HYDRAULICS DIVISION

Technical Note

DATE: June 1980 **REPORT NO:** 80-23

TITLE: Technical Review of Proposal to construct Six Artificial Islands in the Mackenzie River at Norman Wells, N.W.T.

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REASON FOR REPORT: Written in response to a request from the Director, Northern Non-Renewable Resources Branch, Indian and Northern Affairs.

CORRESPONDENCE FILE NO:
1371

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1.0 INTRODUCTION

At the request of the Director, Northern Non-Renewable Resources Branch, Department of Indian and Northern Affairs, the Hydraulics Division of the National Water Research Institute undertook a review of a proposal to construct six artificial islands in the Mackenzie River at Norman Wells, N.W.T.

This technical note consists of the review of the following four reports:

A. "Regime of Mackenzie River at Norman Wells in Relation to Artificial Island Scheme", Northwest Hydraulic Consultants, Oct. 1979.

B. "Design and Construction Plan for Development Islands at Norman Wells", Beaver Dredging Co. Ltd., date unknown.

C. "Some Remarks Regarding Ice Jamming and the Design of Islands in the Mackenzie River at Norman Wells", Beaver Dredging Co. Ltd., date unknown.

D. "Height and Frequency of Ice Jamming on the Mackenzie River at Norman Wells, N.W.T.", Hardy Associates (1978) Ltd., Oct. 1979.

This review is primarily concerned with the problems of ice piling on the islands, ice jamming and flooding and long term effects on the river. However, a number of other aspects such as bottom protection and additional design information are also discussed.

2.0 ICE PILING

Most materials concerning ice piling are contained in the report "Design and construction plan for development islands at Norman Wells" by Beaver Dredging Company Ltd. of Toronto. The comments below are mostly about this report.

As a whole, the report betrays a certain lack of understanding of ice problems in general and the ice piling problem in particular. This, in fact, is confessed by the report itself. Of the references quoted in the report, none are on the subject of ice piling.

Ice piling damages on the proposed artificial islands are chiefly controlled by the following two factors; (1) the water level at the time of ice piling, and (2) the geometry and positioning of the ice piles. Comments on these two points follow.

2.1 Water Level at the Time of Ice Piling

In the report, the water level at the time of ice piling is considered to be 43 metres above the topographic survey of Canada datum, or 4300 TSC. The surface of the islands is designed to be at 5400 TSC, giving a freeboard of 11 metres, a sufficient allowance at first glance.

However, when one refers to the stage record of the site, one quickly notices that the maximum water level recorded was a little more than 5100 TSC. Since ice piling is a fast process, it is affected by the instantaneous water level rather than by the mean water level, so 5100 TSC should at least be used as the design water level, not 4300 as shown in Fig. 12 of the report.

It must be pointed out that the 5100 TSC water level was recorded over a short recording period only. Over a longer period, higher water level is likely to occur. However, no estimate is made of the probability of higher water levels. As noted in the report, high water levels are caused by ice jams. The construction of the artificial islands in the river will undoubtedly increase the probability of ice jamming. Thus, a high water level will be more likely to occur. Nevertheless, in the comments here, the 5100 TSC water level will still be used to demonstrate that even with this conservative water level, the surface structure of the artificial islands will be very prone to damages.

In the report, a maximum surface flow velocity of 3.6 m/s is quoted. Since this velocity occurs when the downstream ice jam from Norman Wells is destroyed, it takes place concurrently with the high water level. The construction of the artificial islands in the river will block the flow. The slowing down of the current will in turn increase the water level in front of the islands as the velocity head of the current is converted to the potential energy of the water level. Taking the simplest approach in assuming that all the velocity head is converted to elevation head, the increase in water level will be

$$\frac{V^2}{2g} = \frac{3.6^2}{2 \times 9.8} = 0.66 \approx 0.7 \text{ m}$$

Adding the above value to 5100 gives a water level at the time of ice piling of 5170 TSC. The freeboard of the islands thus is reduced to only 2.3 metres. Such a freeboard is obviously too small.

