EXPERIENCE WITH RIVER ICE AT THE LIMESTONE SITE

BY R. W. CARSON*

1. INTRODUCTION

Limestone Generating Station will be the fifth hydroelectric site to be developed by Manitoba Hydro on the Nelson River in Northern Manitoba. Its location is shown on Figure 1. It will have a head of approximately 29 m and ten units of 126 MW capacity each. First power is currently planned for the fall of 1988. The general arrangement of the completed structures is shown on Figure 2.

The sequence of construction activities and heights of cofferdams are governed by river ice conditions which are more severe than at any of the previously developed Nelson River sites.

This paper is intended to form an update of two previous papers[1,2] on the project, with concentration on the description of the ice conditions experienced since the construction of the first stage cofferdam.

2. NATURAL ICE CONDITIONS ON THE LOWER NELSON RIVER

As described in some detail in the previous papers[1,2], ice accumulation on the lower Nelson River is a process of ice jam progression upriver from the Nelson Estuary, fed by ice generated in the swift open river. Increases in water levels due to the ice accumulation are typically about 10 m, with some areas as much as 14 m above normal summer levels.

Before the construction of Kettle Generating Station, ice generating potential existed from Gull Lake to Hudson Bay, a distance of some 230 km. The production of enormous volumes of frazil ice from this open water area caused the ice jam to progress as much as 25 km upstream of the Kettle site by winter's end, or a total of some 175 km from Hudson Bay.

After the impoundment of Kettle Generating Station's forebay in 1970, a thermal ice cover was formed on the reservoir early every winter and thus eliminated this open water area from contributing ice to the lower reaches of the river. As a result, the ice jam progression slowed considerably and typically ended just downstream of the Long Spruce site (some 20 km downstream of Kettle Generating Station) in the years 1970 to 1977.

3. PLANNING OF RIVER ICE MANAGEMENT DURING CONSTRUCTION OF LIMESTONE

During the early planning stages of the Limestone development (1974 to 1976), construction of Long Spruce Generating Station was proceeding, but its reservoir had not yet been impounded. The future effect of the loss of ice generating area upstream of Long Spruce therefore had to be estimated. The most important question was whether or not the ice jam progression would be slowed so much as to prevent it from reaching the Limestone site. This would mean that the cofferdams for that project would only have to be

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designed for open water levels (some 12 m lower than for ice conditions), and river diversion through a partly completed spillway or powerhouse would not have to cope with passage of large volumes of solid ice.

Early in the studies, engineering judgement based on approximate calculations of open water areas, ice generation rates, etc, indicated that year round open water conditions could not be expected at the Limestone site after the impoundment at Long Spruce. This was confirmed by the results of a detailed computer model which simulated

- the generation of ice as a function of open water areas and daily mean air temperatures during the winter
- the reduction of open water areas by border ice growth as a function of river velocity and degree-days of freezing
- the accumulation and stability of slush ice at the leading edge of the ice jam
- the submergence of ice at the leading edge if the approaching velocities are excessive, and the deposition of this ice downstream on the underside of the cover
- the shoving and thickening of the ice cover under the computed hydraulic forces exerted on it
- the backwater profile in the ice covered and the open reaches under study.

The decision was made that river diversion during construction must be devised to cope with very severe ice conditions. Detailed hydraulic model studies of the river ice conditions during the plant's construction were then undertaken at Lasalle Hydraulic Laboratory in Montreal.

Construction of the Stage I cofferdam which encloses the area of the concrete structures (see Figure 3) began in 1976, in preparation for completion of the first units in 1983. The construction proceeded over three summer seasons - the upstream leg in 1976, the river leg in 1977, and the downstream leg in 1978. The construction of the rest of the project has been shelved temporarily, due to the slower growth of demand for electricity than was experienced in the early to mid-1970's.

4. EXPERIENCE WITH THE RIVER ICE

1976 - 1977

In the first winter after the construction of the upstream leg, Long Spruce's reservoir had not been impounded. The ice front reached the Limestone site early in the winter and progressed upstream. Because the river flows varied widely on a daily basis, the ice front repeatedly progressed rapidly during times of low flows (early weekday mornings and weekends) and was shoved back when the river flow was later increased. On one occasion, the ice front was forced downstream to the Limestone site from 12 km upstream in a period of about three hours.

