University of Alberta

Analysis of the Post-regulation Freezeup Regime on the North Saskatchewan River

by

James Edward Stanley Choles ©

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ABSTRACT

At the North Saskatchewan River near Rocky Mountain House, the Bighorn Dam has regulated the flow since 1973 to produce hydroelectricity augment winter flows to improve water quality. Due to hydro peaking the dam outflows can vary dramatically over the course of one day and in the winter flooding problems have occurred.
In this thesis the observations from a monitoring program are reviewed and analyzed in light of current knowledge. The long term objective is to develop tools that can be used to optimize winter hydroelectric production and minimize the potential for winter flooding. A hydraulic analysis of the open water condition to determine open water parameters was performed. Computer simulation of two attenuation tests that occurred in 1983 and 1986 are presented. A database with observations going back to winter 1973/74 was reviewed and the details of freezeup over that period are presented. Some analysis using the available data was performed using accumulated degree days and deterministic equations to determine what information can be gleaned from the observations and the adequacy of the data collected for predicting various ice processes.

Approximate rating curves were developed for eight cross sections that will allow the dam operator to estimate the effects of various flows under various conditions at the sites in question. The information the rating curves provide includes open water elevations, Froude criteria curves for predicting if the ice cover will progress upstream and the type of cover and an estimate of the effect of an equilibrium ice jam at that site.

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LIST OF SYMBOLS

A = column cross sectional flow area = BD
A_s = area of water surface = Bx
a, b = empirical coefficients for border ice model
B = mean width of the river
C_i = volumetric concentration of frazil ice
C_o = cohesive strength in Pa
C_p = specific heat of water = 4190 J/kg K
C_s = surface coverage by frazil ratio
C_v = volumetric concentration of frazil ice in suspension
D = depth of flow
e = porosity of the floes
e_a = porosity of the anchor ice deposit
e_p = porosity of the accumulation
F_{rj} = juxtaposition Froude number
F_{rm} = maximum allowable Froude number
f_T = internal strength of ice jam
g = acceleration due to gravity
h_{wa} = heat transfer coefficient between the air and the water
h_{wi} = heat exchange co-efficient between anchor ice and water
KB = effective length of jam with average thickness of t_{eq}
k_i = heat conductivity of solid ice
K_v = passive pressure co-efficient
K_{xy} = lateral stress transfer co-efficient (≤ 1)

L = latent heat of water = 333.4×10^3 J/kg
n = the number of faces on which the ice is growing
Q = discharge
Q_i = volumetric ice discharge = $Q_{is} + Q_{id}$
Q_{is} = surface ice discharge
Q_{id} = suspended ice discharge
Q_{ui} = volume of ice entrained under the ice cover at the leading edge
R_i = hydraulic radius for an ice covered river
S_f = friction slope
S_w = slope of the water surface
t = time
T_a = air temperature
t_{ai} = thickness of anchor ice deposit
t_{eq} = equilibrium thickness
t_f = thickness of ice floe
t_i = total ice thickness = $t_s + (1-e_p)t_{fr}$
t_{fr} = surface frazil ice thickness
T_a = air temperature
T_m = melting point of ice

T_o = temperature of the upstream boundary
T_s = surface temperature of the ice
t_s = solid ice thickness
T_w = mean cross section water temperature
u = mean channel velocity in the downstream (x) direction
u_b = vertical velocity
u_B = depth averaged open water velocity immediately adjacent to the border ice
u_C = maximum velocity at which an ice particle can adhere to the ice
V_j = volume of jam
x = distance along channel
x_j = length of channel
Δx = distance along river from ice front
y = transverse direction
z = vertical direction
α, β = constants to be determined for heat exchange between solid ice and atmosphere
ε_x = longitudinal dispersion coefficient
ε_y = transverse dispersion coefficient
ε_z = vertical dispersion coefficient
ϕ = angle of shearing resistance
ϕ_B = heat transfer from bed
ϕ_E = evaporative heat transfer
ϕ_{GW} = heat transfer due to groundwater
ϕ_H = conductive heat transfer
ϕ_{HL} = heat transfer due to head loss
ϕ_L = long wave radiation
ϕ_P = heat transfer due to precipitation
ϕ_S = solar radiation (short wave radiation)
ϕ_T = total net heat transfer from the water
ϕ_{wi} = heat exchange between the anchor ice and the water
= $h_{wi}(T_i-T_w)$
γ = frazil ice deposition coefficient
γ_e = $0.5\rho_i g(1-\frac{\rho_i}{\rho})(1-e)$; $\gamma_e t_i$ = buoyant force on ice jam
μ = internal friction coefficient
v = velocity in the y direction
v' = vertical mixing turbulence
v_{Le} = velocity of the leading edge
θ = exchange co-efficient (varies with vertical mixing turbulence, v', ,ie. $\theta\downarrow$ as $v'\uparrow$, $(0\leq\theta\leq1)$
$\theta u_b C v B$ = ice exchange between suspended and surface ice layers
ρ = density of water
ρ_i = density of ice
σ_x = longitudinal stress

σ_y = flexural strength of solid ice
τ_b = shear along bank
τ_i = shear along the bottom of the jam due to the water flow
ω = velocity in the z direction

1.0 INTRODUCTION

In order to receive the maximum possible utility from the Bighorn Dam, *TransAlta Utilities Corp.* needs to be able to make hydro releases in response to electrical demand. However, in the winter, especially when the ice cover is just forming, hydro peaking can cause shoving in the ice cover that can result in flooding and property damage. As a result of the winter flooding concern, *TransAlta Utilities Corp.* has modified the winter release schedule from the Bighorn Dam during freeze up. During the freeze up period the river is monitored to gauge the ice pack progression. Presently, when the ice bridges or the front arrives at mile 152, a staged operations process is initiated that is designed to minimize the risk of winter flooding due to the ice jamming or shoving. Just before the ice front reaches Rocky Mountain House, the dam outflow is maintained at a steady flow with some hydro peaking permitted. The hydro peaking allows the dam operator some flexibility in operation and is also thought to contribute to the ice cover strength by packing it. This flow regime is maintained until the ice front is upstream of Rocky Mountain House and the ice cover in town has stabilized. A better understanding of how the flow interacts with ice cover formation would allow the dam operator more flexibility in operating the dam and would allow *TransAlta Utilities Corp.* to make better use of the Bighorn power plant during the winter months.

What makes this problem especially difficult is the effect of hydro peaking throughout the day. Flows can vary from 40 to 140 m^3/s over the course of a day. A suitable routing model is required to calculate the flow peaks attenuation It must also be able to simulate the ice processes and the interaction between the flow and the ice. A first step in this process is to develop an understanding of the freezeup processes as they apply to the North Saskatchewan River.

The objectives of this study were to:

1. to establish a database of the freezeup observations and measurements made since the Bighorn Dam came on stream;

2. to assess the adequacy of the data collected to date in terms of its value in understanding the ice processes on the North Saskatchewan River in the study reach;

3. to do a qualitative and a quantitative assessment of events associated with freeze up on the North Saskatchewan River downstream from the Bighorn Dam to the confluence with the Brazeau River; and

4. to make recommendations on how the monitoring programs should be

restructured and what additional data needs to be collected to optimize the operation of the Bighorn Dam during the winter season.

The first step in the assessment was to review the current literature to provide the background on the pertinent ice processes. Previous studies conducted in the study reach concerning this problem were also reviewed. The literature review is presented in Chapter 2.

The second step was to develop an open water hydraulic model of the study reach to determine the open water parameters and to provide benchmark open water elevations to compare with the water levels caused by ice processes. Also, computer simulations of the attenuation tests carried out in the fall 1983 and 1986 were conducted using the *cdg1-D* dynamic flood routing model. The hydraulic analysis and results are discussed in Chapter 3.

The third phase involved a qualitative description of freezeup in the study reach using the historical observations and other data recorded in the database. These descriptions are summarized in Section 4.2 and detailed in Appendix B.

The fourth phase involved reviewing the available data and performing some analyses to determine what information can be gleaned from the historical record. This is discussed in Section 4.3.

In Section 4.4 approximate rating curves were developed that can be used as tools by the dam operator for assessing the effects of different discharges at locations in and around Rocky Mountain House. Chapter 5 provides conclusions and recommendations for restructuring the monitoring program.

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

In order to evaluate the data and observations collected, an appreciation of freezeup processes is necessary. The data collected will be reviewed in light of the present theory concerning freezeup. Ideally the data will allow an evaluation of the existing theory as it pertains to this particular situation and allow some calibration of the various process models presented. An understanding of the ice processes involved in freezeup will assist in making decisions about how the monitoring program can be improved. This section will provide a review of the current literature on freezeup and also review the previous studies that have been done in the study reach.

Figure 2.1 illustrates the setting of the North Saskatchewan River, and its major tributaries, upstream of Edmonton. The numbers marked along the channel length represent river mileages measured along the channel centerline with the origin taken at the High Level Bridge in Edmonton. The study reach extends downstream from the Bighorn Dam to the confluence with the Brazeau River, a distance of 131 miles.

2.2 OVERVIEW OF FREEZEUP ON REGULATED RIVERS

The ice cover on a typical river forms by the accumulation of frazil floes. In a natural river, the flow is slowly decreasing in the fall, usually reaching a minimum in late winter. Frazil floes, formed by the accumulation of frazil ice on the water surface, lodge or bridge at a point, forming the downstream end of the ice cover for a reach of river. From that point the ice cover builds upstream as the floes accumulate. Under natural conditions, a river may have several bridging points during freezeup.

When a river is regulated, the natural annual flow pattern is often disturbed. Flow regulation has influenced the annual flow distribution for the North Saskatchewan River at Rocky Mountain House as shown in Figure 2.2. The mean monthly winter flows in the November to April period have increased by 57 to 182% and the mean monthly summer flows in May to October have decreased by 47 to 75% compared to the pre-regulation flows as measured at Rocky Mountain House. In the case of the North Saskatchewan River, one of the objectives of constructing the Bighorn Dam was to augment winter flows to improve the water quality. Higher winter flows can result in drowning out some bridging points resulting in fewer locations from which the ice cover can build. Also, relatively warm water flowing out of the dam adds additional heat to the system. As a consequence, freezeup is often delayed in regulated rivers. Regulation can also change the character of the ice. Freezeup is often delayed on regulated rivers due to the constant outflow of warm water. Since regulation, the average freezeup date for Rocky Mountain House has been December 30, with the earliest freezeup on November 9 (in 1974) and the latest on January 31 (in 1990), and in three years freezeup did not occur at Rocky Mountain House (1976/77, 1986/87 and 1991/92) over the period of record (1974 - 93). Since, there is open water downstream of the dam throughout the winter frazil ice will form throughout the winter instead of just during freezeup. The frazil can form into anchor ice or be carried under the ice cover and deposit in slow moving areas of the flow, similar to sediment transport. Also with higher discharges there are higher river velocities resulting in the formation of a rougher cover.

Two approaches to modelling freezeup events will be reviewed in this study, the empirical degree day and the deterministic approaches. One method that has been used to quantify freezeup is the degree day approach. This method tries to characterize the heat balance between the river and the atmosphere by summing the number of degree days of freezing (the number of days where the mean daily temperature is less than 0°C). The number of degree days of freezing were matched with various events such as ice front progression in an attempt to characterize the freezeup process at a site. The deterministic approach attempts to derive energy balance and hydrodynamic equations to model water-ice behavior in order to develop predictive tools for assessing freezeup processes at a particular site.

2.3 WATER COOLING AND TEMPERATURE

The water temperature of a river is a function of the amount of heat in the river and it also reflects the amount of heat present in the environment surrounding it. When the environment is warmer than the river, as is the case in spring and early summer, heat flows from the surrounding environment into the water, raising its temperature. Similarly, as the weather cools in the fall, heat flows from the river into the cooler atmosphere.

Equation 2.1 describes the cooling of a three dimensional flow. The heat transfer for a river water volume $\partial x \partial y \partial z$ can be described as follows (Gerard, 1988):

$$[2.1] \quad \frac{\partial T_w}{\partial t}+u\frac{\partial T_w}{\partial x}+v\frac{\partial T_w}{\partial y}+\omega\frac{\partial T_w}{\partial z}=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial T_w}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial T_w}{\partial y})+\frac{\partial}{\partial z}(\varepsilon_z\frac{\partial T_w}{\partial z})-\frac{\phi_T}{\rho C_p}$$

where T_w = water temperature
x = downstream direction
y = transverse direction
z = vertical direction
u = velocity in the x direction
v = velocity in the y direction
ω = velocity in the z direction
ε_x = longitudinal dispersion coefficient
ε_y = transverse dispersion coefficient
ε_z = vertical dispersion coefficient
ϕ_T = total net heat transfer from the water
ρ = water density
C_p = specific heat of water = 4190 J/kg K

t	= time

Simplified for a one dimensional simulation the river is assumed to be well mixed with the water temperature constant across the width and through the depth. The equation for water temperature in a cross section averaged, one dimensional form that neglects dispersion, is described in Equation 2.1a (Poothrikka P., E. Macagno and J. Kennedy (1974); Lal and Shen, 1991).

[2.1a] $$\frac{\partial T_w}{\partial t}+\frac{\partial u T_w}{\partial x}=-\frac{\phi_T}{\rho C_p D}$$

where	D	= depth of flow
	T_w	= water temperature
	t	= time
	x	= distance along channel
	ϕ_T	= total heat loss
	ρ	= density of water
	C_p	= specific heat

This equation assumes that the water temperature is constant throughout its width and depth. In a deep lake or reservoir, a stratification or layers of water based on relative densities will exist (Krenkel and Novotny, 1980). During the winter, because the density of water is at a maximum at 4°C, the water at the bottom of the reservoir would be warmer than that at the surface. Water flowing out of a thermally stratified lake in a deep slow moving channel may continue to have a temperature gradient for a significant distance downstream which would make the one dimensional assumption of equation 2.1 invalid. In their freeze up model of the St. Lawrence River, Lal and Shen (1993) modelled stratified flow using a simplified two-layer model. In the case of the North Saskatchewan River, the outflow from the dam would be well mixed as it has just gone through the turbines. The North Saskatchewan River is relatively shallow and steep in the study reach, allowing for complete mixing throughout the depth of flow. The one dimensional assumption would be valid for this reach.

2.4 HEAT EXCHANGE

The heat content in a river is the sum of the heat transfer in and heat loss. Equation 2.2 describes the various sources of heat input and output for a river. The heat exchange term ϕ_T is the sum of the heat loss and gain by the river water. Components of heat transfer include long wave and short wave radiation, heat transfer from the bed, groundwater and tributary inflow, effluent from municipal and industrial sources, head loss, evaporative heat transfer and conductive heat transfer. During the fall, sources of heat are typically short wave radiation from the sun, heat transfer from the bed, groundwater and tributary inflow, effluent from municipal and industrial sources, and head loss are heat sources. Typical heat loss terms include long wave radiation, evaporative heat transfer and conductive heat transfer. Precipitation may be a cooling term if in the form of snow or it may be a source of heat if in the form of rain.

[2.2] $$\phi_T = \phi_S + \phi_{GW} + \phi_B + \phi_{HL} + \phi_L + \phi_E + \phi_H + \phi_P$$

where ϕ_T = Total heat exchange
ϕ_S = solar radiation (short wave radiation)
ϕ_L = long wave radiation
ϕ_E = evaporative heat transfer
ϕ_H = conductive heat transfer
ϕ_P = heat transfer due to precipitation
ϕ_{GW} = heat transfer due to groundwater
ϕ_B = heat transfer from bed
ϕ_{HL} = heat transfer due to head loss

Heat sources due to groundwater inflow, heat transfer from the bed, head loss and effluent may have a significant local effect, but over the course of an entire river, their contribution is negligible (Tsang, 1982). Head loss will be important in steep reaches of a river such as rapids. Similarly, heat losses due to precipitation can be significant locally but are insignificant over the length of the entire river (Tsang, 1982). Also, some of these parameters are not measured and so to be used, they would have to be estimated. The error in the estimate could be much larger than the error due to ignoring them. A simplified heat loss equation suitable for winter cooling considering only the sum of the long wave radiation, evaporation and conduction as represented by equation 2.3 (Beltaos, 1995). Tributary inflow is assumed to have the same water temperature as the main river and so the only consequence of the tributary inflow is increased discharge.

[2.3] $$\phi_T = -h_{wa}(T_a - T_w)$$

where h_{wa} = heat transfer coefficient between the air and the water, typically between 15 to 25 W/m^{2}K (Beltaos, 1995)
= 15 (Andres, 1994 for the Peace River)
= 19.71 for St. Lawrence River (Lal and Shen, 1993)
T_a = air temperature

Assuming constant river width, depth and velocity, equation 2.1 can be integrated to give an explicit equation for calculating the water temperature at any point along the river.

[2.4a] $$T_w = (T_o - T_a)\exp\left(\frac{-h_{wa}Bx}{\rho C_p u A_s}\right) + T_a$$

[2.4b] $$T_w = (T_o - T_e)\exp\left(\frac{-h_{wa}Bx}{\rho C_p Q}\right) + T_e$$

[2.4c] $$T_w = (T_o - T_e)\exp\left(\frac{-h_{wa}t}{\rho C_p D}\right) + T_e$$

where T_o = temperature of the upstream boundary
B = mean width of the river
A = column cross sectional flow area = BD
Q = discharge

Thus, given the upstream boundary water temperature, and the channel hydraulic properties, the water temperature can be calculated for any point along the river.

2.5 FRAZIL ICE FORMATION

The river water will continue to cool until its temperature reaches 0°C. Water can exist as a liquid or solid at 0°C. When water reaches 0°C, an additional amount of heat, called the latent heat of freezing, must be released before it can turn into ice. Frazil ice will form by heterogeneous nucleation (nucleation using a foreign particle such as a soil or dust particle as a centre) when the water is supercooled by up to 0.1°C (-0.1°C) (Osterkamp, 1978; Tsang, 1982). Homogeneous nucleation, the formation of an ice nucleus in pure water, is thought to require supercooling in the order of -40°C±2°C (Michel, 1978). Secondary nucleation occurs when ice particles formed during heterogeneous nucleation are broken apart and the pieces act as nuclei for other frazil particles (Beltaos, 1995). Under natural conditions, ice forms by heterogeneous and secondary nucleation only.

2.5.1 TOTAL FRAZIL IN FLOW

Once the river water temperature reaches 0°C, then the right hand side of equation 2.1a changes to (Lal and Shen, 1993):

[2.6] $$C_i \rho L = -\rho C_p T_w \quad \text{or} \quad T_w = \frac{-C_i \rho L}{\rho C_p}$$

Substituting equation 2.6 into equation 2.1, the frazil ice formation equation is as follows:

[2.7] $$\frac{\partial C_i}{\partial t} + u\frac{\partial C_i}{\partial x} = \frac{\phi_T}{\rho L D}$$

where C_i = volumetric concentration of frazil ice
u = mean river velocity

ρ_i = density of ice
L = latent heat of freezing of water = 333.4×10^3 J/kg

Equation 2.7 assumes that once the water temperature reaches 0°C, frazil production will begin. This is not technically correct as supercooling is required. However, given that the equation is dealing with one dimensional flow and the associated simplifications and since the degree of supercooling is relatively small (<0.1°C), the assumption that frazil production begins when the water temperature is equal to 0°C is a reasonable one.

Figure 2.3 shows a simplified calculation for frazil ice production assuming constant depth. The calculation also has not taken into account the insulating effect of floe formation or the reduction in frazil production at high concentrations of frazil due to the heat released to the water by nucleation. As the water turns into ice, the latent heat is released into the water. Eventually the release of this heat will equal the cooling of the water by the atmosphere and the rate of frazil production will decrease (Tsang, 1982). Tsang (1982) suggested that 0.5% by weight would be the upper limit for the frazil concentration in the flow, based on studies in the Niagara River.

Once the surface ice forms, the heat loss relationship between the water and the atmosphere changes due to the insulating effect of the surface ice. Frazil production will be reduced as the heat loss is reduced.

The depth averaged ice discharge is (Lal and Shen, 1993):

[2.8] $$Q_i = QC_i, \quad Q = uBD$$

where Q_i = volumetric ice discharge

Substituting equation 2.8 into equation 2.7

$$\frac{\partial QC_i}{\partial t} + u\frac{\partial QC_i}{\partial x} = \frac{uBD\phi_T}{\rho LD}$$

[2.9] $$\frac{\partial Q_i}{\partial t} + u\frac{\partial Q_i}{\partial x} = \frac{uB\phi_T}{\rho L}$$

In a well mixed river reach the initial distribution of frazil particles will be uniform throughout the depth. Although there can be a large number of frazil crystals present in the flow, 0.5% by weight seems to be an upper limit on the frazil concentration (Tsang, 1982, reporting on the Niagara River). In supercooled water frazil particles will adhere together and to submerged objects in the flow. This form of frazil is referred to as "active" frazil. Once the water temperature returns to 0°C, the frazil particles become inactive or passive (Beltaos, 1995). After nucleation, the frazil crystals continue to grow and will adhere to one another to form flocs. As a small crystal, the frazil particle can be transported throughout the flow by turbulence. As the frazil particles become larger, either by growth or flocculation, they become more influenced by the effects of buoyancy and gradually float to the surface (Tsang, 1988b). Over time the frazil will tend to become concentrated in the upper layers of the flow.

Lal and Shen (1991) divided the total ice discharge Q_i into Q_{is}, the surface ice discharge and Q_{id}, the suspended ice discharge. The surface ice will consist of two types of ice, solid ice on the top of the floe where the frazil ice has frozen and frazil slush which accumulates on the bottom of the floe.

[2.10] $$Q_i = Q_{is} + Q_{id}$$

where Q_{is} = surface ice discharge
Q_{id} = suspended ice discharge

2.5.2 SURFACE ICE DISCHARGE

The surface ice discharge was defined by Lal and Shen (1991) as:

[2.11] $$Q_{is} = \left[t_s + (1-e_{fr})t_{fr}\right]C_a Bu$$

where t_s = surface solid ice thickness
t_{fr} = surface frazil ice thickness
t_i = total ice thickness = $t_s + (1\text{-}e_{fr})t_{fr}$
e_{fr} = porosity of the frazil ice

The suspended frazil was defined by Lal and Shen (1991) as:

[2.12] $$Q_{id} = C_v Au$$

where C_v = volumetric concentration of frazil ice in suspension

Equation 2.11 may be substituted into equation 2.9 to describe the surface layer of ice growth.

$$\frac{\partial}{\partial t}([t_s + (1-e_{fr})]C_a Bu) + u\frac{\partial}{\partial x}([t_s + (1-e_{fr})]C_a Bu) = \frac{uB\phi_r}{\rho L}C_s + \theta u_* C_v Bu$$

$$\frac{\partial}{\partial t}([t_s + (1-e_{fr})t_{fr}]C_a B + \frac{\partial}{\partial x}([t_s + (1-e_{fr})t_{fr}]C_a Bu) = \frac{C_a B\phi_r}{\rho L} + \theta u_* C_v B$$

using $t_i = t_s + (1\text{-}e_{fr})t_{fr}$

$$\frac{CB\,\partial t_f}{\partial t} + t_f\frac{\partial(CB)}{\partial t} + CBu\frac{\partial t_f}{\partial x} + ut_f\frac{\partial(CBu)}{\partial x} + CBt_f\frac{\partial u}{\partial x} = \frac{CB\phi_r}{\rho L} + \theta u_b CB$$

assuming that $\frac{\partial t_f}{\partial x} = 0$ between nodes

[2.13] $$\frac{CB\,\partial t_f}{\partial t} + t_f\frac{\partial(CB)}{\partial t} + ut_f\frac{\partial(CBu)}{\partial x} + CBt_f\frac{\partial u}{\partial x} = \frac{CB\phi_r}{\rho L} + \theta u_b CB$$

$\theta u_b CvB$ = ice exchange between suspended and surface ice layers
θ = exchange coefficient (varies with vertical mixing turbulence, v'
u_b = vertical velocity

Equation 2.13 describes the changes in the surface ice. The left hand side of the of the equation describes how the surface discharge of ice is changing with respect to distance and time. On the right hand side, the heat loss from the floe surface and the frazil ice exchange with the suspended layer is described. For the surface layer $\theta u_b C_v B$ is positive and for the suspended layer it is negative. Lal and Shen used a value of 0.01 m/s for θu_b.

Initially all of the frazil is suspended in the flow and the surface concentration would be equal to zero. Over time flocs would form and rise to the surface. At first the floes are basically floating slush, but the exposed surface will freeze to form solid ice. Frazil particles and flocs floating upwards will adhere to the bottom of the floes, thickening them. Floes will freeze together to form larger floes. They also bump into each other, the bank and other objects in the flow and tend to have a rounded shape. Because of their rounded shape, the frazil floes are sometimes referred to as "pancake ice" or "frazil pans". The presence of the surface ice changes the heat loss relationship between the water and the atmosphere due to the insulating effect of the surface ice. The water temperature will increase incrementally as the heat loss to the atmosphere decreases and frazil production isreduced as a consequence. Once solid surface ice forms, ϕ_r changes to ϕ_{si}, which reflects the change from heat loss from open water to heat loss from solid ice.

The solid ice thickness on the floes is calculated using equations 2.13 or 2.14 (Lal and Shen , 1993).

[2.14a] $$\frac{dt_s}{dt} = \frac{\phi_{si}}{e_f\rho L} \text{ for } t_p > 0 \text{ and}$$

[2.14b] $$\frac{dt_s}{dt} = \frac{\phi_{si}}{\rho L} \text{ for } t_p = 0.$$

where

[2.14c] $$\phi_{si} = \frac{\alpha + \beta(T_m - T_a)}{(1 + \frac{\beta t_s}{k_i})}$$

where α, β = constants to be determined
T_m = melting point of ice
T_s = surface temperature of the ice
k_i = heat conductivity of solid ice

The thickness of the frazil accumulation on the floes is described by equation 2.15.

[2.15] $$\frac{\partial t_{fr}}{\partial t} = \frac{\theta u_b C_v}{(1-e_{fr})} - \frac{dt_s}{dt}$$

The left hand term describes the increasing thickness of the frazil accumulating from the suspended frazil and the right hand term describes the frazil lost to solid ice production as described in equation 2.13.

2.5.3 SUSPENDED FRAZIL

To determine the concentration of suspended ice, substitute equation 2.12 (the suspended frazil discharge) may be substituted into equation 2.9 (the ice continuity equation).

[2.16] $$\frac{\partial(C_v A)}{\partial t} + \frac{\partial(C_v A u)}{\partial x} = \frac{B\phi_r}{\rho L}(1 - C_s)$$

Expanding

$$\frac{A\,\partial C_v}{\partial t} + \frac{C_v \partial A}{\partial t} + \frac{u C_v \partial A}{\partial x} + \frac{Au\,\partial C_v}{\partial x} + \frac{C_v A\,\partial u}{\partial x} = \frac{B\phi_r}{\rho L}(1 - C_s) - \theta u_b C_v B$$

The terms $\frac{C_v \partial A}{\partial t}, \frac{u C_v \partial A}{\partial x}, \frac{Au\,\partial C_v}{\partial x}, \frac{C_v A\,\partial u}{\partial x}$ are assumed to be negligible (Lala nd Shen, 1991). This gives

[2.17] $$\frac{A\,\partial C_v}{\partial t} + \frac{C_v A\,\partial u}{\partial x} = \frac{B\phi_r}{\rho L}(1 - C_s) - \theta u_b C_v B$$

The left hand term describes the suspended frazil formed in the flow and the right hand term describes the suspended frazil lost to floe formation. This term is a positive input for equation 2.16.

2.6 ANCHOR ICE

Anchor ice is defined as ice either growing or depositing on the substrate of the river bed

(Calkins, 1993). It can form by one of two mechanisms, underwater nucleation and frazil adhesion. Underwater nucleation occurs when a submerged object acts as a centre of nucleation. The anchor ice formed in this manner typically covers the object with a smooth, dense coating of ice (Tsang, 1982). Frazil adhesion occurs in supercooled water where frazil particles are very sticky and will adhere to submerged objects to form anchor ice. In a river, anchor ice formed by frazil adhesion occurs mainly over boulders, stones, gravels, coarse sands and aquatic weeds, but has not been observed on river beds of packed fine sand, silt or clay (Tsang, 1982). Frazil ice will also adhere to water intakes forming an anchor ice deposit that can plug them up. Anchor ice formed by adhesion has a high surface area and a flaky appearance (Tsang, 1982; 1988a). Arden and Wigle (1972) reported that anchor ice deposits in the Niagara River could reduce the outflow from Lake Erie into the Niagara River by up to 25% over the course of one night. Wigle (1970) reported that anchor ice could grow in reaches with velocities up to 3 m/s and river depths of up to 9 m.

In nature, the dominant form of anchor ice is frazil adhesion to rocks and coarse sand in gravel bed rivers. Anchor ice does not form in fine bed rivers. There are two reasons for this.

1. The bed particles are lifted from the bed due to buoyant action before the anchor ice grows to a noticeable size.

2. If the bottom is smooth, heat radiating from the bed has more influence because there is a laminar boundary sublayer along the bed (Tsang, 1982).

Anchor ice can grow to relatively large sizes, limited by the size of the particle on which it is growing and water temperature. As ice is less dense than water, it has a tendency to float towards the water surface due to buoyant forces. As long as the combined density of the anchor ice-bed particle mass is denser than that of water, it will remain submerged. Once the density of the anchor-bed particle mass becomes less than that of water, buoyant forces will cause it to float to the surface. Anchor ice floes can be identified by their dirty appearance due to the bed material embedded in them (Tsang, 1982).

The strength of the bond between the anchor ice and the river bed is very dependent on the water temperature. Initially the bond between the anchor ice and the bed is very strong due to the negative heat balance in the water. Tsang (1982), reported that the initial bond between the anchor ice and the bed of the Niagara River was strong enough to resist dislodging when an anchor was dragged behind a boat. However, as more heat accumulated in the water, the bond was sufficiently weakened that buoyancy alone could raise the ice from the bed. Anchor ice often forms during cold nights and will separate from the bed during the day if the sun warms the bed sufficiently to weaken the bond.

In regulated rivers and streams during low flow, the exposed bed can cool to a temperature of less than 0°C. When the flow is later increased, the water coming in contact with the cooled bed can become supercooled and form anchor ice through underwater nucleation.

Shen, Wang and Lal (1995) used the following equation for modelling anchor ice growth in the RICEN model.

[2.18] $$\frac{dt_{ai}}{dt} = \frac{1}{1-e_a}(\gamma C_v + \frac{\phi_{wi}}{\rho L})$$

where ϕ_{wi} = heat exchange between the anchor ice and the water
= $h_{wi}(T_i - T_w)$
t_{ai} = thickness of anchor ice deposit
e_a = porosity of the anchor ice deposit
γ = frazil ice deposition coefficient

The left hand term (γC_v) determines whether the bed shear velocity is above one critical value or below another. This assumes that if the bed shear velocity is too low, then the vertical mixing will not be strong enough to transport frazil particles to the bed. If the bed shear velocity is too big, then the frazil particles will not be able to attach themselves to the bed. As the magnitude of these critical values are presently unknown, Shen *et al.* assumed values of 0 and ∞ for the lower and upper values, respectively. In a simulation on the Niagara River, Wang, Shen and Crissman (1995) used a value of 1×10^{-6} for the frazil ice deposition coefficient.

The right hand term describes the growth of anchor ice due to heat exchange. Tsang (1988a) proposed a similar equation that modeled anchor growth by frazil accumulation but did not include a term for growth by heat exchange.

2.7 BORDER ICE

Border ice is the ice that forms on the shallow quiescent flow along the edges of a river. It can grow by two basic mechanisms, heat exchange and the accumulation of frazil pans. Both mechanisms can proceed simultaneously, depending on river conditions. Border ice generally grows in quiet areas of the flow along the banks, in secondary channels, along islands and bars and at bridge piers. It tends to smooth out irregularities along the bank and the open water portion of the flow tends to have a constant width over a reach. The width of the border ice at a site is dependent on the local channel hydraulics.

On smaller streams it is possible that border ice growing out from the banks could eventually freeze together in the middle of the stream, in larger rivers, the extent of border growth is limited by the increased velocities towards the centre of the channel and abrasion by the frazil floes.

Newbury (1968) proposed the following empirical equation based on data collected from the Nelson River in Manitoba.

[2.19] $$B_i = \frac{an}{2(A_s S_w)^b} \phi_T$$

where a, b = empirical coefficients
A_s = area of open water
S_w = slope of the water line
ϕ_T = heat loss during the formation of border ice
n = the number of faces on which the ice is growing

The $\frac{a}{(A_s S_w)^b}$ term defines the proportion of frazil adhering to the border ice.

Michel, Marcotte, Fonseca and Rivard (1982), proposed the following relationship based on data collected from the Ste. Anne River in Quebec.

[2.20] $$\frac{dB_i}{d\phi_T} = \frac{14.1}{\rho L}\left(\frac{u_B}{u_C}\right)^{-0.93} C_i^{1.08}$$

where u_B = depth averaged open water velocity immediately adjacent to the border ice
u_C = maximum velocity at which an ice particle can adhere to the ice
C_i = the concentration of frazil ice in water (dimensionless)

Equation 2.20 is not valid for $u_B/u_C < 0.167$, or in this case, when $u_B < 0.2$ m/s as static ice growth is very rapid for that case (Michel et al., 1982). Also, for $C_i < 0.1$, border ice growth was only by static ice growth. Michel found that $u_C \approx 1.2$ m/s for the Ste. Anne River. Lal and Shen (1993) found that u_C for the upper St. Lawrence River was about 0.4 m/s for typical flow conditions. Matousek (1984) suggested that Soviet authors quoted values of u_C of 0.4 - 0.6 m/s.

2.8 DYNAMIC ICE COVER FORMATION

2.8.1 BRIDGING

At some point along the river, the ice floes lodge and the ice cover progresses upstream from that point by floe accumulation. The process whereby the floes stop and initiate the beginning of a continuous ice cover is referred to as bridging. Bridging sites tend to be the same year to year and a river can have several bridging sites along its length. These sites are usually at constrictions, sharp bends or reaches with slope changes or islands present. At present, most formulae dealing with bridging do not attempt to predict if and when bridging will occur, but rather what happens after bridging has occurred.

From flume studies using blocks and beads, Ettema (1990) demonstrated that jams could be initiated by wall or shore resistance and developed some simplified equations to predict the length of channel required to produce a jam.
The volume of a stationary equilibrium jam can be calculated from equation 2.21.

$$V_j = e(KB)t_{eq}B \qquad [2.21]$$

where V_j = volume of jam
KB = effective length of jam with average thickness of t_{eq}
t_{eq} = equilibrium thickness

Similarly the volume of ice passing a point at some initial concentration can be estimated using equation 2.22.

$$V_j = x_j C_s t_f B \qquad [2.22]$$

where x_j = length of channel

Equating the two volumes, the length of channel required for a jam to occur can be calculated.

$$x_j = \frac{KBt_{eq}}{C_s t_f} \qquad [2.23]$$

The length required may be longer than calculated because not all of the ice would form part of the equilibrium jam. In natural channels the distance may be shorter than calculated here because an obstruction such as a constriction or sharp bend may initiate bridging before bank resistance can (Ettema, 1990).

At present, because of the lack of reliable tools for predicting the timing and location of bridging and the initiation of a stable ice cover, it is considered advisable to rely on field observations (Beltaos, 1995).

2.8.2 ICE ACCUMULATION

Once bridging has occurred, the development of the ice sheet can progress either by juxtaposition or by hydraulic thickening.

Juxtaposition of the ice floes is where the ice floes remain flat on the surface of the water and the ice cover forms by ice floes accumulating in an ice sheet, one floe thick. For an ice cover to form by juxtaposition the river velocities must be low enough that underturning of the floes does not occur. The floes freeze together and any open water between the floes will freeze by static ice growth. Thickening of the ice cover occurs by solid ice growth and under ice frazil deposition. When the ice cover forms by juxtaposition it can grow upstream very quickly.

The ice cover can also form by hydraulic thickening. In this mode the thickness of the ice cover is governed by the conditions at its upstream edge. When river velocities are higher, the additional forces cause the floes to underturn and submerge creating a thicker ice sheet to resist the upstream forces. This process was described by Pariset and Hausser (1961) as a narrow jam. In a narrow jam, the amount of the force or thrust absorbed by the banks at a point grows faster than the upstream load on that point.

The Froude number at the leading edge has been used as an indicator of the mode of dynamic ice progression. If the Froude number at the leading edge is equal to F_{rj} (juxtaposition Froude number) or less, then the ice floes are assumed to accumulate in a juxtaposed mode. When the leading edge Froude number is greater than F_{rj} but less then F_{rm}, (maximum allowable Froude number) then the ice cover is assumed to progress by hydraulic thickening. If the leading edge Froude number is greater then F_{rm}, then the ice cover does not move upstream and all of the surface ice is assumed to be swept under the ice where it may thicken the ice cover or be transported downstream. Values of F_{rj} and F_{rm} are listed in Tables 2.1 and 2.2.

Table 2.1: Literature values for the maximum allowable Froude number for ice cover progression.

Maximum allowable Froude Number for ice cover progression	Reference
0.09 - 0.12	Michel, 1986
0.08 - 0.13	Ashton, 1986
0.13	Kivisvild, 1959
0.09	Shen, 1991

Table 2.2 Literature values for maximum Froude number for juxtaposition of ice floes.

Maximum Froude number for juxtaposition	Reference
0.08 - 0.13	Ashton, 1986
0.06 - 0.08	Kivisild, 1959
0.04	Shen, 1995

2.8.3 SHOVING

Shoving occurs in a section where the forces in the downstream direction increase with distance from the water - ice cover interface. This phenomena was described by Pariset and Hausser (1961); Pariset E., R. Hausser and A. Gagnon (1966) as a wide jam. The balance of forces in a cohesionless ice jam is described by equation 2.24 (Flato, 1988).

$$[2.24] \quad \frac{t_i \partial \sigma_x}{\partial x} = \tau_i - \frac{2\tau_b t_i}{B} + \rho_i g t_i S_w$$

where σ_x = longitudinal stress
τ_b = cohesion with the banks
t_i = ice cover thickness
B = river width
τ_i = shear stress due to water flow under ice cover
S_w = water surface slope

For a shove to occur at a point on the ice cover, the load upstream, defined by $(\tau_i + \rho_i g t_i S_w)$ must be larger than the internal strength and the bank resistance of the ice jam defined by $(\frac{\partial \sigma_x}{\partial x} + \frac{2\tau_b t_i}{B})$. The term $\rho_i g t_i S_w$ describes the increasing weight of the ice jam and τ_i describes the shear due to the river flow under the jam in the downstream direction.

Substituting into equation 2.24,

$$\sigma_x = K_v \gamma_e t_i$$
$$\tau_b = \sigma_y tan\phi = K_{xy} \sigma_x tan\phi$$
$$\tau_i = \rho g R_i S_f$$

$$[2.24a] \quad \frac{\partial t_i}{\partial x} = \frac{\rho_i g S_w}{2K_v \gamma_e} + \frac{\tau_i}{2t_i K_v \gamma_e} - \frac{K_{xy} \tan \phi t_i}{B}$$

where K_v = passive pressure co-efficient = $\tan^2(45 + \frac{\phi}{2})$
K_{xy} = lateral stress transfer co-efficient (≤ 1)
γ_e = $0.5\rho_i g(1 - \frac{\rho_i}{\rho})(1 - e)$; $\gamma_e t_i$ = buoyant force on ice jam
ϕ = angle of shearing resistance (varies from 11 to 65°; Ettema and Urroz, 1989)
R_i = hydraulic radius for an ice covered river
S_f = friction slope

Equation 2.24a is the general one dimensional ice thickness equation for a cohesionless ice jam. The equilibrium section of the ice jam is where the ice thickness is at a maximum. This is the worst case scenario from a flooding perspective as it will produce the highest water levels for a given discharge. At equilibrium conditions the ice thickness is constant with respect to x and equation 2.24a has the form $0 = at_i^2 + bt_i + c$. Rearranging equation 2.24a and using the quadratic formula gives:

$$[2.24b] \qquad \frac{t_{eq}}{S_w B} = \frac{6.25}{\mu}\sqrt{1 + \frac{0.35\mu R_i}{S_w B}}$$

where μ = internal strength parameter = $K_x K_{xy} \tan\phi(1-e)$

t_{eq} = equilibrium ice thickness

Pariset and Hausser (1961) found that μ =1.28. Andres (1994) found that for the Peace River at the town of Peace River the value for μ ranged from 0.8 to 2.0 and averaged between 1.0 and 1.5 for a juxtaposed ice cover. He recommended that the value of 1.0 be used because the higher values were likely due to freezing in the ice accumulation. Ashton (1986) summarized the observations of 11 break up ice jams in northern Alberta and found that the value of μ ranged from 0.6 to 3.5, with an average of 1.23.

This analysis approach assumes steady flow conditions. The steady flow assumption assumes that the shove has no effect on the hydraulics of the river flow. In a real shove situation, there is a change in the flow area under the ice cover and the flow becomes unsteady due to surges, negative waves moving upstream and changes in storage in the ice accumulation. To date, no general equations describing the unsteady phenomena have been developed.

2.8.4 COVER STRENGTH

As the floes accumulate during freeze up, they start to freeze together and solid ice fills up the pores and crevices, strengthening the cover. Whether a shove occurs is a function of how quickly the cover increases its strength versus how quickly the load increases at that point.

Andres (1994) describes the strength of the ice sheet by

$$[2.25] \qquad \sigma_x = \mu\rho_i\left(1 - \frac{\rho_i}{\rho}\right)g t_i^2 + \sigma_s t_s$$

where σ_s = flexural strength of solid ice

t_s = solid ice thickness

Andres does not include the cohesive component of the bank shear $\tau_c t_i$ in his equation.

Lal and Shen (1993) divided the strength of the jam into 3 components, the solid ice, the granular ice and the frazil ice. In the event of a shove, the solid layer would break up and the ice accumulation would act as a granular mass.

2.8.5 COHESION

Ice jams have been modeled as granular accumulations using concepts derived from soil mechanics to explain observed phenomena. To account for the observation that freeze up jams are often thinner than would be expected for corresponding break up jams, it has been postulated that cohesion is responsible. As it would be expected to increase the internal strength of the accumulation. However, it is not clear how cohesion is generated in the ice mass (Beltaos, 1995).

Michel (1978) proposed the following relationship between ice cohesion and air temperature

[2.26] $$C_o = 2.81 \times 10^5 |T_a|^{0.78}$$

where C_o = cohesive strength in Pascals (Pa)

Laboratory tests have generally found cohesion to be less than 100 Pa and this would indicate that the contribution of cohesion to the ice jam strength would be negligible compared to that of internal friction (Beltaos, 1995). Ettema and Urroz (1989), Urroz and Ettema (1987) and Ettema and Schaefer (1986) have suggested that the apparent cohesion is actually freeze bonding between ice blocks and that the soil mechanics analogy for describing the behavior of ice blocks may not be appropriate. They found that the freeze bonding between blocks in water was about four times stronger than freeze bonds formed in air. Other authors (Andres, 1994; Lal and Shen, 1993) have assumed that the apparent cohesion is the result of freezing within the ice accumulation.

2.9 LEADING EDGE PROGRESSION

As the floes accumulate the leading edge of the ice cover moves upstream. The velocity with which it moves upstream can be defined by equation 2.33 (Lal and Shen, 1993).

[2.27] $$v_{Le} = \frac{Q_{is} - Q_{ui}}{(1-e)(1-e_p)t_i B}$$

where Q_{is} = the incoming volume of surface ice

Q_{ui} = volume of ice entrained under the ice cover at the leading edge

e_p = porosity of the accumulation
e = porosity of the floes
v_{Le} = velocity of the leading edge
t_i = thickness of ice accumulation

Equation 2.32 assumes that the velocity of the incoming floes downstream is much larger than the velocity of the leading edge moving upstream. The porosity of the incoming floes is included and this implies that the incoming floes are not crushed and the porosity altered. Suspended frazil does not contribute to the progression of the leading edge as it is carried under the ice downstream. If the Froude number at the leading edge is greater than F_{rm} then all of the surface ice will be entrained by the flow and swept under the ice cover. The initial thickness of the ice accumulation would be determined by the leading edge Froude number.

2.10 PREVIOUS INVESTIGATIONS

Only one study has been conducted documenting pre-regulation freeze-up processes on the North Saskatchewan River and that was limited to the reach between the Brazeau River confluence and Edmonton. This study, conducted by Schulte (1963) (as reported by the *Montreal Engineering Co. Ltd.*, 1977) is unavailable. Consequently, our knowledge of the pre-regulation freezeup processes in the study reach are limited to government records of data collected by the Atmospheric Environment Service (AES) of Environment Canada and the Water Survey of Canada (WSC).

Table 2.3 summarizes the available information from AES for the period 1956 to 1974 as reported by Allen (1977). Prior to regulation, the first permanent ice occurred as early as October 23 (in 1960) and as late as November 27 (in 1965). After regulation, the first permanent ice occurred as late as December 9 (in 1974). Prior to regulation, complete freeze over occurred as early as November 17 (in 1960) and as late as January 12 (in 1969). An incomplete ice cover occurred in 1958, 1966 and 1974. The maximum ice thickness averaged 1.02 m prior to regulation. The WSC records report an average maximum ice thickness of 0.76 m at the gauge in Rocky Mountain House for the period from 1955 to 1971 (WSC, 1974).

Several studies have attempted to examine the nature of freeze-up on the North Saskatchewan River since construction of the Bighorn Dam. These studies and their findings are summarized below.

In 1977 *Montreal Engineering Co. Ltd.*, did a study which examined ice problems related to winter flooding on the North Saskatchewan river due to regulation. Based on the examination of pre-regulation photography, they concluded that the ice cover formation before regulation was a dynamic one. It was also concluded that the winter flooding was mainly due to higher winter flows and that the construction of flood protection measures to reduce the risk of flooding along with some limitations on the hydro plant operations during ice cover formation at key sites was the best way to balance public safety and

Table 2.3 Summary of Atmospheric Environment Canada's freeze-up records at Rocky Mountain House.

(Source: W.T.R. Allen, 1977)

Ice Year	First Permanent Ice	Complete Freeze Over	Incomplete Ice Coverage	Ice Safe for Traffic	Max. Ice Thickness (m)
1956	Nov 15	Nov 29		Jan 1	0.76
1957		Dec 09		Jan 1	
1958	Nov 20		Jan 03		
1959	Oct 28	Nov 25			0.73
1960	Oct 23	Nov 17		Nov 27	1.04
1961	Nov 21	Dec 25			
1962	Nov 10	Dec 02		Dec 31	1.10
1963		Jan 10		Jan 10	0.73
1964	Nov 09	Nov 29		Dec 16	0.91
1965	Nov 27	Jan 01			0.91
1966	Nov 07		Dec 29		
1967		Dec 31			
1968	Nov 06	Dec 31			1.10
1969	Nov 13	Jan 12		Jan 12	1.46
1970	Oct 25	Nov 28		Dec 30	1.07
1971		Dec 31			
1972					
1973	Oct 29	Dec 31			1.28
1974	Dec 09		Jan 21		0.30

reducing damage with hydro production. *Monenco Limited*, conducted a study in 1982 which documented the impacts of winter flooding in the river reach immediately upstream and downstream of Rocky Mountain House. The impacts of winter flooding on agriculture, wildlife, fish, recreation, infrastructure and heritage resources were examined.

In 1982, *Acres Consulting Services Limited*, reported on the effects of regulation on the ice cover formation. They provided some preliminary figures that could be used as guidelines for operating the plants, but the figures would need to be confirmed by quantitative analysis of the ice processes in the study reach. They also concluded that the necessary routing procedures to evaluate the scope for utilizing the full installed capacities at Bighorn and Brazeau were not available at that time.

A data collection program was initiated after the Bighorn Dam started operation. Initially, just the dates that the ice front passed certain locations were recorded. As part of the *Montreal Engineering Co. Ltd* (1977) report, ice front progression data was collected throughout the winter. In the early eighties more extensive observations were collected by *TransAlta Utilities Corp.* staff including ice front location, character of the ice and surface concentration of frazil ice. The extent and level of detail of the observations increased throughout the eighties and continued into the nineties. Recently the level of effort to collect observations has been reduced.

In 1976, a series of ice gauges were established along the North Saskatchewan River from Devon to Horburg upstream of Rocky Mountain House. These gauges were placed at locations where they could be accessed easily in the winter. Several have since been destroyed and new ones have been added. The locations of the gauges are shown in two internal reports from *TransAlta Utilities Corp.*, "North Saskatchewan River Gauges Upstream of Brazeau River Confluence," and "North Saskatchewan River Edmonton to Bighorn Dam" and are summarized in tabular form in Table 2.4. For most of the gauges, the maximum ice affected water level for the year was recorded manually either during the winter or in the spring. When the maximum ice affected water level for the year data was recorded in the spring, the date that it occurred would not be known. Two gauges, at Prentice Creek (mile 184.94) and at Rocky Mountain House National Historic Park (mile 193.09) have dataloggers and provide a continuous water level reading throughout the winter. Also the WSC gauge (05DC001) "North Saskatchewan River near Rocky Mountain House," is at mile 190.5 and operates continuously throughout the winter.

Table 2.4 Active ice gauges in the study reach.

Mile	Gauge Name
157.0	TransAlta Powerline
158.2	Dome Petroleum Oilwell
161.0	Dome Petroleum Pumphouse
161.5	Baptiste River
166.7	
168.0	Pembina Oil Pipeline
170.1	Dome Well
174.0	
176.1	Mouth of Buster Creek
180.6	Powerline crossing on Perry farm
184.8	Amerada Hess Pumphouse
187.5	No. 11 Hwy Bridge
188.3	above McCabe Farm
188.6	A.F.S Station
189.5	Gravel Pit Road
189.9	
190.5	WSC Gauge
191.9	Texas-Pacific
193.0	Parks Canada York boat site
193.1	West of National Monument
194.8	W.J. Fisher Farm
196.1	Ferrier Bridge
201.0	AGTL Pipeline

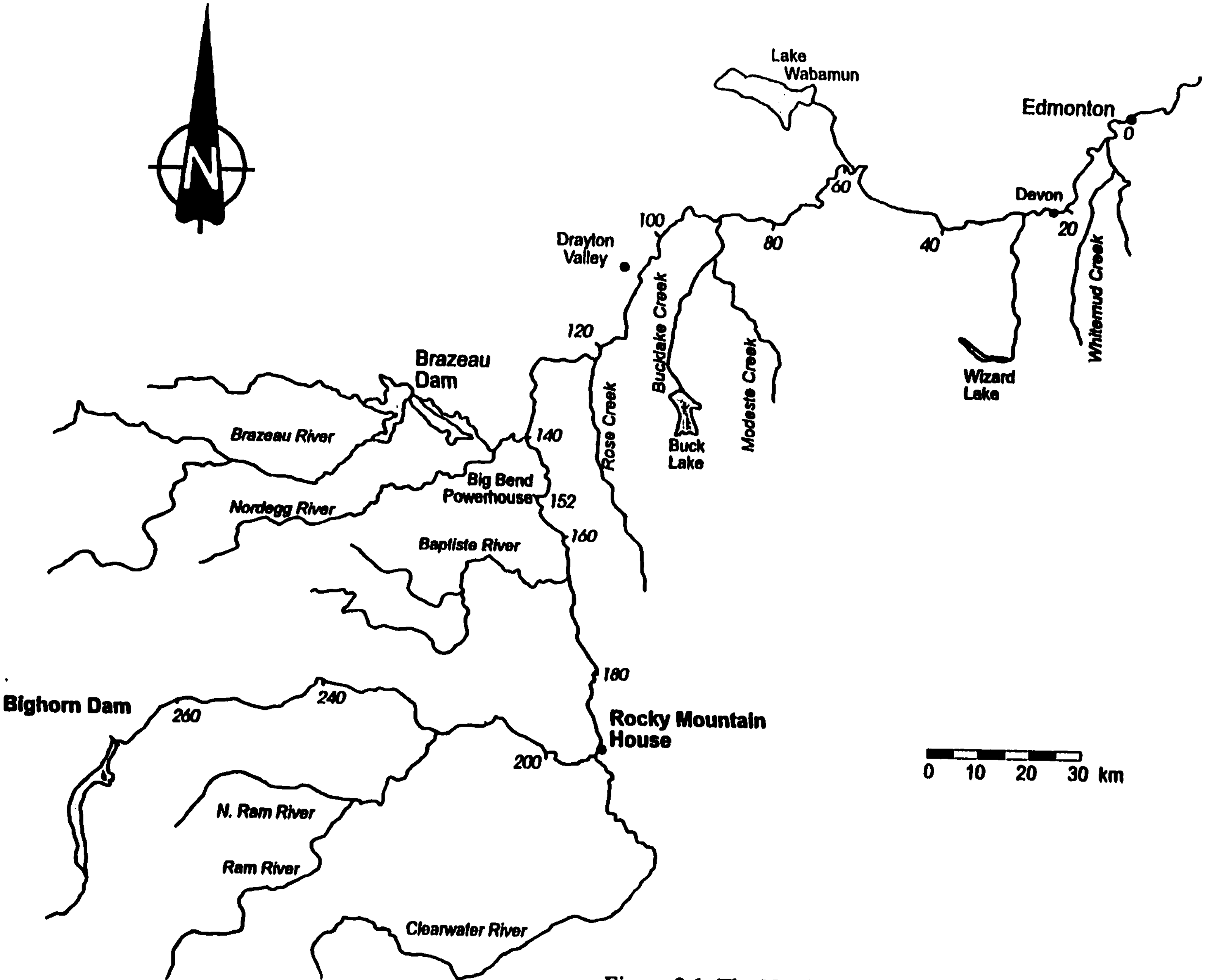


Figure 2.1 The North Saskatchewan River upstream of Edmonton.