2.2 Geometry and Positioning of Ice Pile

The report on ice piling is not entirely correct. One has assumed in the report that the three major components of the acting forces are (1) the water drag, (2) the wind drag, and (3) the component of the weight of the ice floe in the flow direction. Using these forces and unsubstantiated assumptions, ice pile heights of 37 m and 14.5 m are calculated for the upstream island and the downstream islands respectively.

It should be emphatically pointed out that ice piling is not the result of forces acting on the ice, but a dynamic process involving the conversion of the kinetic energy of a moving ice floe to the potential energy of the piling ice (Tsang, 1974, 1975)*. The formula for calculating the pile height given by Tsang (1974)** is

$$H = V_i \quad \frac{NL \sin \beta}{g(1 + f \cot \beta)}$$

where V_i is the drifting velocity of the ice floe, N is the coefficient of virtual mass and is approximately equal to 2, L is the length of the ice floe, β is the base angle of the ice pile, g is the gravitational acceleration and f is the friction coefficient between gliding ice floes and is equal to 0.02. Using the above equation, one can calculate the height of the ice pile if all the parameters are known.

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* Tsang, G., "Ice Piling on Lakeshores, with Special Reference to the Occurrences on Lake Simcoe in the Spring of 1973", Scientific Series No. 35, IWD Report, Environment Canada, 1974.

** Tsang, G., "A Field Study on Ice Piling on Shores and the Associated Hydro-meteorological parameters", Proc. of 3rd Int. Symp. on Ice Problems, IAHR, Hanover, 1975.

In the report, the size of the ice floe controlling the pile height on the upstream island is assumed to be 13 km^2 and the size of the ice floe controlling the pile height on the downstream islands is assumed to be 2 km^2 (see Fig. 6 of report). There is no justification in assuming these floe sizes except that they appear to be the maximum floe sizes possible to be placed in front of the islands shown in the map. Field observations show that in natural rivers the ice floes that drift with the current seldom would have a linear dimension greater than the width of the river. For the few exceptional ones that happen to have a linear dimension greater than the width of the river, they only drift with a fraction of the current velocity because their movement is retarded by their continued grinding with the banks. As a matter of fact, these floes usually only move a short distance before bridging across the river; and in many cases initiate ice jams. Thus, if one considers that the ice piles on the islands are produced by ice floes drifting with the surface current, then ice floes should only have a length equal to the width of the river, and not 10 km as shown in the report. From Fig. 6 of the report, the width of the river between the river bank and French Island is measured to be 2360 m. The design length of the drifting ice floes should be 2360 m.

It may be pointed out that even the above design floe length is on the conservative side. In a study by Mock et al (1972)* studying the distribution of pressure ridges in the Arctic Ocean, they found that few ridges were more than 500 metres apart or that few floes are larger than 500 m. Although in the Arctic Ocean the constant movement of the ice field tends to break up the ice floes more and the sea ice is not as strong as fresh water ice, and thus is easier to break, the present adoption of design ice floe length of 2360 m does seem to be conservative enough.

It was mentioned earlier that the maximum surface velocity of the river is 3.6 m/s. However, it is very unlikely that the whole large ice floe, which is carried by the average current instead of the maximum current, would drift at this maximum velocity. The design velocity of 3.0 m/s used in the report, thus is judged to be more appropriate as the drift velocity of the ice floe.

According to the above discussions, one arrives at the following floe length and drift velocity:

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* Mock, S. J., Hartwell, A. D. and Hibler IV, W. D., J. of Geophysical Research, Vol. 77, No. 30, 1972.

$$L = 2360 \text{ m} \quad \text{and} \quad V_i = 3.0 \text{ m/s}$$

for the calculation of the ice pile height using Tsang's equation.

Tsang's equation also contains the variable β. Field measurements by Tsang (1974) showed that the base angle of an ice pile can be as large as 45^o, but the common angle is 30^o. Using these β values and the L and V_i values shown above, the height of the ice pile is calculated as follows:

$$\beta = 30^o, \quad H = 45.8 \text{ m}; \quad \beta = 45^o, \quad H = 54.8 \text{ m}$$

The above pile heights are for both the upstream and downstream artificial islands.