During this time, an estimated volume of 70 000 000 m^3 of ice passed through the 360 m wide diversion channel between the end of the cofferdam and the south river bank. Only minor damage due to ice gouging at the corner of the cofferdam was incurred. The resistance of the cofferdam to damage was attributed mainly to the surface freezing which had occurred prior to the arrival of the ice jam.

Later, the ice front resumed its upstream progression and eventually reached within 2 km of the Long Spruce cofferdam before the arrival of spring. The maximum water level recorded that winter at the Limestone cofferdam was el 70.5 m, which correlated well with the hydraulic model simulation of el 70.0 m, for comparable flow conditions.

In the spring, the ice behind the cofferdam became grounded as predicted by the hydraulic model studies, and there were large areas of stranded ice 5 to 10 m thick. Fortunately, the strong flow of water past the end of the upstream leg cleared the area where construction of the river leg was to resume, and work was able to start late in June.

1977 - 1978

In the fall of 1977, the Long Spruce reservoir was impounded, and as expected, the ice front progression in the ensuing winter was markedly slower than in previous years. The winter was very mild, and the ice front only reached the foot of the rapids below the Limestone cofferdam and did not progress through the diversion channel. The maximum water level was approximately el 65 m, or only about 5 m of staging above open water conditions.

In the spring of 1978, even though the ice did not reach its maximum potential thickness, considerable volumes were left stranded in the area where work was to resume on the downstream leg of the cofferdam. The ice delayed the resumption of work until early July. Fortunately, the construction schedule was reasonably flexible in that final year and the downstream leg was still completed before the onset of winter.

1978 - 1979

By 1978, the decision to postpone construction of the Limestone plant had been made by Manitoba Hydro, and the ensuing winter was the first of many through which the cofferdam was to remain.

During the construction of the cofferdam, the crest level was purposely chosen to be approximately 2 m lower than the maximum level indicated by the hydraulic model tests. The logic behind this was as follows

- while the computer model indicated clearly that the ice could reach the Limestone site in mid- to late winter, there was still some uncertainty as to whether the ice front could progress upstream past the site the 10 km necessary to generate the maximum levels predicted by the model

5. SUMMARY

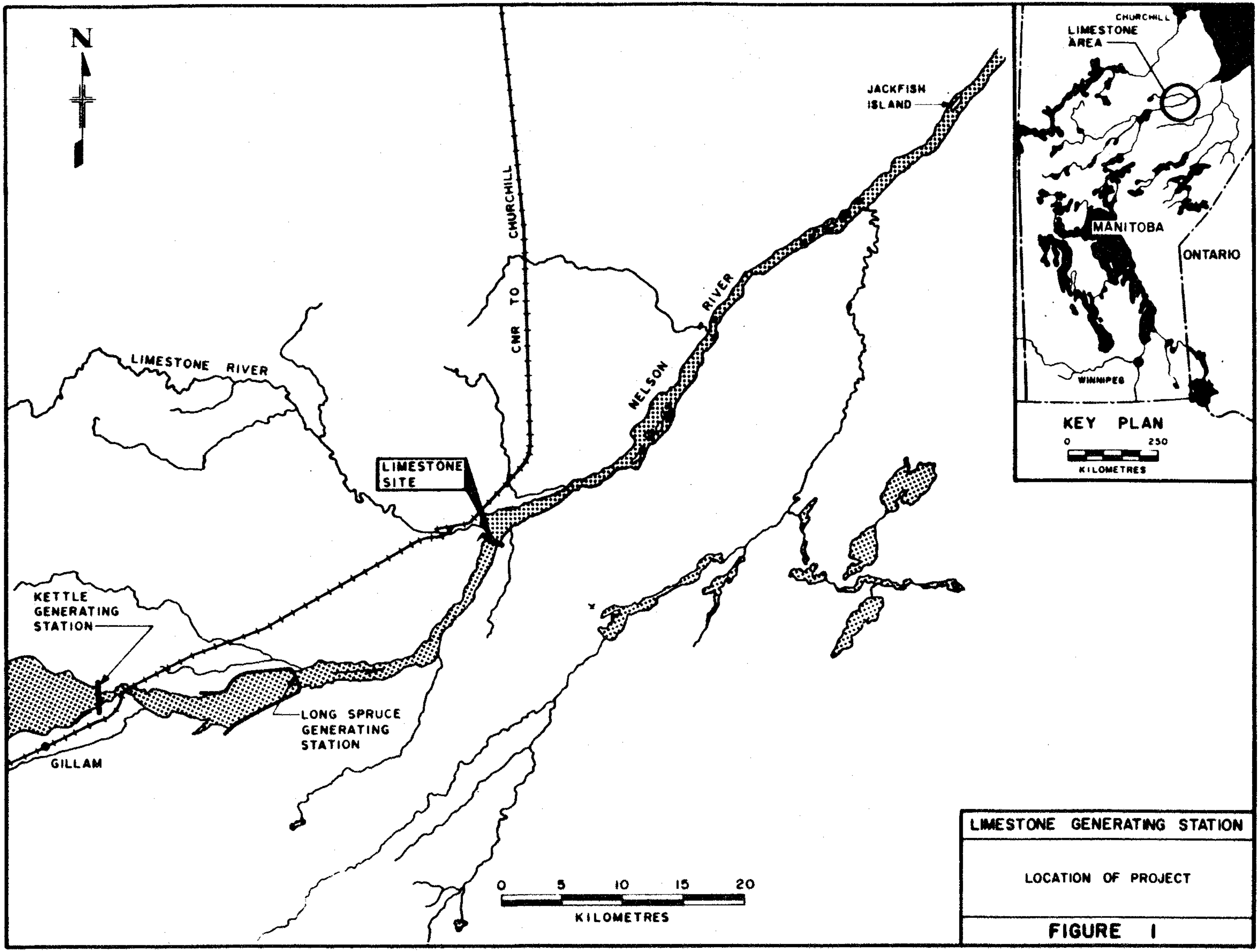
Mathematical and physical models were used to plan the concept of river ice management for the construction period of the Limestone plant. The predictions of both models relative to the first stage of river diversion have been verified by the observations of the river behaviour since the completion of the cofferdam. Topping up of the cofferdam by 2 m will be required before resumption of the plant construction, which may be as early as the summer of 1982.