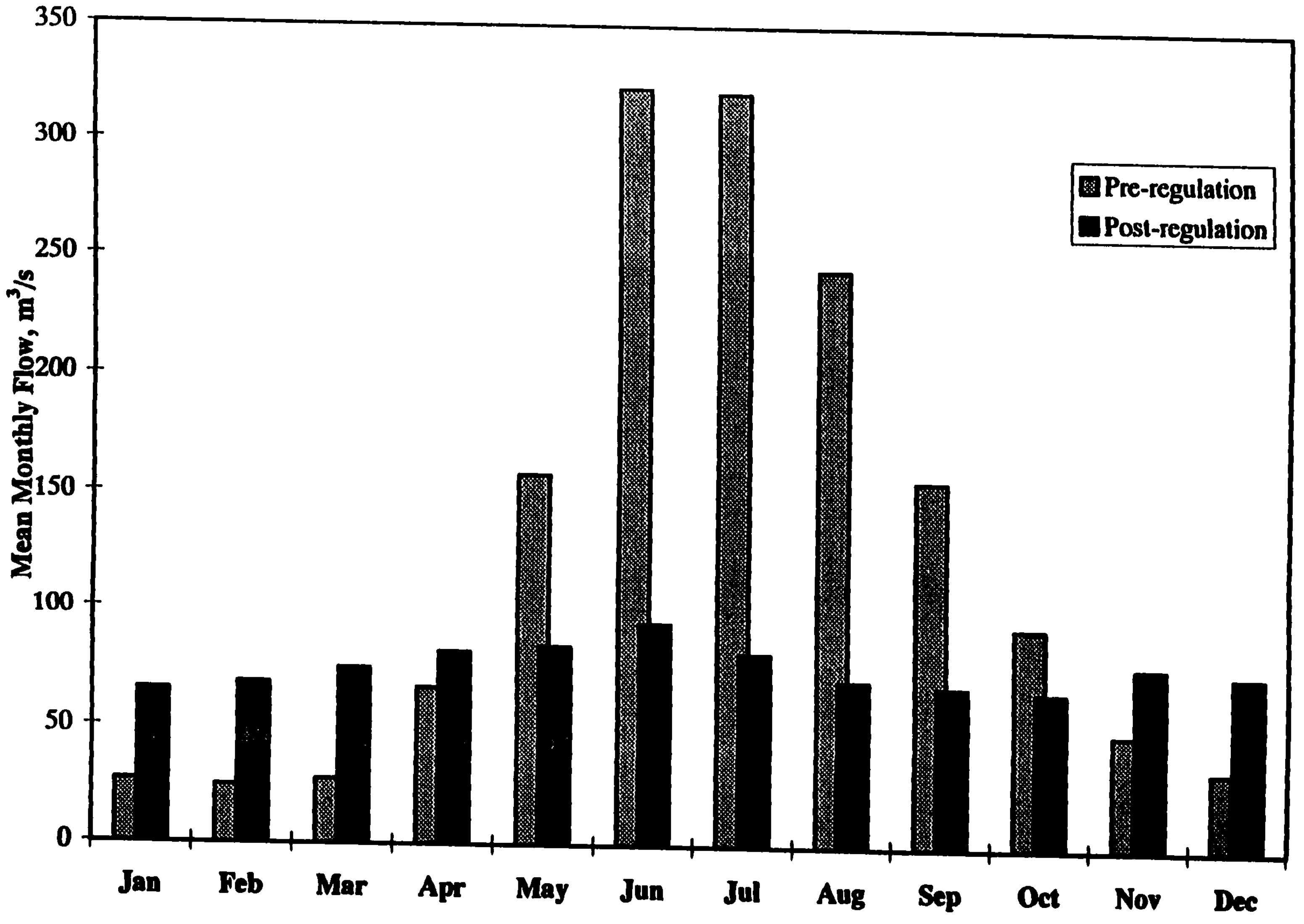


Figure 2.2: Mean monthly flows for the North Saskatchewan River for the pre and post-regulation conditions.

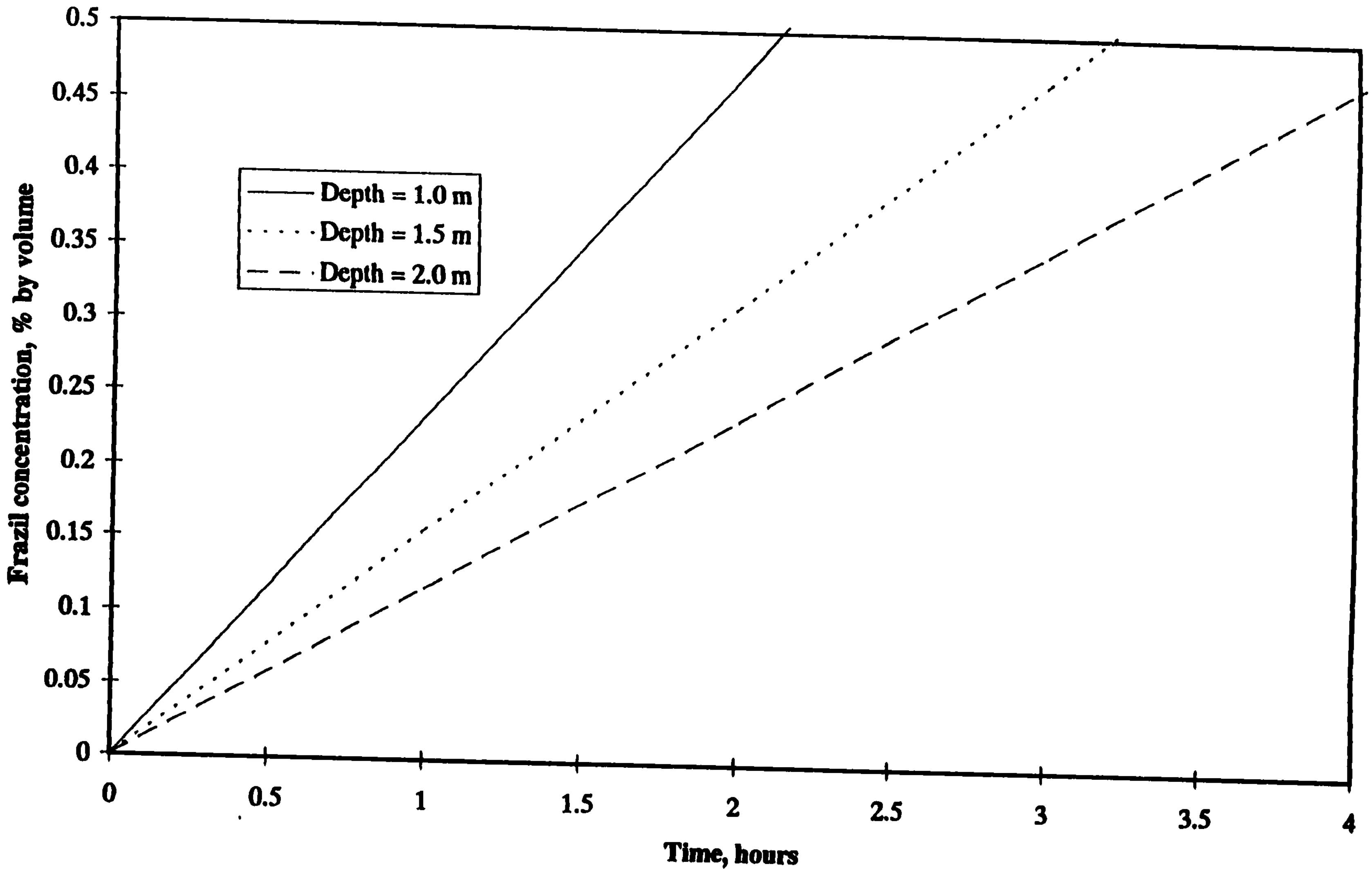


Figure 2.3: Simplified comparison of frazil ice production for various depths of flow using equation 2.7.

3.0 OPEN WATER HYDRAULIC ANALYSES

3.1 INTRODUCTION

As determined in the Acres study, (1982), establishing the feasible operating range of power plant releases during the freeze-up period requires two key types of information. First, it is necessary to establish the tolerable range of flows at each point of interest. Second, the attenuation of peak flows between the plant and each critical river reach must be determined. As both types of information require an hydraulic analysis, the logical first step is to establish the open channel flow characteristics within the study reach.

3.2 OPEN WATER FLOOD LEVELS (STEADY FLOW ANALYSIS)

3.2.1 INTRODUCTION

The steady flow analysis is required to establish hydraulic resistance parameters, specifically Mannings *n* for the river bed. Kellerhals, Neill and Bray (1972) provide values of Mannings *n* for various sites along the North Saskatchewan River, as summarized in Table 3.1 and Figure 3.1. However, as the table and figure indicate, there is a considerable variation from site to site. Therefore, it was considered appropriate to conduct a steady gradually varied flow analysis with the available data to determine appropriate resistance values for use in the hydraulic modelling.

3.2.2 EXISTING GEOMETRIC DATABASE

Surveyed cross section data were provided by *TransAlta Utilities Corporation* in HEC-2 format. The details of the origin and date of surveys for these sections are summarized in Appendix A, which also provide plots. High water mark information for selected cross sections are included on the rating curves in section 4.4. Most of the cross sections in the database were based on surveys conducted by the Alberta Research Council (circa 1969) and Alberta Environmental Protection (in 1983). River stations, or locations along the channel length, were based on the system established by *TransAlta Utilities Corporation*. Each of the available surveyed cross sections was referenced to this stationing system, as were all major tributaries and key sites of interest. Table 3.2 presents the location of various key sites along the North Saskatchewan River, in terms of their distances upstream of the High Level Bridge.

The surveyed cross sections in the HEC-2 database are located between mileages 153.31 and 213.22, starting just upstream of the Big Bend powerhouse and extending about 17 miles past the Ferrier (C.N.R.) Bridge (upstream of Rocky Mountain House). Most are situated at or near the ice gauge sites established by *TransAlta Utilities Corporation* for monitoring water levels under ice conditions. It is significant to note that the original HEC-2 file had the bridge piers coded into the GR cards, which will produce erroneous results. These were corrected but the special bridge routine was not employed to introduce the piers into the calculation, as the file was to be used for both open water and ice scenarios.

Table 3.1 Mannings *n* for various locations along the North Saskatchewan River.
Source: Kellerhals, Neill and Bray (1972)

Location	**Frequency**	**Discharge (c.f.s.)**	**Discharge (m^3/s)**	**Mannings *n***
Saunders	Long term	3,490	100	0.072
	2 year flood	17,000	480	0.043
	5 year flood	21,000	595	0.040
	10 year flood	23,300	660	0.040
Rocky Mountain House	Long term	5,080	145	0.036
	2 year flood	24,400	690	0.029
	5 year flood	33,000	935	0.028
	10 year flood	39,000	1105	0.028
	Bank full	52,000	1475	0.028
Edmonton	Long term	7,700	220	0.020
	2 year flood	42,000	1190	0.022
	5 year flood	62,000	1755	0.024
	10 year flood	80,000	2265	0.025
	Bank full	120,000	3400	0.031

Table 3.2 Location of key sites along the North Saskatchewan River.

Location	**Station (miles)**
Bighorn Dam (WSC05DC010)	**271**
Saunders	238
Ram River confluence	*218*
Horburg	213
Rocky Mountain House data logger	193
Clearwater River (Prairie Creek) confluence	*191.5*
Rocky Mountain House (WSC05DC001)	**190.5**
Prentice Creek data logger	185
Baptiste River confluence	*165*
Brazeau River confluence	*140*
Rose Creek data logger	123
Drayton Valley	107
Devon	24
Edmonton (High Level Bridge)	**0**

3.2.3 MODEL CALIBRATION

The resistance data available from Kellerhals et al. (1972) are limited to flow rates at the long term mean discharge and above (e.g. in excess of 5000 c.f.s. at Rocky Mountain House). However, as the earlier studies indicated, freezeup related flooding occurs at much lower flows. To determine the channel resistance at low flows, a water surface profile was measured at *TransAlta Utilities Corporation's* ice gauge locations throughout the study reach in October of 1976.

The discharge was spatially varied during the October, 1976 water level measurements (due to the variable outflows at the Bighorn dam) with the average flow rate estimated to be about 2700 c.f.s. (76.5 m^3/s). At that time, in order to bring the data to a common discharge, the measured water levels were adjusted by determining the discharge at each ice gauge at the time the water level was measured. This was done by first determining the time of travel of the water parcel from the Rocky WSC gauge to the particular ice gauge (based on an assumed flow velocity of 4.5 m/s), and then using the measured water level and rating curve at the Rocky WSC gauge to determine the flow rate at the WSC gauge at the time the parcel of water passed it. The water level at the ice gauge was then adjusted up or down, by assuming that the stage change at the ice gauge would be the same as at the Rocky WSC gauge for the same discharge difference. The resulting data provided an estimated (or "adjusted") water surface profile for 2700 c.f.s. flow rate. Figure 3.2 presents the calibrated water surface profile obtained using the HEC-2 steady gradually varied flow model. A Mannings *n* resistance factor of 0.050 was found to minimize the error in computed water level at this discharge. As this value was considerably higher that the values obtained at Rocky Mountain House by Kellerhals *et al.* (1972) for higher flows, it was considered appropriate to assess the calibrated model performance at the WSC gauge at Rocky Mountain House in comparison to the established rating curve at that site. Figure 3.3 presents the calibrated rating curve obtained with the gradually varied flow model. These calibrated values are shown in Figure 3.4 along with the other values obtained in the Rocky Mountain House reach. In the latter figure it is seen that the calibrated resistance value of 0.050 at 76.5 m^3/s is consistent with the data of Kellerhals *et al.* (1972). The values obtained when matching the rating curve at the WSC gauge are lower. However, the trend with discharge is consistent between the two. The upper values are recommended as they are based on a calibration of a profile rather than a calibration at a single point. This curve was used in the subsequent analysis.

3.2.4 CALCULATED FLOOD PROFILES

To establish a basis for the assessment of the severity of ice related flood events, steady gradually varied flow profiles were computed for various open water floods. The open water flood magnitudes were established based on a frequency analysis of the pre-regulation, historical flood record at the WSC gauge at Rocky Mountain House. Table 3.3 presents a summary of the historical data from the WSC gauge at Rocky Mountain House. Maximum instantaneous data were filled in using the average of the ratio between the maximum daily flood discharges and the maximum instantaneous values.

Table 3.3 Historical flood record at the WSC gauge at Rocky Mountain House.
(Source: Water Survey of Canada)

YEAR	Max. Instant. Discharge	Max. Daily Discharge	Ratio	Log transformation of Max. Instant. Discharge	Log transformation of Max. Daily Discharge
1913	*708*	646		2.850	2.810
1914	*559*	510		2.747	2.708
1915	4110	3680	1.117	3.614	3.566
1916	*1162*	1060		3.065	3.025
1917	*615*	561		2.789	2.749
1918	*826*	753		2.917	2.877
1919	*490*	447		2.690	2.650
1920	*673*	614		2.828	2.788
1921	*525*	479		2.720	2.680
1922	*618*	564		2.791	2.751
1923	1270	1260	1.008	3.104	3.100
1924	*739*	674		2.869	2.829
1925	*1129*	1030		3.053	3.013
1926	*963*	878		2.983	2.943
1927	*859*	784		2.934	2.894
1928	*987*	900		2.994	2.954
1929	*932*	850		2.969	2.929
1930	*630*	575		2.800	2.760
1944	971	937	1.036	2.987	2.972
1945	*490*	447		2.690	2.650
1946	*788*	719		2.897	2.857
1947	*724*	660		2.859	2.820
1948	*1283*	1170		3.108	3.068
1949	*447*	408		2.651	2.611
1950	*1129*	1030		3.053	3.013
1951	*658*	600		2.818	2.778
1952	1990	1600	1.244	3.299	3.204
1953	742	711	1.044	2.870	2.852
1954	1260	1060	1.189	3.100	3.025
1955	586	583	1.005	2.768	2.766
1956	464	439	1.057	2.667	2.642
1957	422	419	1.007	2.625	2.622
1958	*783*	714		2.894	2.854
1959	779	719	1.083	2.892	2.857
1960	609	558	1.091	2.785	2.747
1961	566	541	1.046	2.753	2.733
1962	504	473	1.066	2.702	2.675
1963	680	648	1.049	2.833	2.812
1964	790	776	1.018	2.898	2.890
1965	1460	1050	1.390	3.164	3.021
1966	835	733	1.139	2.922	2.865
1967	626	617	1.015	2.797	2.790
1968	558	547	1.020	2.747	2.738
1969	963	906	1.063	2.984	2.957
1970	1290	1120	1.152	3.111	3.049
1971	*807*	736		2.907	2.867
1972	1880	1470	1.279	3.274	3.167
Mean	912.3	822.5	1.096	2.910	2.871
St.Dev.	589.1	505.7	0.101	0.191	0.179
Skew	3.809	4.159		1.297	1.364

These synthesized values are shown in italics in the table. Four distributions were considered in the frequency analysis, specifically the normal, 2 parameter lognormal, Pearson III and log Pearson III distributions. As the calculated skew coefficients indicate, the normal and lognormal distributions are inapplicable as the normal distribution assumes a symmetric distribution of the random variable (discharge in the case of the normal distribution and the log of the discharge in the case of the lognormal distribution). The Pearson III distribution is also inapplicable as the skew of the maximum instantaneous discharge flood series is in excess of 3.0. Consequently the log Pearson III distribution was employed. Based on that analysis, the 1:2, 10, 25 and 100 year maximum instantaneous flood discharges were calculated to be 740, 1465, 2050 and 3325 m^3/s (26180, 51660, 72390, 117390 c.f.s.), respectively.

Figure 3.5 illustrates the computed open water profiles for the various return frequencies, calculated using the recommended relationship for Mannings *n* versus discharge presented in Figure 3.4. The high water mark (HWM) data for the 1986 flood (773 m^3/s) and the 1915 flood (4100 m^3/s) are presented for comparison. The 1986 HWM values compared favorably with the computed 1:2 year flood profile, despite the fact that the bridge characteristics (specifically the pier losses) were not considered in HEC-2 analysis. It is significant to note, however, that there is a discrepancy at the WSC gauge site. This would explain the low Mannings *n* values obtained when calibrating to the WSC rating curve, and justifies the decision to use the higher values.

3.3 DEVELOPMENT OF THE HYDRAULIC FLOOD ROUTING MODEL

3.3.1 INTRODUCTION

As discussed earlier, one of the key conclusions of the Acres ice study (1982) was that determining the attenuation of peak flows between the Bighorn plant and the sites of concern along the river is critical to establishing the feasible plant operating range during freezeup. In that study, flow attenuation analyses were conducted using the Muskingum flood routing technique. However, a consistent set of calibration parameters for the Muskingum model could not be obtained. This difficulty can be explained, in part, by the fact that hydro-power peaking operations are very dynamic. This is clearly shown in Figure 3.6, which presents the discharge release from the Bighorn Dam during the 1983 flow attenuation tests conducted by by *TransAlta Utilities Corp.* As the figure illustrates, the Bighorn releases result in almost instantaneous increases in river discharge, which would involve significant acceleration of the flow. The Muskingum flood routing technique is a ***hydrologic*** flood routing approach which, because of the conceptual way in which the physics of the flow are handled, cannot handle such dynamic events. The alternative is to apply ***hydraulic*** flood routing models which, being ***deterministic***, are based on the direct application of physical laws (which include flow acceleration terms). One of the key limitations of hydraulic flood routing techniques is that, being deterministic in nature, they require physical data describing channel geometry and resistance effects. This can be a very significant disadvantage in flood routing applications, as the cost of obtaining channel geometry data over long distances can be prohibitive. Fortunately, it has been shown that for situations in which floodplain inundation does not occur, an adequate representation of the of the salient geometry can be developed from limited survey data supplemented with topographic map data, by employing a rectangular channel approximation (Hicks and McKay, 1996; McKay, 1997).

In this investigation, the applicability of the limited geometry modelling approach to hydro-peaking operations on the North Saskatchewan River was tested using the flow attenuation tests conducted by *TransAlta Utilities Corp.* on the North Saskatchewan River between the Bighorn Dam and Rocky Mountain House during November 5-12, 1983 and November 13-16, 1986. First the development of the geometric database is described, then boundary and initial conditions are described and finally the results of the flow simulations are examined in comparison to the measured data.

3.3.2 DEVELOPMENT OF THE GEOMETRIC DATABASE

The basic data requirements for the limited geometry model include details of the effective bed profile, channel widths, and hydraulic resistance characteristics of the river channel. River stations, or locations along the channel length, were based on the system established by TransAlta Utilities Corporation. Each of the available surveyed cross sections was referenced to this stationing system, as were all major tributaries and key sites of interest. In addition to the digitized cross sections provided with the HEC-2 database, some old surveyed cross sections measured just prior to dam construction were available in graphical form. These were located between the Bighorn Dam site (mile 271) and Saunders (mile 239). Only data at those cross sections which were tied into the Geodetic Survey of Canada (G.S.C.) datum were considered.

The channel widths used in the hydraulic model were obtained from 1:50,000 scale National Topographic Series (N.T.S.) maps, by measuring the channel top width with scale and dividers at one mile intervals along the channel centreline. Figure 3.7 shows the top widths obtained by this approach. Top widths from the surveyed cross sections are also shown for comparison purposes. In general, it appears that the top widths determined from the N.T.S. maps are higher than those from the surveyed cross sections. This is likely due to the fact that the top widths at the surveyed cross sections are based on the water level on the day of the survey and such surveys are generally conducted at low water levels for safety purposes. Although the computational model is robust enough to allow for the use of such varying widths, such noise in the data does dramatically increase computational effort. Therefore, the channel top widths were smoothed, as shown in the figure. Previous studies (Hicks, 1995 and McKay, 1997) have shown that the model accuracy is not sensitive to this variable.

Water surface slopes were obtained from 1:50,000 scale N.T.S. maps by identifying locations where the topographic contours intersected the river channel. The corresponding stations, in terms of distance upstream of the High Level Bridge, were then used to determine water surface slopes.

A mean bed elevation was obtained for each of the surveyed cross sections by determining the hydraulic mean depth (equal to the flow area divided by the water surface width) at the water level on the day of survey, and then subtracting this mean depth from the water level. Although there is some inconsistency in this approach, because of the fact that the cross sections were surveyed at different times (and therefore at different flows), it was found that because of the typically high channel aspect ratio (width to depth ratio) the mean bed elevations obtained were not sensitive to the water level used.
To establish the "effective" bed profile at even 1 mile increments for the hydraulic model, a best fit line was drawn through the mean bed points from the surveyed cross sections. Effective bed levels between the surveyed reaches were estimated by projecting values in the surveyed reaches using the water surface slopes obtained from the 1:50,000 N.T.S. maps. Figure 3.8 shows the N.T.S. water surface profile, the mean bed elevations at the surveyed cross sections, and the effective bed profile obtained by this method.

3.3.3 BOUNDARY AND INITIAL CONDITIONS

In addition to a geometric description of the river, the routing simulation requires specified input in the form of boundary and initial conditions. The boundary condition required in this case are the inflows at the upstream end of the modelled reach, the tributary inflows, and the outflows, water levels or a rating curve at the downstream end of the modelled reach. In addition, the flow conditions (stage and discharge) at the beginning of the simulation must be specified at each computational node.

The upstream boundary conditions for the two simulations were the outflows from the Bighorn Dam. These data were digitized from the graphical information by *TransAlta Utilities Corp*. Figure 3.9 presents the data for the 1986 flow attenuation tests. The 1983 data were presented earlier in Figure 3.6.

Practically speaking it is often the case, especially in a forecasting situation, that the downstream boundary condition is unknown. In this case, the most downstream data provided for the two flow attenuation test events was the measured stage record from the Water Survey of Canada gauge at Rocky Mountain House (WSC05DC001). However, these data are unsuitable for use as the downstream boundary condition, as this is the area of interest in this study and therefore, the Rocky Mountain House gauge data are required for a comparison to the model output. Fortunately, if the downstream boundary is located far enough below of the most downstream point of interest, then a constant stage may be assumed for the downstream boundary condition. The required distance is that which is sufficient to ensure that backwater and drawdown effects resulting from the assumed boundary condition would not affect the model's output at the site of interest. For this analysis, the downstream boundary was taken at mile 123, 67 miles downstream of the WSC gauge at Rocky Mountain House. A sensitivity analysis was conducted to verify that the effect of the chosen station and stage for the downstream boundary on the modelled output was negligible.

The North Saskatchewan River tributaries are shown in Figure 2.1. Only those situated upstream of Rocky Mountain House were significant to this assessment of the hydraulic model, as the comparison between measured and computed flows occurred there. The available tributary data consisted of mean daily flows obtained from the HYDAT CD-ROM, included: the Ram River (WSC05DC006), the Clearwater River (WSC05DB006) and it's tributary, Prairie Creek (WSC05DB002).

The initial conditions for the pulse routing simulations were established by first estimating the stage at each computational node for the discharge at the beginning of the simulation (using the initial flow rate), and then running the model at this constant flow rate using the time stepping scheme to iterate to the steady flow solution. The steady flow solution at the initial discharge then provided the initial conditions for the flow attenuation tests.

3.3.4 MODEL VERIFICATION FOR OPEN WATER ROUTING

In this study the cdg-1D hydraulic flood routing model was used to model the propagation of flood flows along the North Saskatchewan River. This model employs a Petrov-Galerkin finite element method known as the *characteristic-dissipative-Galerkin* scheme (Hicks and Steffler, 1990, 1992) to solve the fully dynamic, one-dimensional unsteady open channel flow equations. Details of the equation formulation and the numerical solution scheme are provided in Appendix A.

Channel resistance, specifically Mannings *n*, is the only calibration parameter required for this hydraulic flood routing model. The values for channel resistance for the study reach were estimated from the recommended values obtained in the steady flow analysis. As an initial estimate Mannings *n* was taken as 0.028 for the entire reach.

To facilitate comparisons of computed and measured results, the stage hydrographs at the Rocky Mountain House gauge were digitized from the graphical information provided by *TransAlta Utilities Corp.* using the established rating curve at the gauge (presented in the data report for the 1986 flow attenuation tests).

As only the peaks and troughs of the hydrographs at Rocky Mountain House were available for the 1983 events, the 1986 event were modelled first. Only discharge "estimates" of the tributary flows were available from WSC for the period during the November 1986 pulse tests, as ice conditions in the tributaries rendered the open water rating curves invalid. In examining the base flows occurring at the dam and at Rocky Mountain House during this period, it was observed that the estimated tributary inflows in the WSC records were slightly low. To correct for this discrepancy, the tributary inflows were adjusted to ensure the baseflows were consistent between the dam and Rocky Mountain House. The correction was apportioned to the tributaries based on their percentage of the total flow contributed to the North Saskatchewan River, based on the WSC estimates for the period.

Figure 3.10 presents the computed and measured flows at Rocky Mountain House for the 1986 flow attenuation tests obtained using the adjusted tributary records and a Mannings *n* of 0.028 throughout the modelled reach for the entire simulation. As the figure indicates, the chosen value of Mannings *n* provides fair agreement. Despite the rectangular channel approximation and the limited available data, the timing of the pulse arrivals are nearly exact for these highly dynamic releases, an extremely promising result.

Although the peak magnitudes are overestimated this can likely be attributed primarily to the constant value of Mannings *n* used in the simulation. Referring back to Figure 3.9, peak flows released from the Bighorn Dam were as high as 140 m^3/s, while baseflows were as low as 25 m^3/s. It is likely that varying Mannings *n* as a function of discharge would improve the results (requiring a modification to the *cdg1-D* model). In addition, as the values in Table 3.1 illustrated, values of Mannings *n* might be expected to be higher in the upper reaches. Therefore it might also improve the results to vary Mannings n along the modelled reach. At this point in time, however, with such a limited amount of geometric information in the upper reaches and no comparative hydrograph data at intermediate points between Rocky Mountain House and the dam, such refinements are not warranted.

Figure 3.11 presents the computed and measured flows at Rocky Mountain House for the 1983 flow attenuation tests, again using a Mannings *n* of 0.028 throughout the modelled reach for the entire simulation. As mentioned earlier, continuous data were not available at Rocky Mountain House, only the peaks and troughs of the hydrograph were available. Also, as in 1986, the tests were conducted in November, at a time when ice was present on the tributaries. However, in this case, with the limited comparative data at Rocky Mountain House, it was decided to first assess the model performance without adjusting the tributary estimates.

As Figure 3.11 illustrates, the agreement between measured and computed values was considerably poorer for the 1983 flow attenuation tests than for the 1986 case. Although the timing of peak arrivals is again good, measured troughs are considerably higher than the computed values, reflecting the inaccuracy of the tributary flow estimated obtained form the WSC record. However, more significant is the fact that the magnitudes of the computed pulses are two or more times the measured values. This is, again, most likely due to the inapplicability of the low Mannings *n* value used. It was not considered warranted to try to refine the calibration, given the limited data available for these pulse tests.

3.4 KEY LIMITATIONS AND RECOMMENDATIONS

A preliminary assessment of the open water hydraulic flood routing model indicates that the limiting factor at this point in time is a lack of adequate data with which to assess the adequacy of the geometric model and to facilitate a refinement of the calibration. At this stage it would be appropriate to conduct a new series of flow attenuation tests at a time of year when the tributaries were ice free. In addition, it would be highly desirable to establish at least one or two sites between the Bighorn Dam and Rocky Mountain House

at which water levels are monitored during the tests. It would also be necessary to establish rating curves for these intermediate sites to aid in the calibration of variations in Mannings *n* with discharge, in the upper reach. It would also be valuable to establish a monitoring site downstream of Rocky Mountain House to facilitate the evaluation of the model performance through the downstream reach of interest.

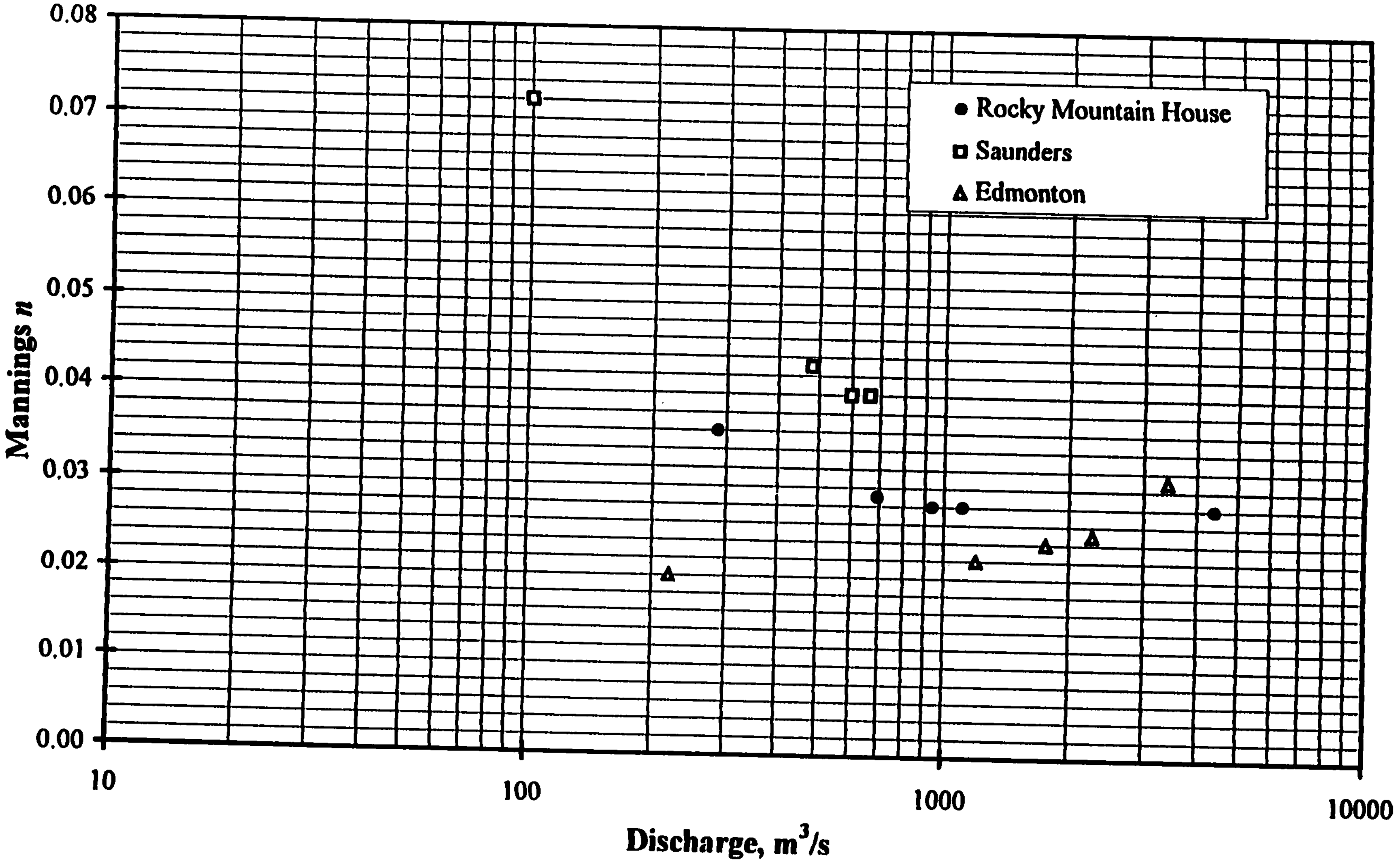


Figure 3.1 Mannings *n* values for the North Saskatchewan River (Kellerhals *et al.*, 1972).

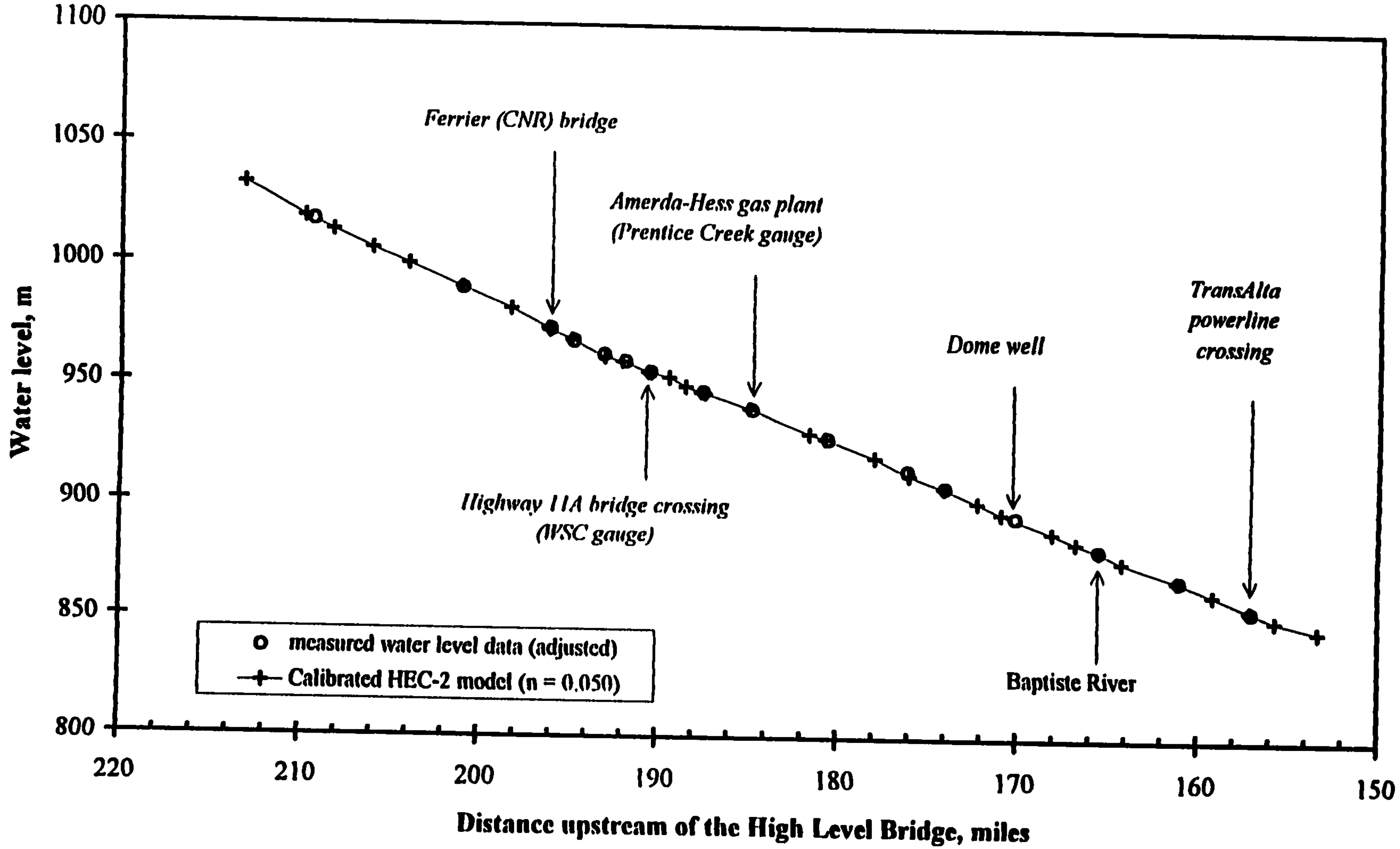


Figure 3.2 Calibration results for the North Saskatchewan River at a discharge of 2700 c.f.s. (76.5 m^3/s).

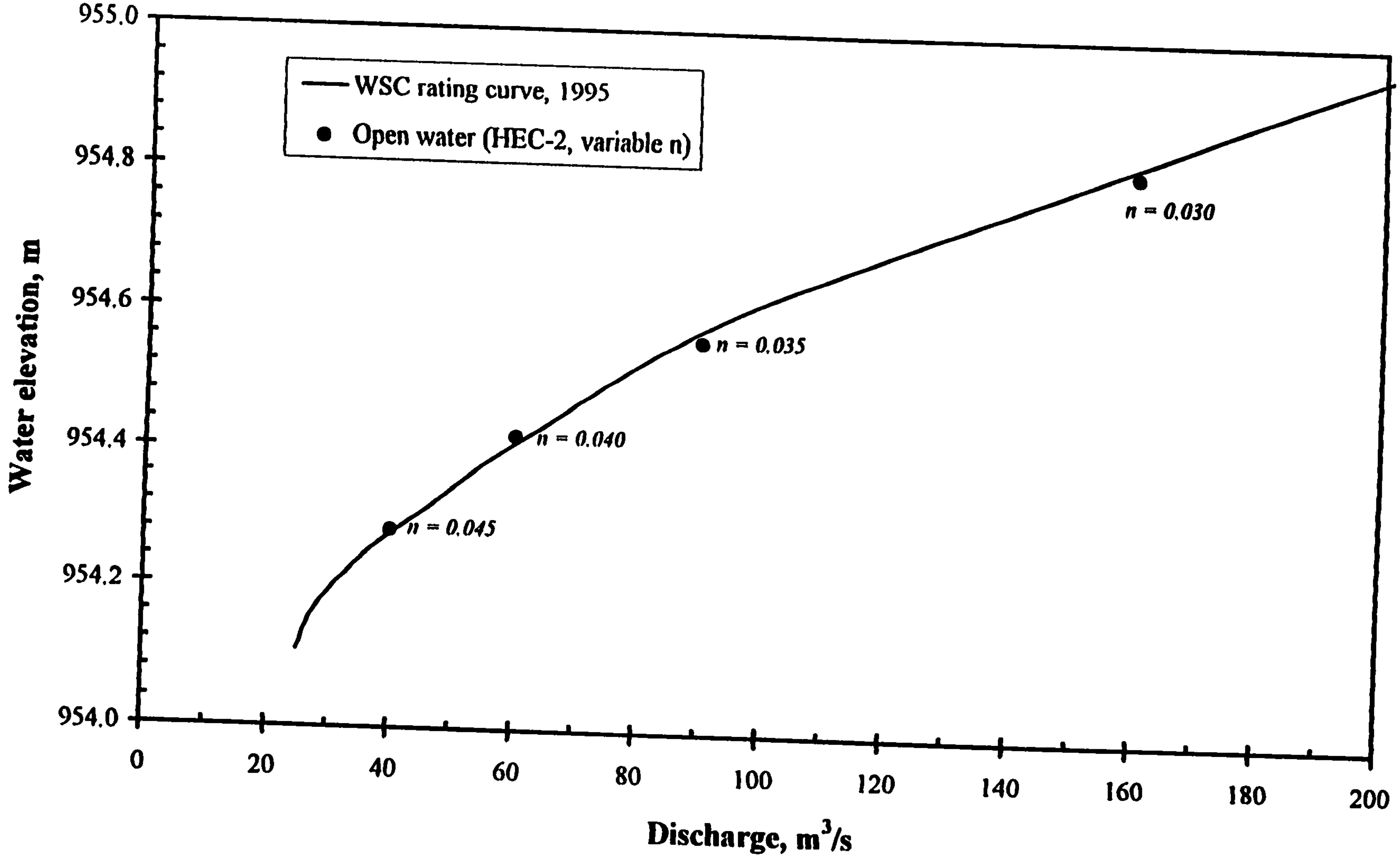


Figure 3.3 Comparison of computed (HEC-2) water levels and the WSC rating curve for the N. Sask. River at Rocky Mountain House.

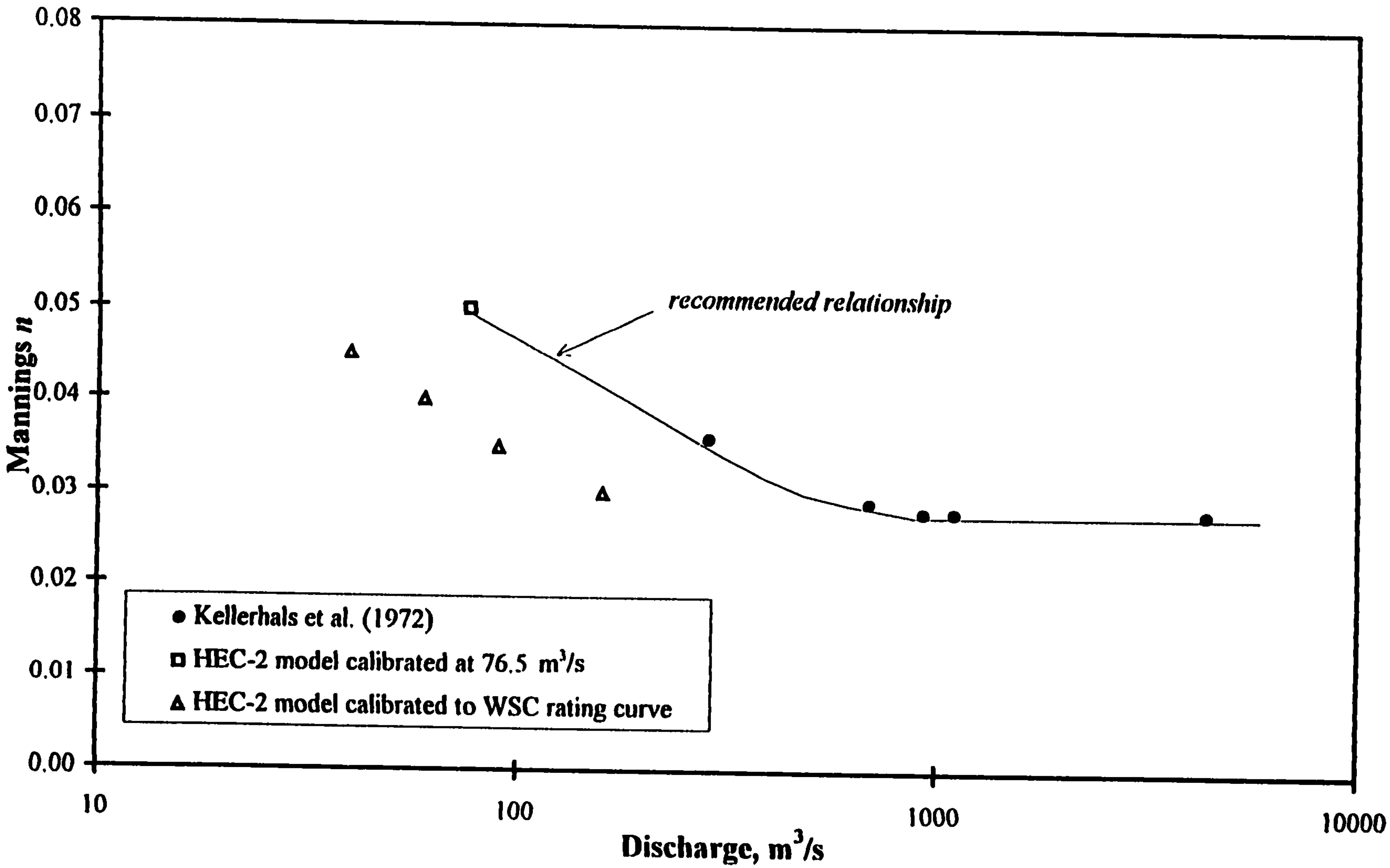
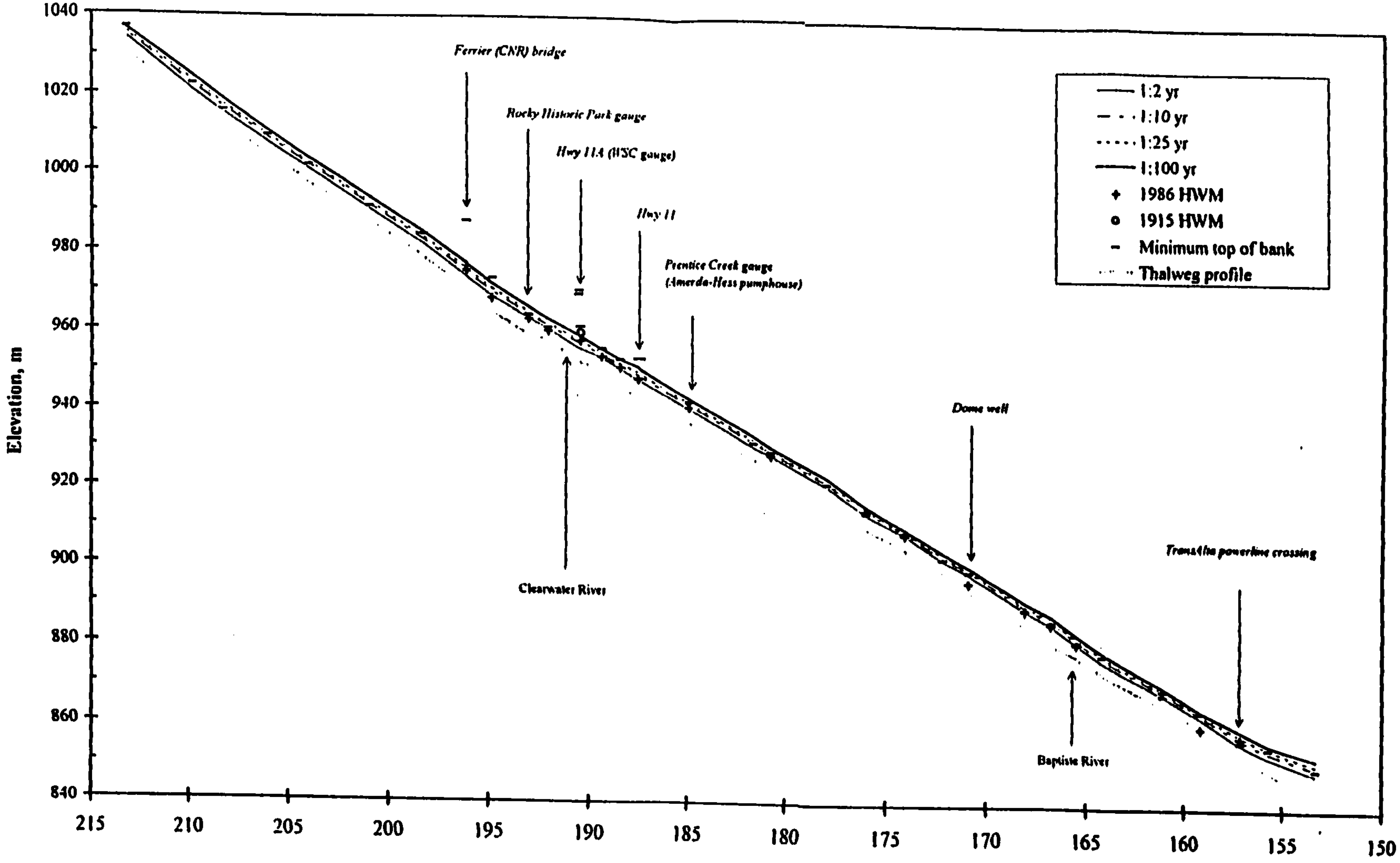


Figure 3.4 Mannings n values for the North Saskatchewan River near Rocky Mountain House.



Distance upstream of the High Level Bridge, miles

Figure 3.5 Calculated open water flood profiles on the North Saskatchewan River near Rocky Mountain House.

