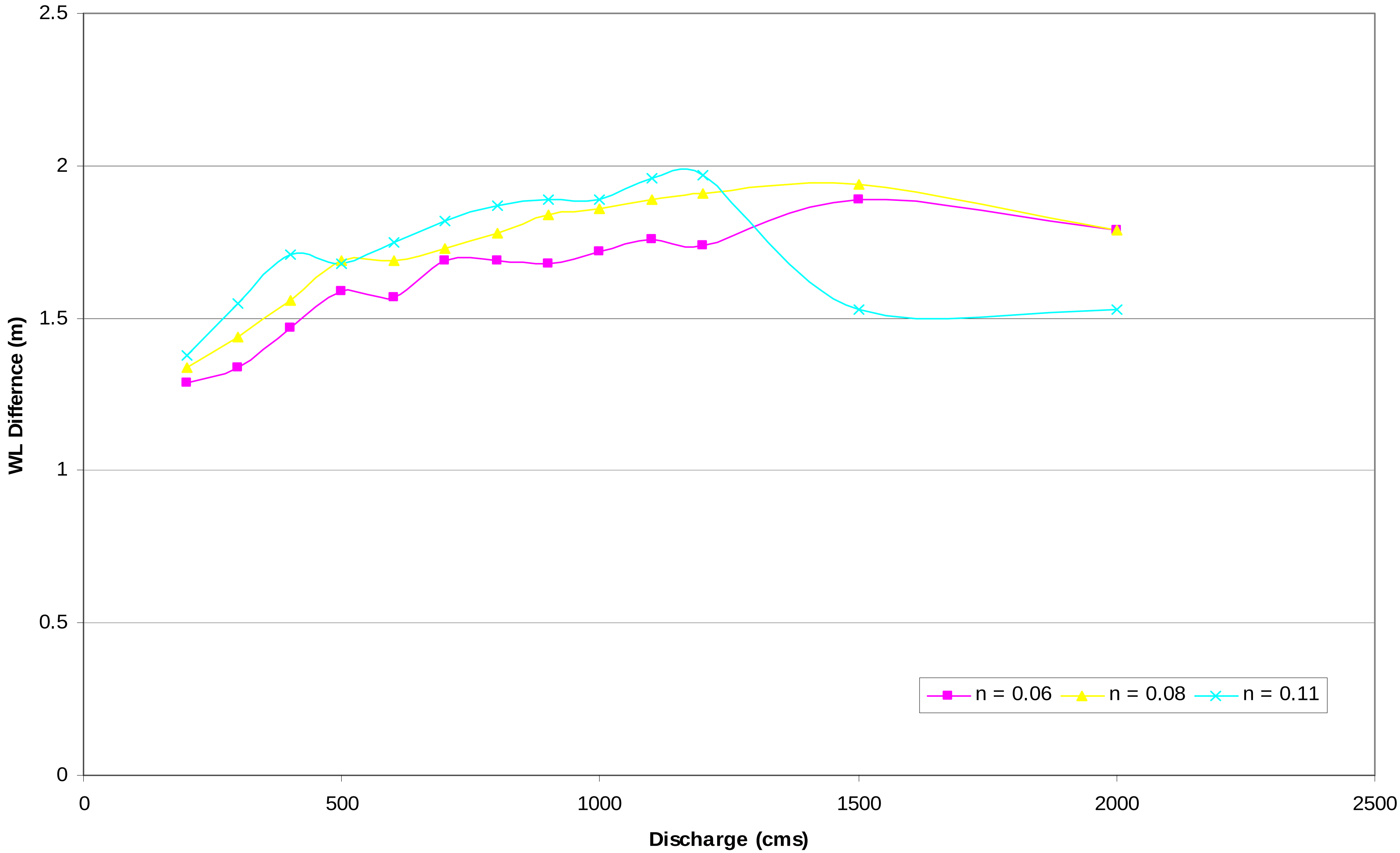

Figure 6.1 Delta H for varying discharge and roughness (sewage lagoons toe location)

