A NATURAL ICE BOOM

A Thesis
Presented to
The Faculty of Graduate Studies and Research
The University of Manitoba
in Partial Fulfillment
of the Requirements for the Degree of
Master of Science

---

by
H. R. Hopper

ABSTRACT

Observations of the natural ice formation and destruction processes on the Nelson River have shown that stage increases in excess of 40 feet have occurred in some reaches before a stable ice cover was formed.

Stage increases of this magnitude are more critical than those resulting from flood flows during the open water season and become the criteria for cofferdam design. The usual frequency-design choice does not apply.

Experience on the St. Lawrence River has shown that some degree of control over ice action is possible by the judicious placement of log booms or ice control structures. On the Nelson River the formation of natural ice booms has been observed as a random occurrence. These too affect the natural sequence of ice cover formation and can reduce the severity of ice action and river stage for some distance downstream.

It is reasonable to assume that the severity of ice conditions at a proposed development on the river can be substantially reduced during the construction period by the placement of booms upstream. If the required boom could be replaced by one of natural ice then considerable savings could result by the use of the resources at hand.

The experiment undertaken was to introduce an ice sheet of sufficient magnitude and competence into the open water main stream

where it would be carried downstream and eventually wedge at a narrow section between the border ice growth, thus creating a natural ice bridge or boom. Under favorable circumstances this boom would initiate the progression of the ice cover from its location on upstream, cutting off the downstream reach from the ice producing potential of the upstream reach. Ice would still be generated downstream but the length of the reach between the proposed ice boom and development site would have to be short enough that a supply of ice sufficient to cause critical jamming would never enter the reach.

PREFACE

The following experiment was an attempt to effect a means of control over the natural ice formation and accumulation process on the Nelson River.

Although the experiment did not attain its objective, the results were by no means negative. The chances of success are good provided certain well defined criteria are met. The exercise can be considered as only the first step in ascertaining the difficulties to be overcome in order to achieve reliable control of the natural ice process. More analysis and experimentation are required and should be undertaken because control of the ice action is mandatory if future development of the river is to take place. If successful the benefits would be more than significant.

I wish to thank the personnel of Manitoba Hydro, Nelson River Projects Division who made it possible for me to undertake this experiment. In particular, Mr. James D. McKeowan at the construction site of the Kettle Generating Station who organized the necessary men and materials, also, Mr. D. B. Butterworth who prepared some of the necessary sketches and finally Mrs. Elaine Olsen who typed the manuscript. All photographs unless otherwise noted were taken by personnel of Manitoba Hydro.

LIST OF PLATES

LIST OF PLATES

LIST OF FIGURES

LIST OF FIGURES

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Amex II	a CIL tradename for a blasting agent
Forcite	a CIL tradename for dynamite
Primacord	a CIL tradename for a fuse
B	width of a river channel in feet
C	slush ice concentration in pounds per square foot
D	mean depth in feet
F	thrust exerted by friction
F_r	Froude number of the flow in front of the upstream edge of the ice cover
H	depth of water in feet in front of the upstream edge of the ice cover
K	$m \tan \phi$
K_α	a coefficient of active thrust
K'	a form factor for ice
L	distance upstream from boom where thrust T on the boom approaches a minimum
N	mp
T	total thrust exerted on an arch
T_α, T_{max}	maximum thrust exerted by an ice sheet
V	velocity in feet per second in front of the upstream edge of the ice cover
V_c	critical velocity in feet per second that an ice cover cannot progress against
V_o, V_υ	average velocity in feet per second under the ice
f	central deflection of a boom
g	acceleration due to gravity

h	mean depth of water in front of the ice cover
h_0	depth of water under the ice
m	Poisson's ratio for ice
n	Manning's coefficient
n_1	Manning's at the undersurface of the ice cover
n_2	Manning's at the bed of the river
p	normal stress
p_0	hydromatic force on the frontal edge of an ice cover due to flow and wind
r_1, r_2	shear stress from the sides
t	thickness of ice concentration
x	distance upstream from boom where thrust "T" is calculated
y	mean depth of water in front of ice cover
α	angle of internal friction for ice
ε	porosity of ice concentration
γ	unit weight of water
σ_{n_1}	one of the principal stresses on an ice arch
σ_{n_p}	limiting condition of equilibrium
σ_y	normal stress in the y direction
θ	a coefficient equal to $\sin\psi\tan^2(45^\circ - \frac{\psi}{2})$
ρ	specific gravity of water
ρ'	specific gravity of ice
ϕ	angle of internal friction for ice
ψ	angle of friction of ice accumulation with border ice
λ	a coefficient equal to $\frac{p_0 + .26\tau B}{3.6\tau B}$