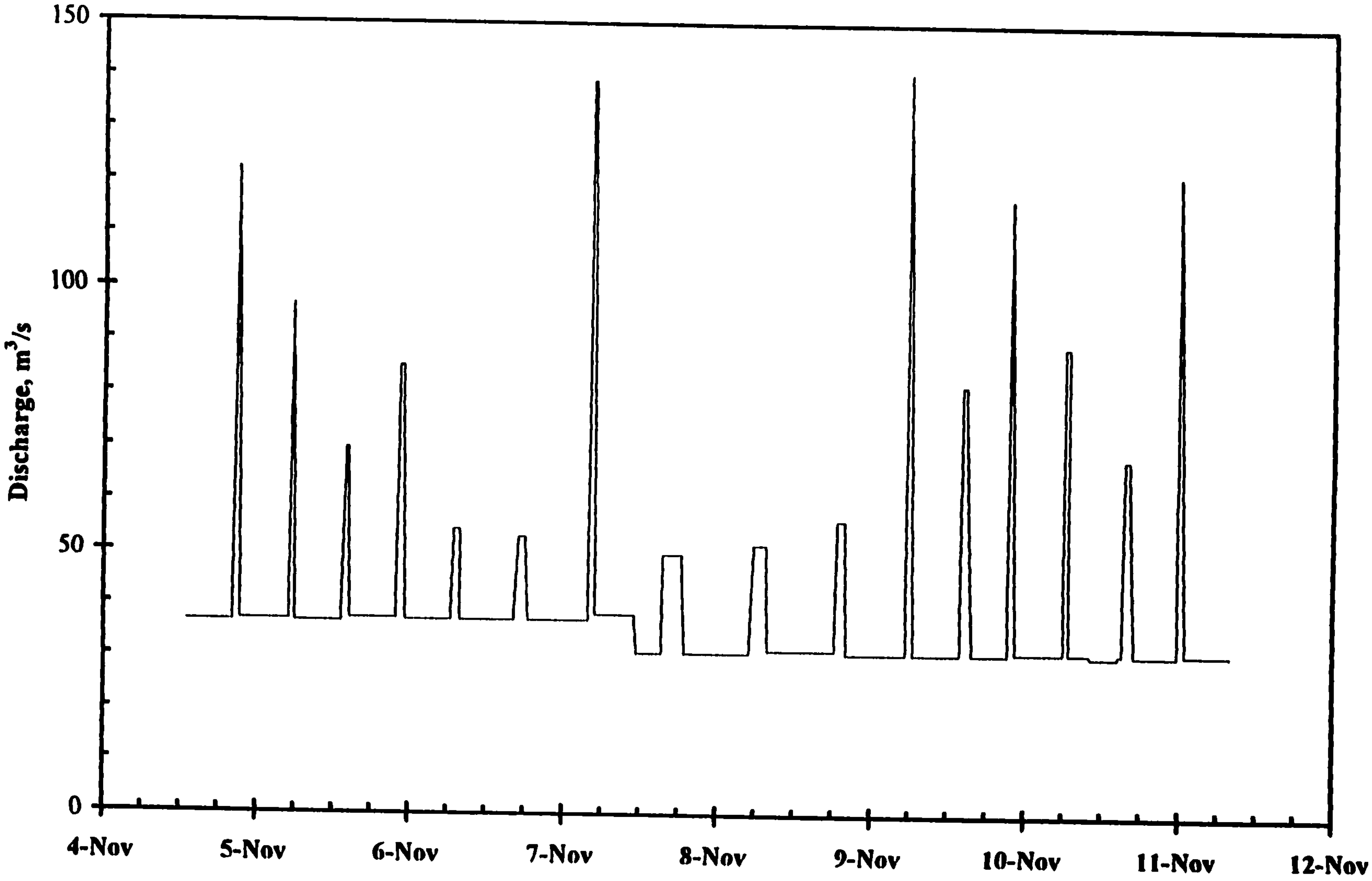


Figure 3.6 Discharge releases from the Bighorn Dam during the 1983 flow attenuation tests.

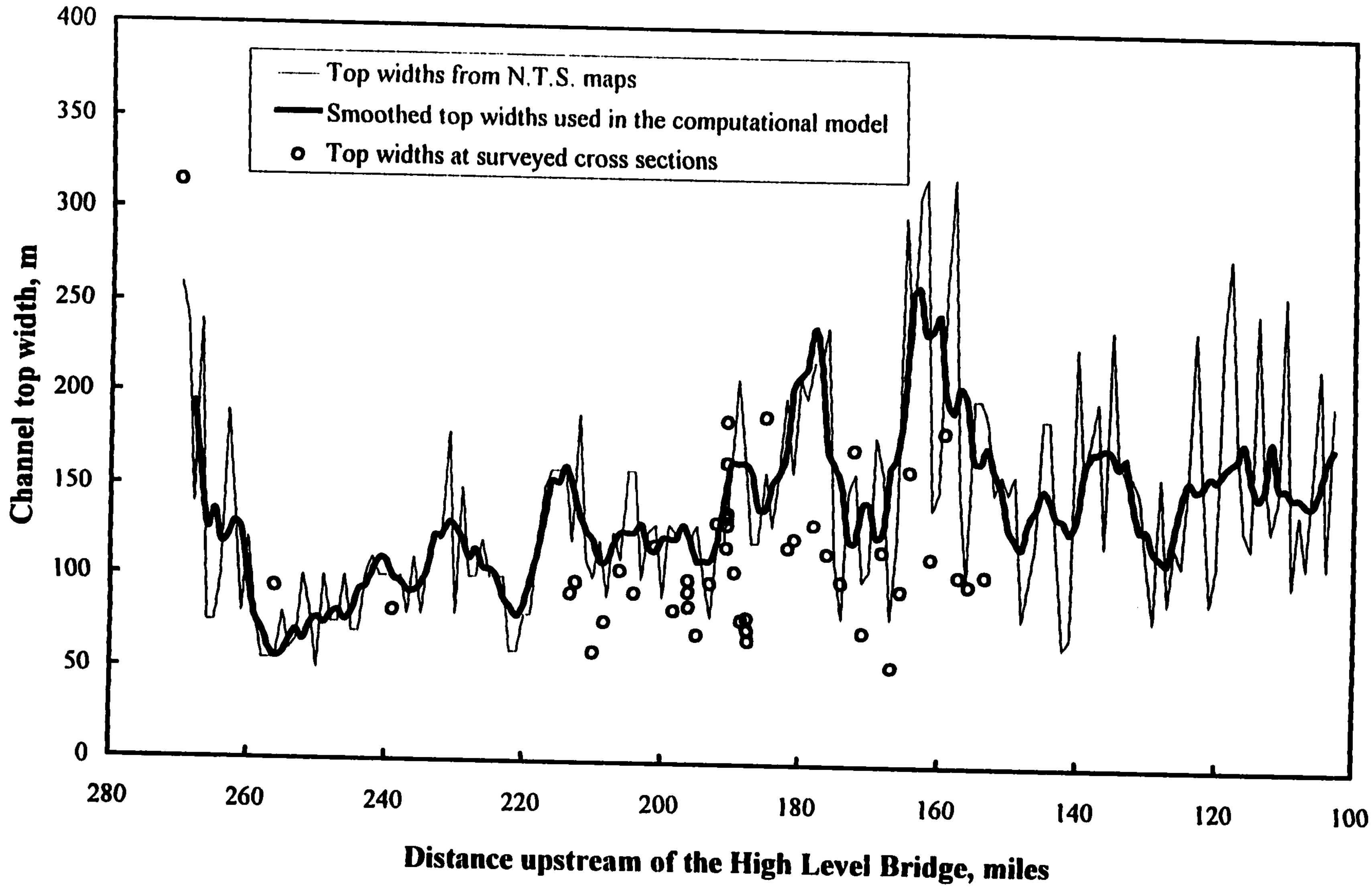


Figure 3.7 Channel top widths for the North Saskatchewan River downsteam of the Bighorn Dam.

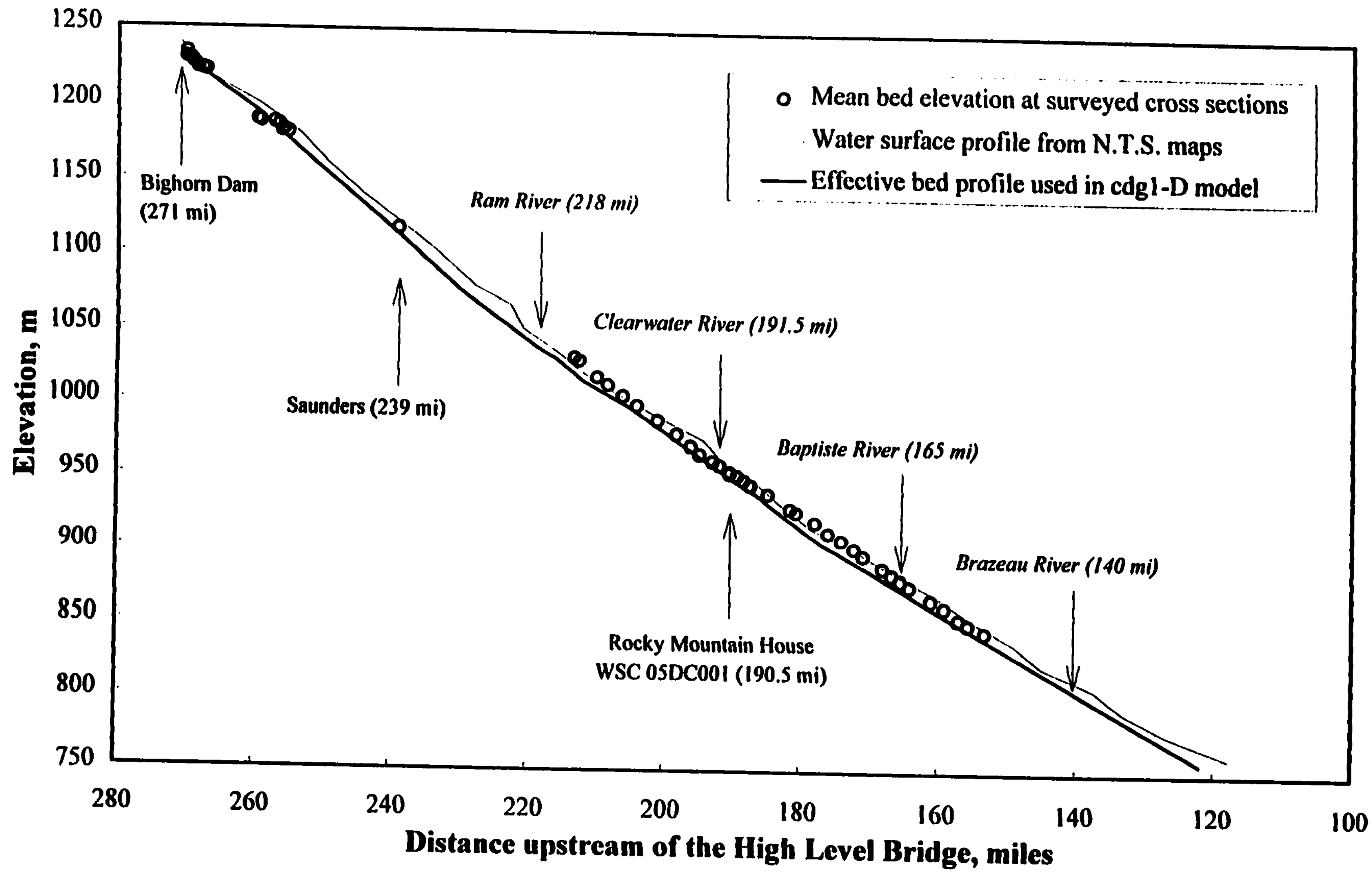


Figure 3.8 Effective bed profile of the North Saskatchewan River used in the hydraulic pulse routing model.

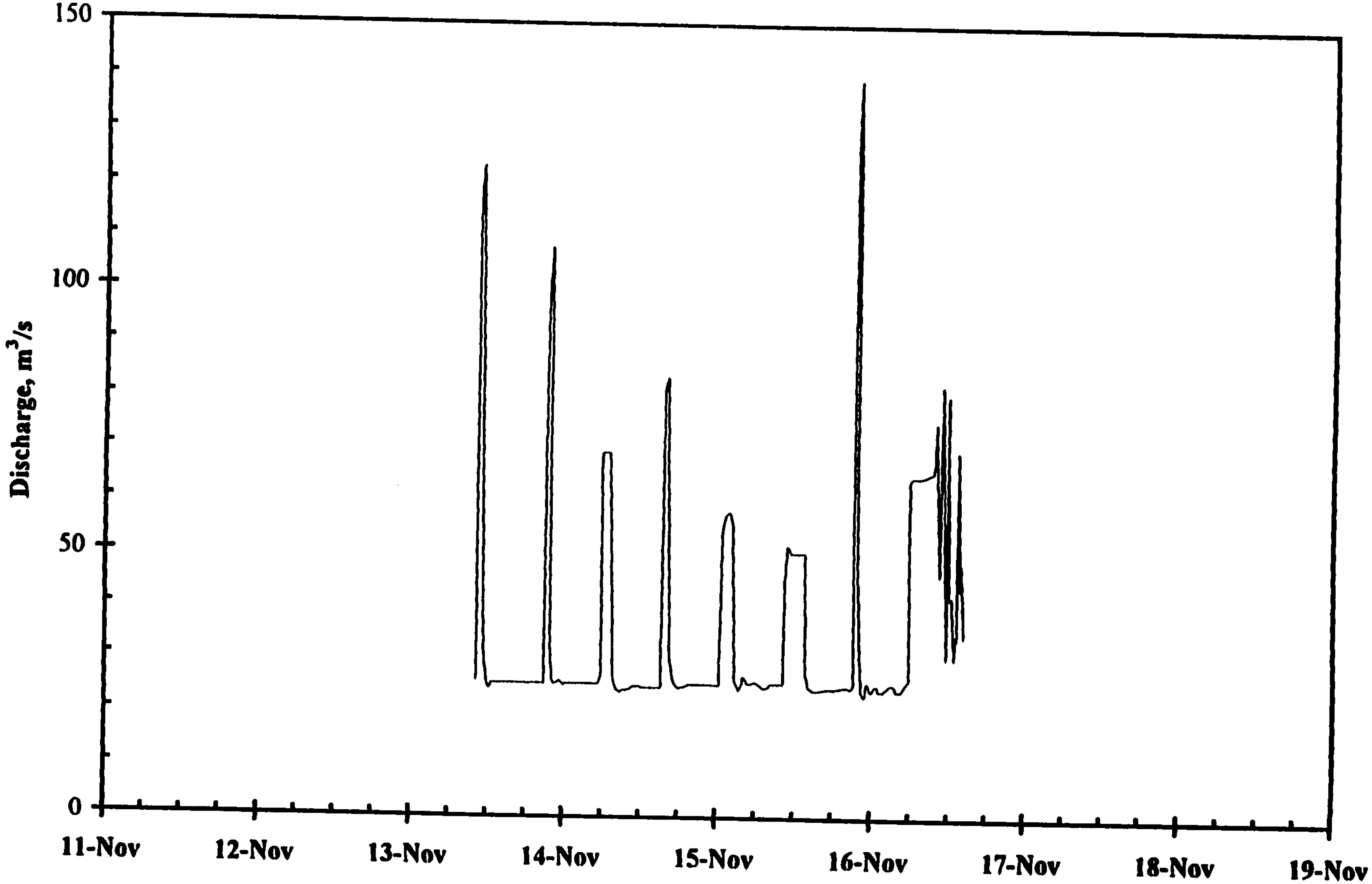


Figure 3.9 Discharge releases from the Bighorn Dam during the 1986 flow attenuation tests.

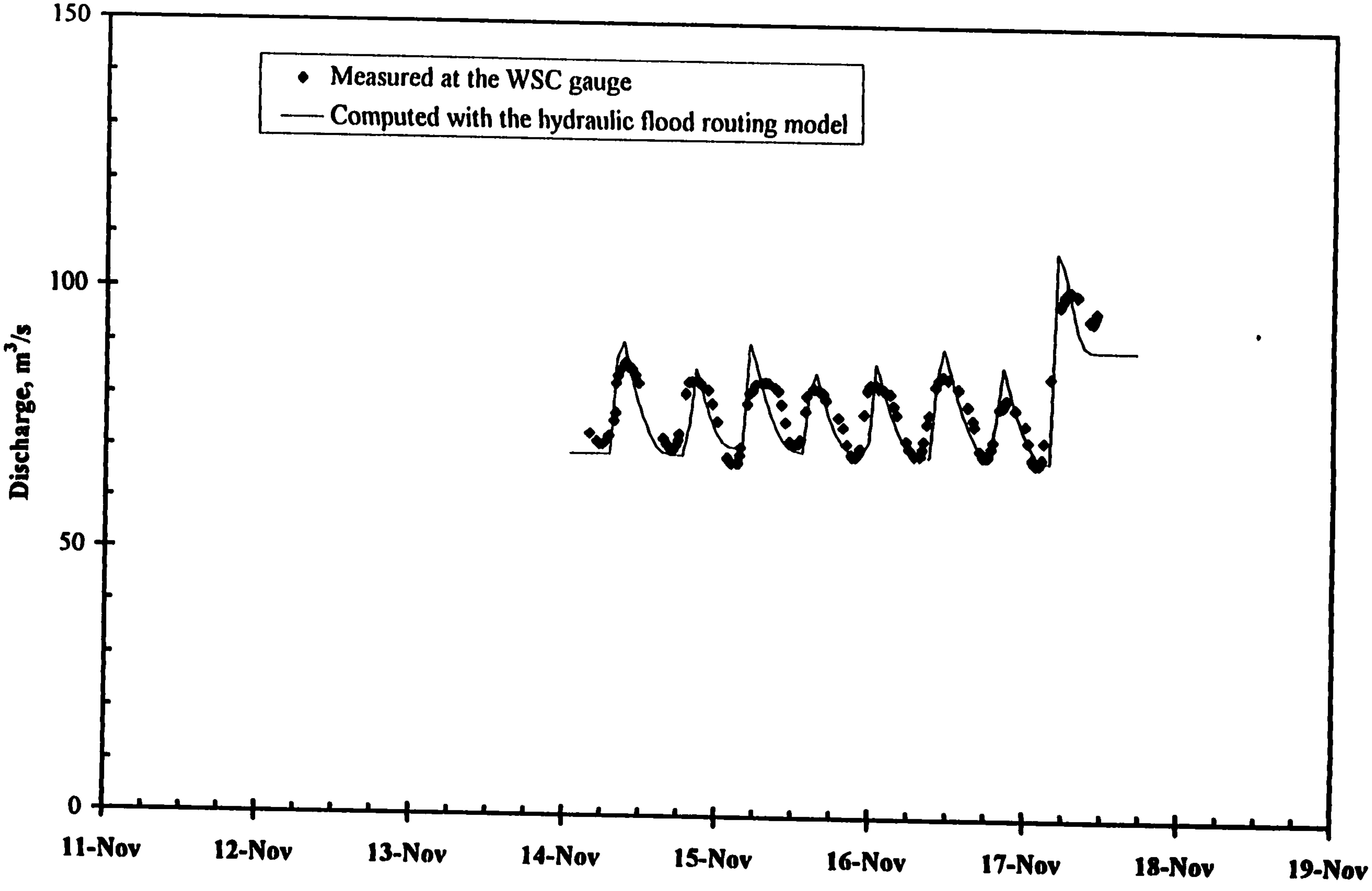


Figure 3.10 Comparison of computed and measured discharge hydrographs at Rocky Mountain House, 1986.

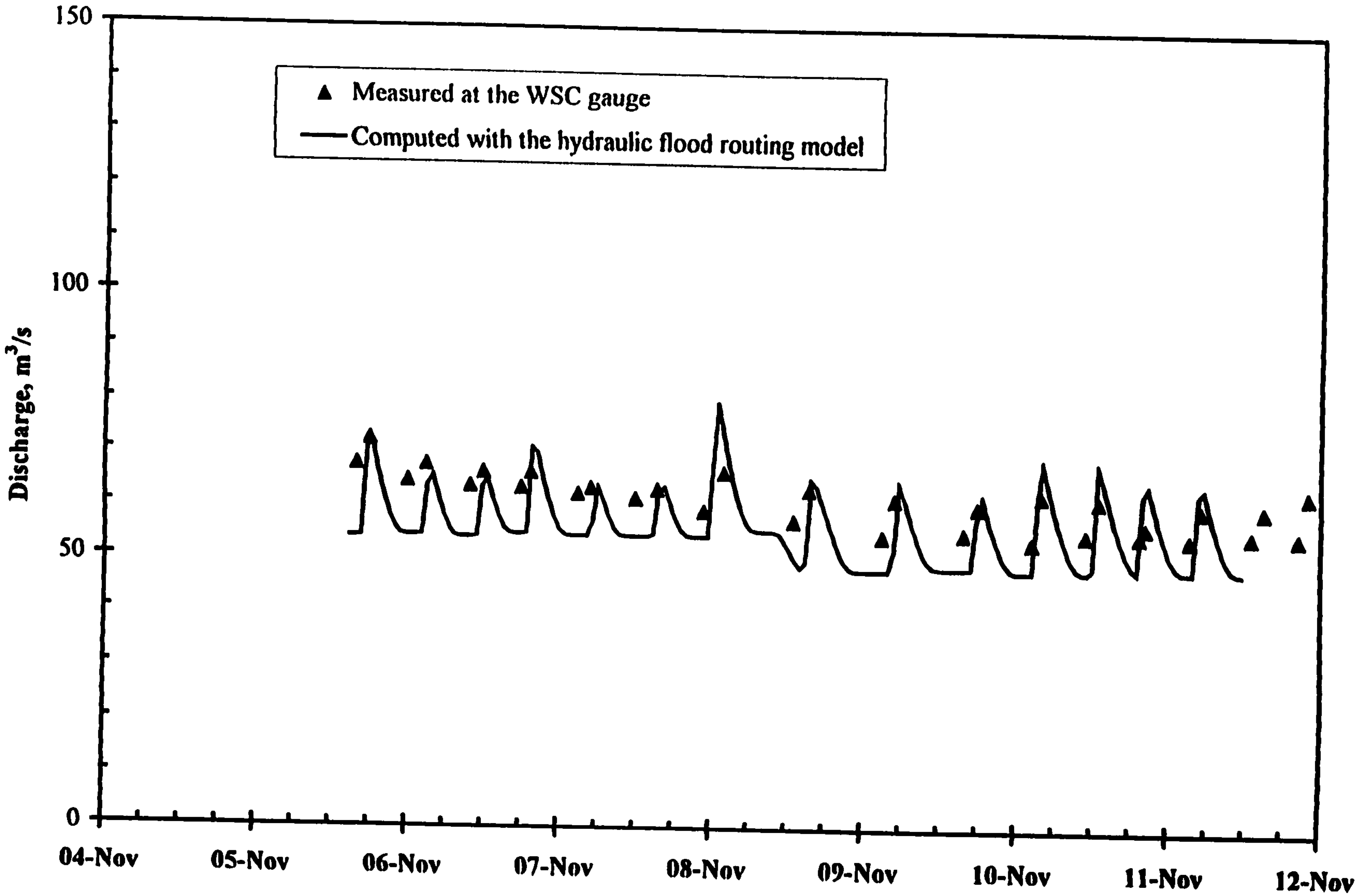


Figure 3.11 Comparison of modelled and measured discharge hydrographs at Rocky Mountain House, 1983.

4.0 ANALYSIS OF THE AVAILABLE FREEZE-UP DATA

4.1 INTRODUCTION

In this chapter, details of the available data documenting the freezeup processes in the study reach are examined. As discussed in Chapter 2.0, there are no quantitative or qualitative records of freezeup processes prior to regulation. Therefore, all of the freezeup data examined here were collected since the Bighorn Dam became operational.

Appendix B presents annual chronological descriptions of freezeup processes extracted from the records provided by *TransAlta Utilities Corporation*. Additional data, in particular temperature data obtained from Environment Canada records are also considered. In section 4.3, the applicability of current freezeup theory to the historical data is examined. Also, the documented ice consolidation event in 1982 is analyzed and ice accumulation parameters determined. Section 4.4 presents a summary of the hydraulic analyses and an evaluation of the potential flood risk at key sites.

4.2 SUMMARY OF FREEZEUP OBSERVATIONS AND DATA

Regular observations of freezeup processes on the North Saskatchewan River have been documented since the winter 1973/74, when the Bighorn Dam became operational. For the most part they are qualitative but are useful for characterizing the ice formation processes. In the earlier years, the observations only documented when the ice bridged at mile 152 and when it reached mile 190 (just downstream of the WSC gauge in Rocky Mountain House) and mile 197 (upstream of Rocky Mountain House). Eventually an observation program was set up to record the progress of the ice cover from Edmonton to upstream of Rocky Mountain House.

One of the key factors affecting the rate of freezeup is the air temperature. Air temperature data are available from the Atmospheric Environment Service (AES) of Environment Canada at five stations in and around the study area: Rocky Mountain House, Red Deer, Edmonton, Lacombe and Winfield. The majority of these data (up to December 1991) was available on the AES CD ROM. Additional temperature data were obtained directly from AES for 1992/93 and 1993/94. Unpublished records for 1994/95 and 1995/96 were provided by Alberta Environmental Protection. The temperature data for the latter two years must be considered preliminary and subject to change. Since the station at Rocky Mountain House is the closest to the river and central in the study area, the data from this station was used in this study. Figure 4.1 illustrates the validity of this approach, comparing average mean daily air temperatures for these five stations (combined) to the mean daily air temperatures recorded at Rocky Mountain House. The historical record of freezeup observations were available from *TransAlta Utilities Corporation* in hard copy only. This included field notes describing qualitative ice processes, location of the ice front and water level measurements. Collating and and digitizing this data record took approximately 3 months.

Table 4.1 summarizes the information collected to date. These observations and comments were transcribed into a database. Initially, the observations mainly recorded when the ice front passed a certain location. In the fall of 1976 a series of ice gauges were setup and the high ice levels were recorded. In the early years these readings were tied to dates and times but later on they were recorded in the spring ands were not tied to a date. Without a date there is no way to calculate the flow or examine the other parameters to model what occurred. *Montreal Engineering Co. Ltd.* collected data in the 1976/77 season but 1976/77 was a mild winter and the ice front did not reach Rocky Mountain House. The findings of their study are in "North Saskatchewan River Ice Study." Data was collected by *TransAlta Utilities Corporation* during a shoving event that occurred in January 1982 and are contained in "Report on January 13, 1982 consolidation Movement at Rocky Mountain House." *Acres Consulting Services Ltd.* collected data during the 1982/83 season as part of an ice study and the results of which are reported in "North Saskatchewan River Review of Ice Conditions." Begininning in the 1983/84 season the observations started to include ice conditions, bridging sites, flooding reports along with ice front locations all along the river and ice gauge readings. Starting in 1987/88 anchor ice and border ice oberservations were also recorded. The observations were viewed from aerial and ground reconnasiance. They were recorded on paper and filed. No photographs or videos are available.

The historical oberservations were digitized into a database. The date and time (if available) were included along with the reach of river that was observed. Ice front locations, bridging points, ice conditions, flooding reports and border ice were entered in separate columns for easy sorting. All of the original comments from the observers were transcribed almost verbatim in the comments column. Some of the terms used in the descriptions were vague, such as referring to the ice cover as "consolidated" or "lightly consolidated" or "heavily consolidated". These terms may be descriptive but are difficult to quantify for modelling purposes. Also, it is not always clear when is not recorded whether it was not present or was not noticed by the observer. Sometimes entries would characterize an entire reach with "the surface ice concentration varied between 40-60% between miles 152 and 190." Site specific comments would be more useful for showing how the concentration varied along the river.

Table 4.1 Summary of data collected during freezeup observations on the North Saskatchewan River 1973/74 to 1995/96

Year	Ice front locations	Flooding	Ice gauge readings	Frazil surface conc	Border ice	Anchor ice	Bridging	Air Temperatures
1973/74	√						√	√
1974/75	√	√					√	√
1975/76	√						√	√
1976/77	√		√				√	√
1977/78	√		√				√	√
1978/79	√		√				√	√
1979/80	√		√				√	√
1980/81	√		√				√	√
1981/82	√		√				√	√
1982/83	√		√				√	√
1983/84	√	√	√				√	√
1984/85	√	√	√				√	√
1985/86	√	√	√				√	√
1986/87	√	√	√				√	√
1987/88	√	√	√	√	√	√	√	√
1988/89	√	√	√	√	√	√	√	√
1989/90	√	√	√	√	√	√	√	√
1990/91	√	√	√	√	√	√	√	√
1991/92	√	√	√	√	√	√	√	√
1992/93	√	√	√	√	√	√	√	√
1993/94	√	√	√	√	√	√	√	√
1994/95	√	√	√	√	√	√	√	√
1995/96	√	√	√	√	√	√	√	√

4.3 APPLICABILITY OF THE FREEZEUP THEORY

4.3.1 INTRODUCTION

In this section the recorded observations are examined in light of the theory outlined in Chapter 2, in an attempt to characterize the ice cover formation on the North Saskatchewan River near Rocky Mountain House quantitatively. Prior to regulation, freezeup usually occurred on the North Saskatchewan River at Rocky Mountain House on approximately November 9, with October 22 (in 1919) being the earliest and December 24 (in 1954) being the latest freezeup dates recorded for the period of record (1913-30, 1953-72). At present, most of the data is in the form of observations that were taken intermittently throughout the winter. In this section the existing data will be examined and where possible, some analyses will be done to look for trends and relationships. Based on these analyses, recommendations can be made regarding the refinement of the data collection program, given the ultimate goal of developing a quantitative model of freezeup for the study reach.

4.3.2 WATER COOLING AND ICE COVER FORMATION PROCESSES

The energy budget must be considered in any attempt to quantify freezeup processes. During the freezeup period, the convective heat loss is the primary component in the overall energy budget, as heat input from solar insolation, heat exchange due to evaporation and condensation, and other heat exchange components tend to be far smaller (Ashton, 1986). Consequently, it is common practice to consider the energy budget in an empirical way, using "accumulated degree days" as an index of heat loss from the system. The accumulated degrees days of freezing are calculated by summing mean daily temperatures through the freezing period. A number of conventions have been proposed: starting on a specific date, starting with the first five consecutive days of temperatures below 0°C; considering days above 0°C as reductions in the total accumulated degree days, and neglecting days when the mean daily temperature is above 0°C. Each of these various conventions can be justified conceptually, particularly given the empirical nature of the approach. The important thing is to be consistent throughout the analysis. In this study, degree days of freezing were calculated starting with the first five consecutive days of temperatures below 0°C; considering days above 0°C as reductions in the total accumulated degree days beyond this point, as this is one of the more common approaches seen in the literature.

As mentioned earlier, there were five Atmospheric Environment Service (AES) meteorological stations in and around the study area which could provide mean daily air temperature data: Rocky Mountain House; Edmonton International Airport; Lacombe; Red Deer and Winfield. However, as Figure 4.1 illustrated, the data from Rocky Mountain House are considered representative of the area and were therefore used in this analysis. Figure 4.2 illustrates the accumulated degree days of freezing for the 22 years of available data. As the figure illustrates, there is considerable variation from year to year.

Figure 4.3 shows the ice front progression compared to the rate of accumulation of the degree days of freezing. The trend of a higher rate of ice front progression for an increased rate of accumulation of degree days of freezing is apparent, but there is considerable scatter. One reason for this is that mean daily temperatures are too coarse for defining phenomena that can take place over minutes to hours rather than days. Factors such as the varying heat content of the river as well as the effects of the hydraulics of the flow are also important parts of the process and need to be considered to refine this analysis.

Water Temperature and Cooling

The ability to quantify the water temperature variation downstream of the Bighorn Dam during the freezeup period is important to the quantification of freezeup processes, as ice generation cannot begin until the water temperature reaches 0°C. Since water density is a maximum at 4°C, the reservoir can potentially maintain a temperature gradient through the winter, with the cooler (0°C) water located at the top and the warmer water (between 0 and 4°C) in the layers below. Therefore, it is likely that the water released from the Bighorn Dam is at a temperature above 0°C throughout the winter.

Thus, the first step towards quantifying freezeup processes would be to calculate the heat loss from the flow exiting the reservoir to establish the location along the river where the water temperature initially reaches 0°C, known as the location of the "zero degree isotherm". Ice would be expected to form some distance downstream of the zero degree isotherm due to the latent heat release and supercooling required. Thus, given the location of the zero degree isotherm, the heat exchange rate (primarily based on the air temperature) and the river discharge, one would be in a position to quantify the amount of ice being formed at various locations along the river.

The exact location of the zero degree isotherm depends on both flow and climatic conditions. Unfortunately, the temperature of the water released form the reservoir has not been measured in the past. Therefore, the location of the zero degree isotherm cannot be calculated with the historical data. Nevertheless, it is possible to illustrate the effects of streamflow and climatic conditions on water temperature in this river using equation 2.4b, assuming steady state conditions (i.e. a constant air temperature and river discharge):

[2.4b] $$T_w = (T_o - T_a)\exp\left(\frac{-h_{wa}Bx}{\rho C_p Q}\right) + T_a$$

To illustrate how the discharge, the air temperature and the initial water temperature affect the rate of cooling, three figures were plotted varying these parameters using equation 2.4b (Figure 4.4). In the first plot, three discharges, representing the expected range of dam outflows during the freezeup period, were chosen to illustrate the effect of discharge on water cooling for a constant air temperature of -20°C and initial water temperature of 2°C. For the second plot, the discharge was held constant at 100 m^3/s and the air temperature was varied between -10 and -30°C, with a constant initial water temperature of 2°C. Finally, the initial water temperature value was varied between 1 and 3°C for a constant discharge of 100 m^3/s and constant air temperature of -20°C. In this simplified example it can be seen that an increase in outflow or initial water temperature or a increase in the air temperature will increase the time (and distance) required to cool the water to 0°C.

The zero degree isotherm will move up and downstream throughout the winter in response to the climatic and flow conditions that exist at the time. Monitoring the water temperature of the dam outflow along with several temperature profiles along the river would allow for the calibration of a cooling model that could more accurately predict the temperature profile along the river and the onset of ice production. Observations of the upstream locations where ice is first noticed would also give an indication of the location of the zero degree isotherm.

Frazil Ice Production

After the water has cooled sufficiently, frazil ice production will begin. Depending on hydraulic and climatic conditions, the frazil ice may agglomerate and then float to the surface to form pancake ice; it may attach itself to the bed to form anchor ice; or, if the flow is sufficiently turbulent, the frazil particles may remain in suspension.

Observations of the surface concentrations of frazil ice have been recorded since the winter of 1987/88, but have often consisted of only a few observations over a relatively short reach of river, and in particular, with no observations upstream of Rocky Mountain House. In some cases, long reaches were just characterized by a range of surface frazil concentrations. However, on two days in December, 1987, specifically December 23 and 30, more detailed observations of surface frazil concentrations were made along the North Saskatchewan River recording 12 and 10 observations, respectively. The reaches were both relatively long, starting at Rocky Mountain House at the upstream end and going downstream to miles 85 and 140, respectively.

These observations, which are plotted in Figure 4.5, show that the surface concentration of frazil increased in the downstream direction as generated frazil came out of suspension and floated to the water surface through agglomeration. As the surface concentration of frazil floes increased, the water became insulated from the atmosphere and the heat loss decreased, resulting in a reduction in frazil production. This is clearly seen in the observations from December 30. The surface concentration is increasing at a decreasing rate by mile 170.

The effect of temperature on frazil production can also be seen in Figure 4.5. The frazil surface concentrations for December 23, when the mean daily air temperature was -8.7°C, increased more slowly than those for December 30, when the temperature was -20.5°C. Both days started off with similar surface concentrations at Rocky Mountain House (mile 190), but the frazil surface concentration for December 30 increased to 70% by mile 170 while on December 23, the surface concentration did not reach 70% until mile 85.

The data from December 23 also demonstrate that the hydraulics of the flow have a significant effect on floe formation and frazil production. At mile 152, there is a rapids section which broke up some of the frazil floes and reduced the surface concentration. The rapids are very turbulent and increase the heat exchange between the water and the atmosphere through increased mixing. The broken frazil floes can also provide ice particles that can be used as centers of nucleation for secondary nucleation. The result of this was a dramatic increase in surface frazil concentration at mile 140.

A more complete and methodical collection of surface frazil concentration data would assist in calibrating a model of freezeup processes. It would be better to have 10 to 20 observations over a long reach rather than a few observations over a short reach. The time of day should also be recorded. Also, aerial observations (documented by video camera) would likely be more useful as a more complete picture of the river reach emerges rather than isolated observations that may or may not be representative of conditions along the entire reach.

Anchor Ice

Anchor ice may form on the river bed any time after frazil ice production has begun. Adherence of active frazil to the bed substrate is the main form of anchor ice. The presence of anchor ice can affect the hydraulics of the flow by increasing the bed elevation and by decreasing the effective flow area. Also it represents "stored" ice that can float to the surface and join the surface ice cover at times when the climatic conditions are warm enough to cause a weakening of the bonds between the anchor ice and the bed substrate. As mentioned earlier, it is likely that warm water (i.e. in excess of 0°C) is released from the reservoir throughout the winter. Consequently, open water is maintained for some distance downstream of the dam and frazil production will continue throughout the winter. Diurnal fluctuations in the dam outflow can contribute to anchor ice formation, as low flows during the night can expose portions of the bed to temperatures much lower than 0°C (which is the minimum bed temperature under water). When the flow is increased in the morning to meet the increased electrical demand, large amounts of frazil ice may be generated, causing anchor ice to form on the previously exposed bed material.

Observations of anchor ice were made intermittently starting in the winter of 1987/88. Typically, the presence of anchor ice was accompanied by very cold weather, either on the day of the observation or immediately before. One observation, on December 22, 1994 seems to be an anomaly. Significant anchor deposits were observed between miles 132.5 to 190. There had been lows of -18°C on December 16 but daytime highs had been up to 9°C on December 20 which should have been warm enough to cause lifting of any anchor deposits.

A common observation in the historical record was that lifted anchor ice was present and possibly constituted a significant fraction of the ice floes. The mean daily temperature was usually warmer than about -10°C when lifted anchor ice was documented. When the mean daily temperature is -10°C, then the daytime high could potentially be close to 0°C and together with direct sunshine, the temperature at the interface between the ice and the substrate may warm sufficiently to release the anchor ice. Anchor ice has also been observed to lift in colder weather. In this case, the anchor ice accumulation likely has reached sufficient mass for the buoyancy to overcome the weight of the substrate materials, and float to the surface bringing sand and gravel particles with it. The December 9, 1994 observation suggests that an anchor ice deposit in the Brazeau River was flushed out when the outflow from the Brazeau plant was increased. This may be possible, but nothing was found in the technical literature describing velocities where anchor ice could be eroded away from the bed. In fact, Wigle (1970) had found that anchor ice deposits could form in reaches with velocities up to 3 m/s.

Anchor ice observations should start upstream where the first ice is noted. Observations should include what part of the channel the anchor ice is growing on and if some of these sites were exposed during the diurnal flow fluctuations. Observations should be site specific as general comments about a long reach are not very helpful.

Bridging

Bridging sites are locations where the ice floes lodge and an ice cover starts to build upstream by the accumulation of ice floes. Although it is possible to identify potential bridging sites based on the appearance of obstructions and channel morphology, with the present state of knowledge of ice processes it is not possible to predict whether or not bridging may occur at a given location and time. For *TransAlta Utilities Corporation*, the location of bridging sites downstream of Rocky Mountain House is important because bridging at these sites signals the beginning of a staged process of outflow restrictions designed to ensure that the ice cover progression through Rocky Mountain House is uneventful.

Figure 4.6 shows the frequency of bridging at various sites in the study reach. As the figure indicates, bridging has occurred at mile 152 in 20 of the 23 years that observations were recorded. The river at mile 152 forms a sharp bend and there is an island present which splits the flow, making it a very likely spot for ice bridging to occur. However, although mile 152 is the most frequent ice bridging location in the study reach, bridging does occur at other sites, as well. It is important to note that bridging at mile 152, does not preclude the possibility of bridging at other locations creating a discontinuous ice cover through the study reach (as was documented in several of the years of record). Detailed observations were made during three bridging events at mile 152. These were reviewed and compared in an attempt to determine what factors are important in initiating bridging in the study reach.

Several observations of the bridging sequence were made at mile 152 during December 1983. On December 5, when the temperature was -10°C., it was noted that border ice had narrowed the open water width. Temporary bridging was noted on December 7, when the mean daily temperature was -19°C, with all the incoming slush passing under the ice. The mean daily air temperature ranged from -21°C on December 9, to -14°C on December 12.

By December 9 the temporary bridging had washed out, but it reformed on December 12. The incoming concentration of surface ice was 80-90% on December 12, and downstream of the bridging point the concentration was 50 to 70%, indicating that although some floes were accumulating upstream, the majority were being swept under the ice cover. On December 14 it was noted that all of the surface slush was passing under the bridging point, but by December 16 the ice front was at mile 154.5 and at mile 170 on December 19.

Observations were also made at mile 152 before and after bridging occurred in late December 1987 and early January 1988. On December 23 it was observed that border ice had reduced the open water channel at mile 152 to one quarter of its normal width. On December 30 it was recorded that the opening was 15 m (50 ft.) wide and that the ice that had bridged there before had since washed out. The date and time of the temporary bridging was not recorded. The coverage of the water surface by frazil floes was 50% with a temperature of -20°C. On January 4 it was noted that border ice growth had reduced the open water width to 9 to 12 m (30 to 40 ft.). The cold weather had continued with a temperature of -21°C on January 4 and the surface concentration of frazil floes had increased to 90%. Based on a January 7 observation, it was deduced that bridging had occurred during the late evening of January 4 or the early morning of January 5. By January 7 the ice front was reported to be at mile 163.

On November 27 and December 3, 1989, the surface concentration of frazil pans was observed to be around 50% going into the bend at mile 152. In the bend the floes congregated and the surface concentration increased to 90%. On December 3 the floes were reportedly forming rafts in the bend and breaking in the rapids downstream. By December 20 the mean daily temperature was -30°C and the incoming concentration of surface ice was 90 to 100%, with the ice forming rafts in the bend and breaking up downstream. On December 22 bridging was reported to have occurred at mile 152 and the ice front had already progressed upstream to mile 166. It is likely that bridging occurred between December 20 and 22. The mean daily temperatures for December 21 and 22 were -29°C and -13°C, respectively.

Based on the observations of these three bridging sequences the following similarities were noted.

1. In two of the three years it was noted that border ice had narrowed the open water width. In the December 1987 bridging event, the opening was narrowed to less than one quarter of its open water width.

2. The surface concentration of frazil floes was very high just prior to bridging. In the 1983, 1987 and 1989 bridging events it was reported as 80 to 90%, 90% and 90 to 100%, respectively.

3. The mean daily temperature was relatively low. It was either -20°C or colder on the day bridging occurred or on the day before. Cold weather would

increase the frazil production and thus the concentration of floes which is an important factor as noted above.

4. Temporary bridging is a common occurrence. In two of the three years it was observed that temporary bridging formed and subsequently washed out. Initially bridging appears to be very fragile.

Bridging was also reported at mile 144 twice, three times at mile 162 and once each at mile 160, 164, and 174 over the period of record (Figure 4.6). There were several other bridging points upstream, as well. In 1994/95 bridging was reported at mile 92 and the pack built upstream from that point, reaching mile 158 on January 5. The other bridging sites are at sites where the river narrows (mile 174) or where islands are present (mile 92, 160, 162). Mile 164 is just downstream of an island and mile 144 does not appear to have any obvious obstructions. If bridging occurs a little upstream of mile 152 (up to mile 174) then bridging is not likely to occur for a ways downstream as most of the incoming floes would be intercepted by the ice cover at the upstream bridging site. A sufficient quantity of ice floes to cause bridging 10 or 20 miles downstream of an existing bridging site will not form unless it is extremely cold.

Figure 4.7 shows the relationship between accumulated degree days of freezing with bridging location. There is wide scatter in the results. The accumulated degree days of freezing required for bridging at mile 152 ranges from close to zero to more than 700.

Since mile 152 is obviously an important bridging point, a gauge with a continuous recorder should be placed there. This would record the stage and also record the exact time that bridging occurred and also record the time when the bridging is washed out. More frequent observations around bridging time or placing an observer or video camera at the site would allow for the collection of more complete information. Observations should include notes on border ice growth, frazil surface concentration, and the role of rafting in the bridging process. Flows from the dam should be also routed downstream in an effort to quantify the influence the daily flow variation has on bridging events.

Upstream Progression of the Ice Front

The upstream progression of the ice front has been documented in the historical record and, as illustrated in Figure 4.8, in many cases the extreme upstream limit of the ice front progression was documented as well. As the figure indicates, the ice front progressed through Rocky Mountain House, at least as far upstream as mile 197 (1 mile upstream of the Ferrier Bridge crossing) in all but 4 of the 23 years of record. In many years, observations were discontinued after this time and, therefore, the extreme upstream limit is not known. However, based on the data that are available, it would appear that the ice front typically progresses upstream to a point between miles 200 and 230.

The maximum upstream extent of the ice cover is related to the location of the zero degree isotherm, in that the ice front cannot progress upstream of this point. Similarly, the extent to which the ice cover can progress upstream is a function of both hydraulic and climatic conditions. The temperature influence is particularly significant, as seen in Figure 4.9, where the accumulated degree days of freezing for selected years are compared to the average accumulation rate for the entire period of record. For the four years in which the ice cover did not make it upstream as far as Rocky Mountain House, the accumulation of freezing degree days was at or below average. For the extreme case of 1984/85, during which the ice front made it upstream to within about 10 miles of the dam (to mile 260.5) the accumulated degree days of freezing were far above average. The upstream extent of the ice cover is also noted on the figure and the fact that there is no trend in that value amongst the warmer years indicates that hydraulic influences are still a factor to be considered in any quantitative or predictive analysis.

Figure 4.10 presents the freezeup ice front locations as a function of the accumulated degree days of freezing for the period from 1973/74 to 1992/93. The degree of scatter in the data indicates that the dynamic influence of streamflow regulation is too significant to be neglected in developing a model of freezeup progression on the North Saskatchewan River in this reach. This is further illustrated in Figure 4.11, where it is seen that the accumulated degree days of freezing at the time the ice front passes through Rocky Mountain House has varied from approximately 100 to 800°C-days over the record period.

4.3.3 HYDRAULIC ANALYSIS OF THE DOCUMENTED CONSOLIDATION EVENTS

Introduction
Consolidation movements or "shoves" occur when the forces acting on a developing ice cover (specifically the downslope component of ice weight and flow drag on the underside of the ice cover) exceed the internal strength of the ice cover and cause it to collapse. When a shove takes place there is a thickening of the ice cover and often an increase in the roughness of the underside, both of which combine to cause water level to increase in and upstream of the thickened accumulation. Often the water levels that result from shoves are the highest winter water levels. Consequently, consolidation events are often associated with flooding problems.

In order to quantify the effect of ice cover and ice jam formation on water levels in the North Saskatchewan River near Rocky Mountain House, an ice jam model must be calibrated to known shoving events. This would allow for the determination of typical values for the parameters describing the ice accumulation's strength and resistance characteristics.

The consolidation event that occurred on January 12, 1982 was the only event in the historical record with sufficient information to attempt such a calibration. The location of the toe of the jam had been identified along with the locations of the ice front at various times. The shove occurred near the WSC gauge which provided a continuous water level record for the event. Also, the incoming flow could be quantified as *TransAlta Utilities*

Corporation had maintained a steady outflow from the Bighorn Dam while the ice cover progressed through Rocky Mountain House.

Description of the January 1982 Consolidation Event
On January 12, a consolidation occurred as part of the normal adjustment in the ice cover that occurs as it builds. A day later, on January 13, the arrival of chinook weather conditions resulted in a dramatic increase in air temperature, from a low of -18.8°C earlier in the day to +4.7°C by 4:00 PM. Two and a half hours after the increase in temperature, there was a dramatic shove during which the ice front moved downstream by about four and one half miles.

In the *TransAlta Utilities Corporation* report entitled "Report on January 13, 1982 Consolidation Movement at Rocky Mountain House," it was suggested that the cause of the shove might be attributed to anchor ice releasing from the bed upstream due to the water being warmed by the chinook conditions. The sudden inflow of lifted anchor ice floes would have the potential to increase the downstream load on the ice cover and precipitate a shove. A reconnaissance flight on January 10 noted that there were large amounts of anchor ice on the bottom of the North Saskatchewan River. Also, very little floating anchor ice was observed in Rocky Mountain House on January 11 or 12, so it is reasonable to assume that it was still in place before the chinook on January 13. Therefore, the theory that the consolidation was precipitated by lifted anchor ice seems a reasonable one.

It was also hypothesized that there was additional flow in the river due to restricted frazil ice production during this warm period. The report by *Acres Consulting Services Ltd.*, (1982) did not mention the anchor ice, but hypothesized that the shove was caused by increased flow in the river due to the decrease in the frazil ice production, as well as to the release of water stored in the ice cover pores. However, it is likely the volume of water lost to ice production is very small. From the literature, Tsang (1982) has suggested that a concentration of 0.5% by weight is a maximum frazil concentration. This would represent a flow increase of roughly 0.25 m^3/s on the day in question, which is small compared to the release from the Bighorn Dam at that time which was approximately 50 m^3/s. Therefore, any flow increase due to suspension of frazil production would likely be inconsequential.

Interpretation of the WSC Gauge Record
On January 10, when the ice front was at mile 180, the Bighorn outflow was restricted to a constant flow of about 48.1 m^3/s (1700 cfs) while the ice front progressed through the town of Rocky Mountain House (as was illustrated in FigureB.10). Figure 4.12 show the effect at the gauge as the ice front approached. Even though there was initially open water at the gauge, the water level on January 11 was still about 0.1 m higher for the steady discharge than would be predicted by the gauge rating curve. This was likely due to backwater from the approaching ice front.
At approximately 10:00 AM on January 11, the ice front progressed upstream to a point

about 0.5 miles downstream of the gauge and, as Figure 4.12 shows, the stage at the gauge began to increase dramatically. The ice front likely passed the gauge on the afternoon or evening of January 11 and the river stage increased by almost 2 m as a result. Based on a gradually varied flow analysis using the known discharge and water level at the gauge, and assuming a Mannings *n* for the underside of the ice cover of 0.020, which is typical of freezeup accumulations (Nezhikhovskiy 1964) the ice thickness at the leading edge of the advancing front was calculated to be about 1.25 m. This indicates that the ice cover was being formed by hydraulic thickening rather than by juxtapositioning, as the individual ice floes would likely be no more than 0.3 to 0.5 m thick.

The stage continued to increase after the ice front passed the gauge indicating continued ice cover thickening at the gauge. The stage increased at a fairly steady rate with several small shoves and consolidations until about 3:00 AM January 12 when it stabilized at about 955.9 m for 6 hours. Repeating the gradually varied flow analysis, under the same assumptions as described above, this new water level produced a corresponding ice thickness of 2.15 m at the gauge.

At 8:50 AM on January 12 the ice front was reported at mile 192.2 and at 9:00 AM the first shove occurred. The ice front was pushed downstream just over a mile, but still remained upstream of the gauge. The stage increased to a maximum of 956.4 m between 9:30 and 9:45 before stabilizing at about 956.2 m around noon, a level about 0.25 m higher than that preceding the shove. The stage remained stable for the next 24 hours. Another gradually varied flow analysis showed that the ice thickness was likely close to 2.5 m at the gauge. The air temperature remained cold after this shove and the ice front continued to build upstream.

As mentioned earlier, around 16:00 on January 13 the weather warmed considerably increasing to a high of 4.7°C, from a low of -18.8°C earlier that day. At 6:27 PM on January 13, when the ice front was estimated to be at mile 193.5, the shove that pushed the ice front downstream of the gauge to about mile 188.9 was initiated. The stage at the gauge increased to a maximum of 957.3 m at 6:30 PM and dropped to a minimum of 955.5 m at 10:45 PM. The increased stage resulted in some flooding of the road passing under the Highway 11A bridge, 76 m downstream from the gauge. Although the flooding was sufficient to deposit slush ice on the road under the bridge there was no reported property damage.

The warm temperature conditions continued through the night, ending at 9:00 AM on January 14, when the weather again turned cold. During the night the ice cover rebuilt upstream passing the WSC gauge site at noon the next day (January 14). As it passed the gauge site the water elevation at the gauge was about 955.4 m and the water level continued to rise for another 12 hours. The stage restabilized at 956.6 m, corresponding to an ice thickness of 2.5 m at the gauge, roughly the same elevation as before the shove on January 13.