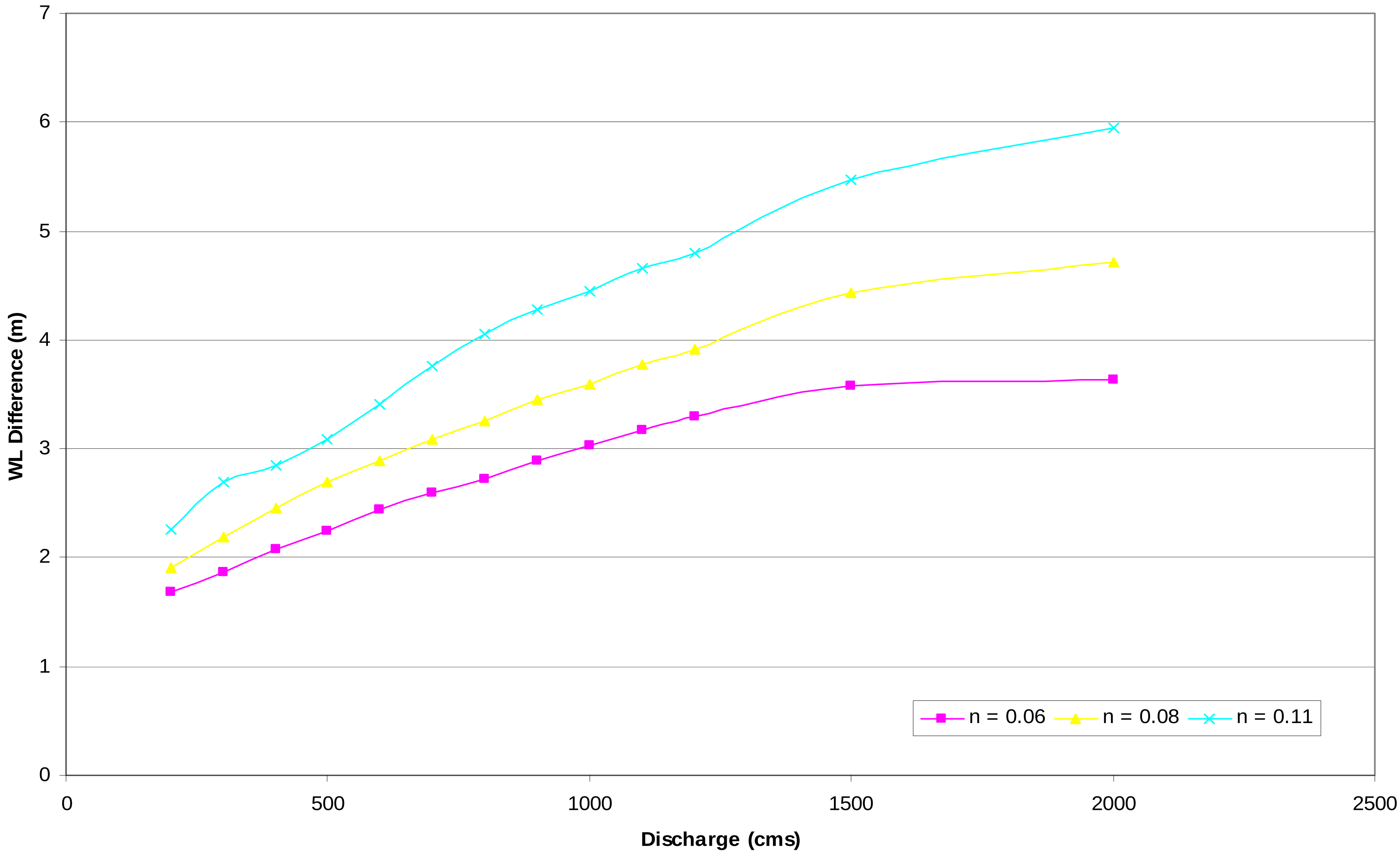

Figure 6.2 Delta H for varying discharge and roughness (Clearwater toe location, t_{sim} = 0.6m)