τ	tangential force per unit area in the direction of flow equal to
τ_o	tangential force due to weight of cover
τ_w	tangential force due to friction under the cover
τ_a	tangential force due to wind

TABLE OF CONTENTS

TABLE OF CONTENTS

APPENDICIES

CHAPTER 1

THE NELSON RIVER

CHAPTER 1

1.1 The Nelson River

The Nelson River in Manitoba drains all of the waters emptying into Lake Winnipeg. These include such river systems as the North and South Saskatchewan, the Red and Assiniboine, the Winnipeg and English together with numerous smaller watersheds tributary to Lake Winnipeg and the Nelson Valley itself. (Plate 1).

The Nelson River flows from the outlet of Lake Winnipeg at Warren Landing, some 420 miles in a northerly and easterly direction to Hudson Bay. It descends a total of 712 feet to sea level and in its upper reaches consists of lake like expanses joined by short reaches of rapids. From Lake Winnipeg to Sipiwesk Lake it falls 104 feet in a distance of 120 miles. For the next 70 miles it flows in a well defined channel varying in width from 1,000 to 2,000 feet to the Kelsey Generating Station. The normal gross head at Kelsey is 53 feet and the normal tailwater elevation is 552. The remaining 140 miles from Split Lake to Hudson Bay is generally confined within a channel 2,000 to 3,000 feet wide. It is this reach of the river that is arbitrarily referred to as the Lower Nelson and is the area where the major portion of the current ice observation programmes are being carried out.

The total drainage area of 415,000 square miles extends from the eastern slopes of the Rockies to the head of the Great Lakes and from the headwaters of the Mississippi and Missouri to the divide between the Athabaska and Churchill Rivers. This area lies between longitudes

90°W and 116°W and latitudes 46°N and 57°N.

Precipitation over the watershed is diversified and varies from annual minima of 11 inches in the Paillister Triangle to a maximum of 24 inches at Kenora, Ontario in the Winnipeg River watershed.

The average outflow from Lake Winnipeg is 68,000 cfs and the average Nelson River flow at Split Lake is 82,000 cfs increasing to 85,000 cfs at its mouth. Lake Winnipeg is a natural and effective regulating basin which maintains a favourable ratio of high to low flows in the order of 6:1. The maximum outflow is recorded at 136,000 cfs and the minimum, a Winter flow of 23,500 cfs. A discharge of 205,000 cfs has been recorded 330 miles downstream of Lake Winnipeg during the construction period at the Kettle Generating Station.

In all parts of the Nelson drainage system the climate is severe enough to cause ice conditions in lakes and rivers for a variable period of time during the Winter season. However, it is in the Nelson Valley itself that the severest Winter conditions prevail. The temperature varies from extremes of approximately 50°F below zero in January to 90°F in July. The mean annual temperature is 23°F with the mean monthly temperature from November to April below freezing and the average duration of the frost free period is in the order of 100 days.

It is interesting to note that there was no significant data available on freeze-up or break-up on the Nelson River as late as 1962. Continuous observations of ice behaviour were not started until 1963 at which time Manitoba Hydro initiated its Nelson River investigations and it was not until 1966 that full appreciation of the ice formation processes were observed and reported on by Newbury.(1.1)

1.2 The Natural Ice Regime on the Nelson River

The annual cycle of freeze-up and break-up on the Nelson River has been summarized by Newbury in a paper presented to the 1968 Spring meeting of the Canadian Electrical Association.(1.2)

The formation of ice covers presents a great variety of physical conditions, from the smooth ice cover formation on lakes and low velocity sections, to the jagged formation of thick ice jams in reaches of high velocity.

To appreciate the ice conditions a cofferdam is required to provide protection against, a summary of the ice formation and destruction processes is presented; as Winter begins the first formation of ice is along the channel boundaries and is termed border ice. In lake-like expanses the rate of border ice growth is extremely rapid and channel closure or bridging occurs a few days after the initial formation, subdividing the river into shorter reaches of open water.