Calibration
To prepare for assessing the potential flood risk areas, the hydraulic conditions immediately after the shove of January 12 were modelled. At 11:30 AM on January 12, the ice front was observed at mile 191.2. This was the furthest downstream that the ice front was observed and the water level at the WSC gauge had just stabilized. Based on this, the upstream end of the shove was assumed to be at mile 191.2. The toe of the shove was observed to be approximately at mile 188.8. The ice jam was modelled at this point in time because the ice cover had just stabilized after a shove and the flow could be considered to be relatively steady.

The ICEJAM model, developed by Flato (1988), was used to model the ice jam hydraulics. ICEJAM calculates an ice jam profile for gradually varied flow conditions by solving equation 2.24a for a steady discharge. The main advantage of Flato's model over previous models was that it was possible to calculate an ice jam profile without having to presuppose that an equilibrium section existed in the jam. This allows the calculation of an ice jam profile for conditions when the jam is too short to develop an equilibrium section or when channel geometry was irregular.

Several variables needed to be established for the analysis of the ice accumulation: specifically: the ice jam strength parameter, μ, the passive pressure with the granular accumulation, the thickness at the head of the ice jam and the accumulation roughness. Because of the limited available information, in particular because of the lack of a water surface profile through the accumulation, it was not possible to calibrate all of these parameters. Therefore, those parameters known to vary within a limited range were quantified based on the previous investigations.

Based on the current literature, a value of 1.1 was chosen for the ice jam strength parameter μ. This is within the range suggested in the literature, but is lower than the values of 1.2 to 1.3 often used. Andres (1994) recommended that the value of 1.0 be used because the higher values were likely due to freezing in the ice accumulation. Using a lower strength value is conservative and will allow a thicker jam to form for a given set of conditions. Given that one of the objectives is to evaluate the flood risk from ice jams and the uncertainty about the actual value, a value of 1.1 was considered appropriate.

The upstream ice cover thickness also needed to be specified. As the head of the ice jam was less than one mile upstream from the WSC gauge, the water level at the gauge would be sensitive to the ice thickness chosen. The ice thickness for the toe is chosen also, but it is far downstream and errors in that choice will have a minimal effect on the calculated water level at the WSC gauge. When the ice front was approaching the gauge on January 12, an ice thickness of 1.25 m matched the water level adequately. As an approximation, a value of 1.0 m was chosen for the ice thickness at the head.

To calibrate the ice roughness, runs were made using the ICEJAM model and the ice jam roughness was adjusted until the computed water level at the WSC gauge matched the gauge record. The roughness was varied in steps of 0.05 as it was felt that given the inaccuracies present in the analysis, further refinement of the roughness could not be justified. After calibration the ice roughness chosen was 0.030. This value matched the water level at the WSC gauge the best and it was consistent with values of ice roughness found in the literature. In analyzing freezeup jams on the Peace River, Andres (in Beltaos, 1995), found the composite ice roughness to be 0.027. It was his assessment that the bed and ice roughness were approximately equal, giving an ice roughness of 0.027 which is comparable to the value obtained here. The final calculated ice jam profile is shown in Figure 4.13.

4.4 EVALUATION OF POTENTIAL FLOOD RISK AT KEY SITES

4.4.1 INTRODUCTION

Winter flooding is a concern at certain locations along the North Saskatchewan River near Rocky Mountain House. To categorize the flooding reports, the river was broken up into 5 mile reaches and the number of over bank flooding reports recorded within that reach over the period of record is shown in Figure 4.14. The vast majority of flooding reports occurred in the reach between mile 190 and 195. Most of the flooding reports within that reach involve flooding in and around the Rocky Mountain House National Historic Park (about 30 reports). Usually the incidents involved flooding in the picnic area, backwater up the side channel, flooding in and around the footbridge, and flooding in the area around the York boat. The observations did not record the extent of damages, if any.

Here, rating curves were developed for eight sites along the North Saskatchewan River within and near Rocky Mountain House to assess their flood risk and to develop tools that the dam operator could use to avoiding or reduce flooding problems in the future. The sites chosen were at surveyed cross section locations close to ice gauge sites along the river. The rating curves are shown in Figures 4.43 to 4.50. The curves compare the water levels for open water flow together with water levels for simple ice covers and equilibrium ice jam conditions, for the range of discharge expected over the course of a winter.
The open water curves were calculated for uniform flow and gradually varied flow. For the uniform flow calculations, a constant slope of 0.002 was used for the eight sites. This slope was chosen because it was representative of the entire study reach, but not necessarily of each particular site. The gradually varied flow profiles were calculated using the HEC-2 gradually varied flow model, calibrated in Chapter 2. The bed roughness values were adjusted for discharge using Figure 3.4.

4.4.2 POTENTIAL FLOOD RISK ANALYSIS

Curves using the Froude criteria were developed to identify the hydraulic conditions where the ice cover would form by juxtaposition or hydraulic thickening. The Froude numbers used were 0.08 for F_{rj} and 0.154 for F_{mr}. These values are consistent with those in the literature and were chosen specifically because they had been used before in the *Acres Consulting Services Limited* report of 1982. These two curves defined the river conditions where the ice cover would be expected to form by juxtaposition, hydraulic thickening or not form at all.

The simple ice cover curve was developed using the HEC-2 ice option and assumes presence of an ice cover of 0.3 m thick (which is the estimated thickness of individual frazil pans) with a roughness of 0.020. This curve illustrates what the rating curve would look like if a simple juxtaposed ice cover formed at a given location. As the figures indicate, in most cases the hydraulic conditions would not permit it to form, as discussed below.

The worst case scenario considered was an equilibrium ice jam forming at a site. The water levels for the equilibrium ice jam condition were calculated using the calibrated ICEJAM model. To calculate the equilibrium water levels, the ICEJAM input file was expanded to include the entire study reach. For each discharge, the equilibrium ice thickness was calculated for the head and the toe using equation 2.24b so the calculated ice thicknesses in between would be equilibrium values. The parameters (ice roughness n_i = 0.030, ice jam strength parameter μ = 1.1) used in the calibration of the ICEJAM model of the January 12 shoving event were used in the ICEJAM model of the entire length of the study reach.

The water elevations due to an equilibrium ice jam have the least amount of confidence of the rating curves generated. They are based on a model calibrated to only one point. Although they represent the best estimates of high water levels for ice jams, they should be used with caution until more events can be calibrated. If a shove event should occur, then a water surface profile should be surveyed immediately after it has stabilized and the head and toe locations noted along with estimates of the ice thicknesses at those locations. With more suitable field data more ICEJAM runs can be done and the typical characteristics of the ice cover after a shove will be better defined.

To use the curves, the discharge and the water level need to be known. The discharge can be estimated from the outflow from the Bighorn Dam if the flow attenuation model can be finalized. The water elevation would have to be determined by direct measurement. A point would then be plotted using the discharge and water elevation data and the location of the point on the graph would indicate the type of ice cover that could be expected. If the point is in the juxtaposition zone (between the equilibrium ice jam curve and the hydraulic thickening zone), then the ice cover would form by juxtaposition under normal conditions and the ice cover would be relatively smooth. If the point lands in the hydraulic thickening zone, then the ice cover would form by hydraulic thickening and be quite rough. If the point lands below the hydraulic thickening zone, the flow is too swift for an ice cover to form. If there is an ice cover downstream, the incoming frazil pans will be swept under it. The frazil pans may accumulate under the upstream end of the ice cover, thickening it and thus increasing the water elevation, decreasing the velocity, until conditions exist where an ice cover can form.

The information from the rating curves is summarized in Table 4.2. Based on these eight cross sections, the most critical locations during open water flooding are at miles 192.11

and 193.09. Both of these locations would be expected to have overbank flooding at something less than a 1:10 year event. For winter flooding, cross section 192.11 is the most critical as overbank flooding would be expected to occur for an equilibrium ice jam at a discharge of about 30 m^3/s. The database confirms this with 38 reports of winter flooding at this location. The next most critical sections are at miles 184.94 and 193.09 where overbank flooding could occur for an equilibrium ice jam at a discharge of as low as 60 m^3/s. Cross section 193.09 is in the same five mile reach as 192.11 and included in the 38 flooding reports. Cross section 184.94 had only one flooding report in the database.

Table 4.2: Summary of rating curves

Cross section	Rating curves	Overbank flooding (open water)	Overbank flooding (equilibrium ice jam)	Juxtaposition	Flooding reports
184.94	Fig. 4.15	<1:100 yr	> 60 m^3/s	no	1
188.51	Fig.4.16	>1:100 yr	> 80 m^3/s	no	1
189.44	Fig. 4.17	>1:100 yr	>130 m^3/s	no	1 (same as above)
190.5	Fig. 4.18	>1:100 yr	no	<20 m^3/s	38 (downstream)
192.11	Fig. 4.19	<1:10 yr	> 30 m^3/s	no	38
193.09	Fig. 4.20	>1:10 yr	>70 m^3/s	no	38 (same as above)
194.93	Fig. 4.21	>1:10 yr	> 130 m^3/s	no	38 (same as above)
196.21	Fig. 4.22	>1:100 yr	no	no	2 (upstream)

The rating curves presented here can be used as a tools for making rough estimates of water elevations at eight cross sections near Rocky Mountain House. The open water elevations are fairly reliable because they come from a calibrated hydraulic model. There is a lower level of confidence in the water levels calculated with the ICEJAM model. The ICEJAM model was calibrated to only one water level for only one event. Assumptions had to be made concerning initial ice thicknesses, ice strength and ice roughness. Clearly more measurements need to be taken on stabilized freezeup accumulations to increase the level of confidence in the water levels presented in these rating curves.

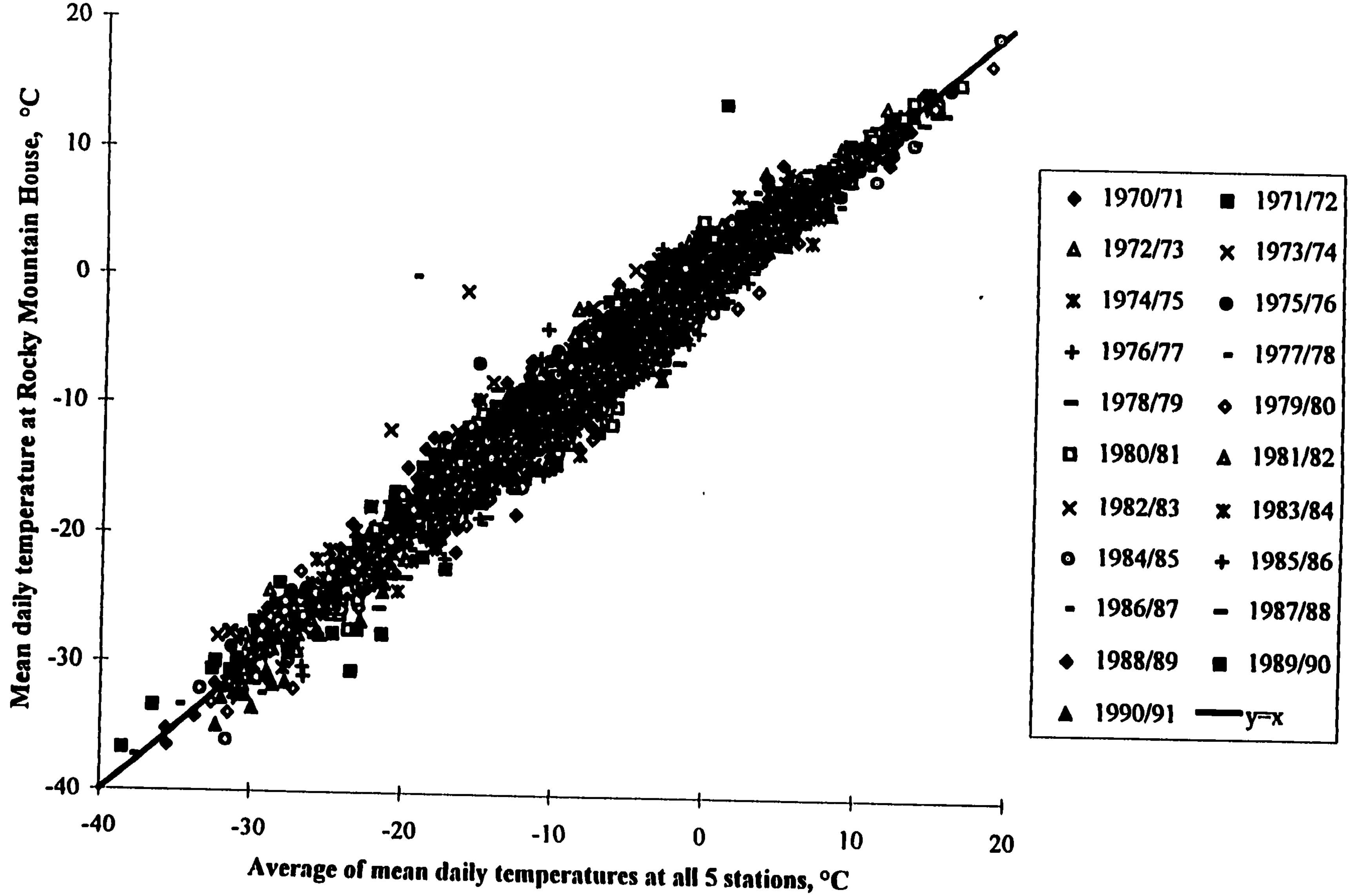


Figure 4.1 Mean daily temperatures at Rocky Mountain House versus the average of the mean daily temperatures at all 5 stations.

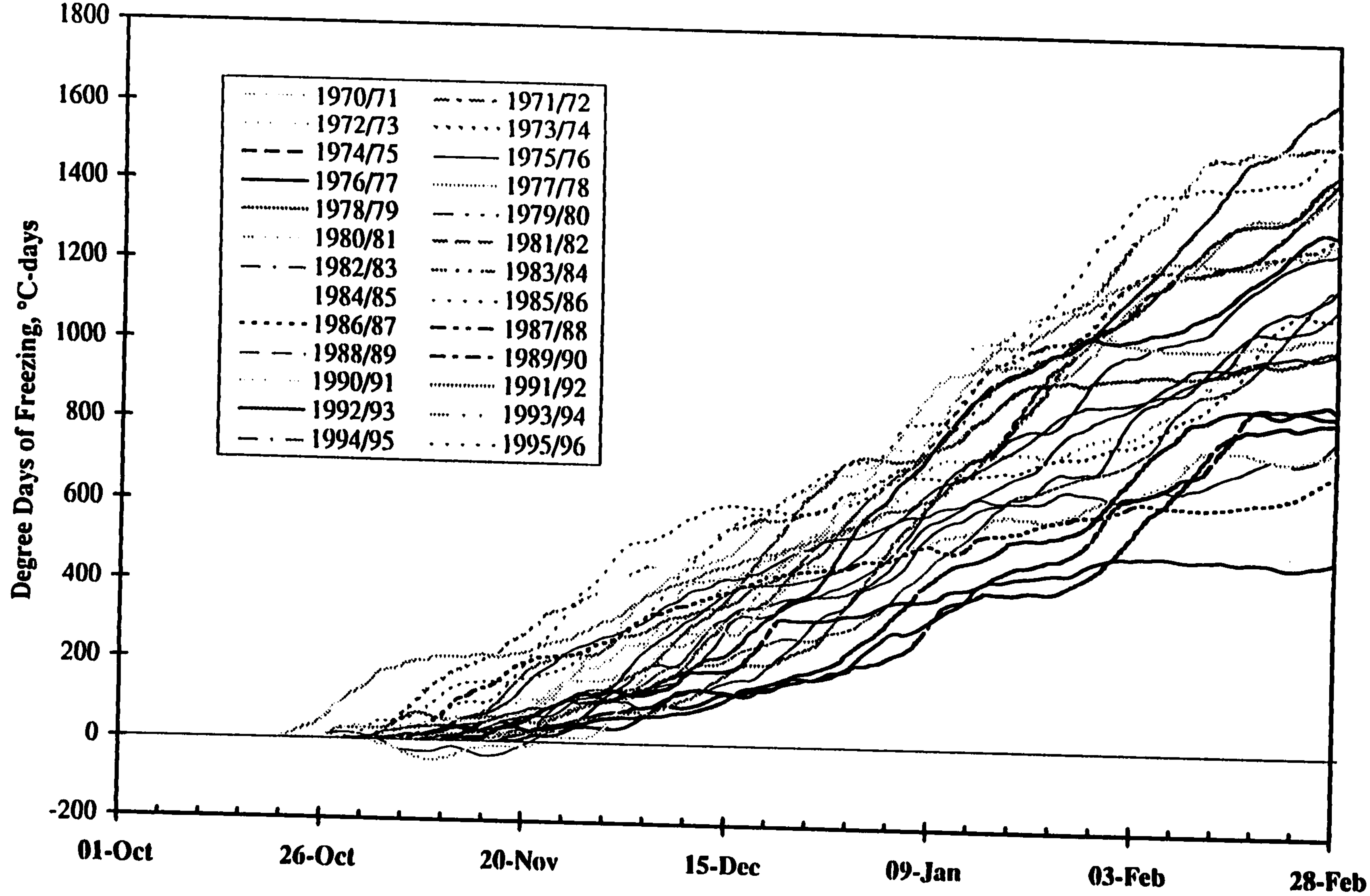


Figure 4.2 Accumulated degree days of freezing at Rocky Mountain House for the period from 1970/71 to 1995/96.

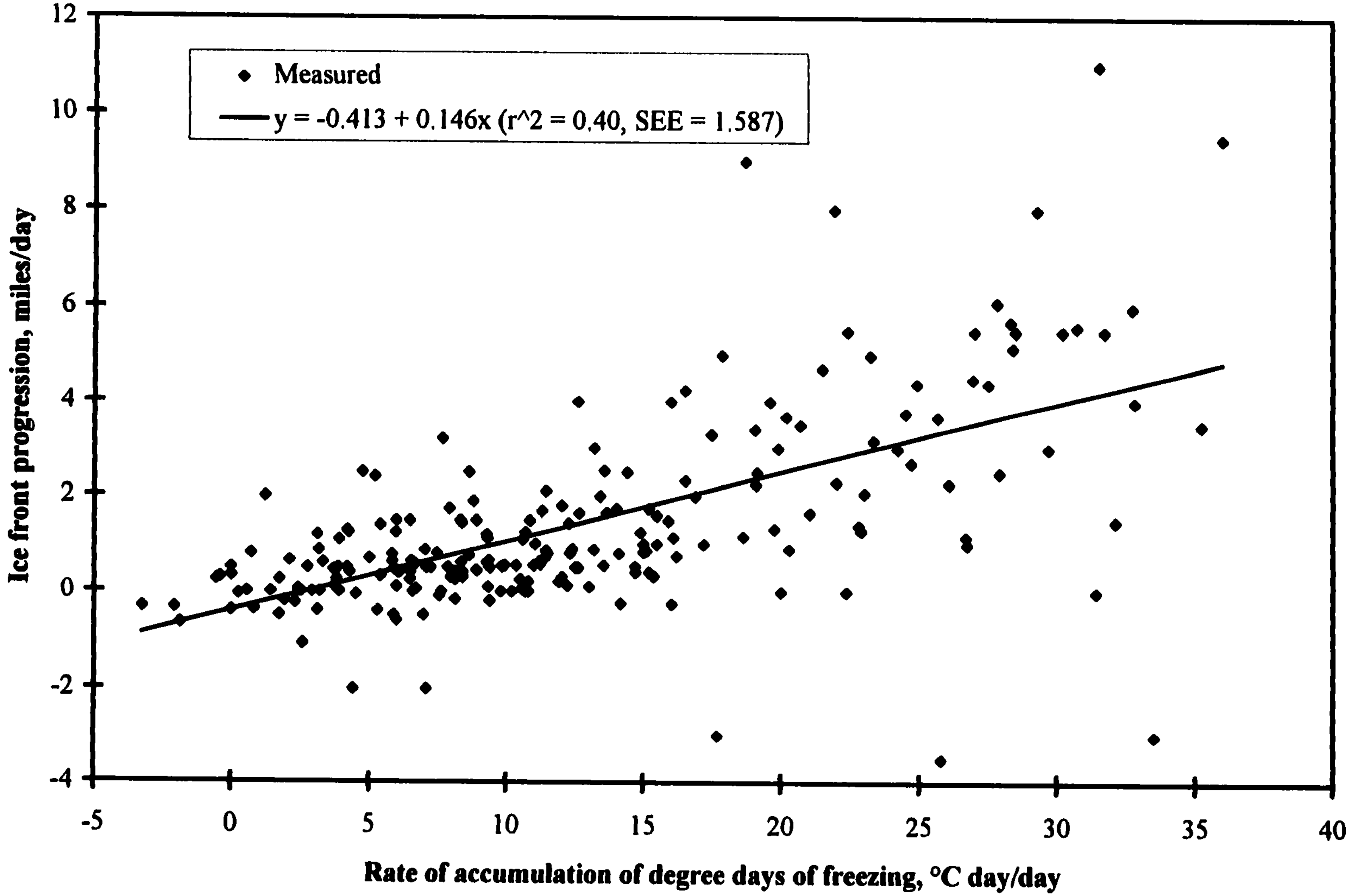


Figure 4.3 Ice front progression versus the rate of accumulation of degree days of freezing.

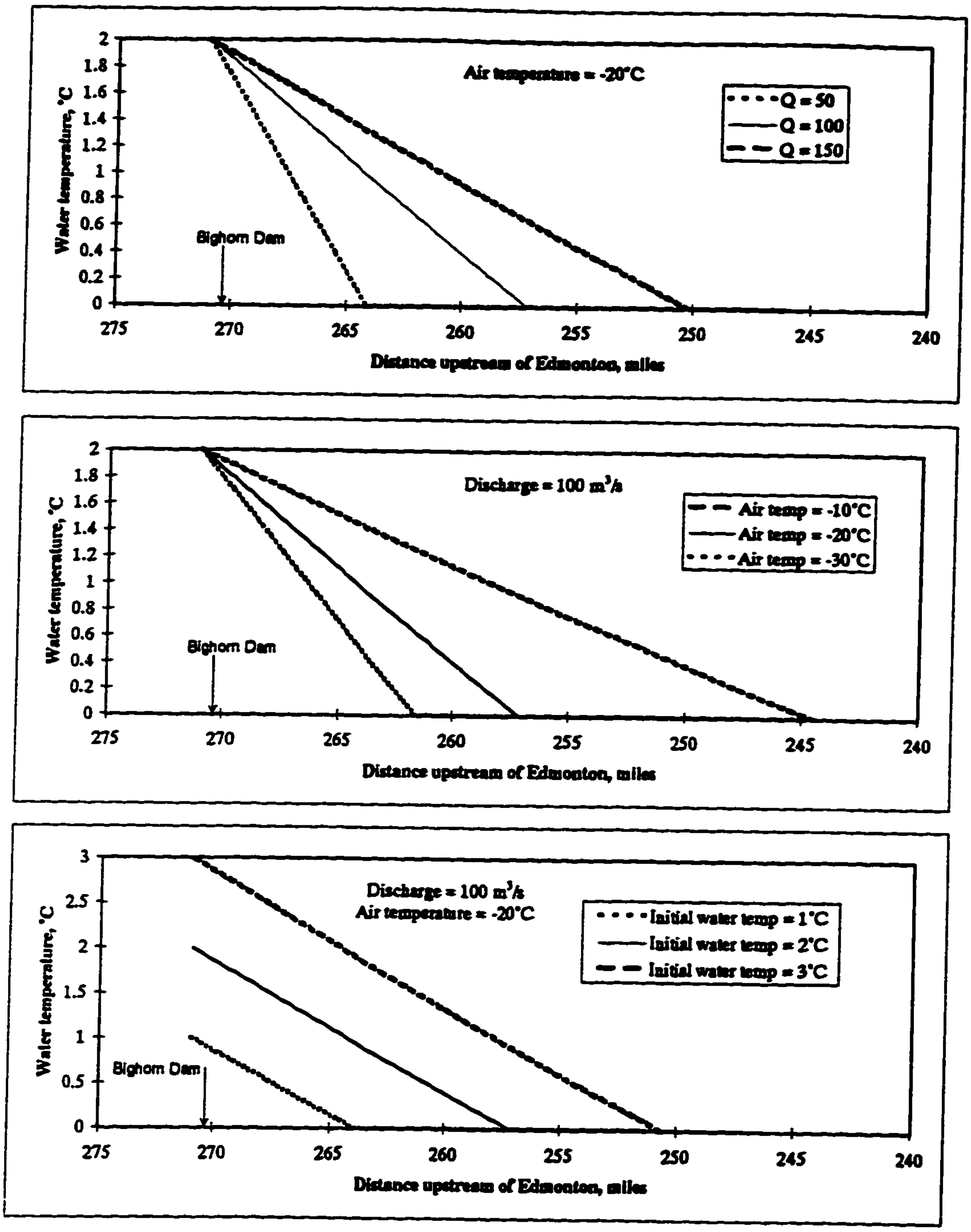


Figure 4.4 Effects of varying discharge, air temperature and initial water temperature on water cooling for a constant river width of 90 m.

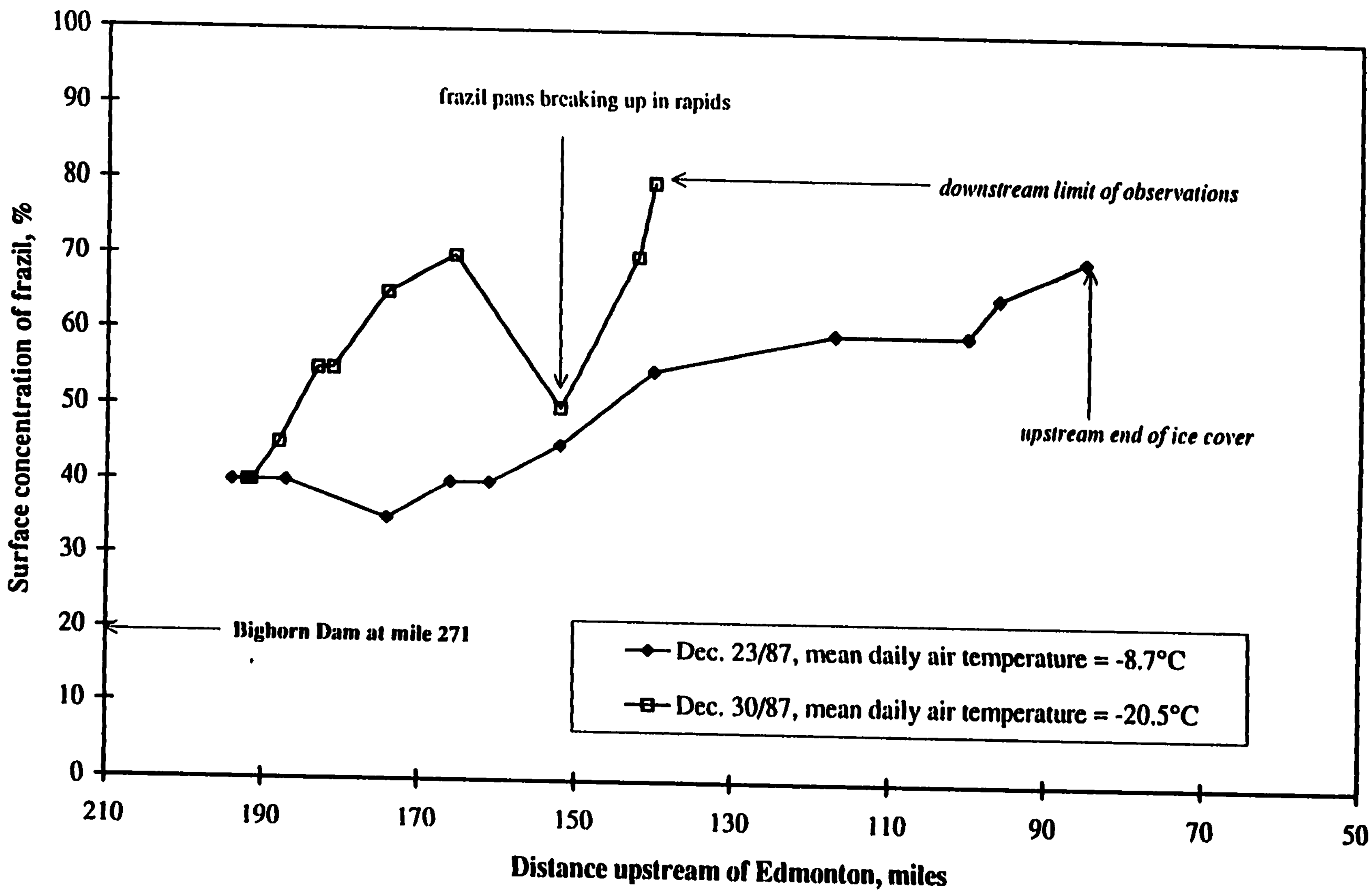


Figure 4.5 Variation in surface concentration of frazil with distance along North Saskatchewan River for two days in December 1987.

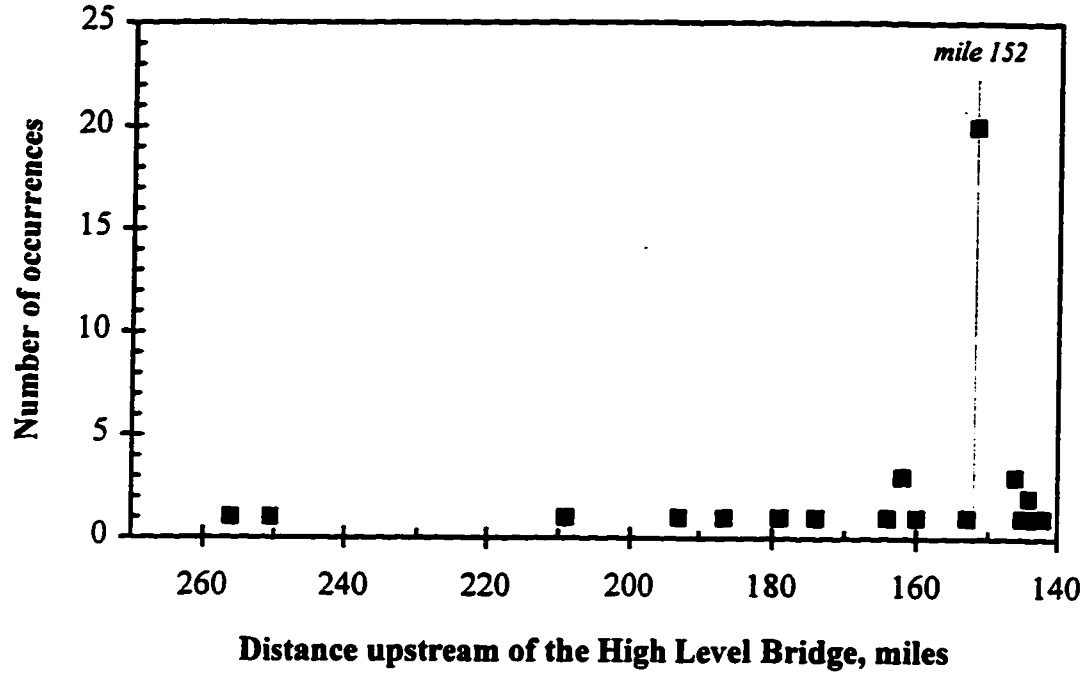


Figure 4.6 Frequency of ice bridging at various sites on the North Sask. River.

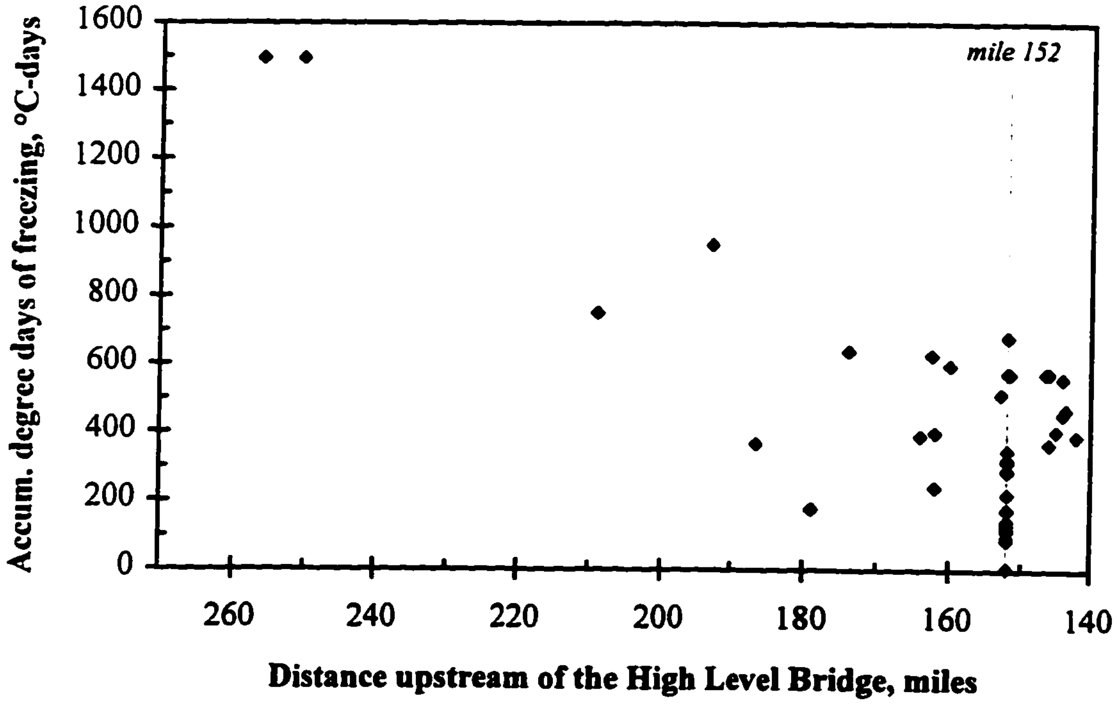


Figure 4.7 Accumulated degree days of freezing at the time of bridging at various locations along the North Saskatchewan River.

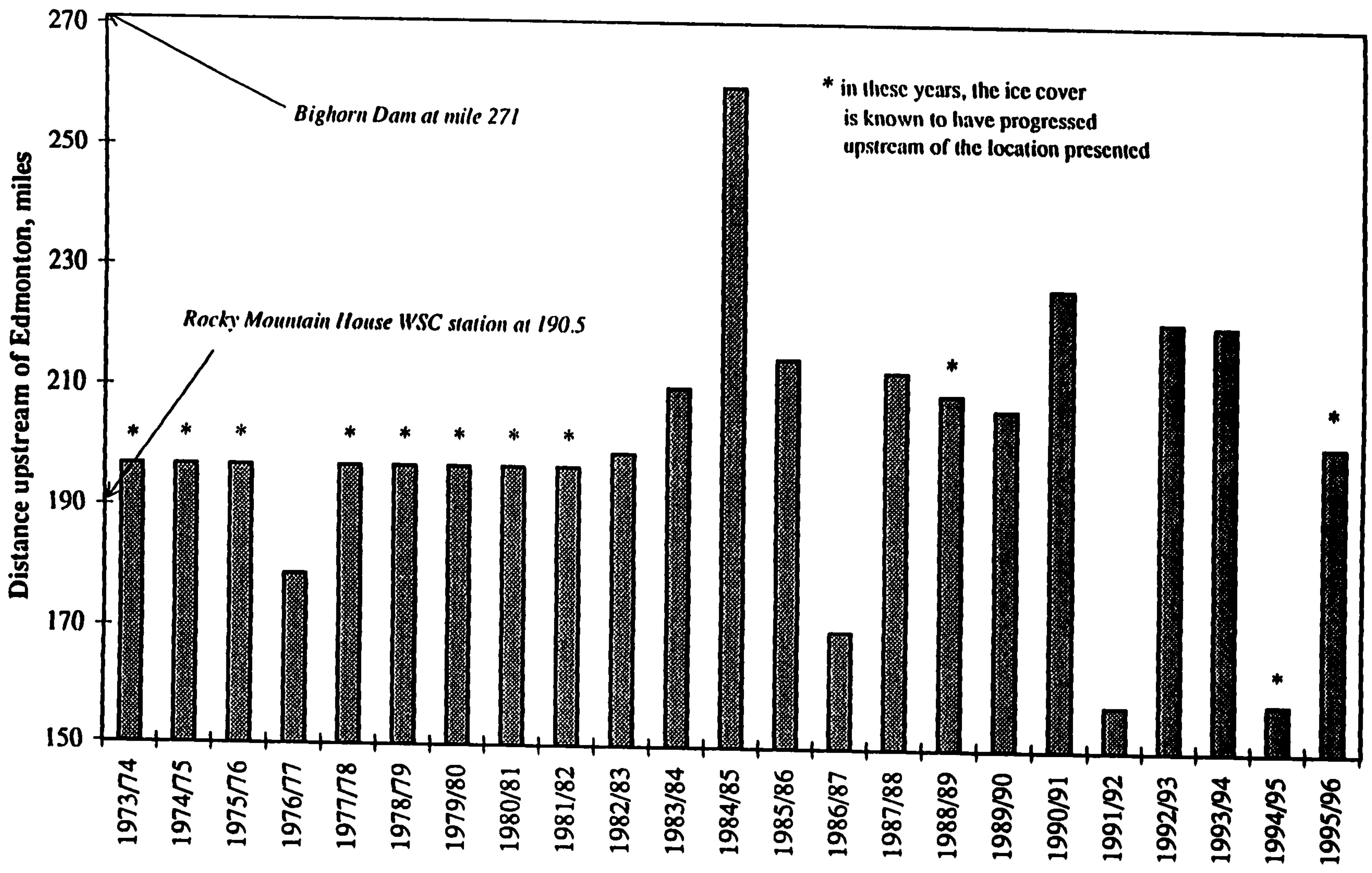


Figure 4.8 Upstream limit of ice cover for the period 1973/74 to 1995/96.

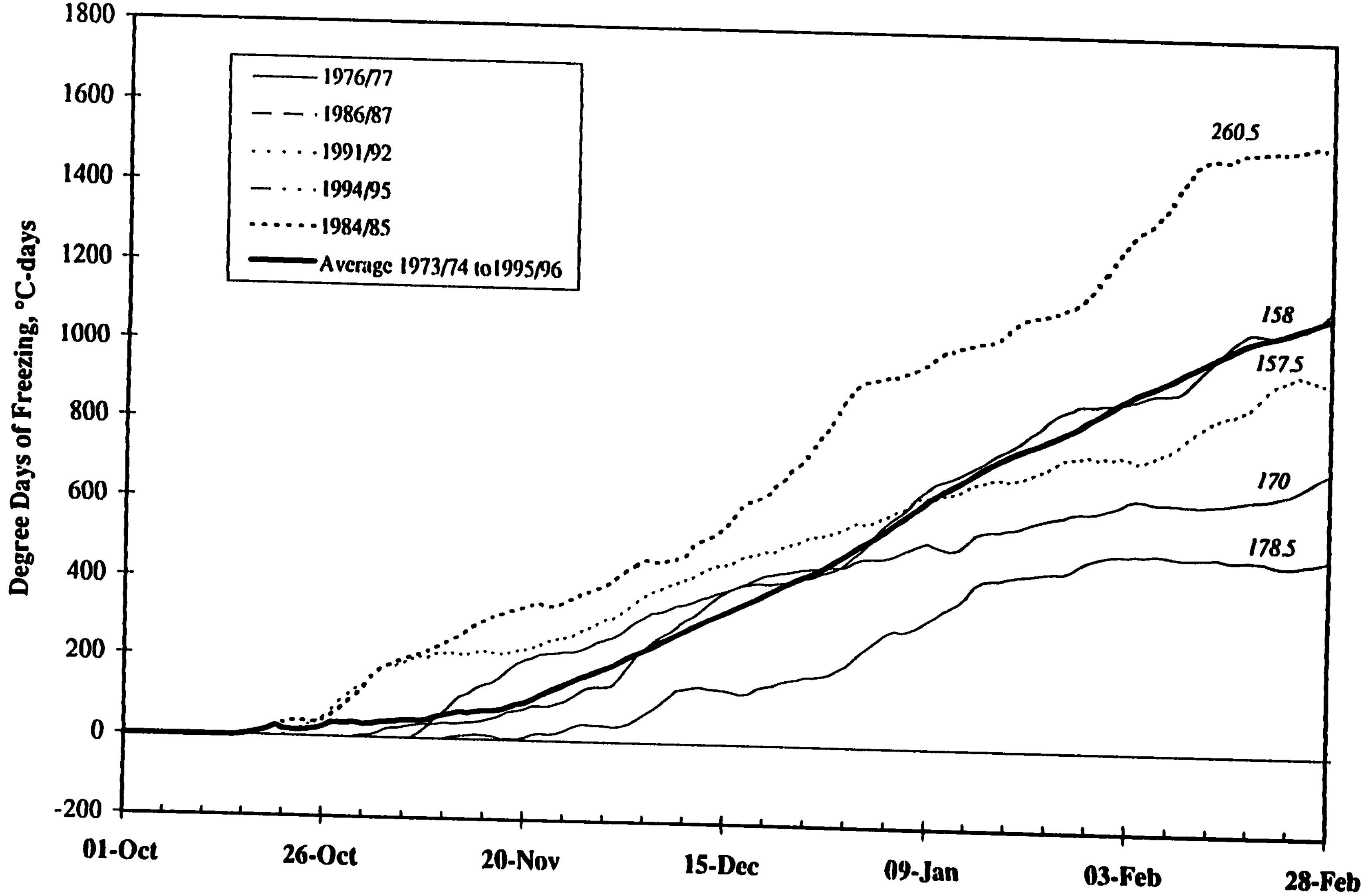


Figure 4.9 Accumulated degree days of freezing at Rocky Mountain House for selected years.

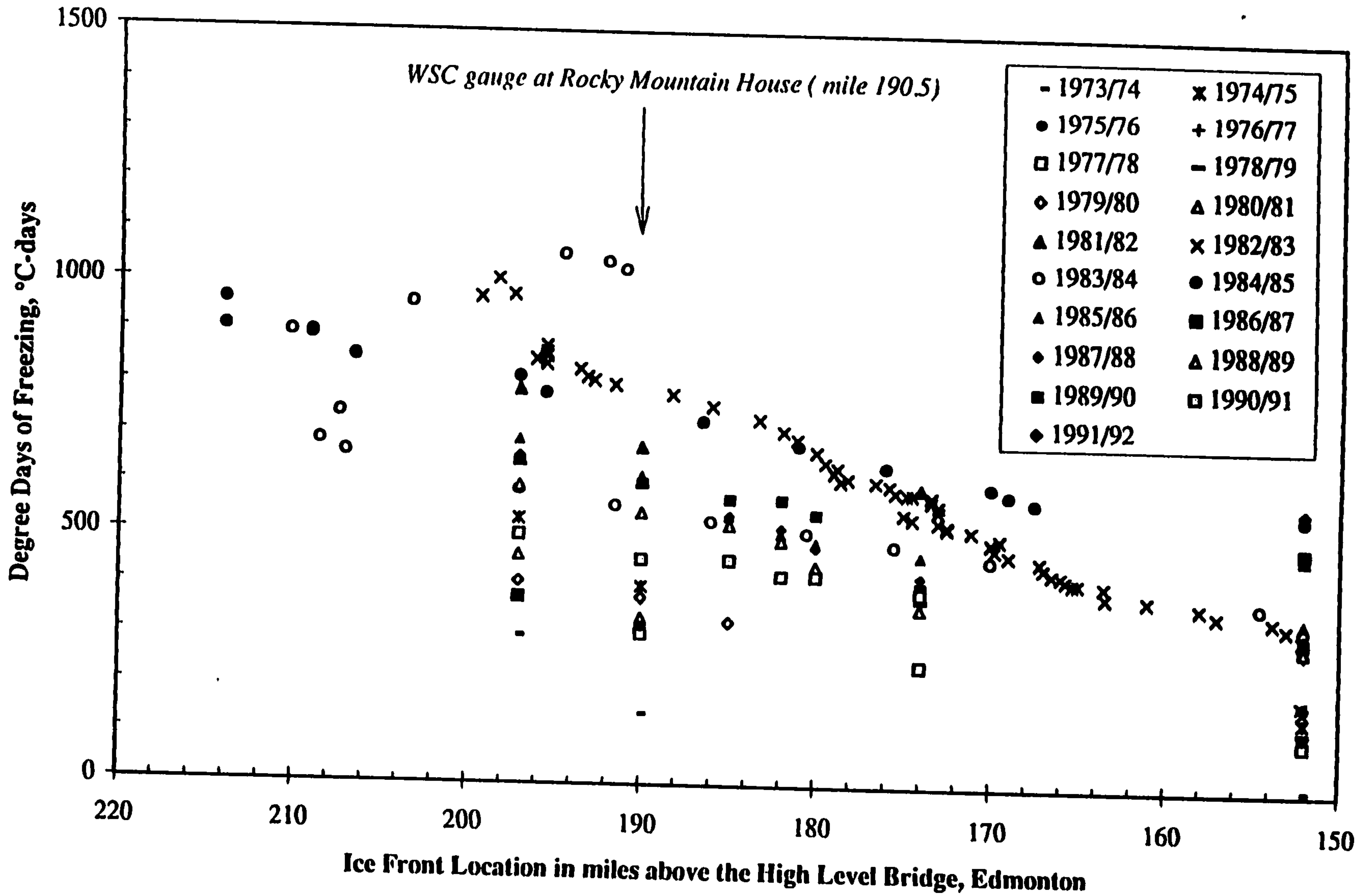


Figure 4.10 Ice front location on the North Saskatchewan River versus the accumulated degree days of freezing.

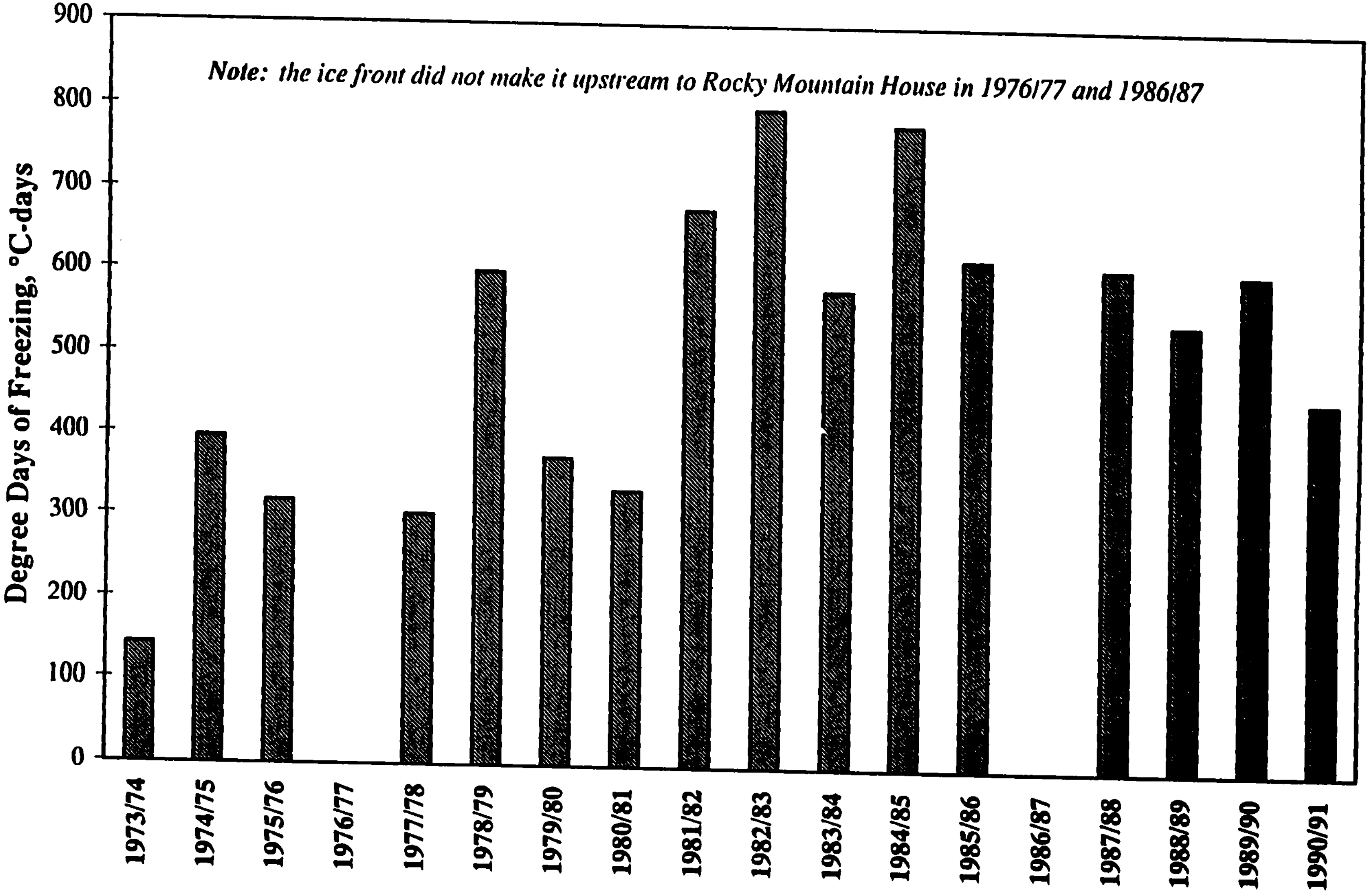


Figure 4.11 Accumulated degree days of freezing at the time the ice front passed through Rocky Mountain House.

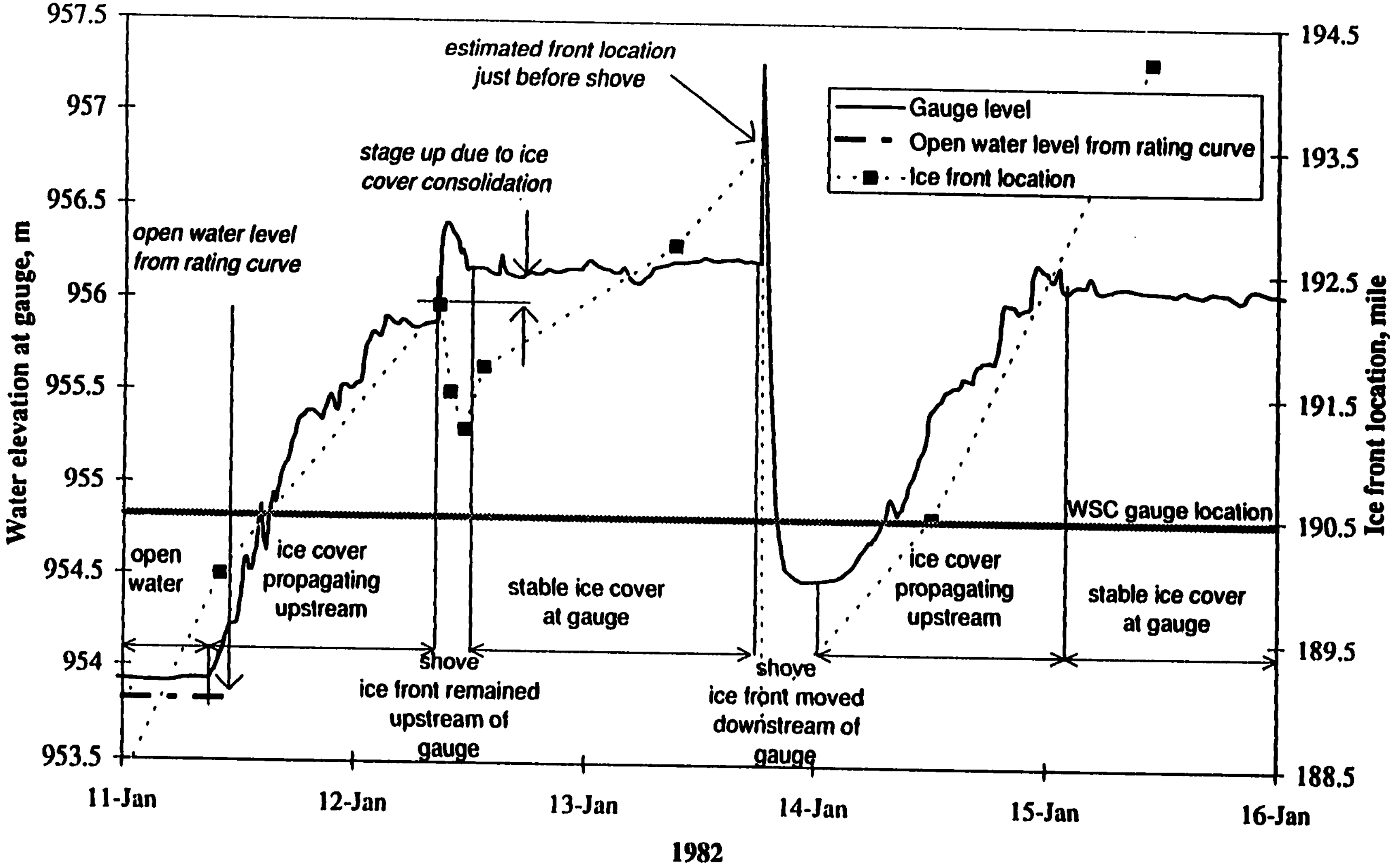


Figure 4.12 Events associated with the ice cover formation at Rocky Mountain House, January 11 to 16, 1982.