The pile heights shown above are for rather extreme situations. For situations one can expect every year, the following parameters may be used: L=2000 m, V_i=1.5 m/s (mean flow velocity without downstream ice jam). Using these values, the following pile heights are calculated:

$$\beta = 30^o, \quad H \doteq 21.0 \text{ m}; \quad \beta = 45^o, \quad H = 25.2 \text{ m}$$

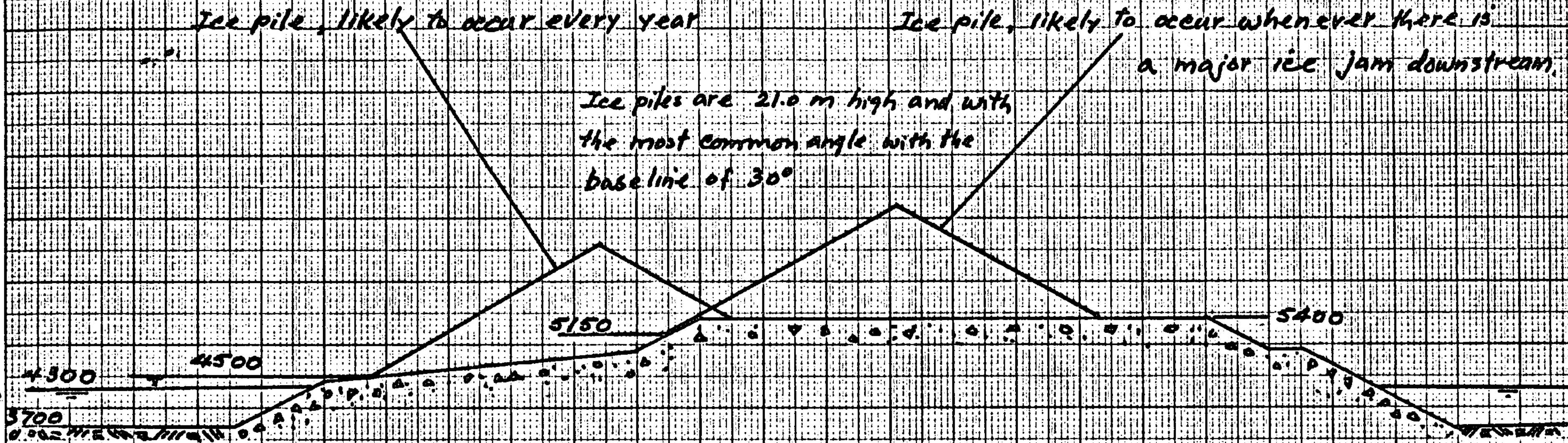
These pile heights are quite reasonable. At Lake Simcoe in Ontario (Tsang, 1974), ice piles 9 m high have been observed to form under a mere 6.75 m/s wind.

In the Beaver Dredging Company's report, ice piles are assumed to be so positioned that their peak is 10 m inshore to the point of changing slope (see Fig. 10 of report). There is no basis for such an assumption. Field study on Lake Simcoe (Tsang, 1974) showed that the toe of the piles was very close to the point of ice piling initiation. The figure on the following page shows ice piles so positioned on the island. The lower pile is plotted for the case of:

$$\beta \doteq 30^o, \quad H = 21.0 \text{ m and water level} = 4500 \text{ TSC}$$

a case that can be expected to occur every year, and the higher pile is plotted for the case of:

$$\beta \doteq 30^o, \quad H = 21.0 \text{ m and water level} = 5150 \text{ TSC}$$



Water levels:

3700 m. TSC – Elevation of river bottom
4300 m. TSC – Used as design level by Beaver Dredging Co.
4500 m. TSC – Likely level to occur every year
5150 m TSC – Max recorded level + Water piling up in front of ile
5400 m. TSC – Surface elevation of island in proposal.

Envisage Ice Damages to the Proposed Artificial Islands.

0 50 m
Scale

a case that will happen whenever there is a significant ice jam downstream from Norman Wells. It is seen from the figure that the proposed artificial island will be threatened every year by ice piling. Should there be a major ice jam downstream, the whole island could very easily be completely buried under the ice pile.