Between the initial closures, border ice continues to grow, narrowing the channel boundaries. Ice crystals are formed within the upper layers of flow in the open water channel and collect on the surface. They are transported downstream as a semi-consolidated mass of ice, termed "slush ice." The blanket of slush ice thickens as it progresses downstream and is broken and reworked as it passes through rapid sections. At the end of an open water reach the leading edge of the next downstream closure is encountered. Depending upon local flow conditions the slush ice may remain on the river surface against the leading edge or may pass under the existing ice cover. If the slush ice remains in place, the front of the cover proceeds by juxtaposition upstream at a rate depending on the quantity of ice transported from upstream. If the ice is drawn under the cover and deposited, ice thickening or jamming occurs causing a channel restriction and a corresponding rise in stage. This changes the flow conditions at the leading edge of the cover and once a favourable stage is reached, the surface velocity is reduced so that there is no under run, the ice accumulation can then proceed upstream until a new higher velocity section is reached and the ice thickening and stage raising process is repeated. In this manner the central channel between the border ice boundaries is gradually covered starting in the Fall of each year at the downstream end of an ice accumulation reach. <u>Stage increases of as much as 40 feet may occur in rapid zones of the Nelson River before maximum cover stability criteria are reached</u>.

As the ice cover progresses upstream the open water reach is shortened and the ice generation capability reduced. The progress of the leading edge of the accumulated ice cover is slowed or stopped as the slush ice input decreases. At this stage, border ice growth may close the remaining central channel but in many cases an open channel remains throughout the Winter below closures.

During Spring break-up approximately 80 per cent of the ice cover rots and melts in place. Ice movement is confined within the reaches between the barriers. It is only during the few days immediately following the destruction of the barriers that there is a general run of ice that might cause damage to structures by direct ice action or damage from flooding because of rising stages caused by ice jams downstream.

1.3 Cofferdamming

Nearly all of the potential power sites in the Nelson River complex are single channel developments. That is, none incorporate an island in their general arrangement so that it is possible to divert the river by one channel while a phase of construction takes place in the other.

A standard sequence of passing the flow of the river during construction is to cofferdam off a portion of the river large enough to construct the spillway section in the dry.

Upon completion of the spillway the cofferdam is breached both upstream and downstream allowing the river to flow through this structure. The cofferdam is then extended to encompass the remaining section of the river where the powerhouse and dam section may be completed in the dry. A portion or all of this cofferdam is then removed as required.

There are two distinct critical periods when ice threatens the safety of cofferdams constructed on the Lower Nelson River. One period, which has been observed as the most critical, is during freeze-up when the ice cover is progressing upstream and proceeding past the cofferdam. At the Kettle Generating Station the first stage cofferdam was constructed to provide protection against a rise in stage up to 22 feet. At the Limestone site protection would have to cope with a rise in excess of 40 feet.