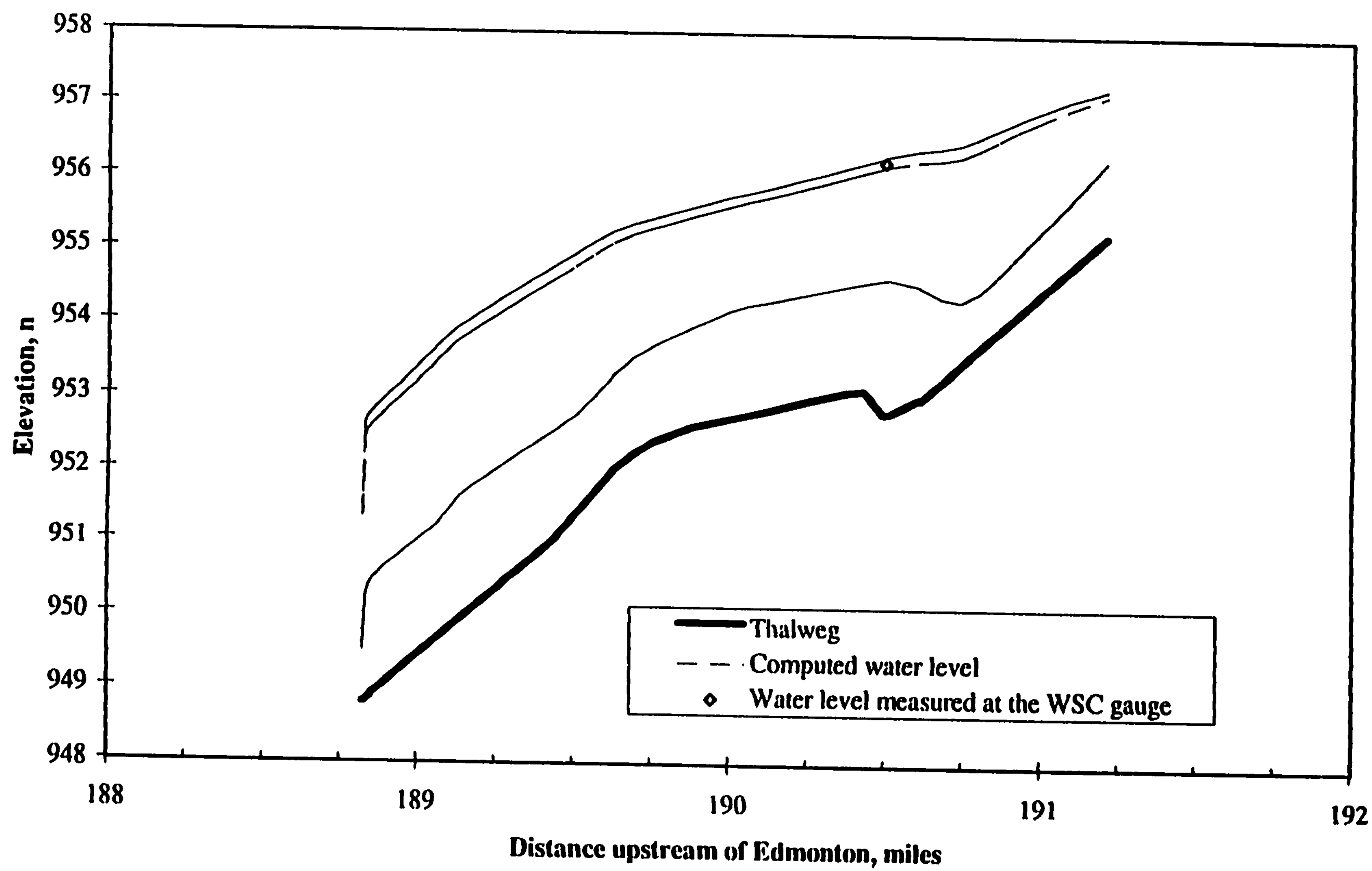


Figure 4.13 Final calculated ice jam configuration for the January 12, 1982 shove event.

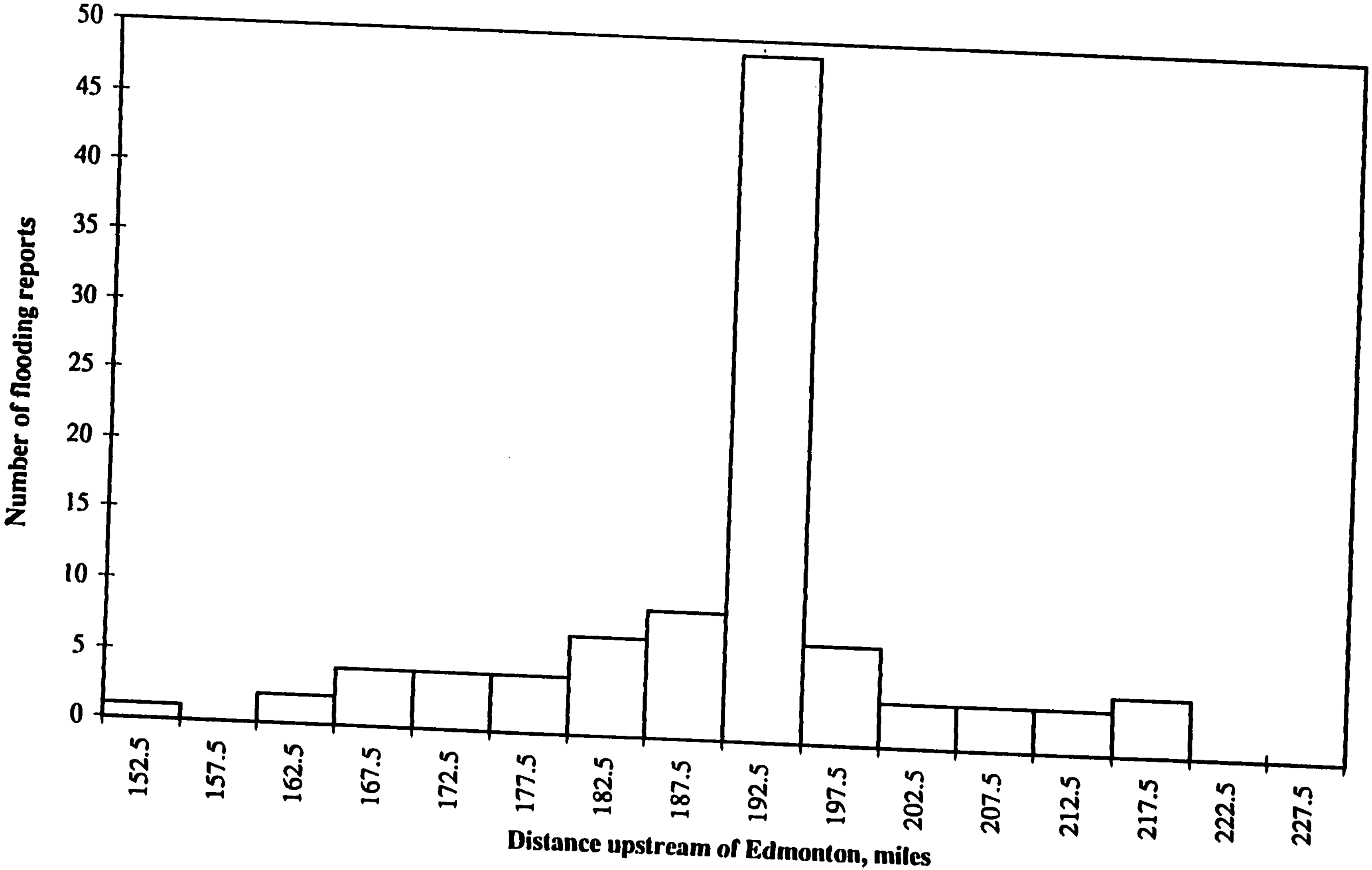


Figure 4.14 Incidents of flooding reports along the North Saskatchewan River near Rocky Mountain House.

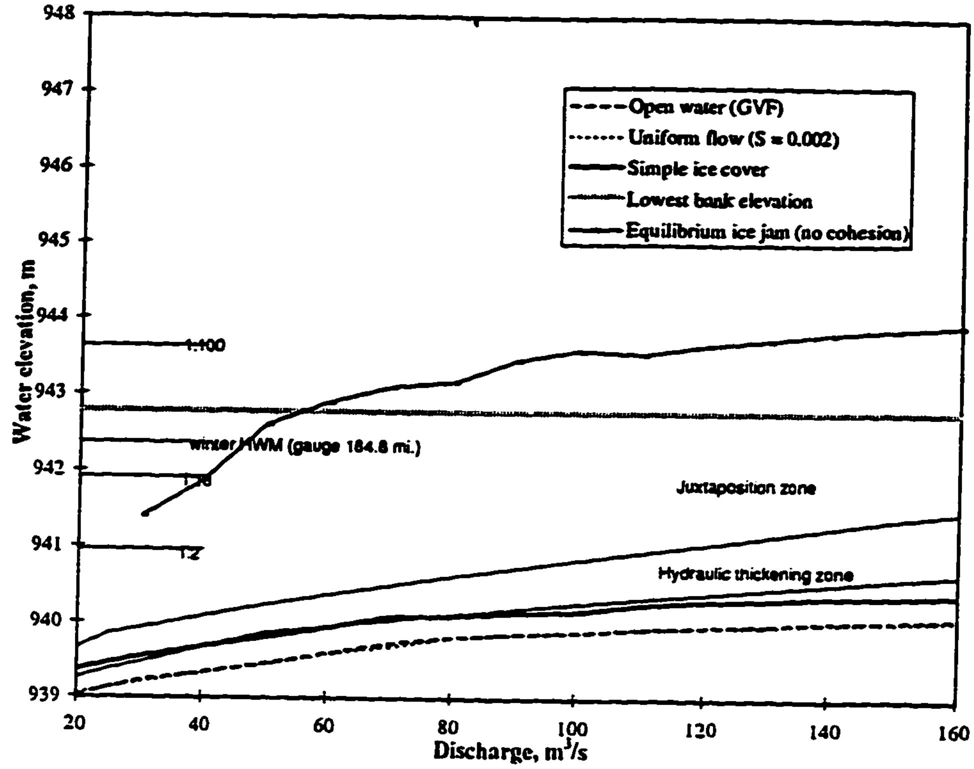


Figure 4.15 Rating curves at the cross section at 184.94 miles (near the Prentice Creek gauge).

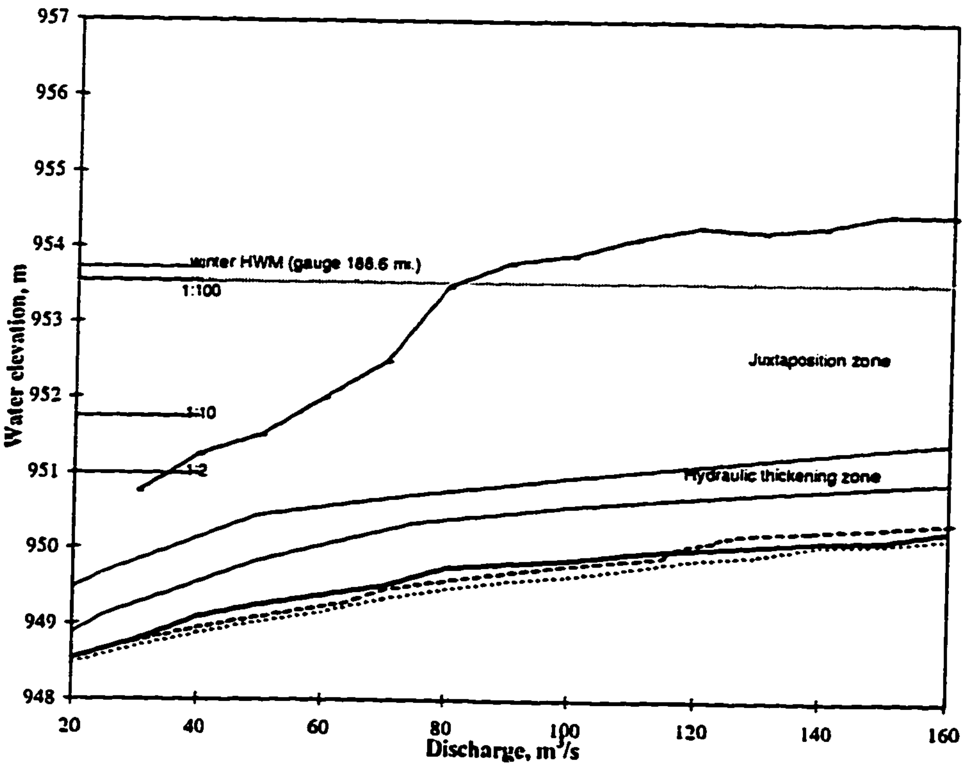


Figure 4.16 Rating curves at the cross section at 188.51 miles (near the A.F.S. station gauge).

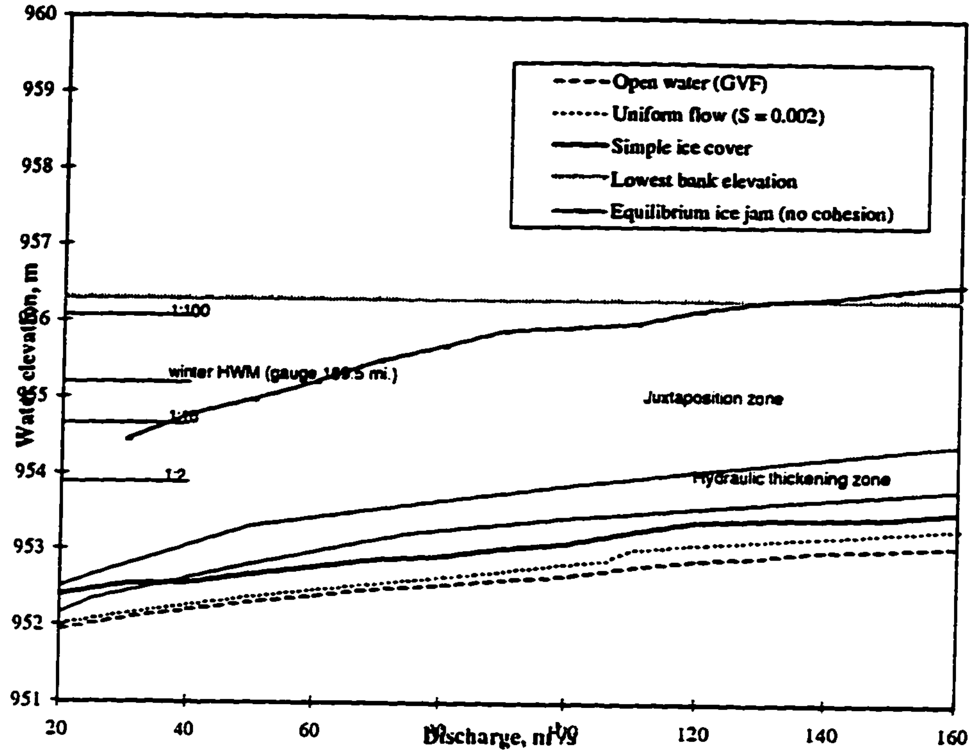


Figure 4.17 Rating curves at the cross section at 189.44 miles (near the Gravel Pit Road gauge).

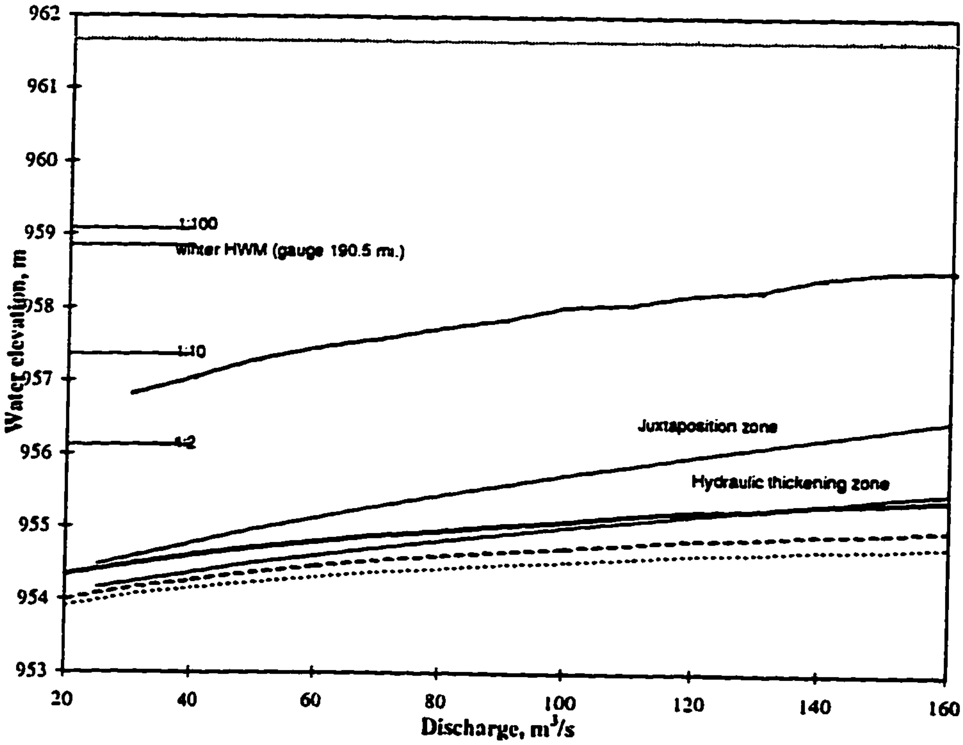


Figure 4.18 Rating curves at the cross section at 190.50 miles (WSC gauge).

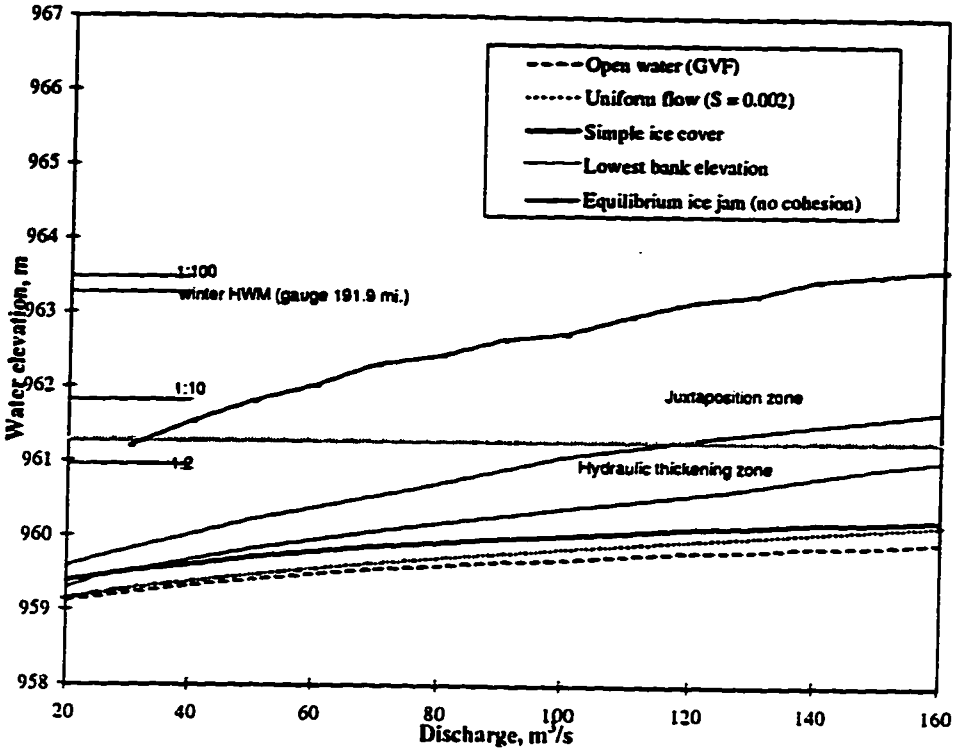


Figure 4.19 Rating curves at the cross section at 192.11 miles (near the Texas Pacific Gas Plant).

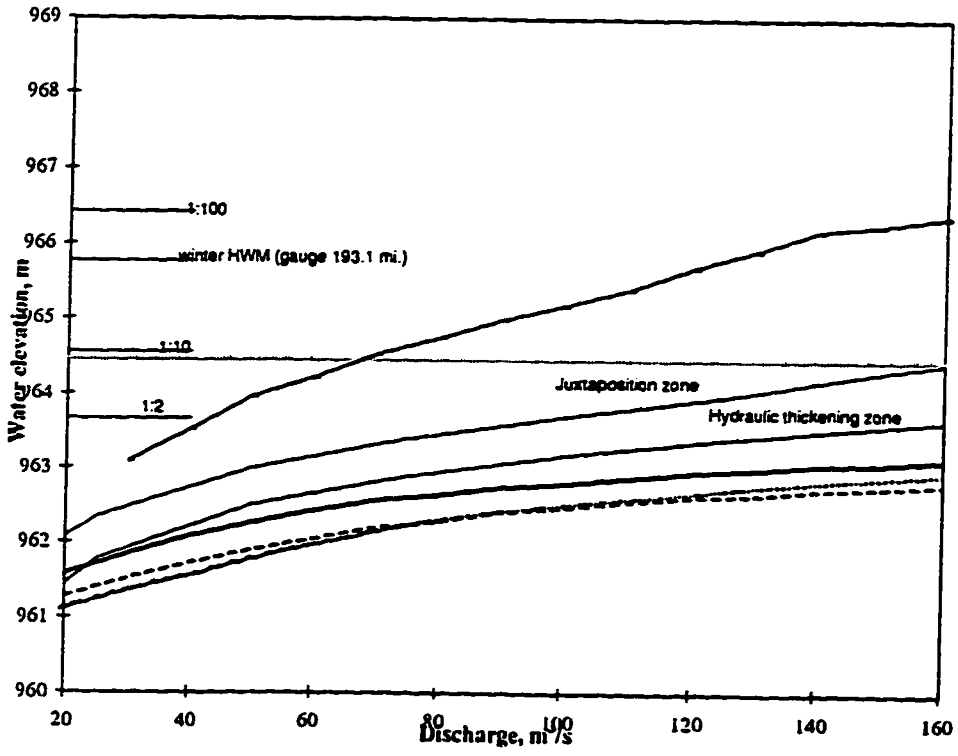


Figure 4.20 Rating curves at the cross section at 193.09 (near the Rocky Historic Park gauge).

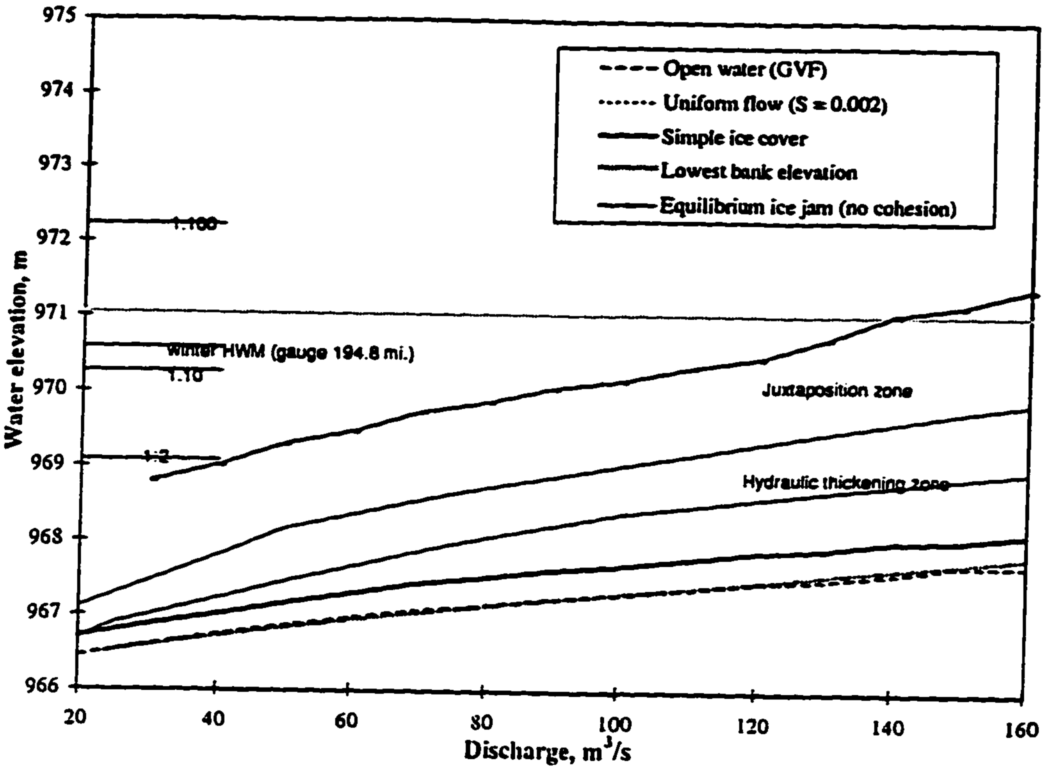


Figure 4.21 Rating curves at the cross section at 194.93 (near the Fischer Farm gauge).

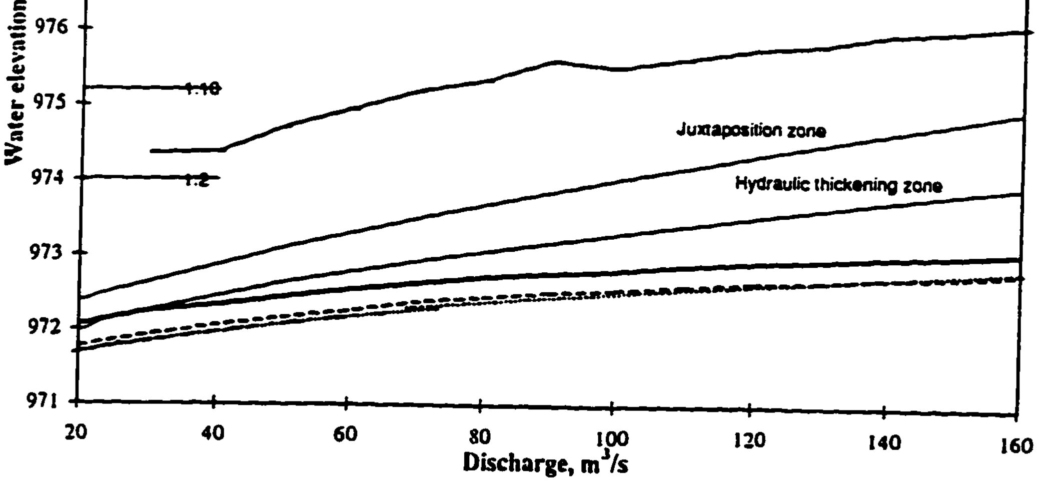


Figure 4.22 Rating curves at the cross section at 196.21 (near Ferrier Bridge gauge).

5.0 SUMMARY AND RECOMMENDATIONS

To develop an understanding of the freezeup processes that are important for the North Saskatchewan River near Rocky Mountain House, a review of the existing data and observations along with some analysis was conducted. The data came from several sources but the majority of it came from ice observations collected by *TransAlta Utilities Corp.* staff from 1973/74 to the present.

From the review of the observations several trends are apparent. Mile 152 is an important bridging point and has been used by *TransAlta Utilities Corp.* as a signal to initiate controlled outflows from the Bighorn dam. From the three detailed observations of bridging at mile 152, it was seen that cold temperatures, high surface concentrations of surface frazil and narrowing of the open water width by border ice are important factors in bridging at that site. Anchor ice growth is a common feature on the river bed during cold weather when there is no ice cover. During warm spells the anchor ice will release from the river bed and will contribute to the surface floes on the river.

Winter flooding can be a problem at certain sites. The main location for flooding concerns is at the Rocky Mountain House National Historic Park, but flooding is also a concern further downstream where oil and gas wells are located. Winter flooding is often accompanied by shoving events, but not always. The water levels associated with shoving events can approach the level of the 1:100 year open water flood level. Approximate rating curves were developed for eight sites in and around Rocky Mountain House to roughly assess the flood hazard from ice processes along the river.

Analysis of ice events terms of accumulated degree days of freezing did not correlate well. There was often considerable scatter and refinement of this analysis will require accounting for the heat content of the river and the effect of the hydraulics of the flow. Additional data are required in order to refine this analysis and are listed in the recommendations.

Specific recommendations concerning the monitoring program are as follows.

1. The first step in understanding ice formation is developing an appreciation of the cooling process. Monitoring the water temperature of the dam outflow along with several temperature profiles along the river would allow for the calibration of a cooling model that could more accurately predict the temperature profile along the river and the onset of ice production.

2. A more complete and methodical collection of surface frazil concentration data would assist in calibrating a model of freezeup processes. It would be better to have 10 to 20 observations over a long reach rather than a few observations over a

short reach. The time of day should also be recorded. Also, aerial observations (documented by video camera) would likely be more useful as a more complete picture of the river reach emerges rather than isolated observations that may or may not be representative of conditions along the entire reach. Ground observations should include estimates of the floe thickness and how the ice cover is progressing.

3. Anchor ice observations should start upstream where the first ice is noted. Observations should include what part of the channel the anchor ice is growing on and if some of these sites were exposed during the diurnal flow fluctuations. Observations should be site specific as general comments about a long reach are not very helpful.

4. Since mile 152 is obviously an important bridging point, a gauge with a continuous recorder should be placed there. This would record the stage and the exact time that bridging occurred, and also the times when the bridging is washed out. More frequent observations around bridging time or placing an observer or video camera at the site would allow for the collection of more complete information. Observations should include notes on border ice growth, frazil surface concentration, and the role of rafting in the bridging process. Flows from the dam should also be routed downstream in an effort to quantify the influence the daily flow variation has on bridging events. Ultimately a better understanding of the bridging process at this location will allow better prediction of when bridging will occur.

5. An intensive effort should be made to gather data in the trouble reaches (roughly mile 158-184 and mile 189-194). Data loggers should be placed along the river at regular intervals so that when a shoving event does happen, the water levels will be recorded by several gauges. This will provide an opportunity to see some of the dynamic effects of the shove. Immediately after the shove stabilizes, a water surface profile should be surveyed and the toe and head locations noted. If possible, ice thicknesses should be measured. Flows should be routed downstream to quantify the effect of flow on shoving. After several shoving events have been thoroughly documented, the more confidence can be placed in any subsequent ICEJAM or equivalent analysis.

6. A calibrated routing model is needed to determine the discharge at a particular site during an event. Because of hydropeaking, mean daily flows are not adequate and the effect of discharge on an event cannot be evaluated. The cdg-1D model simulated the hydropeaking quite well and should be refined further under open water conditions. Rating curves should be established at one or two sites upstream of Rocky Mountain House and one downstream to further refine the analysis. Development of an algorithm to allow the roughness to vary with discharge and along the channel would allow more accurate peak estimates.

7. Observations need to be more methodical and possibly follow a check list. For example, if border ice is not mentioned during an event it is not always clear whether it was not present or the observer did think it important enough to record. Use of a video camera would enhance the observations by creating a photographic record of the observation and allowing others to view the observation as well, allowing for different conclusions.

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APPENDIX A

HYDRAULIC FLOOD ROUTING MODEL: cdg-1D

In this study the cdg-1D hydraulic flood routing model, developed by F. Hicks and P.Steffler, was used to model the propagation of flood flows along the North Saskatchewan River. This model employs a Petrov-Galerkin finite element method known as the characteristic-dissipative-Galerkin scheme (Hicks and Steffler, 1990, 1992) to solve the one-dimensional unsteady open channel flow equations.
Given the approximate nature of the geometric model, a rectangular channel section was assumed. The hydraulic flood routing model was based on the St. Venant equations (Henderson, 1966), which were modified to provide a conservation formulation applicable to rectangular channels of varying width (Hicks and Steffler, 1990):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad \text{[A.1]}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial QU}{\partial x}+\frac{\partial}{\partial x}\left(\frac{gAH}{2}\right)-\frac{gAH}{2B}\frac{dB}{dx}=gA(S_o-S_f) \qquad \text{[A.2]}$$

where:

A = cross sectional area perpendicular to flow;
Q = discharge;
U = cross sectionally averaged longitudinal velocity;
H = depth of flow;
B = width of rectangular cross section;
S_f = longitudinal boundary friction slope;
S_o = longitudinal channel bed slope;
g = acceleration due to gravity;
t = temporal coordinate; and
x = longitudinal coordinate.

This system of equations describing one-dimensional, unsteady open channel flow may also be written in matrix notation:

$$\frac{\partial \{\phi\}}{\partial t}+\frac{\partial \{F\}}{\partial x}+\{f_e\}=\{0\} \qquad \text{[A.3]}$$

where,

$$\{\phi\} = \begin{Bmatrix} A \\ Q \end{Bmatrix} \; ; \; \{F\} = \begin{Bmatrix} Q \\ \left(UQ + \frac{gAH}{2}\right) \end{Bmatrix} \; ; and, \; \{f_c\} = \begin{Bmatrix} 0 \\ -gA\left(S_0 + \frac{H}{2B}\frac{dB}{dx} - S_f\right) \end{Bmatrix}$$

[A.4]

A non-conservation form of the system may also be considered:

$$\frac{\partial\{\phi\}}{\partial t} + [A]\frac{\partial\{\phi\}}{\partial x} + \{f_n\} = \{0\}$$ [A.5]

where,

$$[A] = \frac{\partial\{F\}}{\partial\{\phi\}} = \begin{bmatrix} 0 & 1 \\ c^2 - U^2 & 2U \end{bmatrix}$$ [A.6]

and,

$$\{f_n\} = \begin{Bmatrix} 0 \\ -gA\left(S_0 + \frac{H}{B}\frac{dB}{dx} - S_f\right) \end{Bmatrix}$$ [A.7]

The modified (conservation) formulation of the St. Venant equations has the significant advantage over more conventional (non-conservation) formulations in that it has been shown to be more effective in ensuring conservation of both mass and longitudinal momentum over a broad spectrum of complex flow scenarios (Hicks and Steffler, 1990. 1995).
In this study, the system of equations represented by equation [C.3] were solved using the finite element method. Although many successful hydraulic flood routing models have been developed based on the finite difference method, commercially available finite difference models are based on non-conservation formulations of the governing equations. Furthermore, none of the available models incorporate the effects of ice on the flow. The cdg1-D model employs an accurate, numerically robust, finite element scheme which has been verified by the authors in a number of dynamic applications including the modelling of ice jam release surges on the Hay River, NWT, the Porcupine River, Yukon, and the Saint John River , N.B. It has also been verified in open water flood routing applications on the Peace River and the Oldman/South Saskatchewan Rivers in Alberta. Comparisons of this numerical scheme to more conventional, commercially available finite difference code as well as other finite element schemes (Hicks and Steffler, 1990, 1995) have confirmed the superiority of this finite element scheme in terms of both solution accuracy and numerical stability.

The finite element equations were derived using the Galerkin weighted residual method. The simplest implementation is the Bubnov-Galerkin method (analogous to centered finite differences). In this method the test functions are simply set equal to the basis functions which is analogous to centered differences, that is,

$$\frac{\partial \phi}{\partial x} = \theta \left(\frac{\Phi_{j-1}^{n+1} - \Phi_{j+1}^{n+1}}{2\Delta x} \right) + (1-\theta) \left(\frac{\Phi_{j-1}^{n} - \Phi_{j+1}^{n}}{2\Delta x} \right) \qquad [A.8]$$

where the indices n and j denote the temporal and spatial discretizations, respectively. θ represents the implicitness factor such that $\theta = 1$ represents a fully implicit formulation. Also,

$$\frac{\partial \phi}{\partial t} = \frac{\Phi^{n+1} - \Phi^{n}}{\Delta t} \qquad [A.9]$$

where,

$$\Phi = \frac{\Phi_{j-1} + 4\Phi_j + \Phi_{j+1}}{6} \qquad [A.10]$$

In open channel flow applications, the Bubnov-Galerkin formulation has been shown to be useful for modeling relatively flat waves but it performs poorly in the vicinity of steep gradients in the solution (Katapodes, 1984). An alternative is to use the Petrov-Galerkin method, in which upwind weighted test functions are used to introduce *selective* artificial dissipation, smoothing out spurious, short wavelength oscillations while preserving the physical wave behavior. Essentially, this is equivalent to a Bubnov-Galerkin formulation of the extended system,

$$\left(\frac{\partial \{\phi\}}{\partial t} + \frac{\partial \{F\}}{\partial x} + \{f_c\} \right) - \omega \frac{\Delta x}{2} [W] \frac{\partial}{\partial x} \left(\frac{\partial \{\phi\}}{\partial t} + [A] \frac{\partial \{\phi\}}{\partial x} + \{f_n\} \right) = \{0\}$$

⇐ *original system* ⇒ ⇐ *upwinding terms* ⇒ [A.11]

In which ω is an 'upwinding coefficient' or diffusion parameter, while the matrix, $[W]$, controls the distribution of the upwinding. It should be noted that the upwinding terms are formed from derivatives of the non-conservation form of the original system. Artificial dissipation is introduced through the second derivative in x, and is balanced to third order by the other upwinding terms when a semi-implicit formulation is used. This process corresponds to $\theta = 0.5$.

The Petrov-Galerkin formulations employed in the investigation was the characteristic-dissipative- Galerkin (CDG) scheme originally introduced by Brooks and Hughes (1982) as the Streamline Upwind Petrov-Galerkin (SU/PG). In this approach, the numerical diffusion was incorporated using an upwinding term which was determined based upon the sign of the flow direction. Adaptation of this concept to the problem of open channel flow is defined by (Hicks and Steffler, 1990, 1992):

$$[W] = \frac{[A]}{[A]} = [M]\left[\frac{\lambda_i}{|\lambda_i|}\right][M]^{-1} = \begin{bmatrix} \frac{1}{2c} & -\frac{1}{2c} \\ \frac{U+c}{2c} & \frac{-(U-c)}{2c} \end{bmatrix} \begin{bmatrix} \frac{U+c}{|U+c|} & 0 \\ 0 & \frac{U-c}{|U-c|} \end{bmatrix} \begin{bmatrix} -(U-c) & 1 \\ -(U+c) & 1 \end{bmatrix}$$

[A.12]

A constant value of 0.25 for the upwinding parameter, ω, minimizes dissipation of long wavelengths while achieving good phase accuracy. Phase accuracy may be optimized by employing a value of $\omega = 0.5$, with slightly increased dissipation. As it has been shown that the effect of varying ω on phase and amplitude is only marginal (Hicks and Steffler, 1990, 1992) a constant value of 0.5 was used.

APPENDIX B

CHRONOLOGICAL DESCRIPTION OF DOCUMENTED EVENTS

INTRODUCTION

Regular observations of freezeup processes on the North Saskatchewan River have been documented since the winter 1973/74, when the Bighorn Dam became operational. For the most part they are qualitative but are useful for characterizing the ice formation processes. In the earlier years, the observations were fairly sparce. Eventually an observation program was set up to record the progress of the ice cover from Edmonton to upstream of Rocky Mountain House.

1973/74 Observations

Figure B.1 shows the calculated mean daily air temperatures and the progression of the ice front for the 1973/74 freezeup season. During October the temperature remained above zero until the end of the month. Beginning at the end of October, the temperature slowly dropped to a low of -22°C on November 8. The ice bridged at mile 152 on November 1 and the ice front progressed rapidly upstream reaching mile 190 on November 9. The temperature varied between approximately -20 and -10°C throughout the rest of November. The ice front reached mile 197 on November 22. Further ice front locations were not recorded.

1974/75 Observations

Figure B.2 shows the calculated mean daily air temperatures and the progression of the ice front for the 1974/75 freezeup season. Beginning in early October the temperature began to decline. A low of about -10°C was reached on November 22 and after that time, the temperature varied between about -10 and 3°C until mid-December. Bridging occurred at mile 152 on November 30. Throughout the rest of December and into early January the temperature ranged between -15 and 0°C. On January 6 the temperature started to drop reaching a low of -29°C on January 9. The temperature remained below -20°C for four days and then rose to a similar temperature range as that which occurred in late December. On January 17 the ice front was observed at mile 190. On January 30 the temperature started to drop again, reaching a low of -28°C on February 4. There were 16 days with temperatures colder than -15°C. On February 2 the ice front was observed at mile 197, the most upstream recorded position for that season. During the last part of February mean daily air temperatures increased and remained above -10°C.

1975/76 Observations

Figure B.3 shows the temperatures and the progression of the ice front for the 1975/76 freezeup season. From mid-October to about mid-December there was a gradual drop in temperatures reaching a low of -25°C on December 11. Bridging was observed at mile 152 on November 30. The temperature warmed and averaged just below 0°C for the last part of December and then dropped to a low of -29°C on January 7. The ice front passed through Rocky Mountain House during the last half of December, reaching mile 190 on December 15 and mile 197 on December 23. After January 8 the temperature warmed and ranged between lows of -15 and highs of 8°C.

1976/77 Observations

Figure B.4 illustrates the mean daily air temperatures and ice front locations documented in 1976/77. Mean daily air temperatures remained above 0°C for most of October and early November with the temperature dropping below zero between October 22 and 25, and between November 10 and 14. "First ice" was observed in Edmonton on November 11. The temperature gradually decreased through November and early December reaching a low of -20°C on December 9. Temporary bridging was reported at mile 152 on December 9 but it dislodged soon after, creating a surge that increased the stage at Drayton Valley by 2.1 m (7 ft.) on December 10. The ice eventually lodged at Berrymore Ferry (mile 92), 11 miles downstream of Drayton Valley.

The temperature warmed in mid-December and there were 5 consecutive days of above 0°C mean daily temperatures (December 13 to 17). On December 18, the temperature dropped to -3°C and the next day to -10°C. The ice front was observed at mile 108.2 on December 22 and it continued to progress upstream, reaching mile 119 on December 25. After December 26, the mean daily air temperatures dropped to a low of -18.6°C on December 31, and then warmed over 6 days to a high of 3.9°C on January 6, and there was a report of flooding of an oil company access road, battery, injection well and water well at mile 122.5.. Bridging was thought to have occurred again at mile 152 on January 4, creating two ice covers.

The temperature dropped to -25°C over the next 9 days (January 7 to 15). By January 11 the downstream ice front had progressed to mile 129. The following day, January 12, a consolidation of this downstream ice cover moved the ice front down to mile 121.5. The upstream pack had progressed to mile 175 by January 15 when a consolidation of this ice cover occurred, pushing the ice front downstream to mile 165. Over the next few days (January 16 to 18) the mean daily air temperatures increased, reaching a high of 0°C on January 18. Releasing anchor ice rebuilt the upstream ice cover to mile 169 on January 16 and to mile 172.5 on January 20.

The temperature remained warmer than -5°C for the next 8 days (January 19 to 26). The furthest observed location of the downstream ice front was mile 129 on January 21. Temperatures dropped to a low of -15°C over the next two days and then warmed and remained around 0°C until the last week of February. It is estimated that the upstream ice front reached its maximum recorded upstream location at mile 178.5 around February 7 (the exact date was not documented). The pack was reported as thin at that time and then a slight consolidation moved the ice front downstream to mile 177 on February 11. The ice cover slowly receded downstream over the rest of the month.

1977/78 Observations

Figure B.5 shows the mean daily air temperatures and the progression of the ice front for the 1977/78 freezeup season. Temperatures remained near or above 0°C until mid-

November. Starting on November 15 mean daily air temperatures began to decline rapidly, reaching a low of -22°C on November 22, with six days around -20°C. Bridging was observed at mile 152 on November 22. The mean daily air temperatures began to increase again after this, rising to just over 0°C by November 29. After November 29 the temperature dropped again to a low of -37°C on December 9, with seven days colder than -20°C. During this second cold period the ice front progressed rapidly passing miles 174, 190 and 197 on December 5, 7 and 9, respectively. Mean daily air temperature fluctuated between -20 and -5°C for the rest of January and February except for four days in February, during which the temperature dropped below -20°C.

1978/79 Observations

Figure B.6 shows the mean daily air temperatures and the documented progression of the ice front for the 1978/79 freezeup season. Mean daily air temperatures fluctuated between 12°C and -1°C in Oct. This trend continued into early November them temperatures began to decline, reaching -14°C on November 10. The temperature then warmed up slightly to -7°C before dropping again to -23°C on November 20. The temperature remained cold for 4 days and during this period the ice bridged at mile 152 on November 22.

Mean daily air temperatures gradually warmed to just above 0°C by November 28, and then varied between about -15°C to -5°C for the next two weeks, peaking at 1°C on December 14. The temperature began a declining trend over the next few weeks, dropping to a low of -26°C on January 13. Mean daily temperatures were below -15°C for a total of 17 days over this period and the ice front progressed steadily upstream reaching miles 174, 190 and 197 on December 21, 31 and January 2, respectively. Temperatures continued to remain cold throughout the rest of January and February with the mean daily temperatures ranging from about -29 to -5°C. Between January 29 and February 17 the temperature did not rise above -18°C.

1979/80 Observations

Figure B.7 shows the mean daily air temperatures and ice front progression for the 1979/80 freezeup season. Variable mean daily air temperatures throughout October and early November ranged from 12°C down to just below freezing. On November 9 the temperature dropped down to -10°C and remained around -10°C for five days, before warming up to 6°C. The temperature cooled to around -20°C for five days before warming up and fluctuating between lows of around -15° and highs near zero into mid-December. Two bridging points were observed this year. Mile 152 was bridged on December 10 and mile 179 was bridged around December 16. After mid-December the temperature cooled through January and February. The temperature ranged between lows around -28 and highs between -10 and -5°C. Between mid-December and the end of February, there were 42 days with mean daily temperatures less than -15°C. The ice sheet progressed upstream as ice sheets with the downstream one passing mile 174 on December 17 and the upstream one passing miles 190 and 197 on December 25 and 29, respectively. The date that the two ice sheets joined was not recorded.

1980/81 Observations

The mean daily air temperatures and ice front progression for the winter of 1980/81 are shown in Figure B.8. The mean daily air temperatures remained above 0°C throughout most of October and the first part of November. From November 10 to 27 the temperature varied between lows of about -10°C and highs of 1 to 2°C. On November 28 the temperature started to drop until a low of -31°C was reached on December 5. Temperatures remained fairly cold throughout December except for a seven day period (December 11 to 17) when temperature remained above -10°C and peaked at 8°C on December 16. Bridging occurred at mile 152 on December 2 and the ice cover grew upstream rapidly reaching mile 174 on December 8 and mile 190 on December 19. On December 26 it started to warm up and the temperature ranged between -10 and 4°C for most of January. The temperatures in February were similar to January's except for a brief cold spell where temperatures dropped to a low of -24°C.

1981/82 Observations

The mean daily temperatures recorded for October 1981 to the end of February 1982 and the recorded locations of the ice front are shown in Figure B.9. Temperatures remained fairly warm for most of November and did not drop below -10°C until December 7. Temperatures were colder during early December getting down to a low of -16°C on December 13. The temperatures slowly increased over the next seven days until December 20 when the mean daily temperature was just over zero. Temperatures then dropped to around -10°C for five days (December 22 to 26), then declined to below -20°C for eleven days (December 27 to January 6). The mean daily air temperature was below -25°C on nine of these eleven days. On January 3, the ice front was reported past mile 152, but bridging did not occur there. A shove occurred between mile 165.5 and 170.1 on January 5. Approximately 6 miles of ice was consolidated. It was attributed to a four hour pulse flow averaging 138.8 m^3/s (4900 c.f.s.) released from the Bighorn Dam. This produced the fourth highest stage recorded over the period of record (1976 to 1995) at the ice gauge at the toe of the shove, but no flooding was reported.

The temperature rose slightly to -18°C for one day on January 7, and then dropped below -20°C for three days. Temperatures slowly increased from a low of -25.6°C on January 8 to a high of -7.1°C on January 13. The ice front was observed at mile 174 on January 8, and at Rocky Mountain House (mile 190) on January 12. The outflow from the Bighorn Dam had been restricted to 48.1 m^3/s (1700 c.f.s.) since January 10 as the ice front was approaching Rocky Mountain House.

At 16:00h on January 13, chinook conditions began in the Rocky Mountain House area increasing the air temperature from -18°C to +4.7°C. Before the chinook, the head of the ice cover had been at mile 192.8. By 18:00h a shove had been initiated. It was hypothesized that the chinook had warmed the river water sufficiently to cause the anchor

ice to release from the bed, augmenting the surface flow of ice and precipitating the shove. The mean daily temperatures, outflows from the Bighorn Dam and the measured stage at the WSC gauge during the ice cover formation at Rocky Mountain House are shown in Figure B.10. The shove caused the highest water levels for the period of record for the ice gauges between mile 188.6 and 189.9. Although both access roads under the east and west end of the Highway 11 bridge were flooded, and a loader had to remove ice from the west access road, no serious property damage occurred. The Chinook ended the next morning (January 14) at 9:00h and the air temperature dropped once more. This shove, and the events surrounding it, are discussed in greater detail in Section 4.4.
On January 15 the temperature dropped to -29°C and remained below -15°C for 11 days. The ice front passed mile 197 on January 18. For the rest of January and February the temperatures ranged from -20°C to just under zero.

1982/83 Observations

Figure B.11 shows the mean daily temperatures and the recorded ice front locations for October 1982 to February 1983. Temperatures in October remained fairly warm except for a four day period where temperatures dropped below 0°C. At the end of October the temperature began a declining trend reaching a low of -22°C on November 21. Bridging was observed at mile 152 on November 22. The weather warmed to around -10°C for 13 days (November 23 to December 6) and the ice front remained fairly stable around mile 152.

When the mean daily temperature dropped to -20°C on December 7 the ice front started to progress upstream. The temperature varied between -15 and -5°C with a few exceptions until January 22. By January 22, the ice front was at mile 181.9. Then for three days the temperature dropped to between -20 and -25°C. After that the temperature continued to vary between about -15 and -5°C until February 10. The progress of the ice cover continued, reaching mile 196.1 on January 31. The ice cover stalled at mile 195.5 until February 3, after which it started to progress upstream, reaching its most upstream point at mile 199.3 on February 10. For the last part of February the temperatures ranged between about -10 and 0°C, with a few days with mean daily temperatures above 0°C. The ice front remained stalled between mile 197 and 199, the last recorded location being mile 198.3 on February 24.