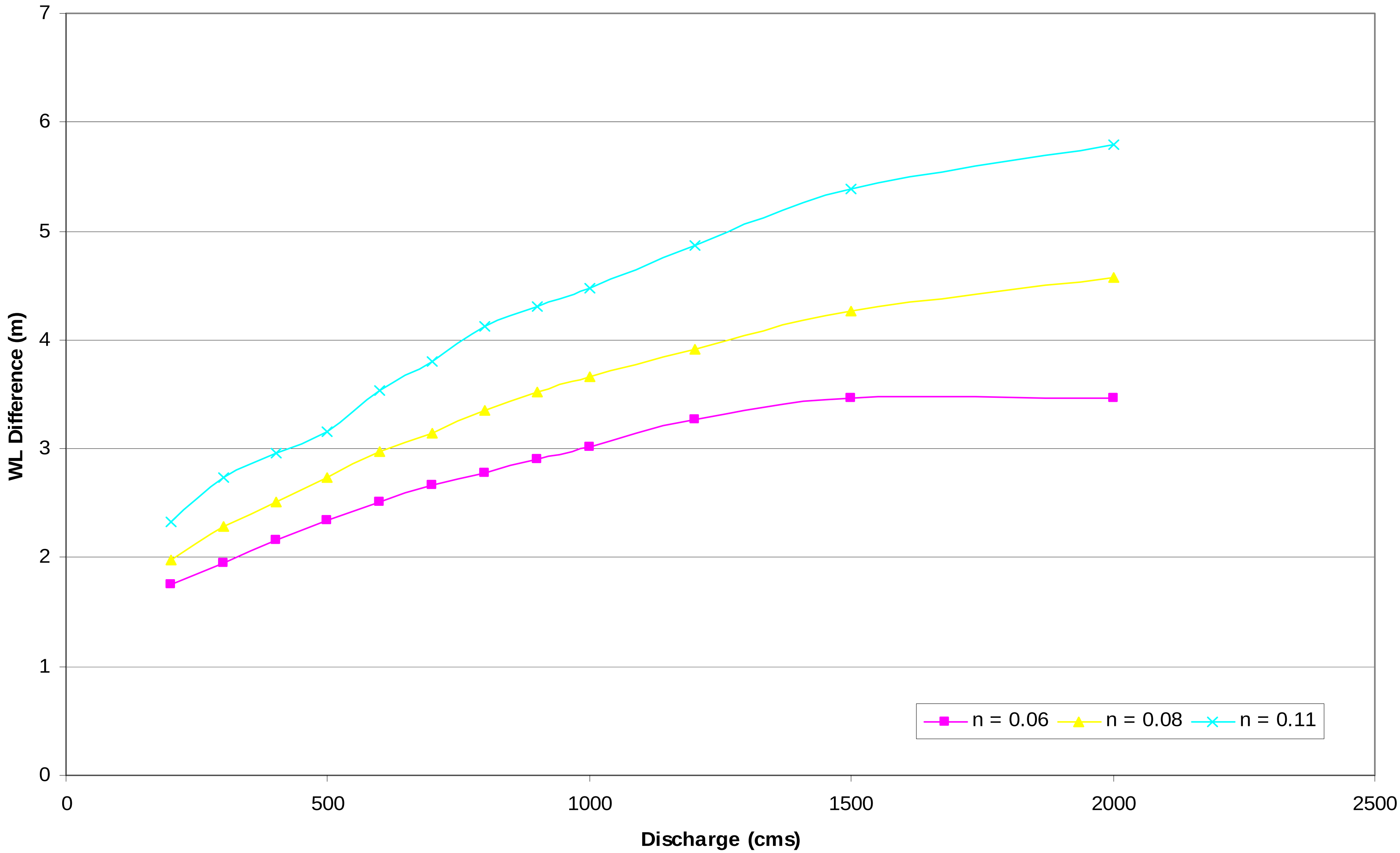

Figure 6.3 Delta H for varying discharge and roughness (Clearwater toe location, t_{sim} = 0.8m)

7.0 Summary

The historical ice jam simulation scenarios have shown that depending on the location of the ice jam, the discharge in the Athabasca River (and certain instances the discharge from the Clearwater River), ice jam thickness, ice jam roughness, and the simple ice cover thickness, the difference between the two water levels can vary from 0.04m to 4.61m. The general parameter analysis also reinforced the notion that there is a large effect on the difference in water levels from the discharge in the Athabasca River and from the roughness of the ice jam. The historical ice jam simulations and the general parameter analysis have both shown that the suggestion that the difference in water level between MacEwan bridge and the Clearwater confluence is approximately 1.0 meters is not valid and that ice jam location, ice jam roughness, ice jam thickness, and the discharge each play an important role in the water levels produced by an ice jam on the Athabasca River at the town of Fort McMurray.

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