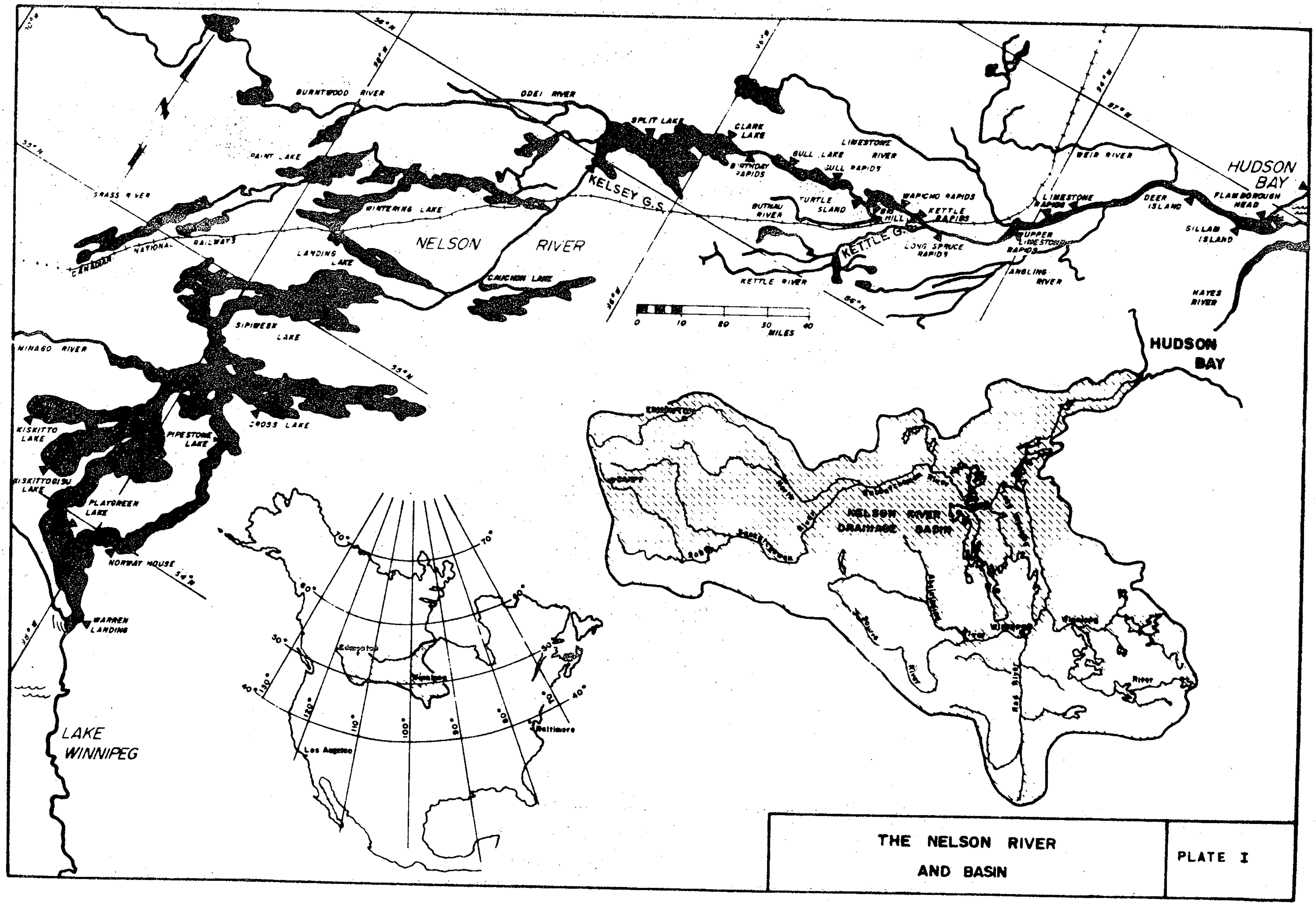
The other critical period is during break-up when ice pans ranging in size from two to thirty feet in diameter and from one to two and one-half feet thick have been observed shifting downstream. Extreme sizes had diameters as great as 50 to 75 feet with thicknesses up to four feet. The danger at this time is two-fold, and becomes critical during the second sequence of cofferdamming. First there is possible damage to the diversion structure and control gates from the ice running in the river and second there is the danger of flooding by a rise in stage caused by an ice jam downstream of the cofferdam. Protection against these conditions at Kettle involves raising and controlling the upstream water level to an elevation such that the surface velocities approaching the structure will be reduced sufficiently to prevent ice from being drawn into the gate openings. (Plate II). Also the increased water level will permit a competent ice cover to form in the immediate forebay which would act as a barrier to any ice runs in the river. The raising of the forebay will initiate the formation of a continuous ice cover upstream of the site to the foot of Gull Rapids very early in the Winter season. This will effectively cut off ice generation in this reach of the river and consequently there will not be sufficient ice generated downstream of the construction site for ice to progress upstream as far as Kettle Rapids. Thus the condition causing the extreme rise in stage during the first sequence of cofferdamming will not exist during the second sequence.

1.4 Proposal

Any method that may be devised to reduce the extreme stages at a cofferdam caused by ice progression upstream during freeze-up or by ice jams during break-up would significantly reduce the risk and, therefore, the cost of cofferdamming.

That man may exercise some degree of control over ice action is demonstrated in Chapter 2 where several examples are summarized. Also illustrated are observed instances where channel closure was obtained by slush ice bridging or sheet ice jamming. It is the natural closure that holds the greatest promise of economy in ice control, provided closure can be obtained at a location and time whereby the extreme stages are reduced in the river reach where a cofferdam is required.

This thesis presents an experiment to cause channel closure by sheet ice wedging and to discuss the criteria necessary to obtain closure and initiate the formation and progression of an ice cover upstream.



THE NELSON RIVER AND BASIN

PLATE I