1983/84 Observations

The mean daily temperatures and the progression of the ice front for the 1983/84 freezeup season are shown in Figure B.12. Temperatures remained above 0°C throughout most of October and early November. A declining trend followed. On November 24 the mean daily temperature was -11.2°C in Rocky Mountain House and 20% of the water surface was covered with frazil ice pans at Highway 11 (mile 187.5). The temperature continued to drop reaching a low of -31.7°C on December 23 after eight days of temperatures below -20°C. The documented surface coverage by frazil pans at the Highway 11 bridge was 80%, 70% and 30% on November 30, December 2 and 5, respectively.

By early December border ice at mile 152 had narrowed the open water surface noticeably and temporary bridging was observed on December 7. At that time all of the frazil floes were being swept under this ice cover and no upstream progession was observed. By December 9 this local accumulation had released. On December 12, bridging was again reported at mile 152, with 80 to 90% of the water surface cover with frazil pans upstream and 50 to 70% coverage downstream. Two days later, on December 14, it was reported that the bridging was still in place but again all of the frazil slush was being swept under the accumulation.

On December 16 it was reported that the ice cover was starting to progress upstream as the head of the ice cover was at mile 154.5. At that time, the maximum outflow from the Bighorn Dam was restricted to 113 m^3/s (4000 c.f.s.) with one unit load control. December 16 was also the start of a 10 day period (December 16 to 25) when the mean daily temperature remained below -20°C. The ice cover progressed rapidly to mile 170 by December 19, and to mile 175.5 by December 20. The baseflow from Bighorn Dam was reduced to 36.8 m^3/s (1300 c.f.s.) with one cumulative hour of 70.8 m^3/s (2500 c.f.s.) over 24 hours (for peaking purposes). The ice front reached mile 180.5 on December 21 and mile 186 on December 22. It moved through Rocky Mountain House the next day and was up to mile 197 on December 24. Cattle were reported stranded on the ice at mile 174 on December 23, possibly due to an open lead developing between an island and the bank. A warming trend started after Christmas culminating in a mean daily temperature of 5.1°C on January 4. The pack continued to progress upstream, reaching mile 208.3 on December 29. The Bighorn Dam baseflow was increased to 39.6 m^3/s (1400 c.f.s.) on December 29 and again up to 42.5 m^3/s (1500 c.f.s.) with no change in the allowable pulse flow. On January 3, the baseflow was increased further, to 46.7 m^3/s (1650 c.f.s.), and again the next day to 51.0 m^3/s (1800 c.f.s.) with the allowable pulse flow increased to 84.9 m^3/s (3000 c.f.s.) for one hour. The baseflow was increased to 56.6 m^3/s(2000 c.f.s.) and 68.0 m^3/s (2400 c.f.s.) on January 6 and 9, respectively with the one hour pulse flow increased to 99.1 m^3/s (3500 c.f.s.).

The mean daily temperature started to drop to about -10°C on January 9. It fluctuated around -5 to -10°C for three days and then dropped to a low near -25°C on January 14. On January 11 the head of the pack was observed at mile 207.4, but there was evidence that it had been up to mile 210 and then eroded back. It warmed up again for two days to between -10 and -15°C and then it dropped to around -25°C again on January 17. On January 12 the Bighorn outflow was increased to a maximum of 127 m^3/s (4500 c.f.s.). It warmed up over the next six days to a high of 2.1°C on January 23.

Planned maintenance on one Bighorn headgate resulted in it being closed for 10 hours on January 24 and on that day the mean daily outflow was only 31.1 m^3/s (1100 c.f.s.). On January 25 the Bighorn outflow was slowly increased from 28.3 m^3/s (1000 c.f.s.) for 12 hours, to 42.4 m^3/s (1500 c.f.s.) for 8 hours, and then to 56.6 m^3/s (2000 c.f.s.) for 6 hours in order to refloat the ice sheet. After this incremental increase the outflow was unrestricted. The temperature remained warmer than -10°C throughout the rest of

January and all of February. The ice front was observed at mile 209 on January 24, the day of the headgate closure and reached its most upstream point of mile 210.2 on January 26.

On February 22 the other headgate was closed for maintenance and the flow schedule was similar to that on January 24 and 25. The ice front had receded over the month and was observed at mile 203.2 on March 1.

1984/85 Observations

The mean daily temperatures and the progression of the ice front for the 1984/85 winter season are shown in Figure B.13. Temperatures in the first half of October were relatively warm, reaching a high of 19°C on October 8. From that point the temperature steadily dropped to -10°C on October 20 before rising over five days to 2.5°C on October 25. From there the temperature dropped to -23°C on November 1. The temperature increased over the next 3 days to -9°C on November 4 and remained above or around -10°C for the next 8 days. On November 13 the temperature dropped to -16°C and then slowly increased to 6°C on November 23. From there the temperature slowly dropped over the next month to a low of -36°C on December 30.

From mid-November to mid-December edge ice was reported along both banks of the river. On December 16 it was postulated that bridging had occurred at mile 152 with the head of the ice cover at mile 156.5 on December 17. Bridging was also reported at mile 160 on December 17 with the head at mile 167.5 and at mile 169 on December 18. Minor flooding was also reported in road ditches between miles 168.5 and 170 on December 18. On December 21 the emergency outflow from Bighorn was reduced to one hour over 24 hours. On December 25 with the ice front at mile 181, the base load from Bighorn was reduced to 31.1 m^3/s (1100 c.f.s.) with a 70.8 m^3/s (2500 c.f.s.) peak for 1 hour 20 minutes over a 24 hour period, with no emergency use. The ice front progressed rapidly upstream passing through Rocky Mountain House on December 27 and 28 and up to mile 209 on December 30. The picnic area in Rocky Mountain House National Historic Park began flooding on December 29 but the water level was down on December 30.
After December 30 the temperature rose rapidly to a high of -1°C on January 5 and remained above -10°C until January 27, except for two four day periods when the temperature hovered between -10 and -20°C. On December 31 the baseflow was increased to 34.0 m^3/s (1200 c.f.s.) with a 2 hour pulse flow of 70.8 m^3/s (2500 c.f.s.) over 24 hours and then to 36.8 m^3/s (1300 c.f.s.) with an 84.9 m^3/s (3000 c.f.s.) pulse flow. The ice front progressed to mile 209, and then 214 on January 2 and 4, respectively. The outflows were slowly increased until all restrictions were removed on February 8 except that a four hour minimum average flow of 34.0 m^3/s (1200 c.f.s.) had to be maintained. Some flooding was reported in the Rocky Mountain House National Historic Park by the footbridge on January 15 and 17, but it was not serious enough to stop increasing the dam outflows.

After a high of -6.8°C on January 27, the temperature dropped and the mean daily temperatures remained colder than -10°C for the next 17 days (January 28 to February 12). Eleven of those days were colder than -20°C. Flooding was reported at a trap line at mile 252 on February 11. An observation flight on February 12 documented four ice packs on the North Saskatchewan River, from mile 152 to 225, 239.8 to 242.3, 250.5 to 251.7 and 256.2 to 260.5 (Figure 4.13). Flooding was also reported between mile 166 and 165. On February 13 the mean daily temperature had risen and it was warmer than -10°C and the temperature remained warmer than -10°C for the rest of the month, with five days above zero. The ice front began a slow retreat and was reported at mile 242 on March 1.

1985/86 Observations

The mean daily air temperatures and the progression of the ice front for the 1985/86 freezeup season are shown in Figure B.14. Temperatures remained warmer than -5°C throughout most of October. Mean daily air temperatures started a declining trend during the first week of November, reaching a low of -21.8°C on November 11. This was followed by a brief warm period during which the mean daily temperature reached a high of 1.9°C. Subsequently, the weather became very cold and the temperature dropped to -31°C on November 22. The temperature remained below -15°C for 17 days, 11 of them colder than -20°C, and 3 of them colder than -30°C.

On November 26 bridging was observed at mile 152 with the head of the ice cover at mile 153.2. A heavy slush flow was reported and the ice front had progressed to mile 160 on November 27. Bighorn Dam flow restrictions were initiated on November 27 with the maximum outflow limited to 113.3 m^3/s (4000 c.f.s.) and allowing two units to be on full load for 2 hours over a 24 hour period. On November 29 the ice front was reported at mile 170 with some minor flooding observed at mile 168. The flow was further restricted on November 29 to one hour of two unit full load (158 m^3/s).

On December 1 a mean daily temperature of -30.3°C was recorded and then a warming trend started during which the temperature rose to -1.7°C by December 5. On December 3 the baseflow from the Bighorn Dam was restricted to 31.1 m^3/s (1100 c.f.s.) with an allowable cumulative pulse flow of 70.8 m^3/s (2500 c.f.s.) for one hour and 20 minutes over 24 hours. By December 5 the ice front was observed at mile 184 and some minor flooding was again reported at mile 168. The time for full load for emergency use was reduced to one hour over 24 hours.

After December 5 the temperature dropped over 4 days to just under -15°C, remaining low for two days. The ice front continued to progress upstream and was observed at mile 184.5, 185.5 and 185.9 on December 7, 9 and 10, respectively. Flooding was reported at mile 183 on December 7 where a fence and an oil road were inundated. Ditches along oilwell roads at mile 184 were also flooded. The outflow from the Bighorn Dam was further restricted with emergency use being withdrawn.

The ice front continued to progress slowly upstream, arriving at mile 189.5 on December

17. However, at the same time the mean daily air temperatures were increasing, and subsequently remained at or above zero for eight days (from December 17 to 24), peaking at 4°C on December 18. The warmer weather caused the ice front to retreat back to miles 187.5 and 186.5 on December 20 and 23, respectively.
By December 27 the mean daily temperature had again dropped, reaching -8°C, and it continued between about -5 and -10°C until January 7. Flooding was reported in a field at mile 181 on December 27 and along a fence located between miles 182 and 183.5. With the cooler weather the ice front started to progress upstream, reaching mile 189.1 on December 27, and mile 197 on January 7. Flooding was reported at the head of the cover between miles 195.5 and 197 at that time.

The temperature varied between -10°C and just over 0°C, for 29 days; with only nine of the 29 colder than -5°C. During this period, the ice cover retreated from mile 197 on January 7 to mile 191.5 on January 20. Some flooding was reported in Rocky Historic Park on January 15, but the water level was observed to be dropping on January 17 and 18. On January 20 the temperature remained between -10 and -5°C for four days and the ice cover advanced to mile 196.8 by January 23 with further flooding occurring in the park. The ice front advanced, then retreated going to mile 192.5 on January 27, mile 197.5 on January 31, and miles 196.3 and 198.5 on February 3 and 7, respectively.
On February 6 the mean daily air temperature began a significant decline, reaching a low of -33°C on February 19. The upstream progression of the ice front continued, reaching mile 215 on February 26. This marked the furthest upstream progression of the ice front for this season. Flooding was reported in Rocky Mountain House National Historic Park with the water 0.06 m (0.2 ft.) over the footbridge deck. Flooding was also reported on the flats downstream of the York Boat site.

1986/87 Observations

Figure B.15 shows the mean daily temperatures and ice front locations for the period from October 1986 to February 1987. The temperature remained warm during most of October, then dropped below 0°C at the end of the month. After warming up above 0°C for four days, the temperature again dropped to -20°C on November 9 and remained in that range for five days. The first run of slush in Edmonton was observed on November 8. Throughout the rest of November and December, and into early January, the temperature generally ranged between -15 and 0°C. Mean daily air temperatures increased around 7°C on January 10 and 11 and then the temperature dropped steadily, reaching -19°C on January 19.

Bridging occurred at mile 152 sometime between December 30 and January 8. Bridging also occurred at mile 153, immediately upstream. After January 15, the temperatures remained warmer than -10°C, rising above 0°C for four days in February (February 5 to 8). The ice front progressed upstream to mile 169 by early February and stalled there for most of February. It reached its most upstream point, mile 171, in early March.

1987/88 Observations

Figure B.16 shows the mean daily air temperatures and the ice front progression for the 1987/88 freezeup season. Air temperatures were mild during October and November and remained around -5°C or more for most of November except for November 16 and 17 when the temperature dropped below -10°C. "First ice" was observed in Edmonton on November 17.

The temperature remained mild until December 10, after which when the temperature declined steadily for seven days to about -15°C on December 17 and then fluctuated between 0 and -10°C until December 29. On December 23 an observation flight documented that an ice cover had formed from mile 26.5 (just upstream of Devon) to mile 85 (just upstream of Modeste-Saskatchewan Provincial Natural Area). The surface coverage by frazil floes was estimated to range from 30% just downstream of Rocky Mountain House to 70% just upstream of this cover. The ice cover itself was fairly smooth with numerous open leads. Along the river upstream of the ice cover, border ice was observed on both banks of the river. At mile 152 the open water width had been narrowed by 75% by border ice growth. At Rocky Mountain House the Clearwater River had frozen over and the North Saskatchewan River was overflooding the Clearwater River ice.

On December 30, after 12 days of above -10°C temperatures, the temperature dropped to -20°C. It was noted that temporary bridging had occurred at mile 152 but had subsequently washed out. Surface coverage by frazil floes ranged from 40% at Rocky Mountain House to 70% at mile 142 (near the Brazeau confluence). The open water width at mile 152 was had been reduced to 15 m (50 ft.). Border ice had also constricted the open water width at mile 162.5, but the ice floes were still being extruded through the constriction. At Rocky Mountain House and immediately downstream (mile 191.5 to 183), significant deposits of anchor ice were observed on the channel bed. At mile 191.5 it was estimated that 80% of the bed was covered with anchor ice.

After December 30 the weather warmed slightly for a few days. Bridging at mile 152 was deduced to have occurred on the evening of January 4 or early January 5. An observation flight at 4:00 PM on January 4 did not report lodgment at mile 152, but the surface coverage by frazil floes was reported at 90% and edge ice growth had reduced the open water width to 9 to 12 m (30 to 40 ft.). Upstream to Rocky Mountain House the surface coverage by frazil floes was 70% with no lifted anchor ice observed. On January 7 the head of the ice cover was reported at mile 163 at 10:30 AM and the outflow from the Bighorn Dam was restricted to a maximum of 113 m^3/s (4000 c.f.s.) with two cumulative hours of two unit full load over 24 hours for emergency use.

By January 8 the mean daily temperature had dropped to -25°C. An observation flight on January 8 noted that the head of the pack had progressed upstream to mile 167 and the open water upstream from there to Rocky Mountain House was 50 to 80% covered with frazil floes. Anchor ice was also observed at various locations along the open water reach of the river. Bridging had occurred at mile 145 and the pack was lightly consolidated with several open leads. Roughly 20 to 30% of the water surface immediately downstream of the bridging site was covered with ice floes, indicating that there were significant amounts of frazil ice flowing under the ice cover.

A ground reconnaissance on January 10 found the head of the ice pack to be at mile 175.5. The surface coverage of the water was observed to be 30% immediately upstream of the ice cover and 20% further upstream in the town of Rocky Mountain House. At the dam, the allowable period of two unit full load over a 24 hour period was reduced to one cumulative hour.

On January 12, the mean daily temperature was warmer than -15°C for the first time in nine days and it remained so until January 29. Two sets of aerial observations were recorded for January 12. At 8:15 AM the head of the ice pack was observed at mile 180 and the toe of the pack was at mile 143 but there was evidence that it had been down to mile 142.5. A later flight flown at 3:30 PM recorded the head of the ice pack at mile 179, indicating that a small shove had taken place. Backwater was reported going up creeks adjacent to the ice pack. The portion of the ice pack that had accumulated since January 10 was loosely packed with open leads.

On January 18 the head was reported at mile 183.5 with 60% surface coverage by frazil floes upstream. The ice pack between mile 175 and 183.5 was reported to be smooth with the occasional open lead. By the next morning the head had progressed to mile 184.5 with 70 to 80% surface coverage by frazil floes upstream. On January 19 the maximum outflow from Bighorn Dam was reduced to 36.8 m^3/s (1300 c.f.s.) with pulse flows reduced to a maximum of 70.8 m^3/s (2500 c.f.s.) for one hour over a 24 hour period. On January 21 minor flooding was reported on a county gravel road at mile 180. Backwater from the river was backing up a ditch drain and flooding the road. Upstream from this point the pack was loose with occasional open leads and the head was reported at mile 187. Upstream of the cover there was 20% coverage of the water surface by ice floes. On January 29 the mean daily temperature dropped to -18°C and the temperature remained colder than -15°C for the next nine days (January 29 to February 6). By February 1 the head of the cover had passed through Rocky Mountain House and was up to mile 199, and by February 5 it was up to mile 207.3 with 70% surface coverage of ice floes upstream. The pack was moderately rough through Rocky Mountain House and some overflooding was reported around Rocky Historic Park. There was ice bridging reported at mile 209 near the head of an island, with ice rafting in a narrow section upstream of mile 210. With the head of the pack upstream of Rocky Mountain House, the maximum time for pulse flows was increased to 1.5 hours over each 24 hour period on February 1, and on February 3 the allowable cumulative duration was increased to two hours over a 24 hour period.

On February 5, the ice sheet was reported to be sagging at two locations in Rocky Mountain House, and immediately downstream. Flooding on top of the ice occurred at three sites between the Rocky Historic Park and the Highway 11A bridge, one of which was a location where the ice cover had sagged. Overflooding was also reported at the head of the ice cover.

The temperature slowly increased over the rest of February reaching a high of 8.9°C on February 20. The pulse flow was increased to 85 m^3/s (3000 c.f.s.) over two hours in a 24 hour period on February 10, and then again to 107.6 m^3/s (3800 c.f.s.) on February 14. The baseflow was increased to 42.5 m^3/s (1500 c.f.s.) on February 15, and again to 48.0 m^3/s (1700 c.f.s.) on February 16. Some short open leads were noted between the Highway 11A bridge and the upstream end of Rocky Historic Park on February 15. On February 16 there was some overflooding at the downstream end of the park and a shear wall 3 feet high was reported (from gouging on both banks). The ice was sagging by about 1.2 m (4 ft.) The two-hour pulse flow was increased to 99 m^3/s (3000 c.f.s.), 113.3 m^3/s (4000 c.f.s.), and two unit full load, on February 20, 22 and 23, respectively. The maximum cumulative time for pulse flows was increased to three hours over a 24-hour period on February 25.

A ground reconnaissance upstream from Rocky Mountain House on February 29 reported fresh flooding in a small parking lot on the east side of the Highway 11A bridge, but not to the extent that had been observed during pack formation. There was 0.6 to 1.0 m (2 to 3 ft.) of sag in the ice cover, and occasional open leads. There was also a small amount of overflooding and a short open lead at the downstream end of the park. Upstream of town the Brierly rapids were open and the ice cover had several open leads. At mile 198 there was a 12 m (40 ft .) wide, long continuous open lead in the bend. The head of the pack was at mile 208 but there was evidence that it had been up to mile 213.

1988/89 Observations

The mean daily temperatures and the ice front progression for the 1988/89 freezeup season are shown in Figure B.17. After nine days of above zero temperatures in late October and early November the mean daily temperature dropped and fluctuated between -5 and 0°C from November 8 to 14. Frazil was first noticed in Edmonton on November 10 where surface coverage by frazil floes was about 25%. The mean daily temperature remained between 0 and -10°C for most of November until it dropped to -16°C on November 26. On November 15, 50% surface coverage by frazil floes was observed on the river in Edmonton. A ground observation trip on November 16 and 17 noted 2 to 5 feet of border ice between Drayton Valley and Devon, and 30 to 50% surface coverage of the water surface by frazil floes. Two feet of border ice was also documented in Rocky Mountain House near Rocky Historic Park.

An observation flight between Edmonton and the Genesee Provincial Natural Area on November 24 found the surface coverage by frazil ice to range from 10-15% at the upstream end to 90% downstream of Edmonton. At mile 69 there was evidence of either temporary bridging that had washed out or a heavy slush flow. On November 26, the temperatures rose over five days to above zero and remained there for six days. Another observation flight on November 28 between Edmonton and the Keephills Pumphouse site found that the floes had bridged the channel at mile 25.5 and the head of the pack was at mile 33. The surface coverage of frazil floes upstream of the pack ranged from 10% at Keephills to 90% immediately upstream of the pack.

On November 29, bridging was reported at mile 68 with the head of the accumulation at mile 70, and surface coverage by frazil floes of 60 to 70% upstream of the pack. On November 30 the river was open at mile 68 with 70% surface coverage of frazil flowing through. Temporary bridging was reported at mile 66 with a pack about 60 m (200 ft.) long. Bridging was also observed at mile 25.5 with the pack extending upstream to mile 44. Ground inspections found the head of the pack still at mile 44 on December 2, and at mile 49 on December 6 with 30 to 40% surface coverage upstream. On December 7 the head of the pack was at mile 51 with the surface coverage by incoming ice ranging from 50% at mile 63 to 90% immediately upstream of the pack.

The temperature dropped below zero on December 6 and fluctuated between -10 and 0°C for 13 days until December 19. On December 8 the head of the pack was observed at mile 56, with the surface coverage by frazil floes ranging from 30% to 90% for a seven mile reach upstream of the pack. On December 10 the head was at mile 72, and mile 78 on December 12 with 50% surface coverage by incoming frazil. One to 1.5 m of border ice growth was recorded in Rocky Mountain House along both banks near Rocky Historic Park on December 14 and 16.

By December 15 the pack had progressed upstream to mile 82.3. The surface coverage by incoming ice floes upstream to mile 152 varied from 10-15% at mile 125 and 152, to 90% at mile 90.5. Immediately upstream of the ice pack the surface concentration was 40%. The decrease in the surface concentration at the pack head was due to a restricted section at mile 83 where the floes were rafting. Anchor ice was visible in the rapid areas from mile 125 upstream to Rocky Mountain House. It was specifically recorded at miles 152, 180 and 187.5. At mile 152 the incoming surface coverage of ice was 40 to 50% with rafting occurring in the bend around mile 152. The surface coverage of ice floes varied from 10% at Rocky Mountain House to 50% in the bends around mile 180.
On December 20 the temperature dropped to below -15°C for eight days (December 20 to 27), and for two of those days ranged between -25 and -20°C. On December 22 an observation flight noted very little border ice areas in the reach upstream of mile 152 but anchor ice was visible in rapids areas. The surface coverage was reported as 60% between Rocky Mountain House and mile 152. Bridging was recorded at mile 152 on December 25.

The weather warmed up for a few days reaching a high of -5°C on December 29. With the ice front at mile 169, the first stage in the flow restriction was initiated with the outflow from the dam restricted to 113.3 m^3/s (4000 c.f.s.) maximum. Over the next eleven days (December 30 to January 9) the temperature dropped to -22°C for one day, warmed up to between -5 and -10°C for three days and then dropped to below -20°C for four days. The pack continued to grow slowly until it reached mile 185 on January 8. On January 7 the Bighorn baseflow was restricted to 31.1 m^3/s (1100 c.f.s.) and the pulse rate to a maximum of 70.8 m^3/s (2500 c.f.s.) for 1 hr 20 minutes over a 24 hour period. The upstream progression rate of the ice cover increased as a consequence of the cooler weather and the ice front passed through Rocky Mountain House on January 9. The weather warmed up again and the mean daily air temperatures remained above -15°C from January 10 to 30, except for 2 days when the temperature was -17 and -21°C and four days when the temperature was above or very close to 0°C. Pack growth was fairly slow, reaching mile 205 on January 27. On January 16 the pulse rate was increased to 70.8 m^3/s (2500 c.f.s.) for 2 hours over a 24 hour period. On January 21 it was increased to 113 m^3/s (4000 c.f.s.) and on January 24 the base flow was increased to 36.8 m^3/s (1300 c.f.s.) with no change in the pulse flow. On January 30 the pulse rate was increased to 84.9 m^3/s (3000 c.f.s.) for 2 hours over a 24 hour period.

Early February was very cold again with temperatures lower than -25°C for four days, and two of them colder than -35°C. The pack progressed to its most upstream observed point, at mile 215, on February 1. For the rest of February the temperature was above -15°C except during mid-February when the temperature ranged between -30 and -20°C for four days. On February 1 the pulse rate was increased to 99.1 m^3/s (3500 c.f.s.), and on February 2 to 113.3 m^3/s (4000 c.f.s.). On February 3 the baseflow was increased to 42.5 m^3/s (1500 c.f.s.) with the pulse rate decreased to 84.9 m^3/s (3000 c.f.s.) and on February 8 the pulse rate was increased to 113.3 m^3/s (4000 c.f.s.) for 2 hours over a 24 hour period. With the warmer weather, the pack started a slow retreat and the head was observed at mile 209.4 on February 22.

1989/90 Observations

Figure B.18 shows the mean daily temperatures and the ice sheet progression for the 1989/90 freezeup season. Temperatures remained fairly warm through October with some temperatures slightly below zero towards the end of the month. Throughout November the temperature ranged from a low of around -15°C to highs above zero. Border ice and frazil floes were observed in Edmonton on November 13. The surface coverage by frazil ice on November 13 was 15% and 50 to 60% on November 16. Ice bridging was reported in Edmonton on November 17.

No bridging was reported upstream until November 27 when five ice packs were identified between Devon and Drayton Valley. Upstream of these packs, the river was open with surface concentrations of frazil varying between 50 to 90% in some bends. At the ice pack forming just downstream of Drayton Valley, lifted anchor ice was documented as part of the ice cover. Also at Rocky Mountain House, lifted anchor ice was observed to be forming part of the surface floes.

The temperature in December followed a similar pattern to that in November with the temperature dropping for one day to -20°C on December 10. The temperature warmed up to just over zero on December 14 and then dropped to -29°C on December 20. For four days the temperature was colder than -20°C. Mile 152 was bridged between December 20 and 22. On December 23 the temperature warmed up to 2.5°C and then fluctuated between about -15°C to zero until the end of the month. Flow restrictions were imposed on December 27. By December 28 the ice front was at mile 168.

The mean daily temperature for the first three weeks of January varied between about -15 and 0°C and the ice cover progressed slowly, passing through Rocky Mountain House on January 31. The mean daily temperatures are shown in Figure B.19 along with the outflow from the Bighorn Dam. By February 14 the ice front had progressed up to mile 207, its maximum extent for this season. Upstream of the ice cover, border ice from both banks narrowed the open water channel to 10 m (30 ft.).

1990/91 Observations

The mean daily temperatures and the ice front progression for the 1990/91 freezeup are shown in Figure B.20. In October the mean daily temperatures remained close to zero until the end of the month and then dropped to -5.5°C. From November 1 to November 10 the temperature fluctuated between -1.5 and +6°C. Then, over the next five days, the temperature dropped steadily to -15°C.

It was not until mid-to late November that the temperature was consistently cold enough to generate significant amounts of frazil ice. A reconnaissance flight on November 27 noted that the river was open but at mile 152 there was a surface coverage of frazil ice of 50%. By the end of the first week in December five different ice packs were growing between Devon (mile 24) and the Blue Rapids (mile 130). The river was also being narrowed by the growth of border ice in the reach between the confluence with the Brazeau (mile 140) and mile 152. The open water between these two sites was 30% covered with frazil floes.

In mid-December the temperature started to drop dramatically, reaching a low of -33°C on December 20. For the last half of December, 9 days were close to or below -20°C. By December 14 the head of the pack was at mile 133.5 and the surface coverage with frazil floes upstream was 60 to 80% between mile 152 and the ice front, and 50 to 60% upstream of mile 152. There was also anchor ice visible on the bed upstream and downstream of mile 152. On December 19 it was noted that the ice had bridged at mile 164 and at mile 142, but no bridging had occurred at mile 152.

By December 21 the ice front was 2.5 miles downstream of the Highway 11 bridge crossing (located at mile 185). The water surface upstream was 50 to 60% covered with frazil ice floes. By December 24, the ice front was upstream of Rocky Mountain House and on December 28 flooding was reported in the Rocky Mountain House Historical Park (which had probably occurred on December 23 or 24).

On December 29 the water level was down but a shove occurred on January 3, with the toe of the accumulation located at mile 190.1. Ice was shoved into the trees at mile 191.8 and Rocky Historic Park was flooded. The cold temperatures continued until about January 12. Another shove occurred, with the toe at mile 192.6, on January 11. On

January 11 the most upstream position of the ice pack was reported to be at mile 227. After this, the temperature warmed and the ice pack did not move upstream significantly.

1991/92 Observations

The mean daily temperatures and the ice front progression for the 1991/92 freezeup are shown in Figure B.21. In late October and early November there were eight days with temperatures colder than -10°C,with five of them colder than -15°C. Surface coverage by frazil ice of 50 and 80% were observed in Edmonton on October 27 and 28, respectively. Upstream of Edmonton to mile 92 (Berrymoor Bridge) frazil ice surface coverages of up to 80% and higher were reported in bends. Frazil ice was observed in Rocky Mountain House and area on October 29 with a surface coverage of 40 to 50% and on November 3 with a surface coverage of 30%. A small amount of border ice was also observed. After November 2, the mean daily air temperature gradually increased to a high of 5°C on November 16. An aerial reconnaissance on November 6 observed two ice sheets forming, one between mile 19 and 24 and one between mile 26 and 65. Upstream of mile 65 the surface coverage of the water by frazil floes varied from 5% to 50% and up to 60% in bends. By November 12 the ice front was had progressed upstream to mile 70. The ice cover itself was inspected on November 14 at several points and it was reported to mostly smooth and unconsolidated (mile 62.8) or lightly consolidated (mile 52.4).
In the latter half of November the mean daily temperatures followed a slow decline to a low of -17°C on December 4. The ice front progressed slowly upstream reaching mile 84 on December 2. After December 4 the weather warmed up and the mean daily temperature generally fluctuated between 0 and -10°C until the beginning of February, although there were several isolated days where the temperature went higher or lower than these boundaries. The ice cover progressed slowly upstream reaching mile 103 on December 9. That same day, border ice was observed at mile 152, and the surface concentration of frazil floes ranged from 5 to 10%. On December 13 the ice front was observed at mile 107.

On December 17 the mean daily temperature went down to -17°C for one day and on December 19 the surface concentration of frazil floes was observed to range from 10% around mile 152, to 50-60% between miles 166 and 174. Just downstream of Rocky Mountain House, the surface concentration was 20-30%. That same day the ice front was observed at mile 112. The ice front continued to progress slowly reaching mile 131.5 on January 15. On that day the river was flown from the ice front, at mile 131, upstream to Rocky Mountain House and the surface coverage by frazil was observed to vary from 40% to 100%. Rafting the full width of the river was observed at mile 152. The rafts would break up further downstream.

Temporary bridging was noted at mile 152 on January 19 although the duration was not recorded. The ice front continued to progress slowly upstream reaching mile 134 and 137 on January 21 and 27, respectively. The ice front remained at mile 137 until at least February 4. On February 4 the temperature peaked at 9.5°C, after several days of above zero temperatures. The temperature then dropped over the next 6 days to a low of -19°C on February 10. It then gradually warmed up over the next six days to a high of -4.5°C on February 16. The ice front was reported at mile 142 on February 12 with 70 to 80% surface coverage upstream. The surface coverage upstream of mile 152 was 50 to 60% and the ice floes were forming rafts and then breaking up downstream.

The air temperatures dropped to a low of -23°C on February 20. The ice front was reported at mile 155 on February 21 with some overflooding reported at mile 154. Mean daily air temperatures increased and were above zero on February 25. On February 26 the ice front was reported at mile 157.5 but although there was evidence that it had been further upstream, the exact location was not documented. This marked the furthest upstream extent of the ice front for this season. With the warmer weather at the end of February, the ice sheet started its retreat downstream.

1992/93 Observations

The mean daily temperatures and the ice front progression are for this year are shown in Figure B.22. Temperatures were fairly mild throughout October and November remaining above -15C until mid-December. Ice floes were first observed in Edmonton on November 12, 1992. By November 27, bridging had occurred at mile 26.5 and the head of the ice cover was at mile 39.5. From there the ice cover was reported at the Genesee Bridge on December 4 (mile 52), Keephills Pumphouse (mile 63) on December 6, Berrymore Bridge (mile 92) on December 16, Rose Creek (mile 122) on December 27, and mile 136 on December 31.

In late November, the mean daily temperatures began a steady declining trend ranging between -35 and -8°C between December 16 and January 20. On December 19 the first observation flight was flown, examining river conditions between Rocky Mountain House and the Brazeau River. The river was open with surface frazil floe coverages of 70 to 80% near Rocky Mountain House and 90 to 95% at mile 152. On December 28 the reach between Rocky Mountain House and the Brazeau was flown again, and the river was still open with 80% surface coverage and rafting of the ice flows in bends. Bridging did not occur at mile 152 this season. It occurred at mile 144, probably late on December 28. On December 28 the maximum outflow from Bighorn was restricted to 133.3 m^3/s (4000 c.f.s.) with two unit full load for two hours over a 24 hour period. This was reduced to two units full load for one hour over a 24-hour period on December 31. There was still open water between the two ice covers between mile 136 and mile 144 with snow covered border ice between mile 140 and 144. The head of the upstream ice cover was between mile 174 and 177 and the surface coverage by frazil floes was 90% upstream. Between mile 144 and 177 the ice cover was lightly consolidated with open leads.
On January 2 the Bighorn outflow was restricted to 42.5 m^3/s (1500 c.f.s.) with no emergency use. By January 3 the ice cover had progressed up to mile 181 with 50% surface coverage upstream. On January 5 the ice front progressed from mile 190 at 2:30 PM, to 192.5 at 11:00 PM. On January 6 there was about 0.6 m (2 ft.) of water in the channel at the foot bridge in Rocky Historic Park.

On January 7 the ice cover was ground inspected through Rocky Mountain House and was reported to be lightly to moderately consolidated. The cover continued to progress upstream, reaching mile 195.5 on January 8, and mile 199 on January 10 with 90% surface coverage upstream. On January 10 evidence of a consolidation movement at the upstream end of the ice cover was noted. The toe of the shove was at mile 193.8 and the head at mile 199. Downstream of mile 199 the ice was solidly packed. On January 12 the head of the ice cover was upstream of mile 205. Figure B.23 presents the Bighorn Dam outflows and the water levels at the Prentice Creek and Rocky Historic Park gauges for this period. Bighorn Dam outflow restrictions were eased on January 13 to 42.5 m^3/s (1500 c.f.s.) baseload with a 2 hour peak of one unit at full load once over a 24 hour period. This restriction was modified to one hour for one unit full load for the morning peak and one hour two unit full load at the evening peak on January 16.

On January 18 a farmer complained that a fence had been knocked down near mile 195.5. Over flooding was reported near mile 199 with the flood waters approaching a fence line. The upstream limit of progression of the ice cover was at mile 221.5, but the corresponding date is not known. Throughout February the restrictions on Bighorn Dam outflows were slowly eased. By February 16, the Bighorn Dam could be used for load control 24 hours a day up to a mean daily flow of 82.1 m^3/s (2900 c.f.s.) with two unit full load restricted to two hours over a 24 hour period.

1993/94 Observations

Figure B.24 shows the mean daily temperatures and the recorded ice front locations for the 1993/94 freezeup season. Temperatures remained fairly mild through October and early November. In mid-November the temperature dropped to -25°C and then warmed up to close to zero again. The first field observations were conducted in Rocky Mountain House on November 23. Border ice 4.5 m and 3.0 m (15 and 10 ft.) wide was reported at the Highway 11 bridge and Rocky Mountain House National Historic Park, respectively. There was 70 to 75% surface coverage of the water surface by frazil ice floes. Observations on November 25 found that the ice had bridged at miles 96 and 106. Ice floes were still moving past mile 152, but there was temporary bridging at mile 163 which later washed out.

In December the mean daily temperatures varied between lows of -15 and highs above zero. On December 17 bridging was observed at miles 82.5, 95.5 and 100. The most upstream head of the ice cover was at mile 117. Surface coverage varied from 90% at mile 127 to 40 to 50% at mile 174. Border ice was noted in the reach between mile 127 and 152.

The temperature dropped in January and remained at -15°C or lower for 14 days. Towards the end of the month it warmed up to close to zero. By January 6 the head of the ice cover had progressed upstream to mile 135 with 70 to 80% surface coverage by frazil floes upstream. In the bends 100% of the surface was covered with moving ice floes. Upstream from mile 152 to Rocky Mountain House the river was covered with heavy ice fog. By January 12 the head of the ice cover was at mile 144 with 70% surface coverage of floes observed at mile 152. Downstream of the head, the ice cover was heavily consolidated. On January 17 the head was at mile 169 with 80 to 90% surface coverage upstream to Rocky Mountain House. It is not clear in the record whether bridging occurred at mile 152 or if the downstream ice cover simply progressed through mile 152.

On the evening of January 19 flooding was reported on the district road, 16 miles north of Rocky Mountain House at mile 174. The site was inspected on January 20, but the water had receded significantly by that time. The location of the head of the ice cover was estimated to be at mile 181 and the river was open at mile 186. Figure B.25 shows the effect of the ice front on water levels as it passed the Prentice Creek and Rocky Historic Park gauges.

The mean daily temperatures dropped in early February reaching a low of -35°C on February 7. There were three days when the temperature was colder than -25°C (February 6 to 8). Observations on February 11 estimated the ice cover head to be between mile 199 and 200. The head of the ice cover was flooded at the centre of the channel. Upstream of the cover there was 60% coverage of the water surface by frazil ice floes. Through Rocky Mountain House there were several open leads and some overbank flooding occurred at mile 194. On February 17 the head of the ice cover was still at mile 199 but the cover was sagging up to 1 to 1.2 m (3 or 4 ft.) in locations, and open leads were observed. On February 17 the temperature dropped below -15°C for ten days before warming up at the end of the month. The furthest upstream extent of the ice cover was at mile 221 and it likely occurred during that period.

1994/95 Observations

Figure B.26 shows the mean daily temperatures and observed ice front locations for the 1994/95 freezeup season. Figure 4.28 shows the water elevations at the Rocky Historic Park and Prentice Creek gauges sites along with the outflow from Bighorn Dam as the ice front progressed through Rocky Mountain House. Observations did not begin until December. Temperatures during October and November remained warmer than -12°C. On December 2 the mean daily temperature dropped to -21°C and remained below -20°C for four days. Then for eleven days it remained around -15°C until December 16. On December 5 it was speculated by the observers that the ice had lodged in the bend between mile 20 and 23 near Devon. Further upstream, observations recorded on the afternoon of December 6 between mile 125 and 190 noted significant border ice growth at mile 152 with 70% surface coverage by ice floes at that location. Anchor ice was observed to be lifting in the vicinity of Rocky Mountain House. No ice bridging was observed in this reach.

On the afternoon of December 9 an ice cover was observed with its toe at mile 92 and its head at mile 124. Upstream of the cover the surface coverage by frazil floes was 70 to 80%. At mile 152 the river was still open with 10 to 20% surface coverage by floes. The temperature varied between -10 to 0°C for 13 days until December 29. By

December 22 the ice cover head was at mile 132.5. Upstream of the ice cover, 25 to 50% of the bed was covered with anchor ice deposits. Further upstream to Rocky Mountain House limited border ice development was noted along with significant anchor ice deposits and a surface coverage by ice floes of 10 to 20%.

On December 30 the mean daily temperatures started to drop reaching a low of -25.5C on January 3 and remained below -15°C for 10 days (December 31 to January 9). On December 30 the head of the ice cover was at mile 137.6. Downstream to mile 133 the cover was smooth or lightly consolidated with some small open leads. Further downstream the cover was well consolidated. Upstream of the cover the surface coverage with frazil floes was 50 to 60% and approximately 50% of the bed was covered with anchor ice. Some of this anchor ice was observed to be lifting. The surface coverage of frazil floes coming in from the Brazeau River was 20%. At mile 152 the surface coverage was 85%, with 50% of the bed covered with anchor ice. The floes were rafting in the bends but no bridging had occurred. Upstream to Rocky Mountain House the surface coverage varied between 70 and 80% with 40 to 60% of the bed covered with anchor ice. Some rafting of the ice floes was occurring in the bends.

An observation flight on January 5 noted that the head of the ice cover was at mile 158 with significant anchor development on the bed. Immediately downstream there were some open leads. It is not recorded whether the ice cover downstream grew up to this point or if another bridging point was found.

The mean daily temperature remained around -10°C for several days before slowly dropping to a low of -18°C on January 24. The mean daily temperature then increased and remained above -10°C until February 9. On February 10 the temperature started to drop, reaching a low of -21°C on February 13 and remaining below -18°C for 6 days. On February 17 the mean daily air temperature warmed up and for seven days was above -6°C (February 19 to 25). The last three days of February were cold again. The ice front passed the Prentice Creek gauge (mile 184.94) about February 14 (Figure B.27). About February 19 the ice front passed the Rocky Historic Park gauge but the water level dropped on February 21, indicating that a shove may have occurred. On February 27 water levels at the Rocky Historic Park gauge rose again, indicating that the ice front was approaching. The water level remained high, indicating that the ice front had passed the gauge.

1995/96 Observations

Figures B.28 and B.29 show the mean daily temperatures and ice front locations, and the water levels for the Rocky Historic Park and Prentice Creek gauge sites together with the Bighorn Dam outflows, respectively. The mean daily air temperatures remained above zero throughout most of October, dropping to around -5°C for the last three days. In early November the temperatures dropped to -13°C on November 1 and -19°C on November 10 with warmer periods in between. On November 28 the temperature went down to -17°C before warming up to around -9°C for four days. On December 4 the mean daily temperature started dropping, reaching a low of -30.5°C on December 8. The temperature remained below -19°C for 11 days (December 5 to 15).

On the afternoon of December 8 the automatic gauge at Rose Creek (mile 122) began staging up and by noon on December 10 the water level had peaked approximately 3 m (10 ft) above the ice free water level. It was estimated that the head of the pack was between mile 122 and 130 at that time. From other reports it was judged that the ice sheet was fairly continuous from Devon (mile 24) to Rose Creek. An observation flight on December 8 between Rocky Mountain House and the Brazeau confluence noted the surface coverage by frazil floes at mile 140 was 20%. No anchor ice was observed. The floes had not bridged at mile 152 but bridging had occurred at mile 162 with the head of the ice cover located at mile 165. No ice was seen flowing downstream from the toe and the surface coverage upstream of the ice cover was 80% to Rocky Mountain House. An observation flight on December 12 confirmed that the ice cover was fairly solid from the TAU pumphouse (mile 62.8) upstream to mile 126. The surface coverage by frazil floes was 50% upstream of the head of the ice cover. Downstream of the Brazeau confluence there was a heavy ice run as the North Saskatchewan upstream of the Brazeau had a surface coverage of 60% and anchor ice from the Brazeau River, possibly flushed out by the Brazeau facility startup, was flowing into the North Saskatchewan. At mile 152 no bridging had occurred and the surface coverage there was 30%. The ice cover with its toe at mile 162 had progressed upstream to mile 180 and upstream of the head there was 80% surface coverage by frazil floes. On December 13 the outflow from the Bighorn Dam was stabilized at 40.9 m^3/s (1445 cfs) as seen in Figure 4.30.

After December 15, the mean daily air temperatures varied from a low of -16°C to highs around zero until January 3. The temperatures then dropped below -20°C for three days (January 4 to 6), with a low of -33°C on January 5. On January 7 the mean daily air temperatures again rose to around zero and remained between -10C and zero until January 12. Then, on January 13 a prolonged cold spell started. Temperatures were below -20°C for 20 of the next 22 days, with seven of those days experiencing mean daily air temperatures -30°C or colder.

A December 18 an observation flight found the ice cover downstream of the Brazeau to be well consolidated. The head was at mile 130 with no frazil floes observed upstream. Upstream from the Brazeau to mile 152 heavy deposits of anchor ice were noted. Anchor ice was still present upstream of mile 152, but in decreasing quantities. The ice cover had extended upstream to mile 194 and some minor flooding was observed at Rocky Mountain House National Historic Park.

On December 22 the head of the ice cover downstream of the Brazeau River confluence was at mile 132, 2 miles upstream from its position on December 18. Immediately upstream of the cover the surface coverage by moving frazil floes was 70%, decreasing to 40% at mile 134, down to 20 to 30% at mile 136, and to 10 to 20% at mile 161. All along this reach major anchor ice deposits were noted. The upstream ice cover's toe was at mile 162.5 and its head was at mile 196.1, with water flooding over the ice at that point. Upstream of the head there was about 30% surface coverage by moving frazil floes. There were several open leads noted including one that was 1.5 mile long. Slush was flowing through all of these open leads.

The last observation flight was conducted on January 6. The head of the ice cover was between mile 201.5 and 209 at that time. Upstream of this some frazil floes were noted. Between Rocky Mountain House and the head, there were several open leads, with some slush flowing in them. At mile 201.5 the ice was well consolidated and there was some water flooding the ice along the banks for 15 to 30 m)50 to 100 ft.).
On February 5 the mean daily air temperature increased and it remained above -10°C until February 24. On February 24 the temperature dropped to below -20°C for four days and then on February 29 it warmed up to -2°C.

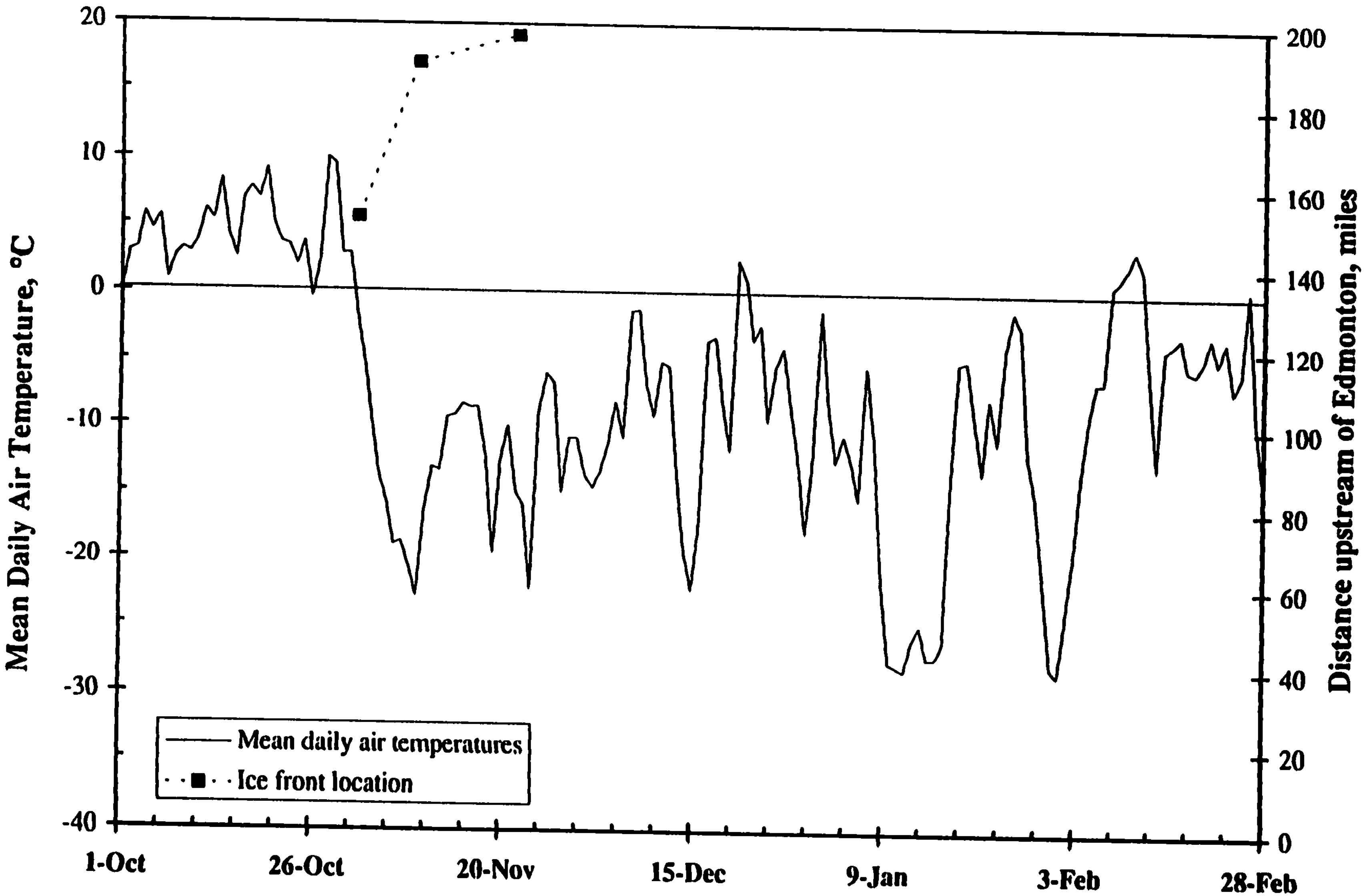

Figure B.1 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1973/74 freezeup season.

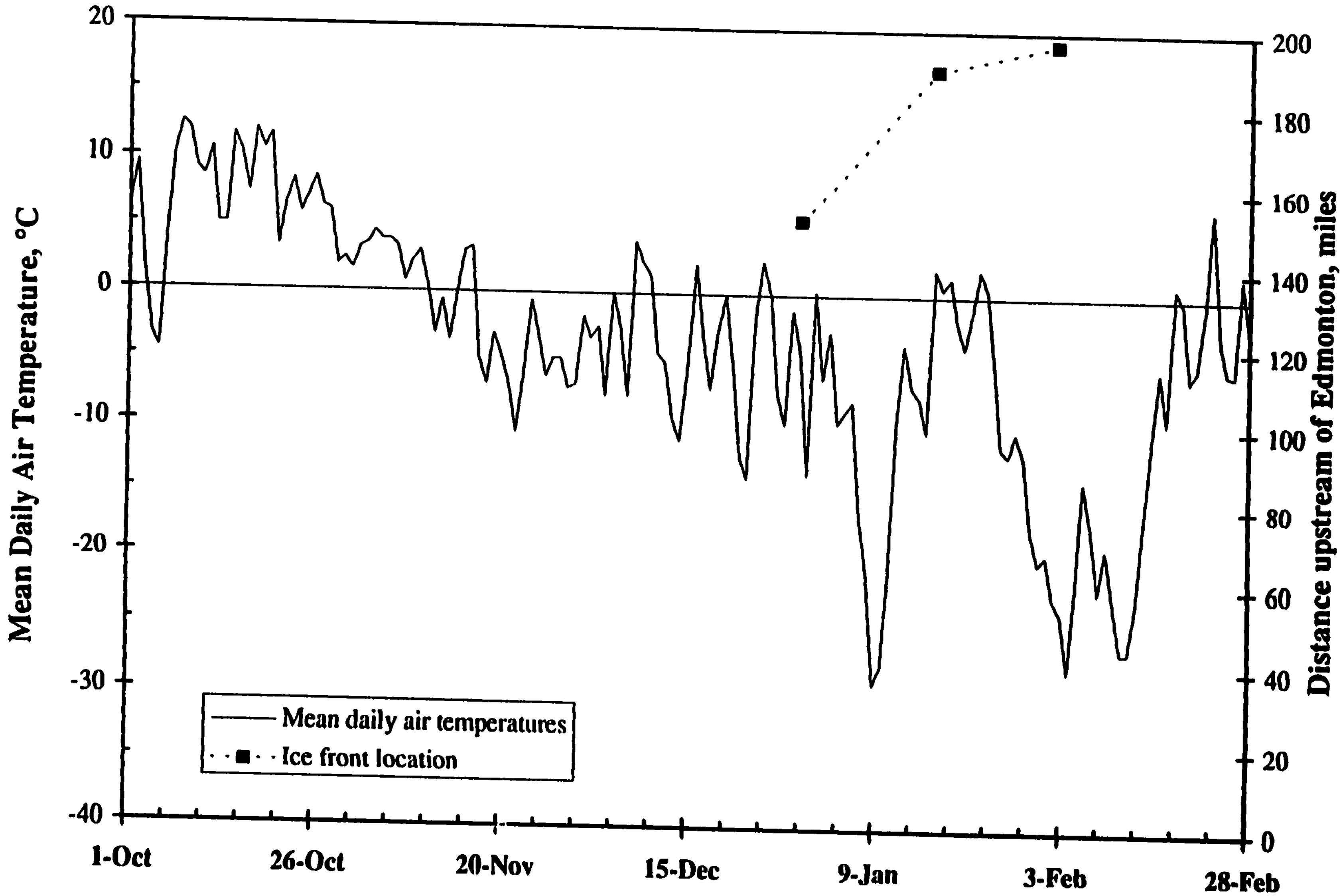

Figure B.2 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1974/75 freezeup season.