REFERENCES

1. "Ice Processes During Construction of Limestone Generating Station", C.P.S. Simonsen and R.W. Carson, Proceedings of the Third National Hydrotechnical Conference, CSCE, May, 1977.

2. "River Diversion During Construction of Limestone Generating Station", By R.W. Carson, L.P. Jonassen and L.C. Leung, Proceedings of the Fourth National Hydrotechnical Conference, CSCE, May, 1979.

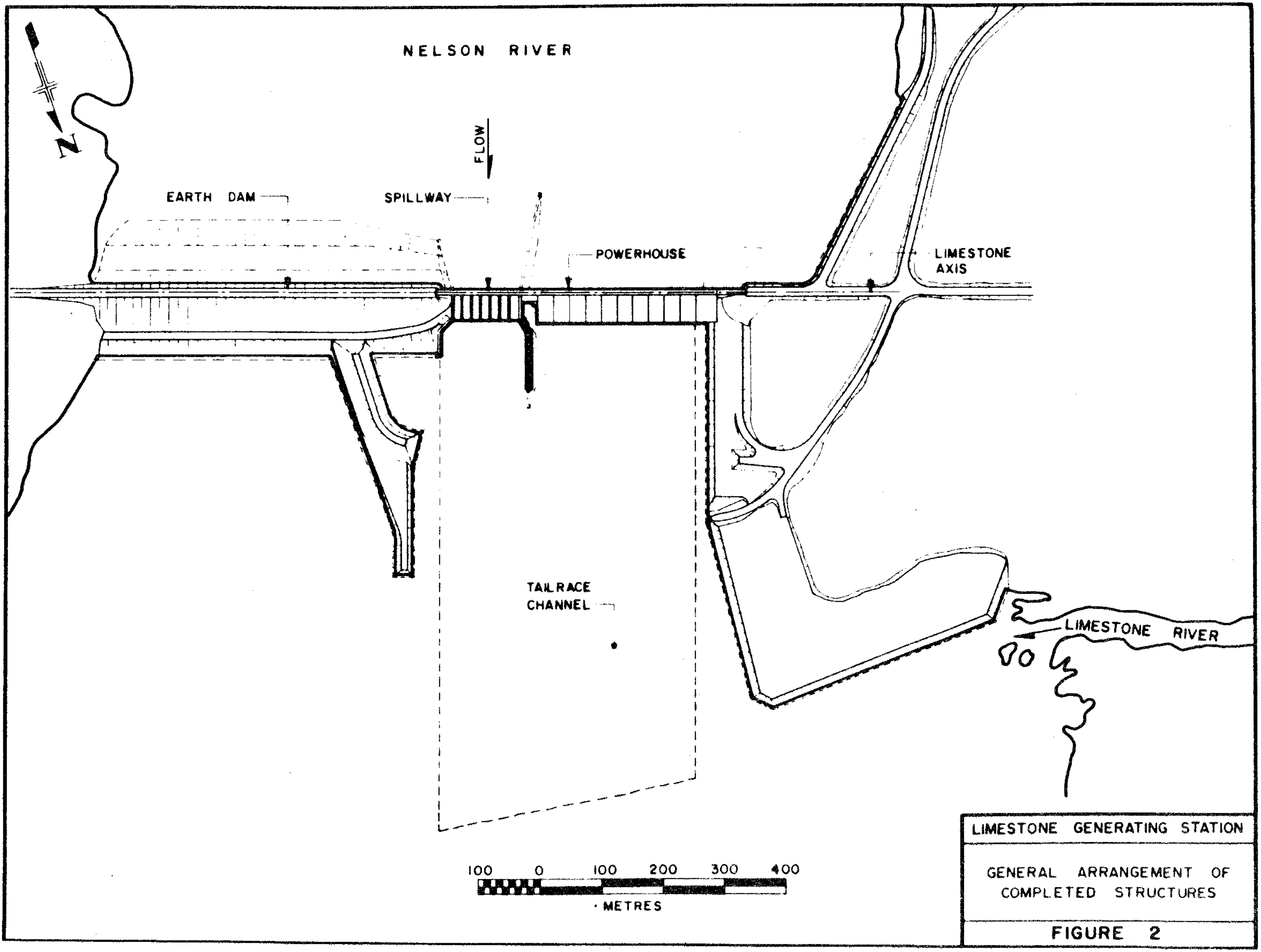
3. "Limestone Generating Station Hydraulic Model Studies of Ice Conditions During Diversion", LHL717, February, 1978, Lasalle Hydraulic Laboratory Ltd., Lasalle, Quebec.