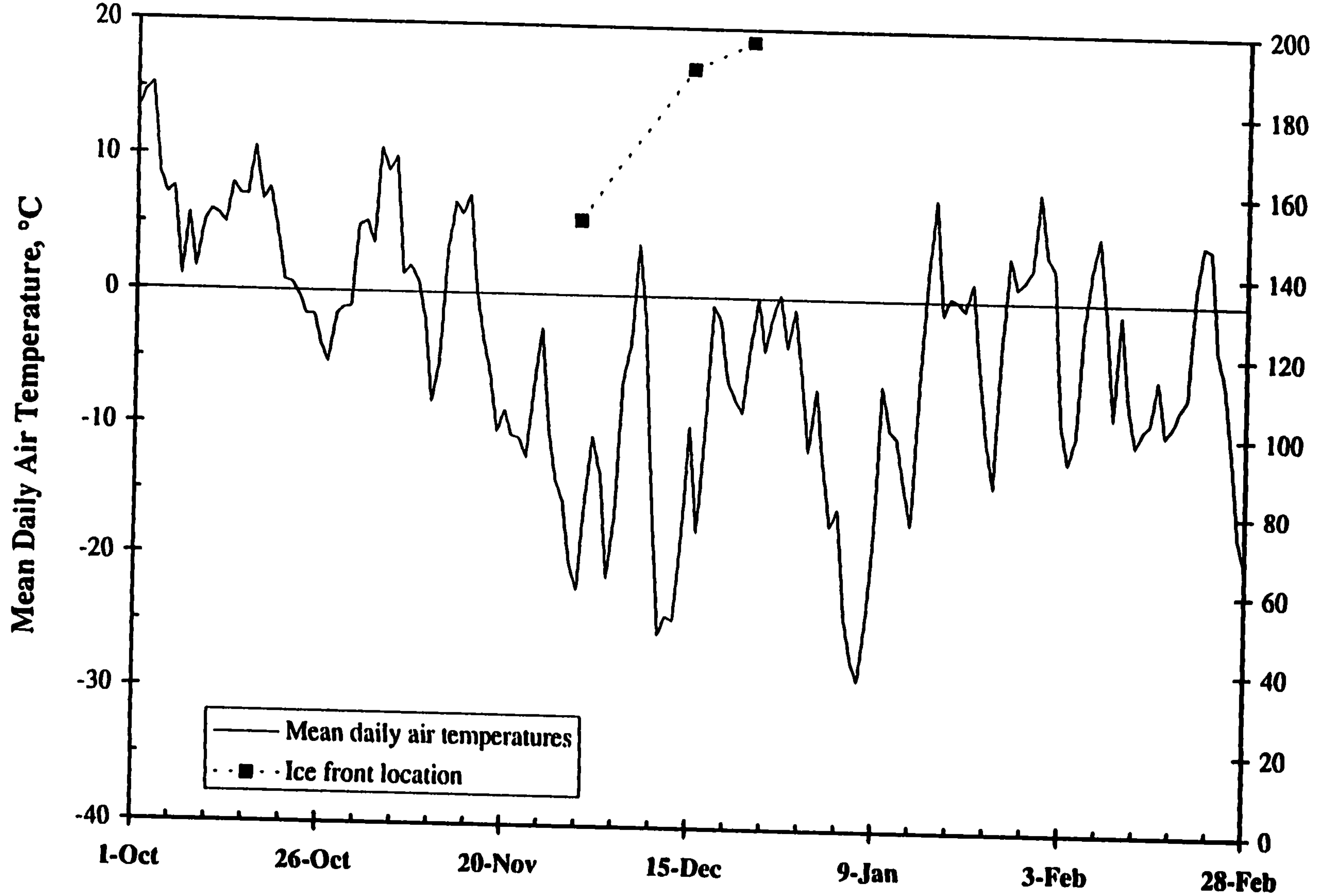

Figure B.3 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1975/76 freeze up season.

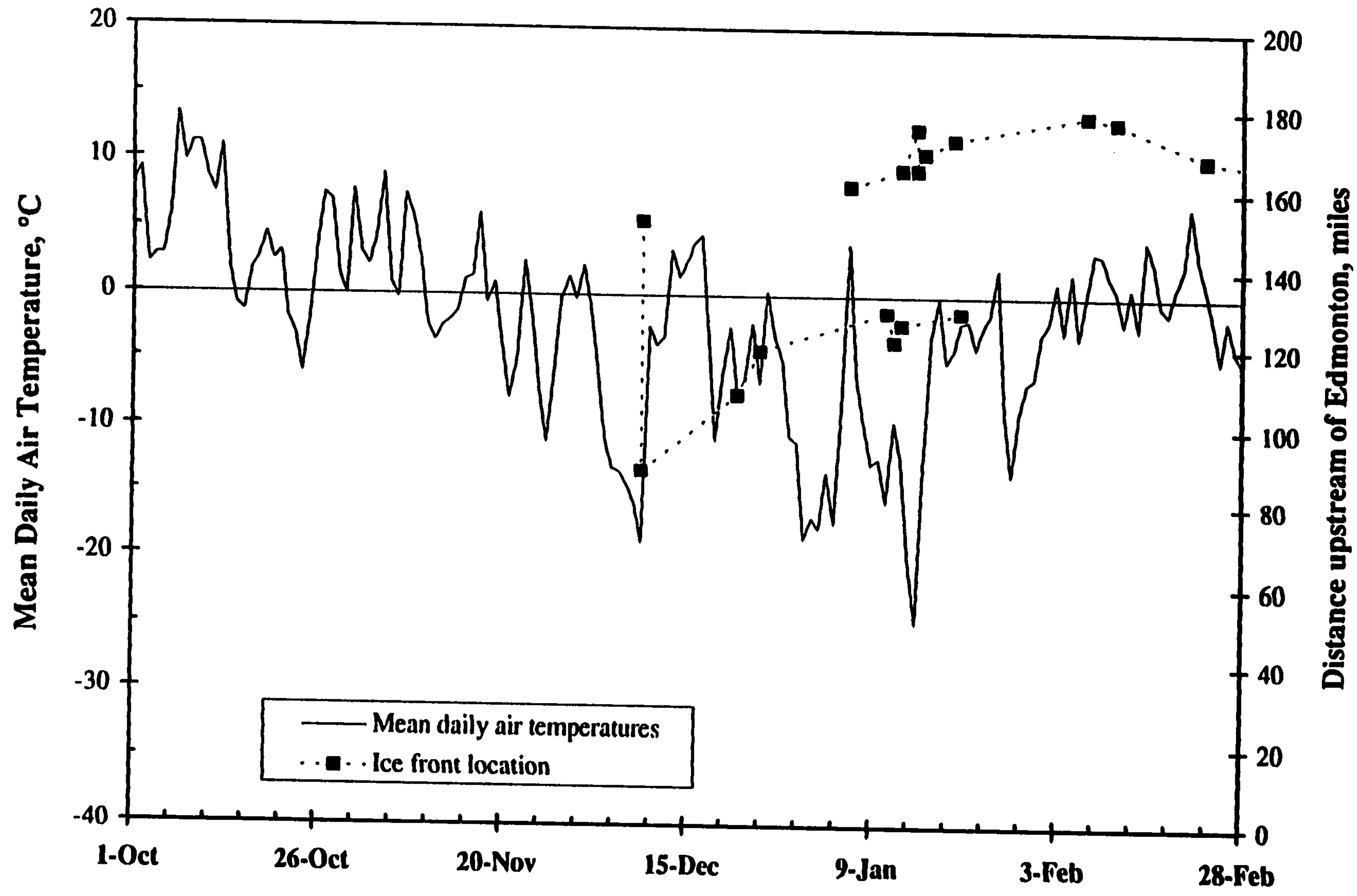

Figure B.4 Mean daily temperatures at Rocky Mountain House the recorded ice front location for the 1976/77 freeze up season.

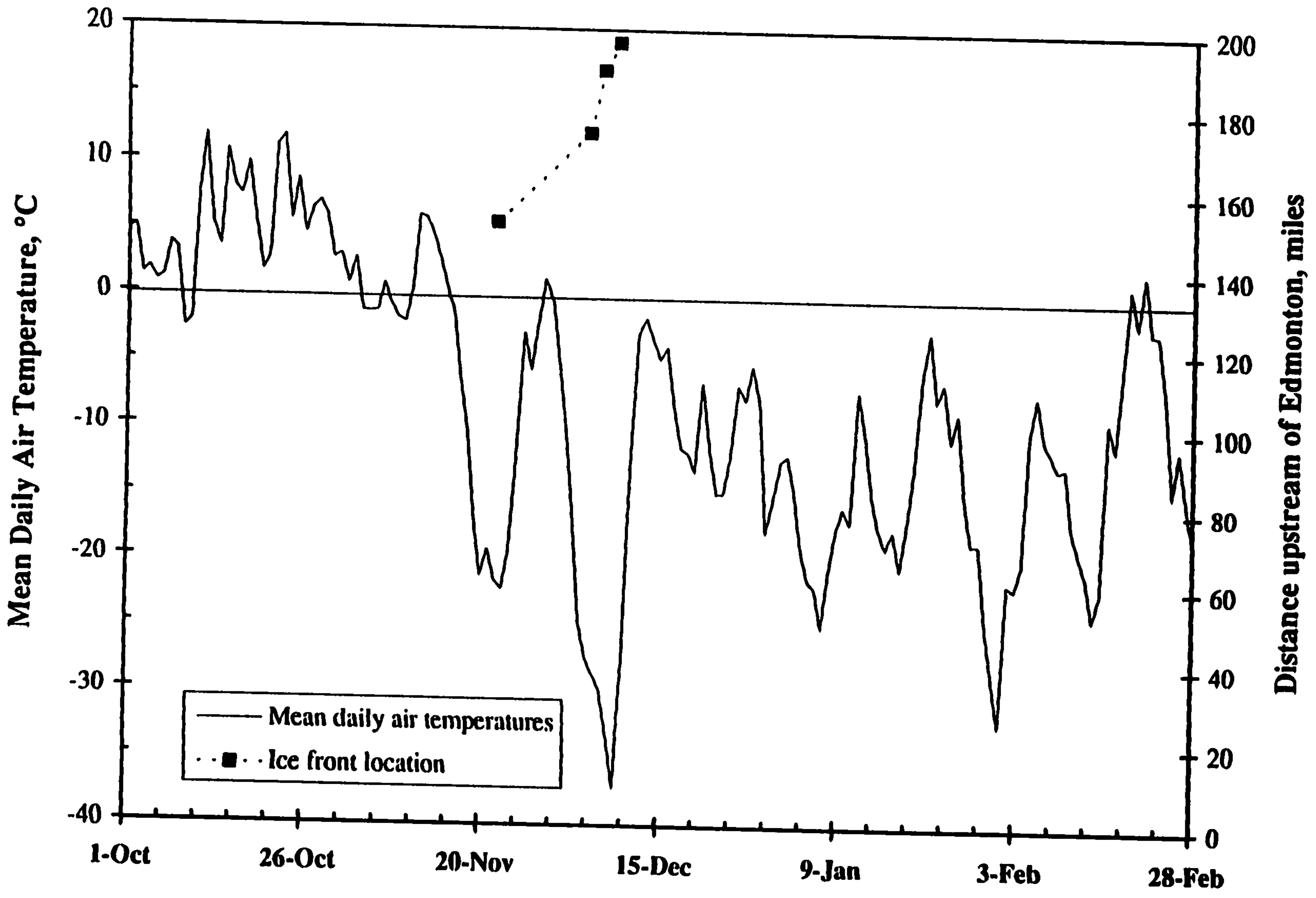

Figure B.5 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1977/78 freeze up season.

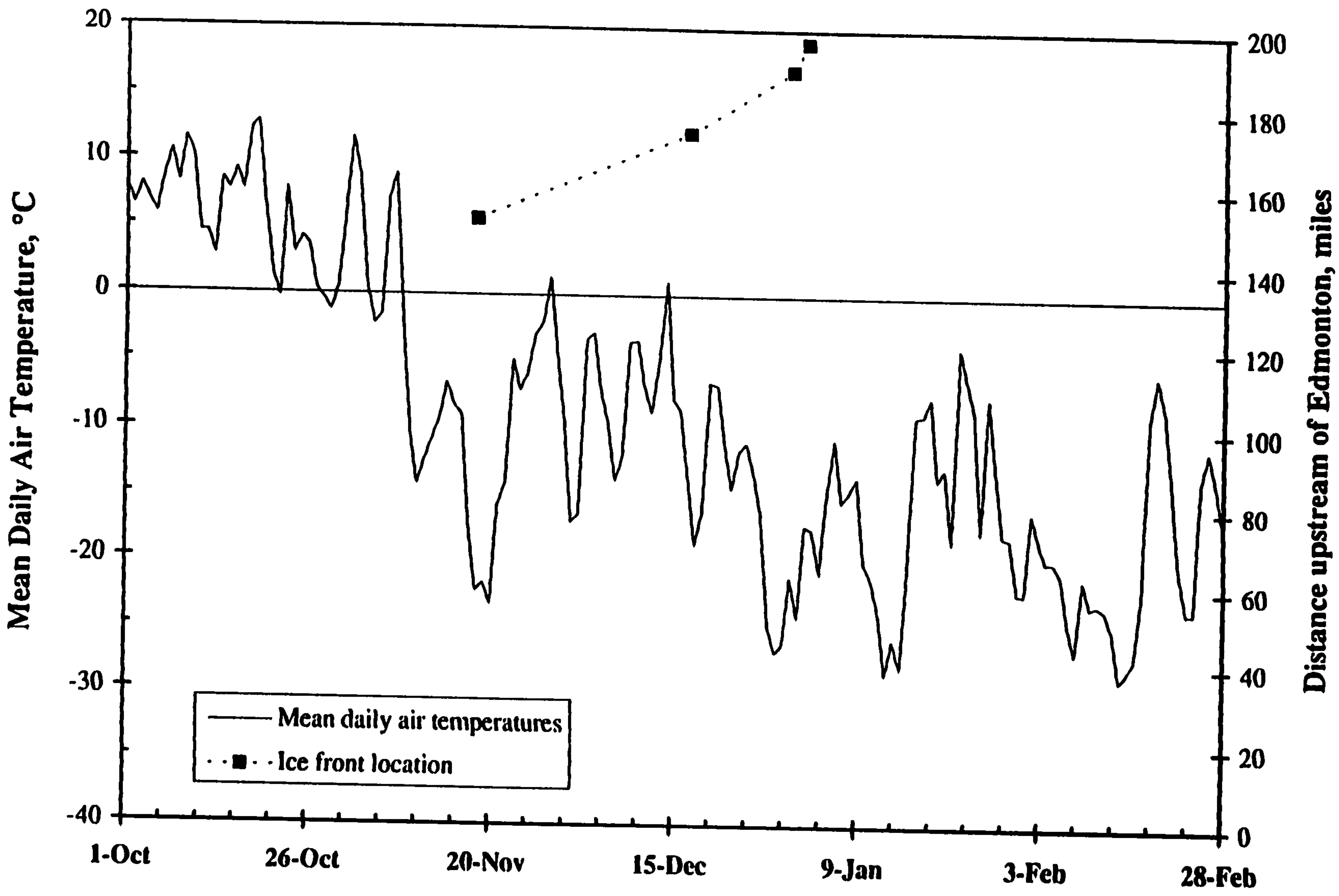

Figure B.6 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1978/79 freeze up season.

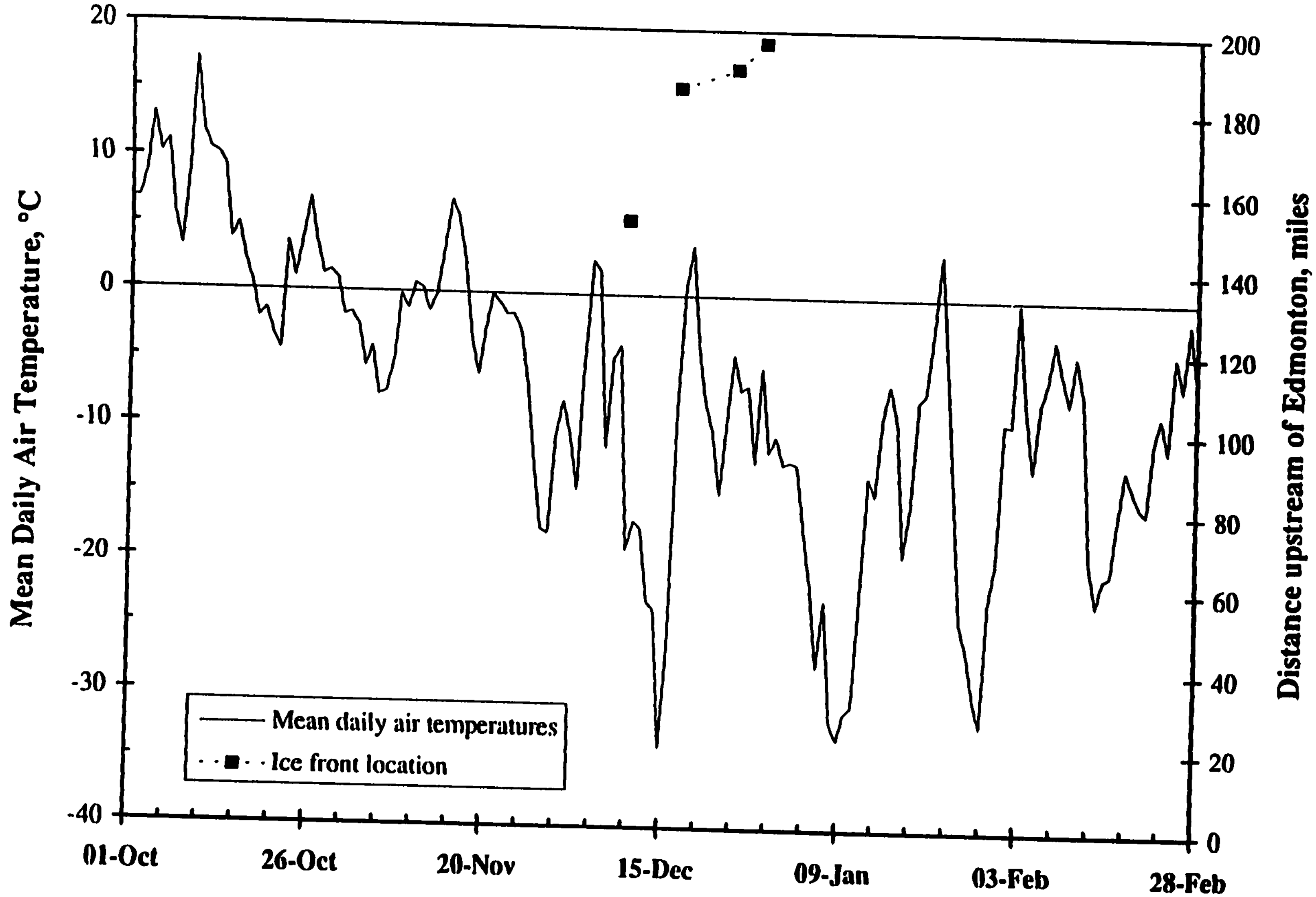

Figure B.7 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1979/80 freezeup season.

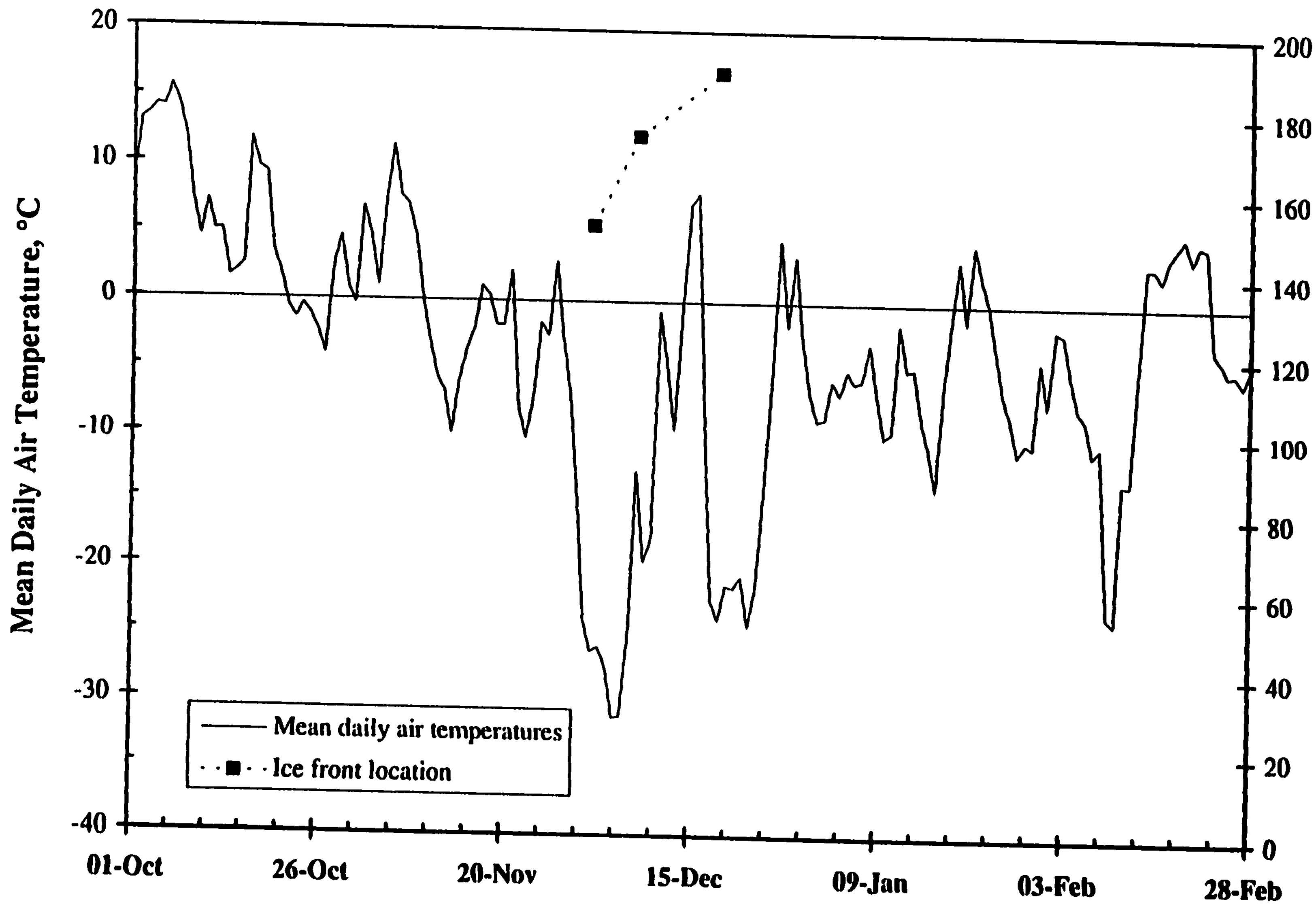

Figure B.8 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1980/81 freezeup season.

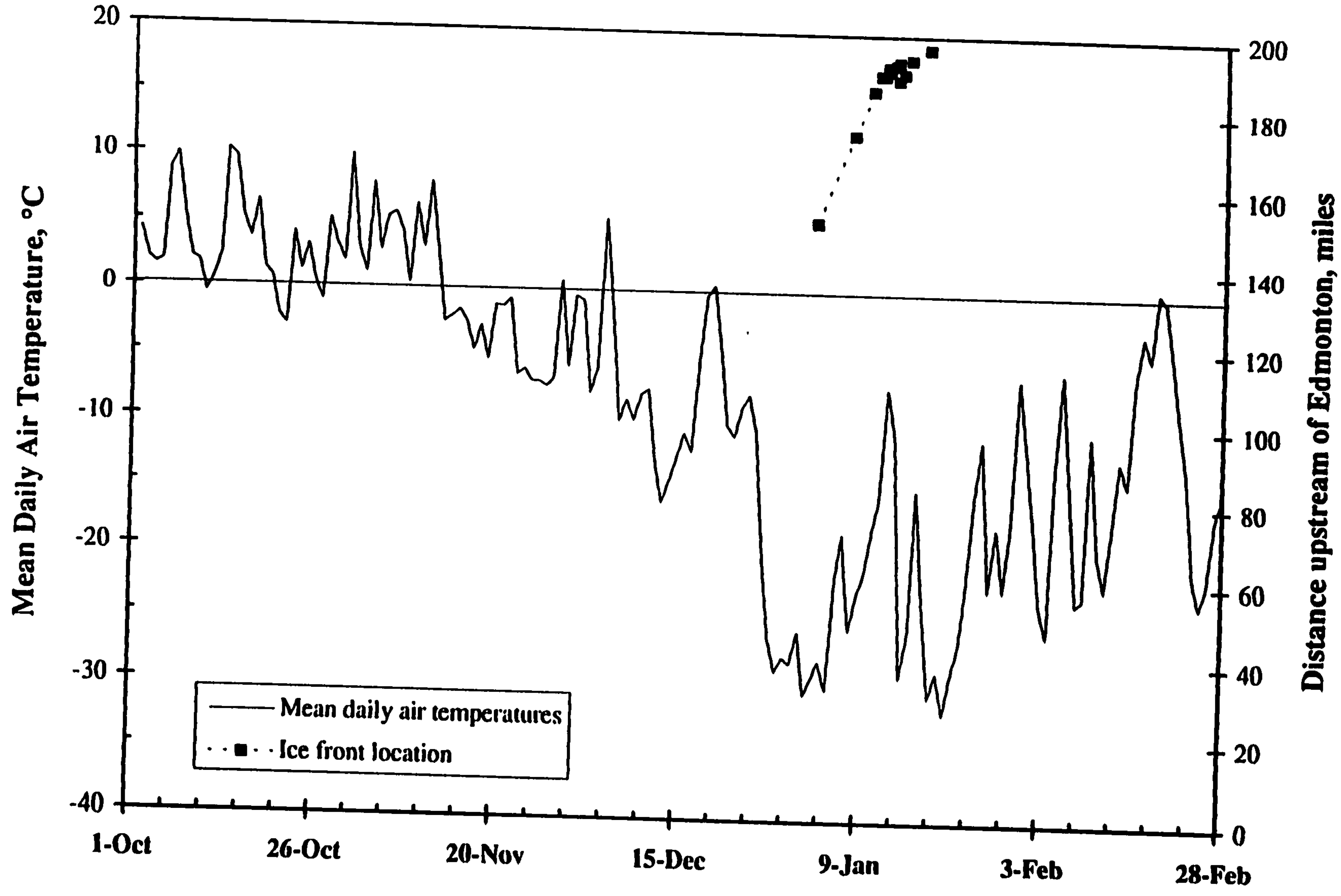

Figure B.9 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1981/82 freezeup season.

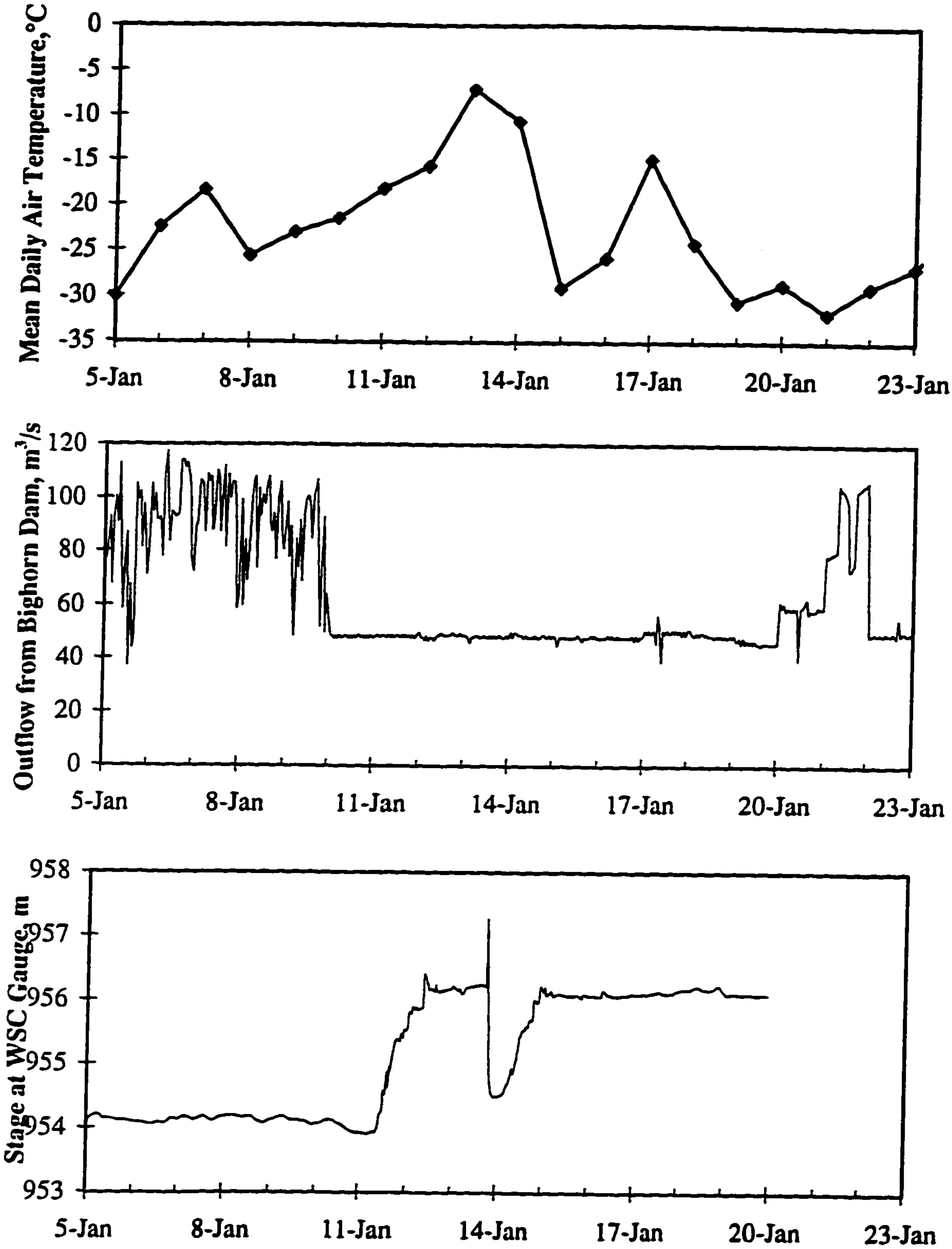

Figure B.10 Mean daily temperature, outflow from the Bighorn Dam, and water level at the WSC gauge during the January 1982 freezeup at Rocky Mountain House.

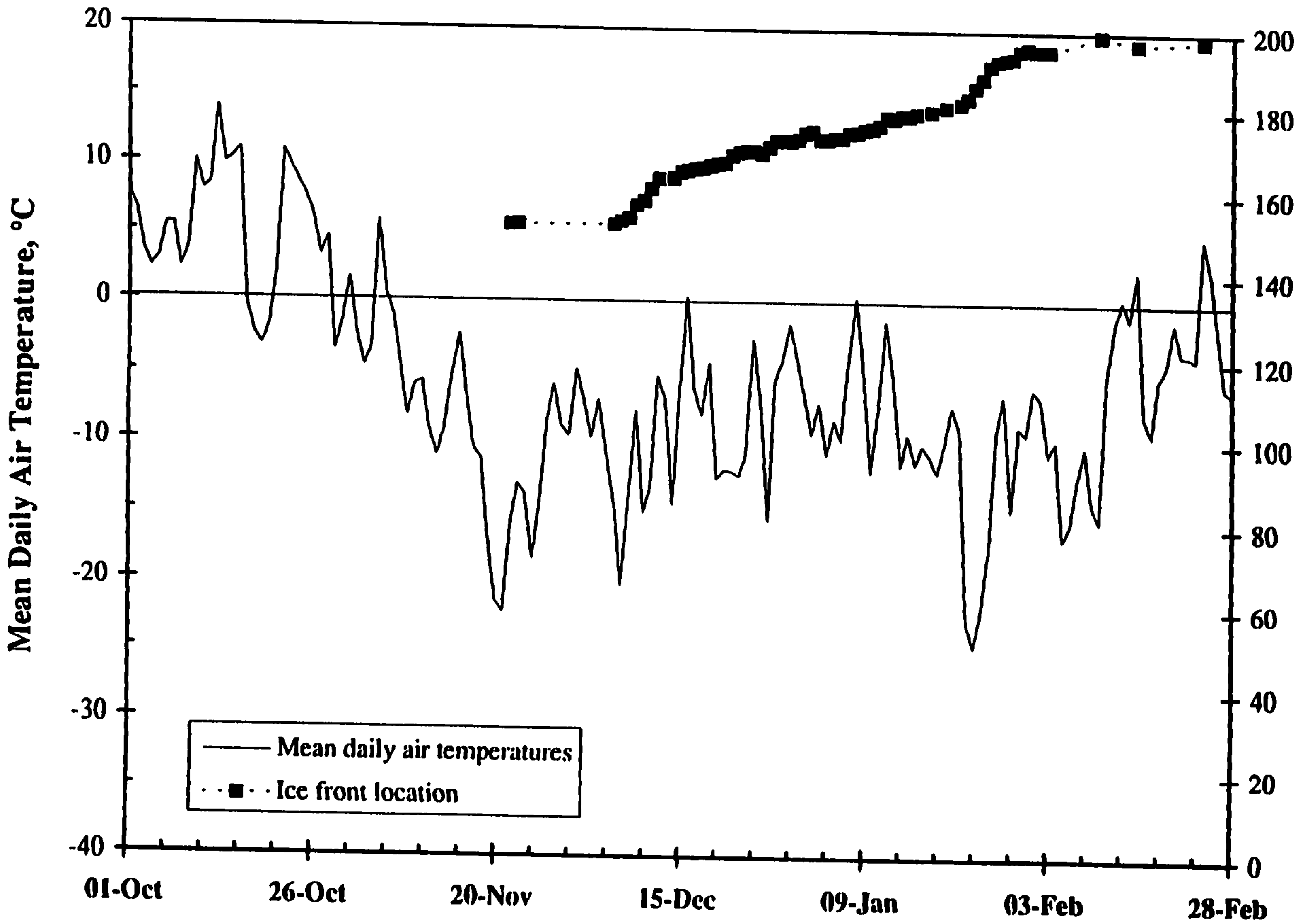

Figure B.11 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1982/83 freezeup season.

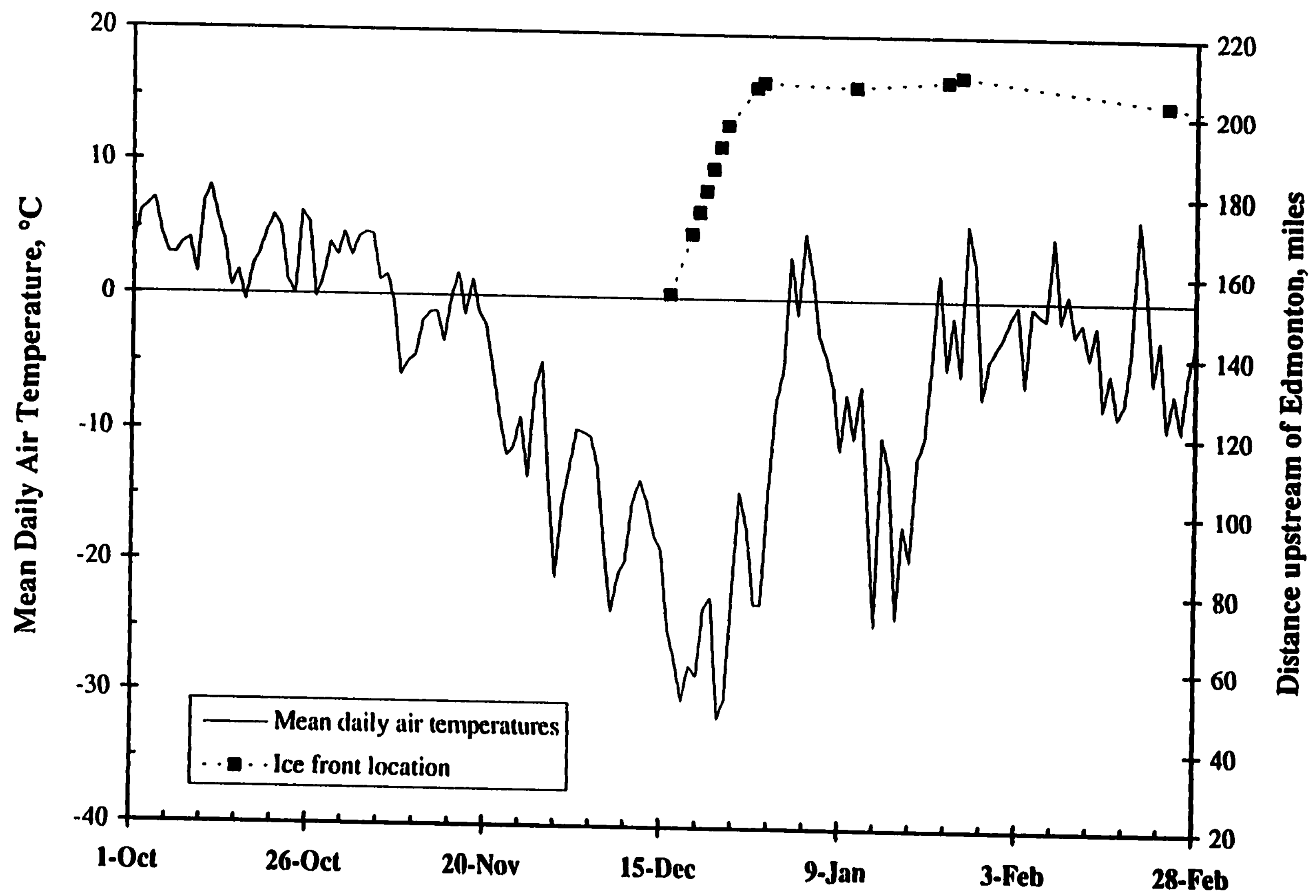

Figure B.12 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1983/84 freezeup season.

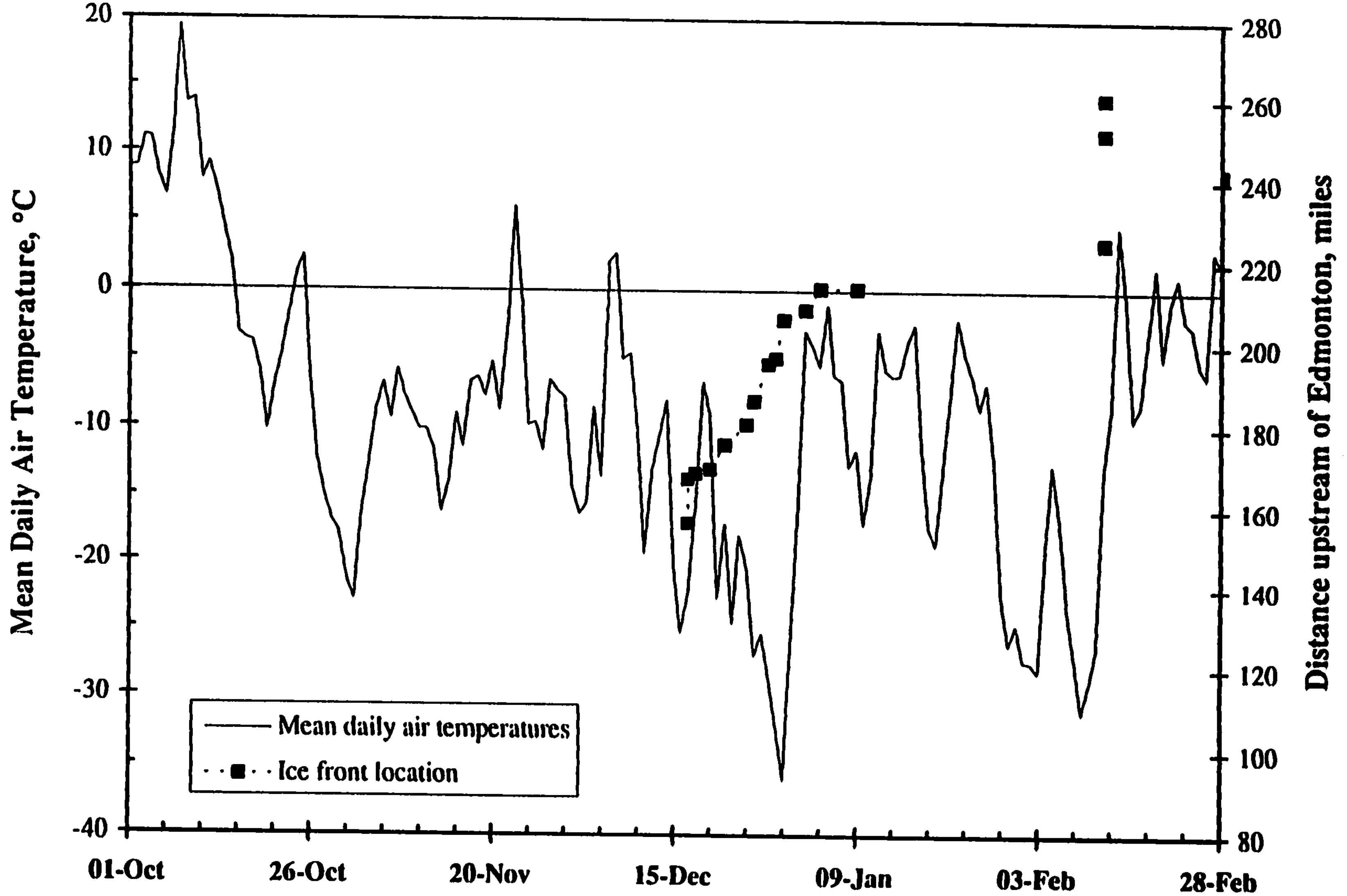

Figure B.13 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1984/85 freezeup season.

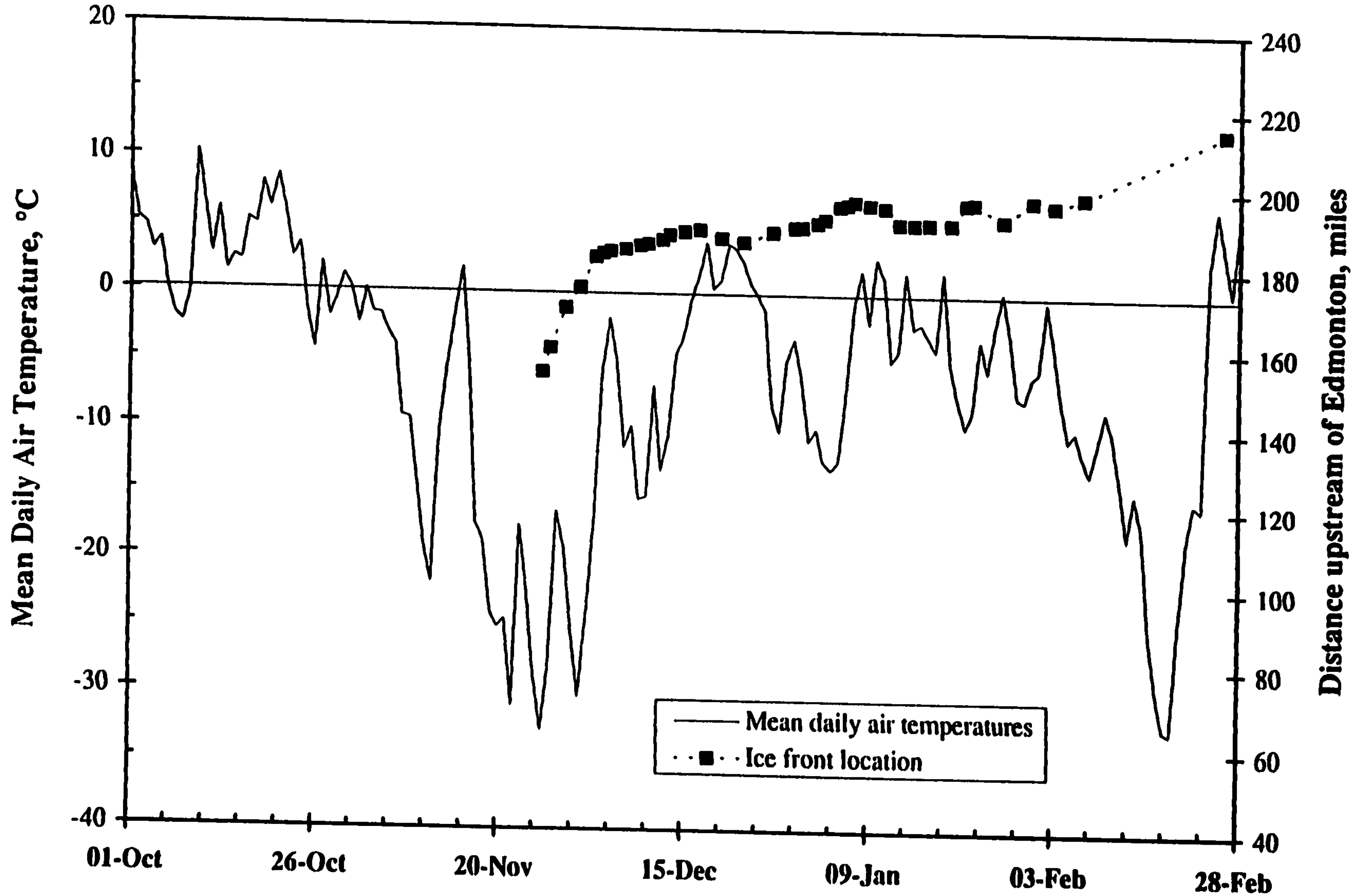

Figure B.14 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1985/86 freezeup season.

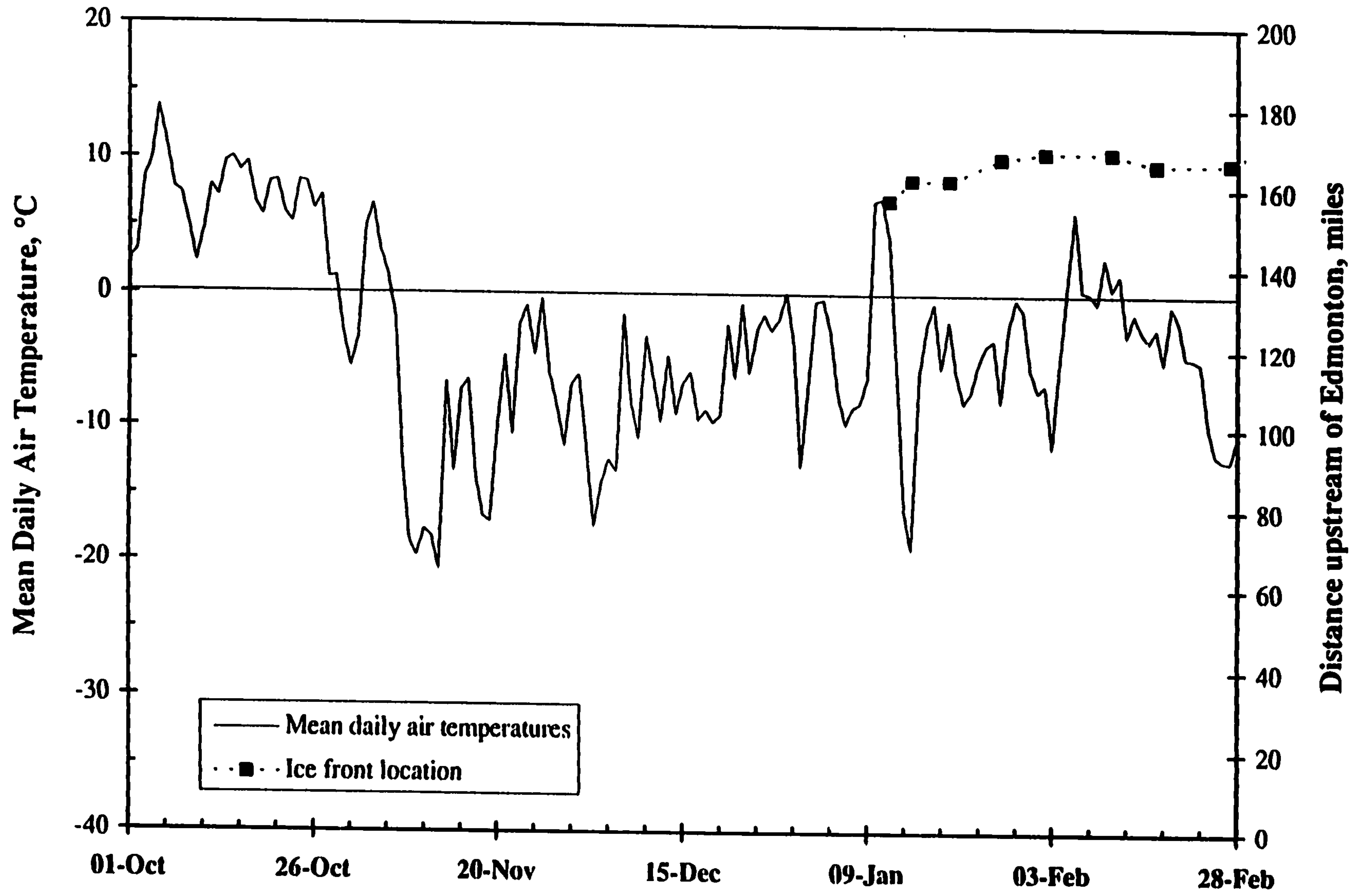

Figure B.15 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1986/87 freezeup season.

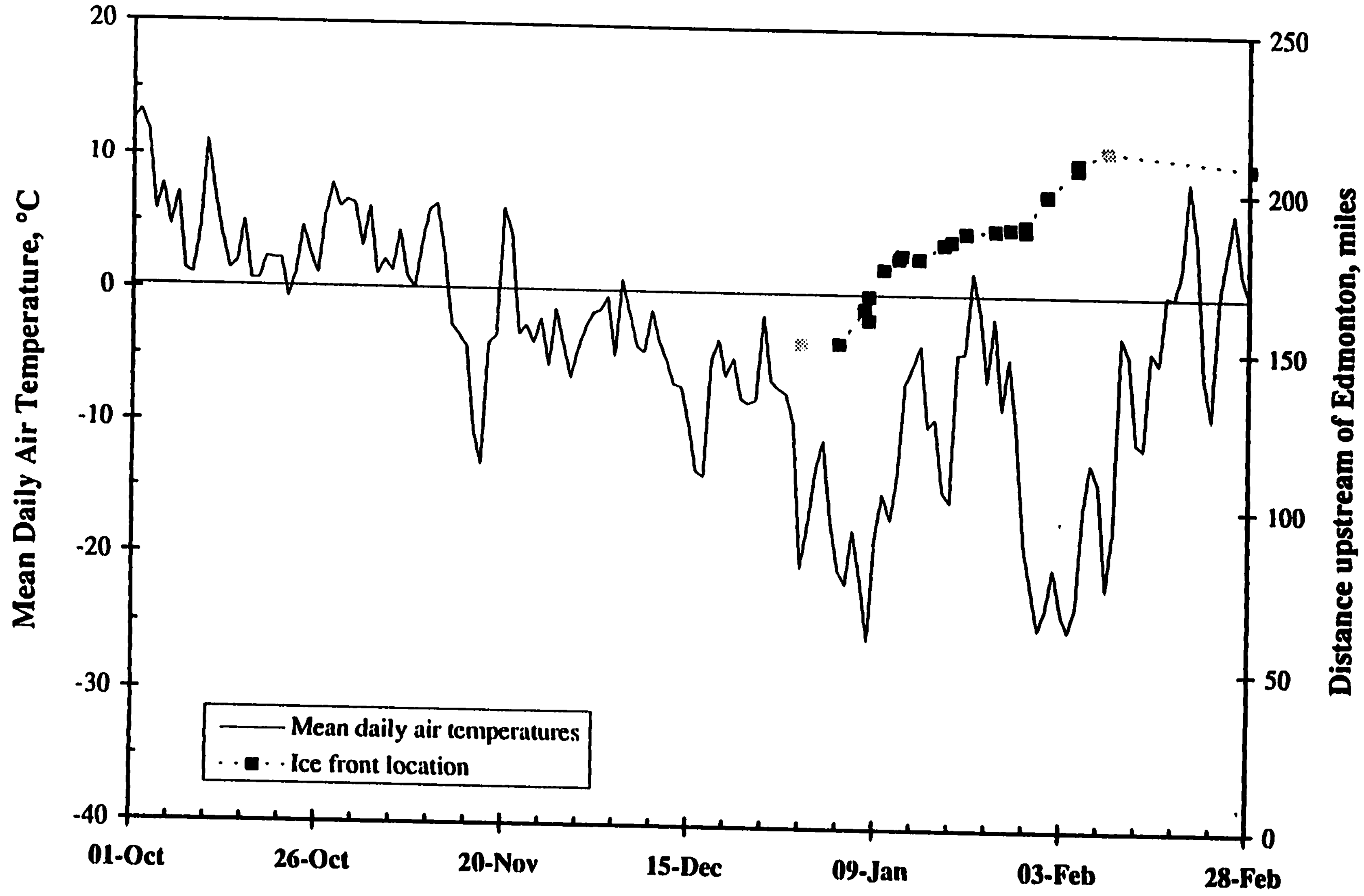

Figure B.16 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1987/88 freezeup season.

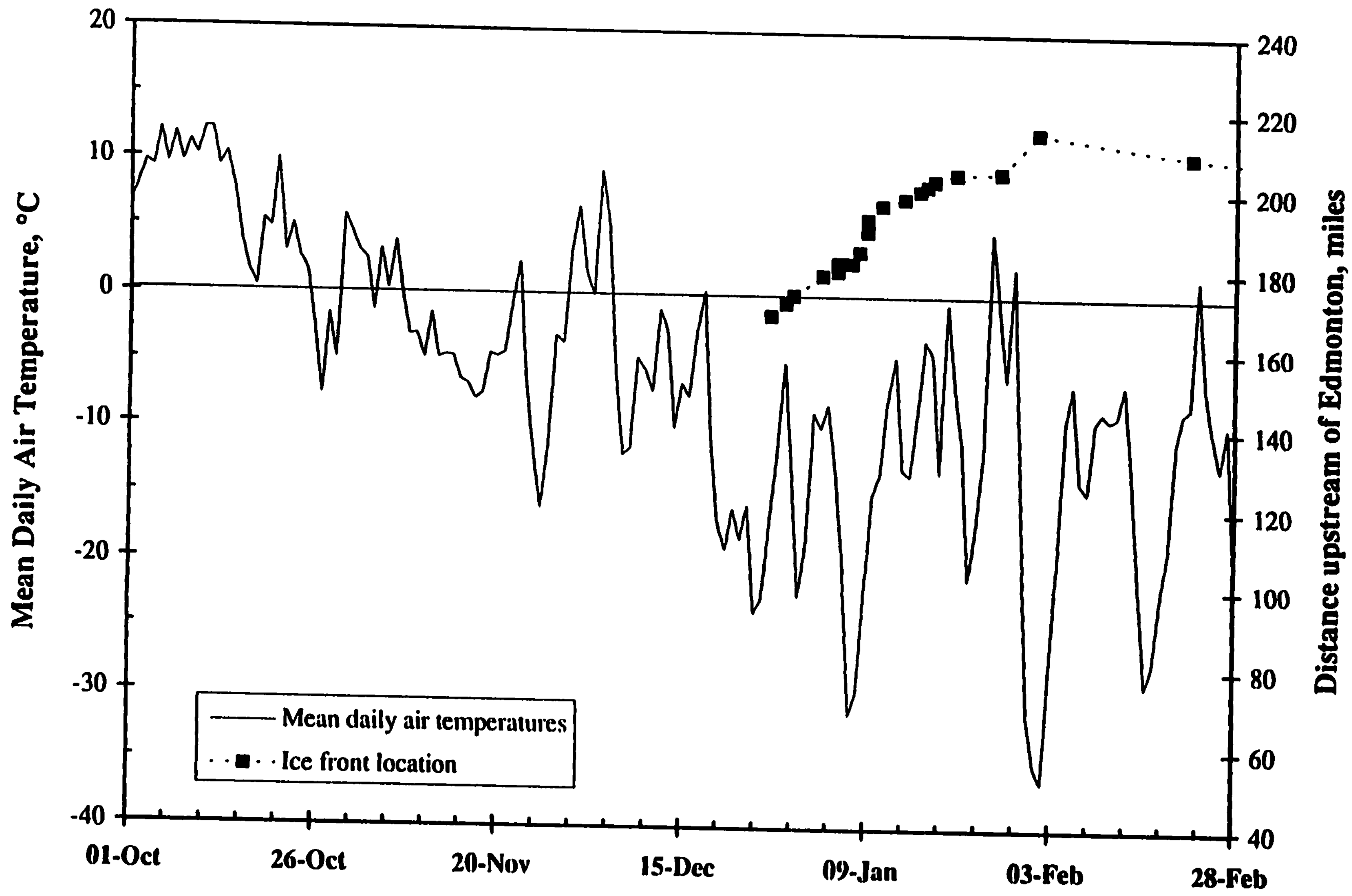

Figure B.17 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1988/89 freezeup season.

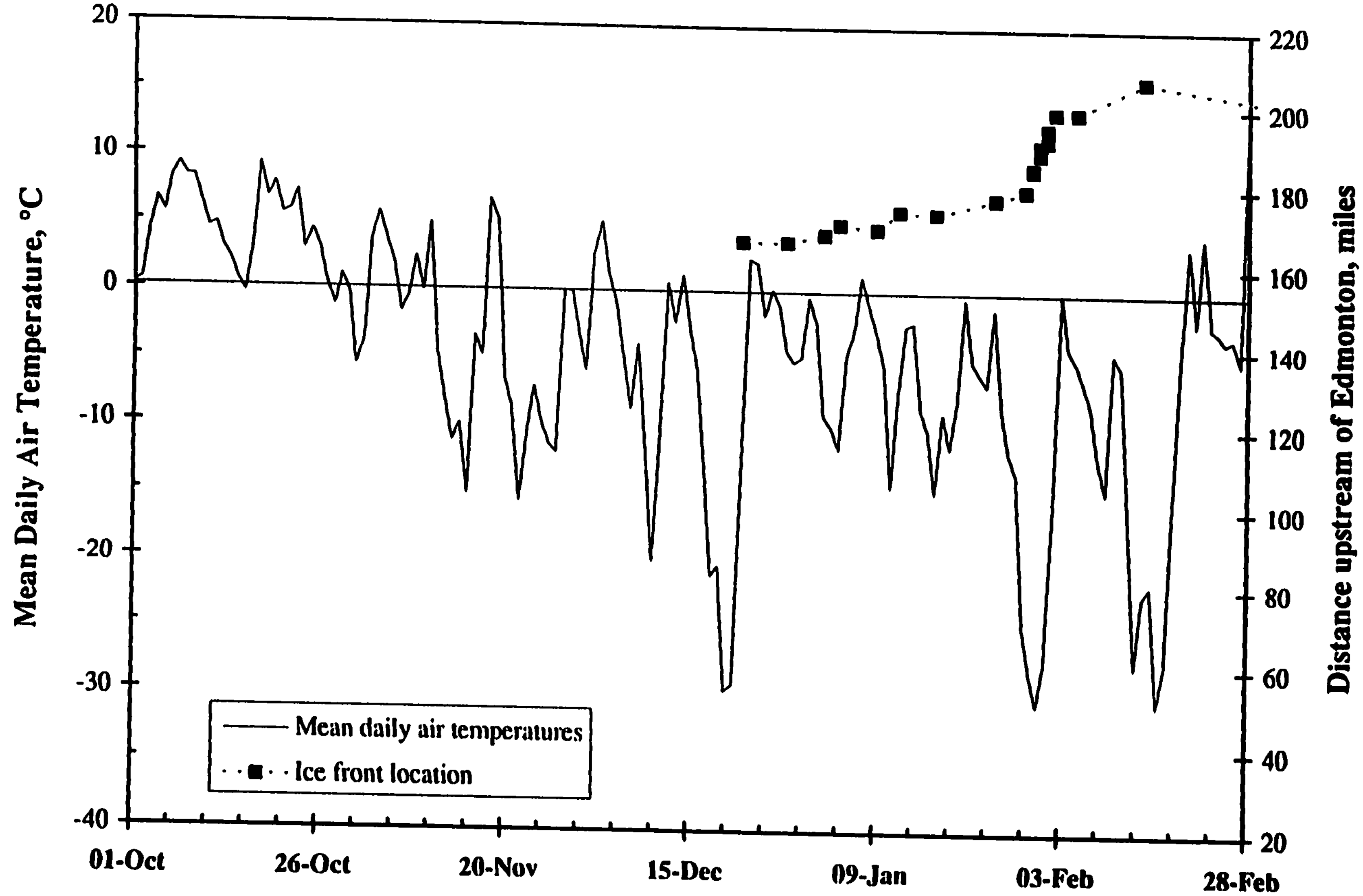

Figure B.18 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1989/90 freezeup season.

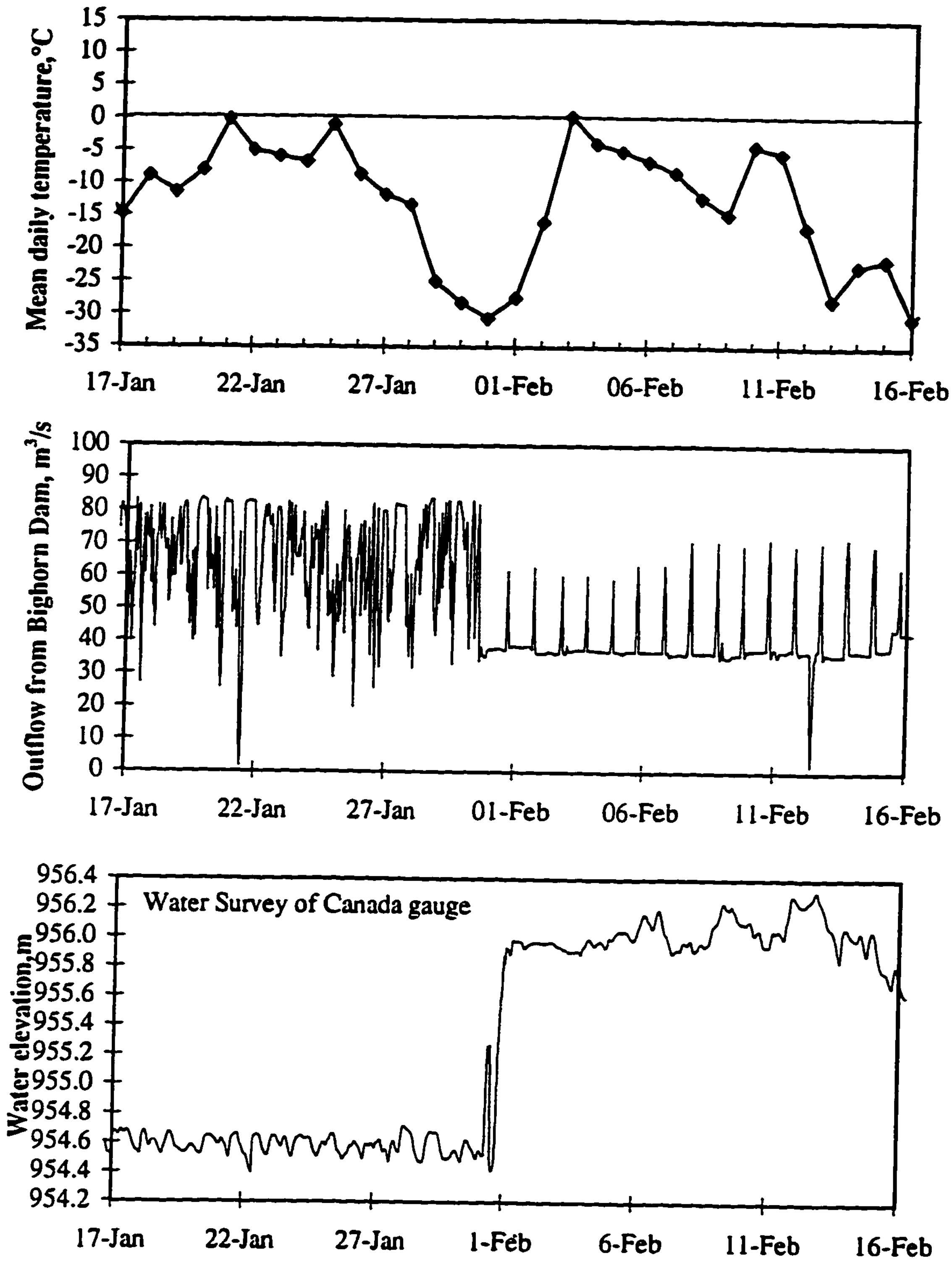

Figure B.19 Mean daily temperature, outflow from the Bighorn Dam, and water level at the WSC gauge during the 1989/90 freezeup at Rocky Mountain House.

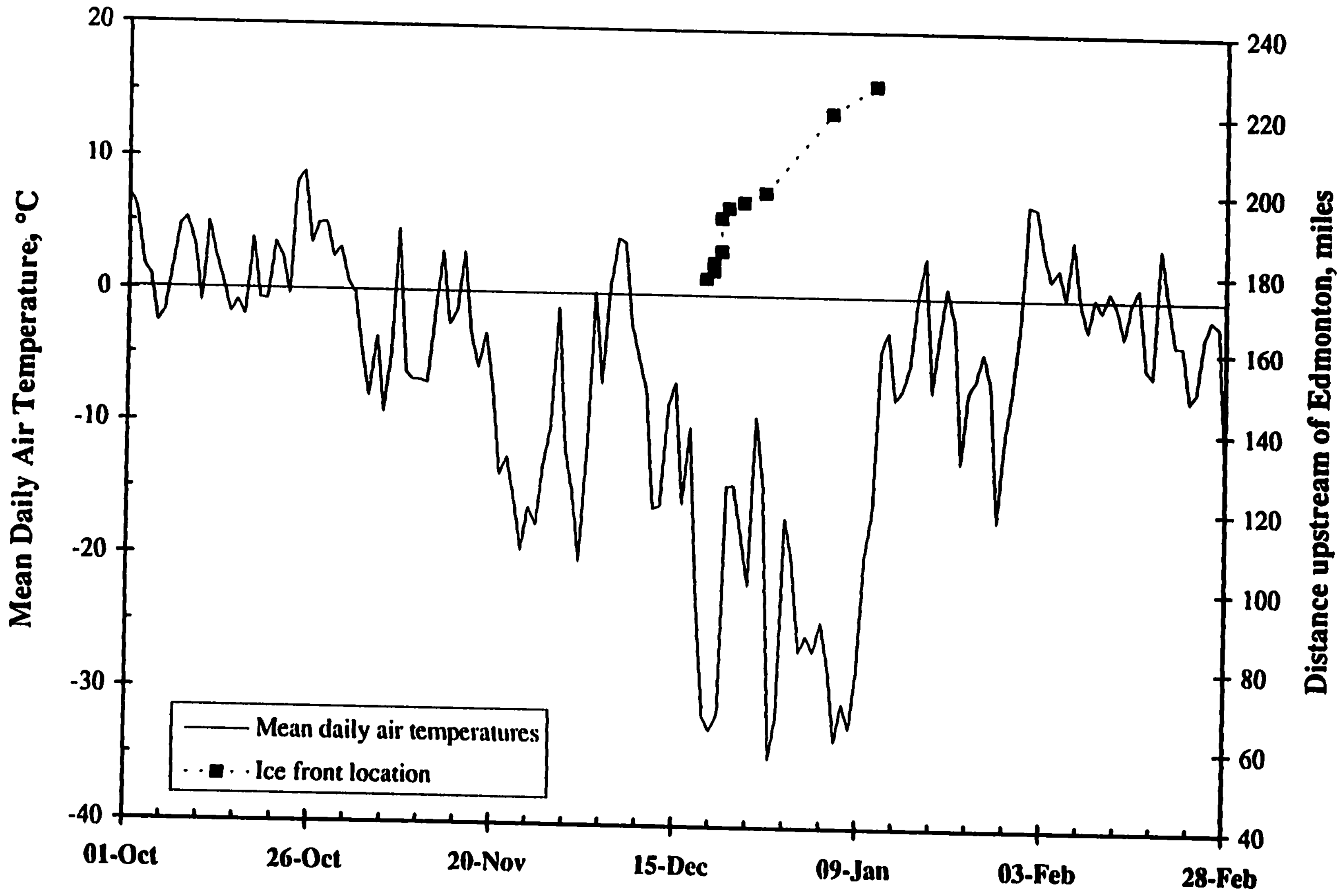

Figure B.20 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1990/91 freezeup season.

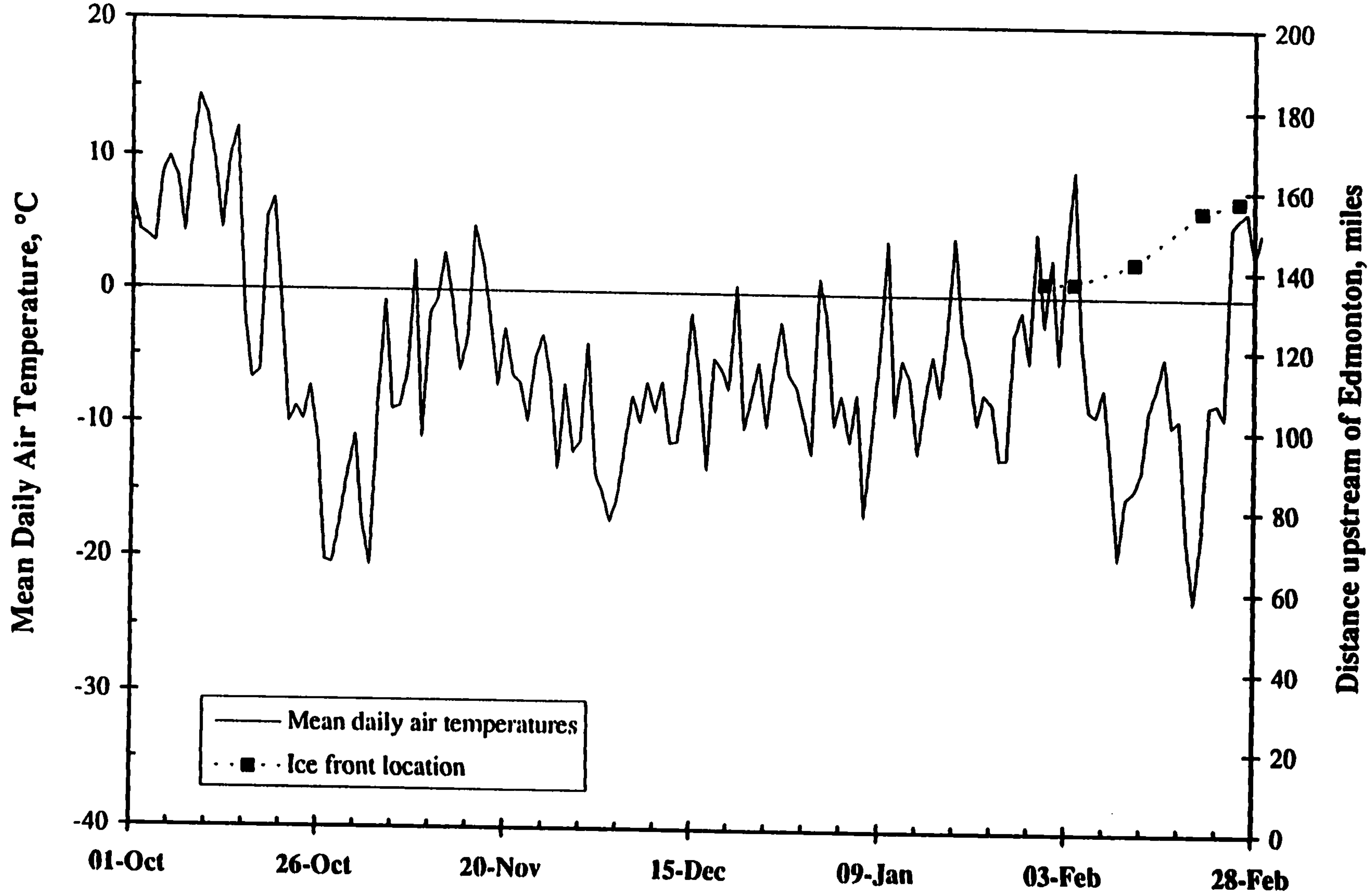

Figure B.21 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1991/92 freezeup season.

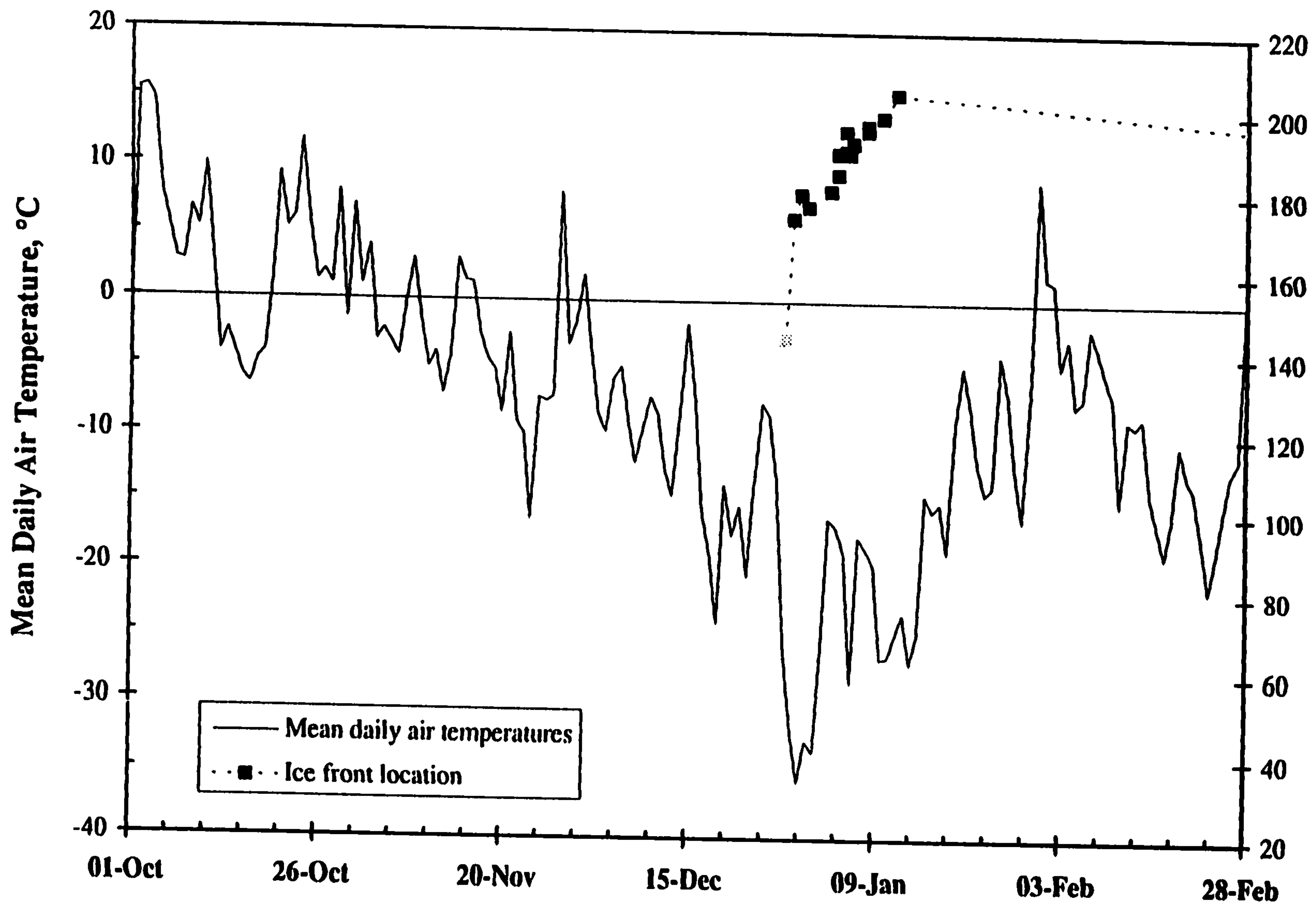

Figure B.22 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1992/93 freezeup season.

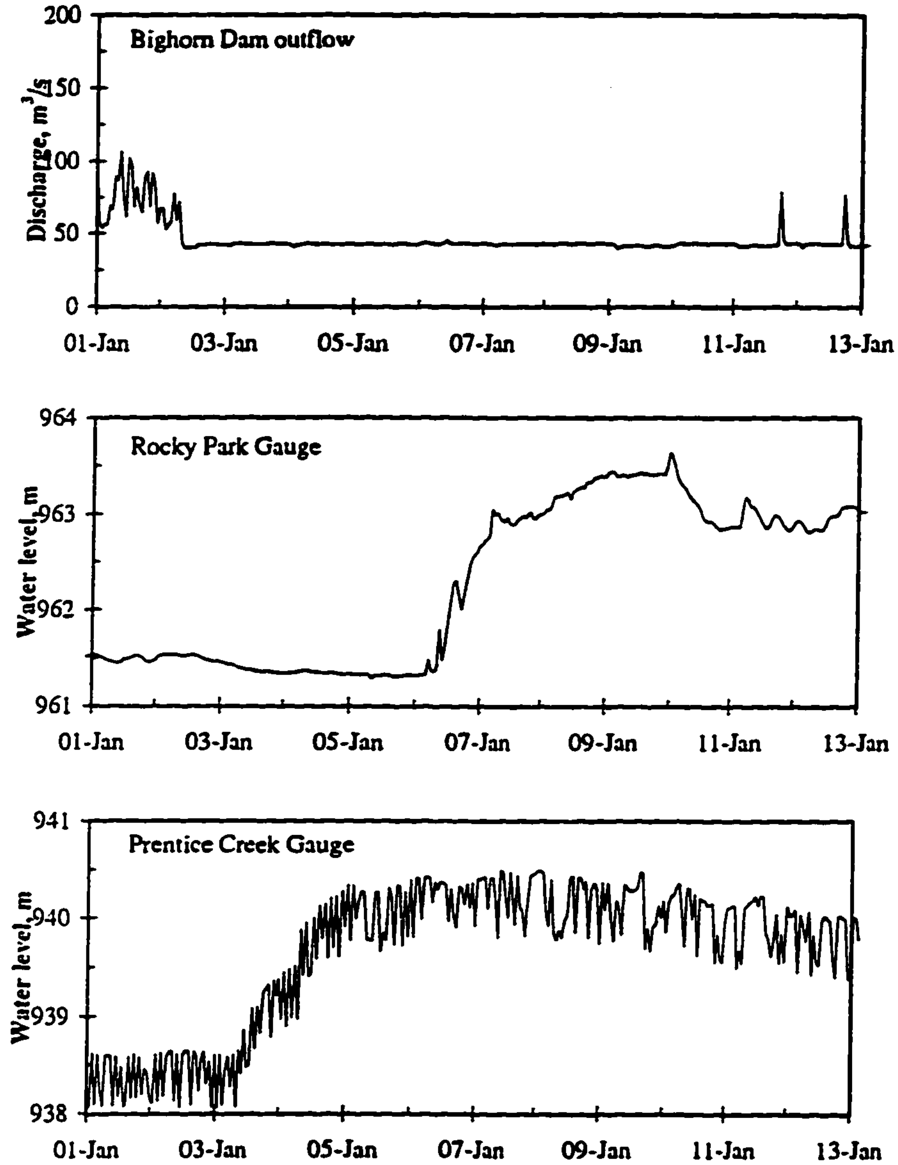

Figure B.23 Bighorn Dam outflows and measured water levels at the TAU recording gauges during early January, 1993.

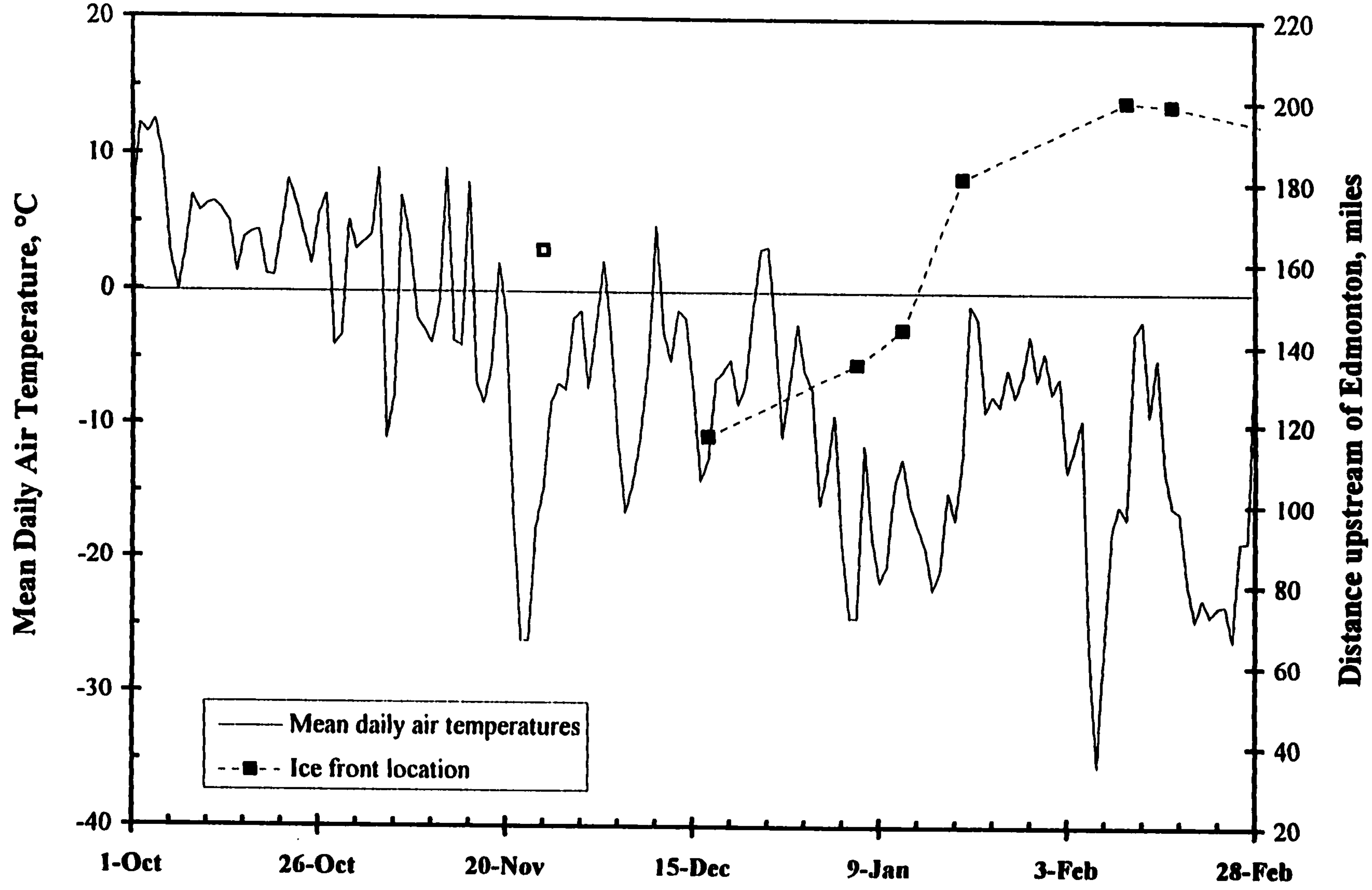

Figure B.24 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1993/94 freezeup season.

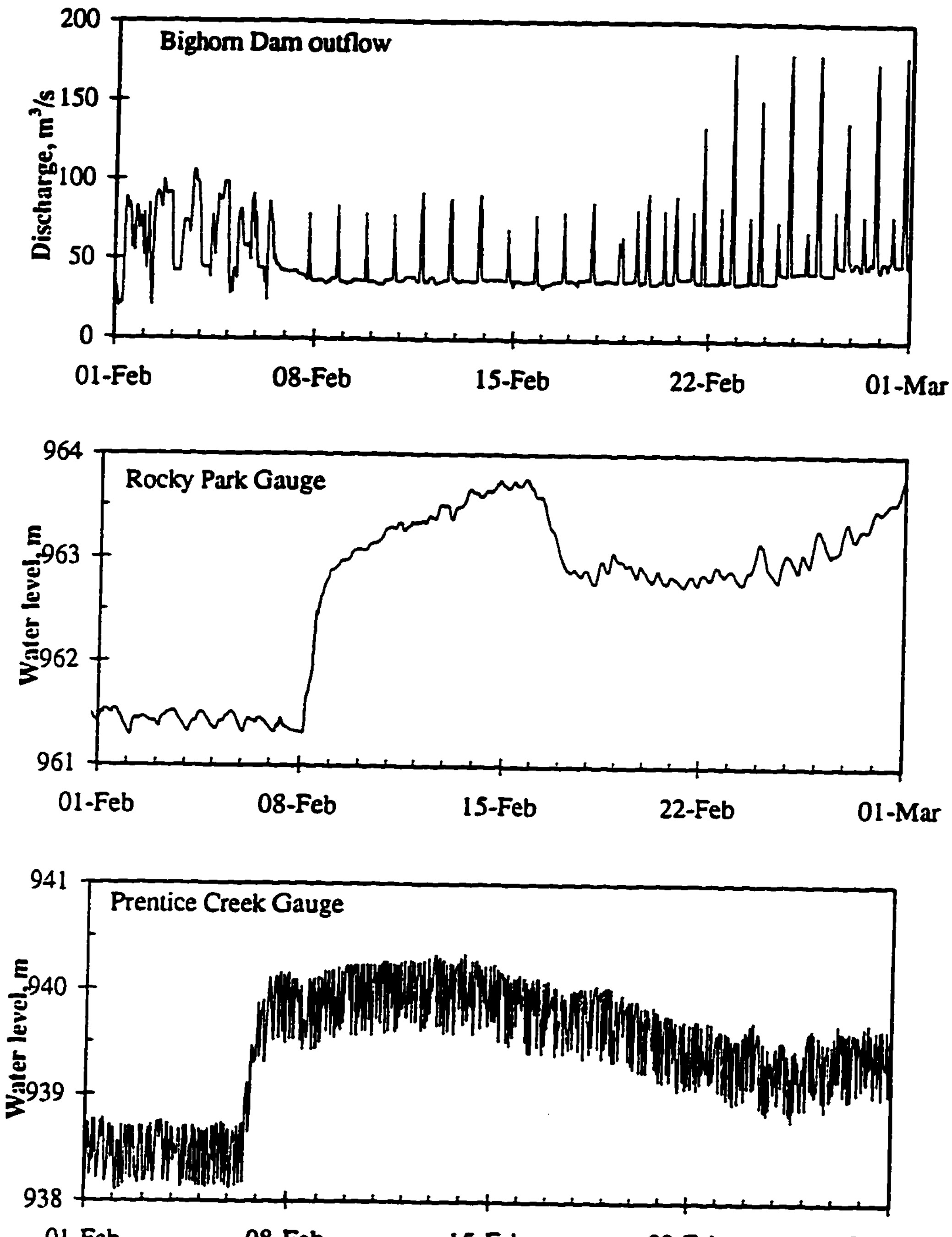

Figure B.25 Bighorn Dam outflows and measured water levels at the TAU recording gauges during February 1994.

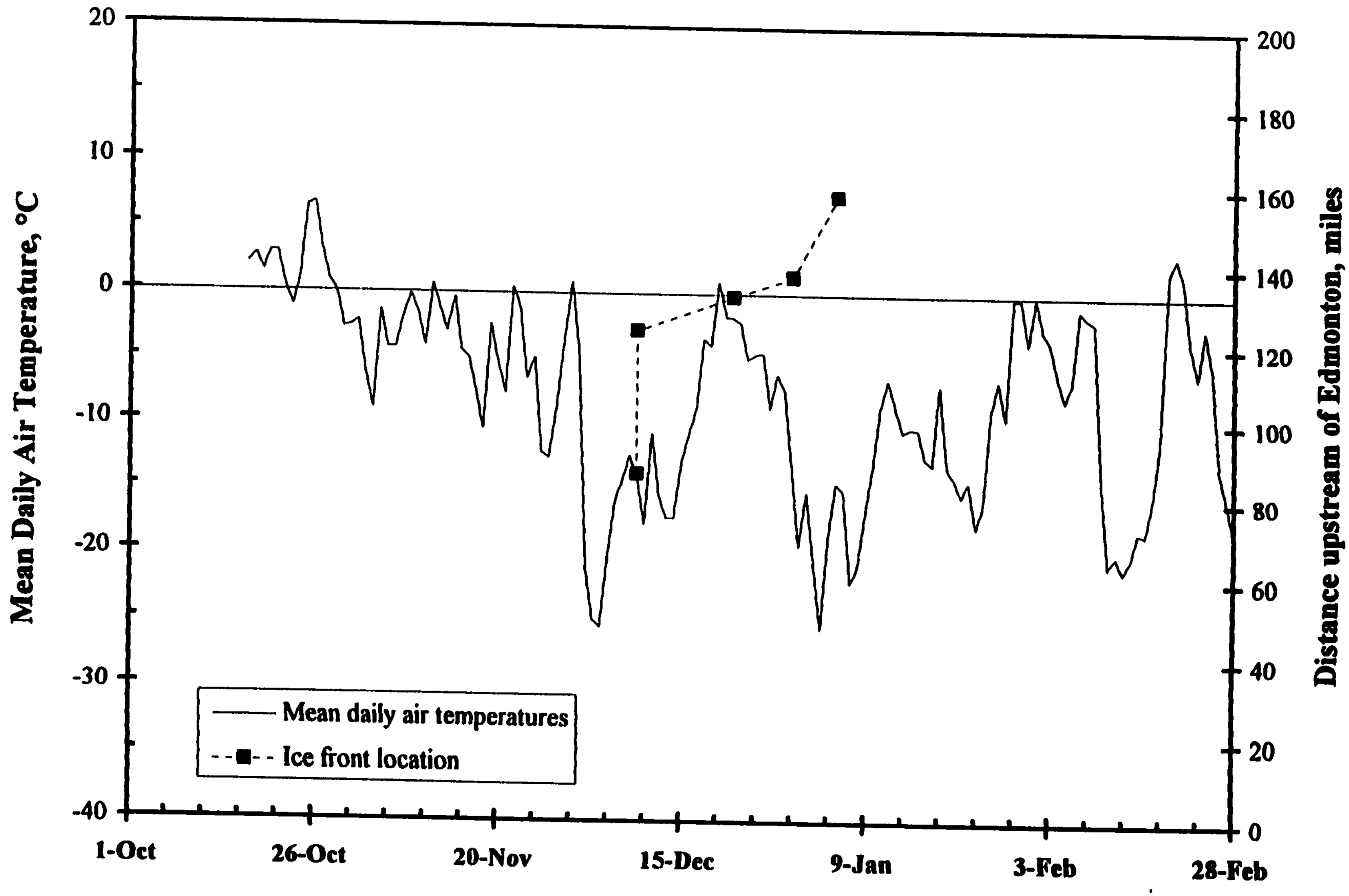

Figure B.26 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1994/95 freezeup season.

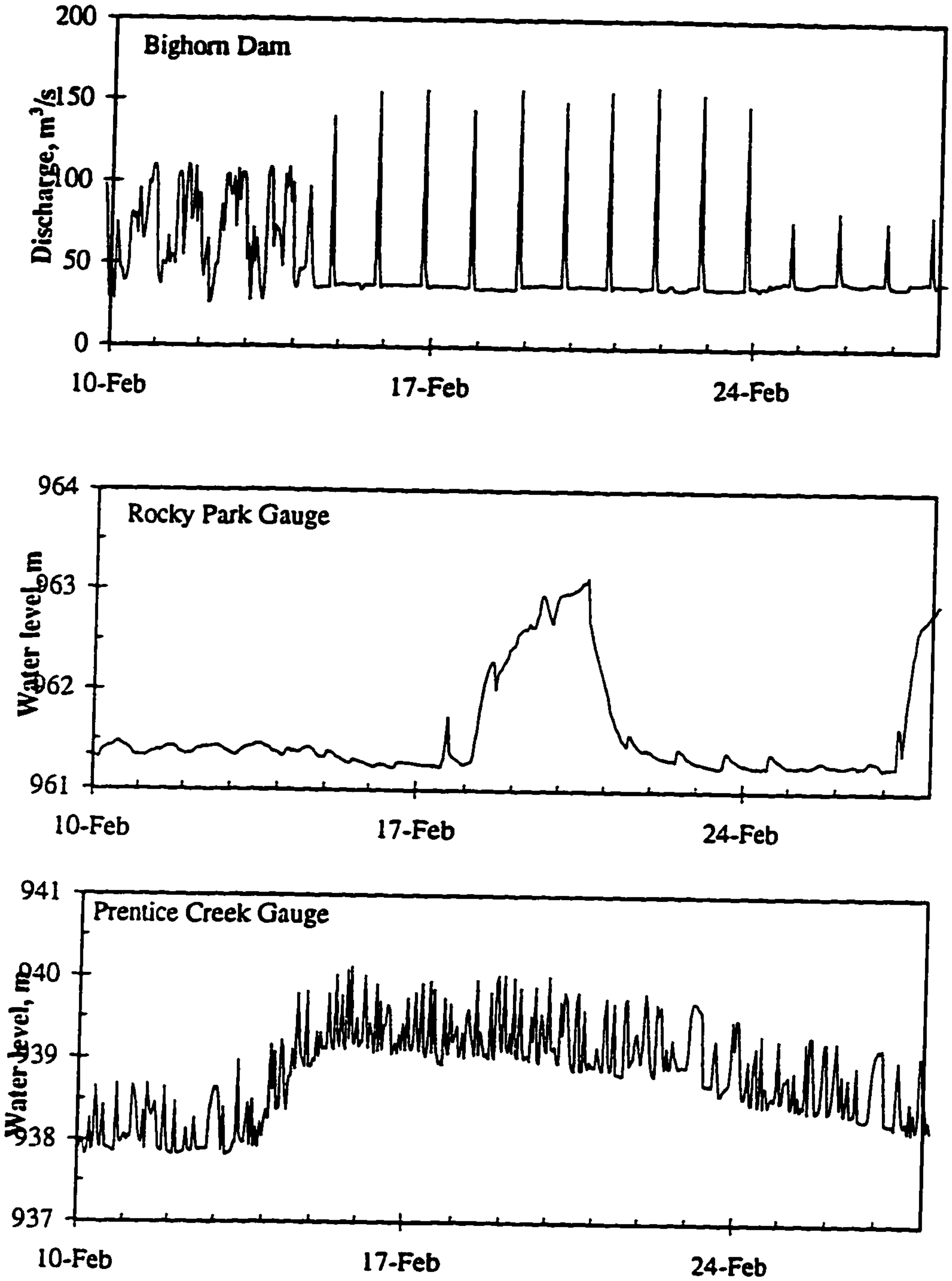

Figure B.27 Bighorn Dam outflows and measured water levels at the TAU recording gauges during February 1995.

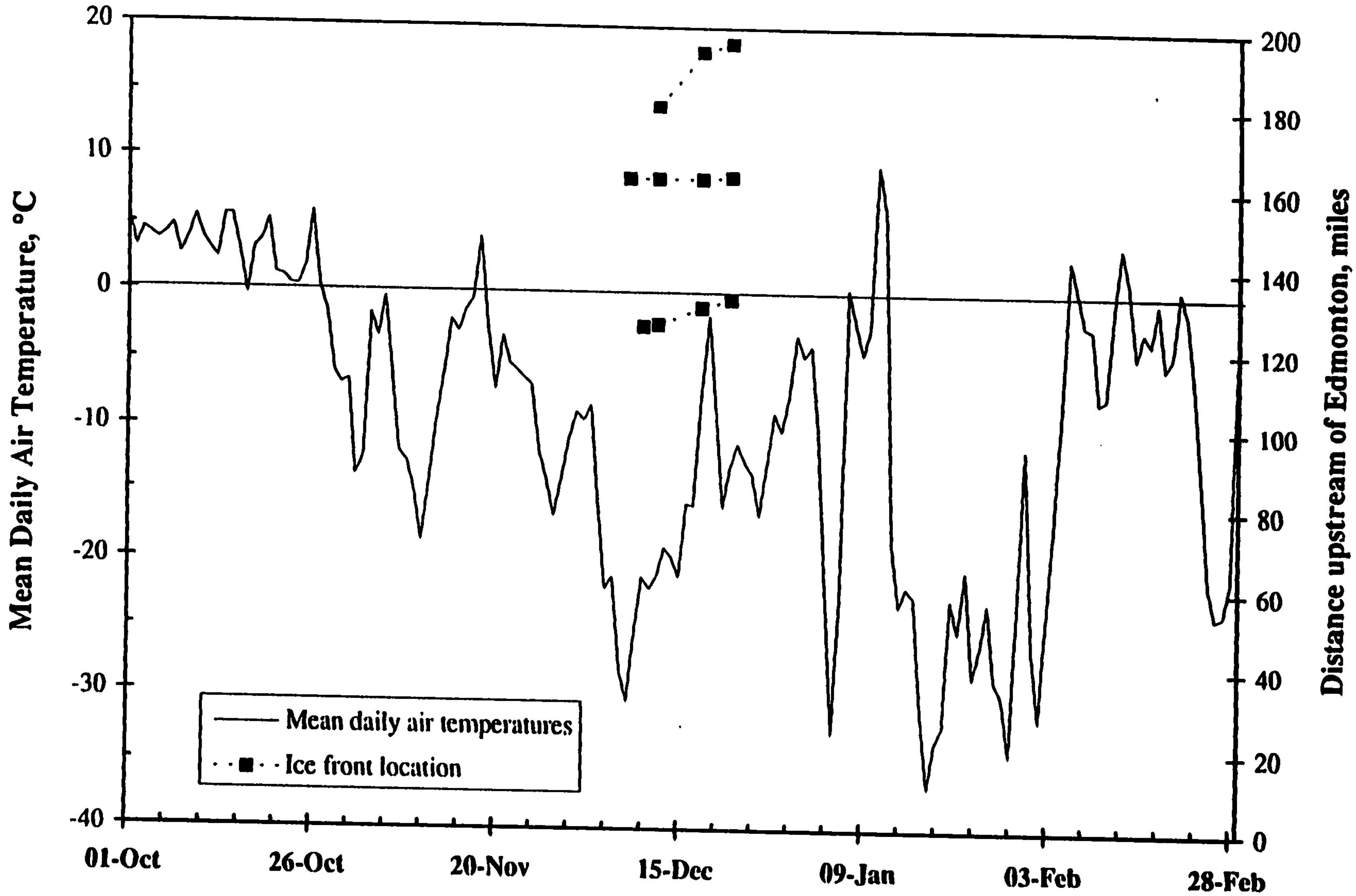

Figure B.28 Mean daily temperatures at Rocky Mountain House and the recorded ice front locations for the 1995/96 freezeup season.

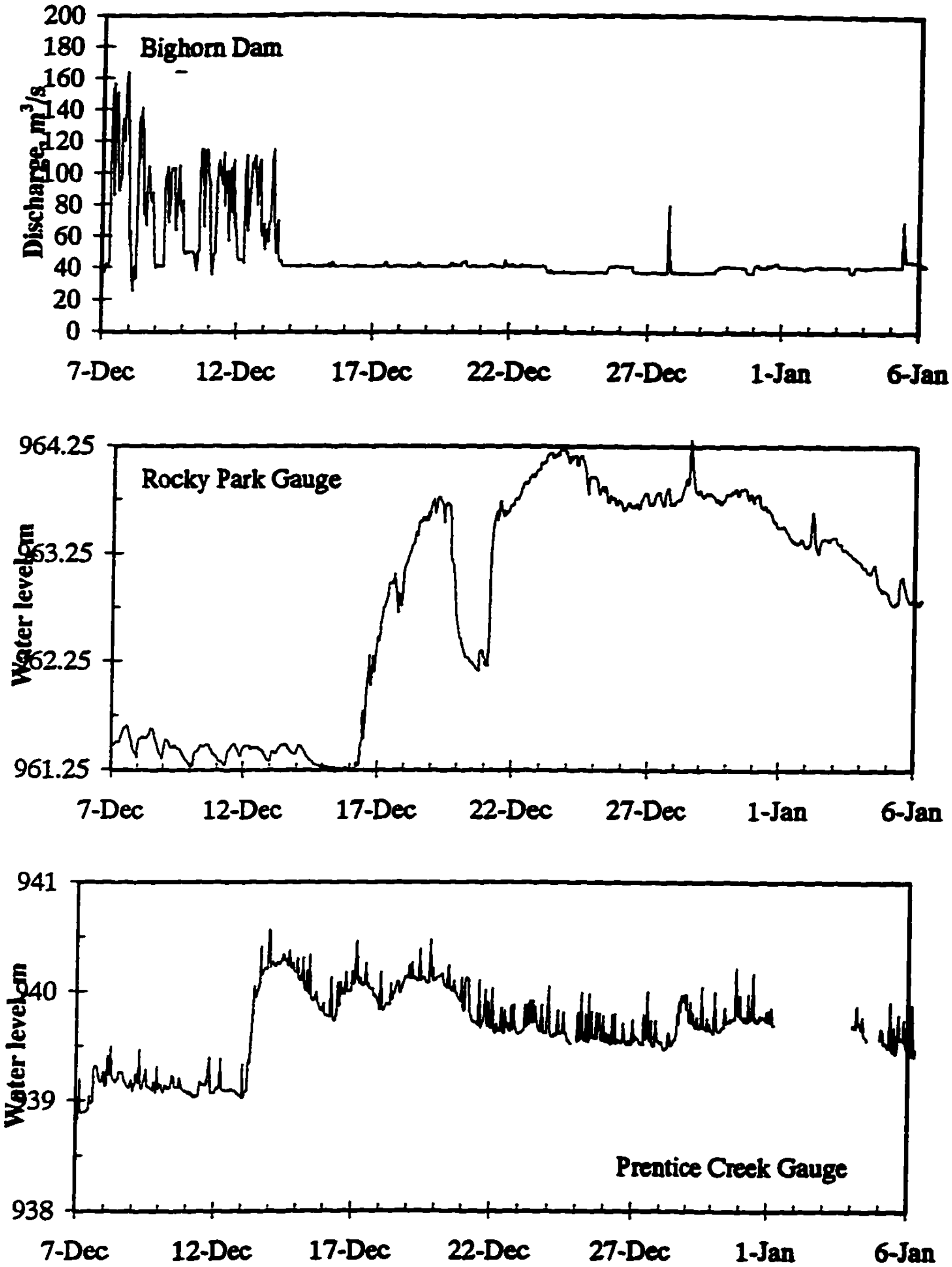

Figure B.29 Bighorn Dam outflows and measured water levels at the TAU recording gauges during the 1995/96 freezeup season.