LIMESTONE GENERATING STATION

LOCATION OF PROJECT

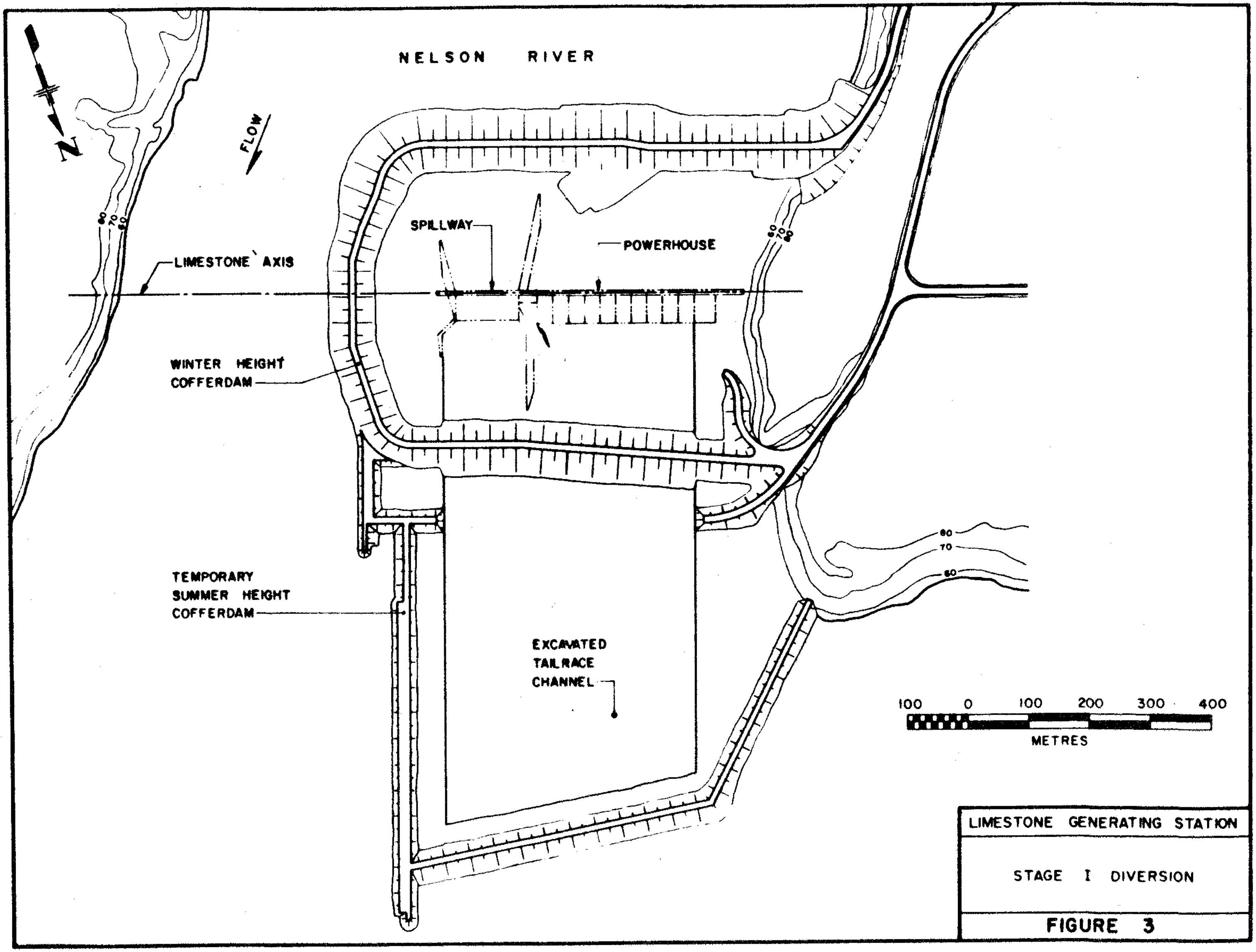
FIGURE 1



LIMESTONE GENERATING STATION

GENERAL ARRANGEMENT OF COMPLETED STRUCTURES

FIGURE 2



LIMESTONE GENERATING STATION

STAGE I DIVERSION

FIGURE 3

DISCUSSION

S. Petryk, Rousseau, Sauve and Warren Inc.

The author has presented a very interesting and useful paper comparing computed and hydraulic model results with field data.

During the workshop presentation, it was mentioned that stable ice cover conditions were observed in the cofferdam opening even though the corresponding mean velocities were relatively high. Also the headlosses between the upstream and downstream sides of the cofferdam were generally higher than observed in the hydraulic model - probably due to the cohesiveness in the packed ice. It would be appreciated if the author would give a quantitative description of flow conditions in the opening when the headloss was a maximum between upstream and downstream of the cofferdam. Specifically what was the discharge, mean depth including ice cover in the opening, and the headloss between the upstream and downstream sides of the cofferdam?

Reply by R. Carson

The maximum headloss between the upstream and downstream cofferdam legs (see Figure 3) occurred during the overtopping of the cofferdam in March 1979. The upstream water level was el 73.6 m, the downstream water level el 68.5 m, with a river flow estimated at 4,000 to 4,300 m^3/s. The riverbed elevation in the diversion channel around the cofferdam is approximately el 55.0 m, with very little variation either laterally or longitudinally. The mean depth including ice cover at the upstream corner of the cofferdam would therefore have been approximately 18.6 m, and at the downstream corner approximately 13.5 m.

R. Gerard, University of Alberta

Is the ice accumulation thickness caused primarily by shoving or simple frazil accumulation from underneath?

Reply by R. Carson

The mathematical model of the ice processes shows that with the strength parameters and n-values used, the final ice thickness is dominated in most of the river by shoves. Nevertheless, the simulations do show deposition of frazil ice which occurs at distinct constrictions in the river, and which triggers shoves further downstream because of the increasing hydraulic forces caused by the growing frazil deposits.

The observations of the physical model of the Limestone reach showed that there was significant shoving occurring, but that there was also movement of ice particles in the flow beneath the cover. It would be safe to say that while the shoving appears dominant, the two processes are inextricably linked in the formation of the ice cover on the Nelson River.

S. Beltaos, Canada Centre for Inland Waters

You mentioned that the ice Manning coefficient had to be increased with ice cover thickness in order to "match" the observations. Did you have observations on ice cover thickness as well as stage or simply stage?

Reply by R. Carson

The majority of the observations were stages at some 18 locations along a 120 km length of the lower Nelson River. However, in the winters when exploratory drilling of the foundations at potential dam sites were done, ice thicknesses were obtained at those sites. Unfortunately, measurement of an overall average ice thickness which could permit a rigorous comparison to the mathematical simulation could not be obtained because the location of the ice/water interface could not be distinctly discerned. Nevertheless, the rough estimates of ice thickness, based on these measurements did support the calculated values. For example, the calculated thickness at the Limestone site was about 9 m. The best interpretation of the drilling done by Manitoba Hydro in 1974 suggested a thickness of 7.5 m. This drilling was done in mid-winter at least six weeks after the ice cover formed. Considering the cover had consolidated to some extent and may have been eroded or smoothed somewhat from the flow beneath it, the comparison appears reasonable. In this area, the best estimate of n-value of the ice to match the observed stage was 0.09.

In the lower reaches of the river, where the slope is much less (0.0003 versus 0.0025 at Limestone) and velocities are lower, the observed stages were best simulated with an n-value of the ice at 0.015 to 0.025. Here, the simulated ice thickness was near 2 m, but no ice thickness measurements were made (no potential dam site). However, it was obvious from the appearance of the ice cover (relatively smooth surface, no large pressure ridges) that it was much thinner than in the steeper reaches upstream.

J. Cowley, Acres Consulting Services Ltd.

For comparison with the investigation described in the last paper (Gerard and Andres) can you mention what range of roughness values were successful in your mathematical modelling.

D. Andres, Alberta Research Council

Most models which attempt to predict the thickness of an accumulation, hence stage, require some knowledge of the roughness of the cover and the internal strength of the cover. Would you comment on the values of each of those parameters used in calibrating the model to match observed water levels.

Reply by R. Carson

The best calibration of the mathematical model was with n-values of ice as follows

Reach 1	km 0 to 12.5	0.05	local steep reach near estuary
Reach 2	km 12.5 to 52.7	0.015	thinnest ice cover, mildest slope of the river
Reach 3	km 52.7 to 60	0.025	
Reach 4	km 60 to 71.7	0.06	
Reach 5	km 71.7 to 120	0.09	thickest ice cover, steepest slope of the river, includes Limestone site

With regards to ice strength, a Pariset and Hausser "μ"-value of 1.5 was used, where

μ = $K_1 \cdot K_2 \tan \phi = 1.5$
K_1 = ratio of lateral stress in the ice cover to the streamwise stress
$\tan \phi$ = coefficient of friction of the ice
$K_1 \cdot \tan \phi$ = 0.18
K_2 = coefficient of internal strength of the ice cover (related to development of passive resistance of the fragmented ice mass)

In calculating the internal strength of the ice cover the mathematical model uses

$$F_{ice} = K_2 \cdot \rho' \cdot \left(1 - \frac{\rho'}{\rho}\right) \frac{g t^2}{2} \cdot W$$

where F_{ice} = maximum ice strength
K_2 = defined above
ρ' = ice density
ρ = water density ($\rho'/\rho = 0.92$)
g = acceleration of gravity
t = ice thickness
W = width of river at that location

Forces transferred to the banks are calculated from

$$F_{bank} = 2 \cdot f_L \cdot K_1 \cdot \tan \phi \cdot t \cdot D$$

where F_{bank} = force transferred to the river banks over a distance D
f_L = streamwise stress in ice cover
$K_1 \cdot \tan \phi$ = 0.18 (as defined above)
t = ice thickness
D = length of increment of river (in the model it is distance between cross sections)

The value for cohesion suggested by Pariset and Hausser in their 1966 paper (80 lb/ft of river length) was used in the simulation, but because of the very thick ice cover, it has very little influence on the stability of the ice cover. The simulation is essentially "cohesionless".

D. Calkins, CRREL

Would you feel confident to apply the mathematical model to the next downstream power plant without doing a physical model also?

Reply by R. Carson

No. While mathematical modelling of ice processes is steadily improving, I do not believe it is quite as good as physical modelling, which, when properly constructed, operated and interpreted, can address three dimensional flow characteristics. The enormous costs of construction of the large cofferdams and structures on the Nelson River gives an economic incentive to use all of the best techniques available.