2.3 Conclusions

The proposed artificial islands by Esso Resources Canadian Ltd. will not be safe as working platforms for petroleum exploitation due to the problem of ice ride-up on the islands.

3.0 ICE JAMMING AND FLOODING

There are some significant factors which have not been considered. The various consultants' reports agree that the presence of islands can cause ice jamming in the vicinity of Norman Wells. However, the consequences of such jamming have not been studied adequately. For example, on p. 12 of report B, four ways in which "ice can affect an island in a river" are identified, without mentioning two important concerns: (i) flooding of the islands that may be caused by high water levels due to ice jams, and (ii) high erosional action on the islands caused by surge speeds during ice jam releases.

The surge problem has been considered in report C but not without certain misconceptions. The initial depth diagrams in Figures 3 and 4 do not imply ice jams of the specified lengths; rather, they represent infinitely long ice jams whose toe sections have the specified lengths. Since the water level falls by the constant amount of 10 m over these lengths, the toe slope decreases with increasing length and has a maximum of 2.5×10^{-3} for a length of 4 km*. Jam toe slopes as large as 5×10^{-3} have been reported for a large river** and it would thus appear conceivable that the design speed of 6 m/s can be exceeded under severe conditions. In addition, the basis of the assumed initial conditions for the surge computations is not clear.

Concerning the problem of possible flooding due to high jam stages, the following questions should be addressed (for ice jams that may be initiated by the islands): (i) what is the jam stage as a function of prevailing river flow, and (ii) based on available records, what is the probability of any given stage being exceeded during breakup.

Another question that needs consideration is the possible effect of the islands on river freeze up. Initiation of significant ice jams during freeze up at the island reach of the river is possible. Once frozen in place, these jams would be much thicker than the normal sheet ice that forms elsewhere in the river. In turn, this might have repercussions on both the anticipated ice thrust on the islands and the probability of dry ice jam formation during breakup.

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* In this light, it is not surprising that surge velocities and water levels were found to decrease with increasing "jam length".

** Doyle, P. F. and Andres, D. D., 1979, "1979 Spring Breakup and Ice Jamming on the Athabasca River near Fort McMurray", Alberta Research Council Internal Report SWE-79-05, Edmonton.

4.0 LONG TERM EFFECTS ON RIVER MORPHOLOGY

The long term effects of the proposed artificial islands in Mackenzie River near Norman Wells were studied in report A.

By plotting the slope of the Mackenzie River against the dominant or channel forming discharge of 28 300 m^3/s, the report classifies the Mackenzie River as the one belonging to stability category 2 (Neil's terminology), i.e. a channel with variable width and some mid-channel bars. When the same slope and discharge values are plotted in a diagram proposed by Lane (1957)* as shown in the attached figure (Fig. A), the Mackenzie River falls under the category of intermediate stream, i.e. a stream pattern lying between a more stable meandering pattern and a highly unpredictable braided pattern. River morphological studies carried out by Lane (1957), Leopold and Wolman (1957)** suggest that in a stream of intermediate pattern, any small increase in the overall channel slope could initiate a tendency toward a braided pattern characterized by its rapid changes in alignment and unpredictable behaviour. Therefore, it appears that the impact of the proposed artificial islands in the long run could be even more severe than that suggested in the report which suggested that the morphological impact of the artificial islands in the form of modification of cross sections and bed-level changes would be limited only to a 4 km stretch of the Mackenzie River adjacent to Norman Wells.

In section 4.3 where the suspension of bed sediment is treated, it is stated that the Mackenzie River under the range of open-water flow conditions (Q=7000 to 28 300 m^3/s) is capable of carrying only fine sand of grain size 0.2 mm or less. However, calculations show that for a discharge of 28 300 m^3/s, the river can carry a sediment of grain size as high as 1.0 mm in suspension. For the grain size of 0.3 mm which is the median size of the bed material according to the report, the ratio between shear velocity and fall velocity is of the order of 2.50 indicating that the bed material can be suspended almost up to the free surface.

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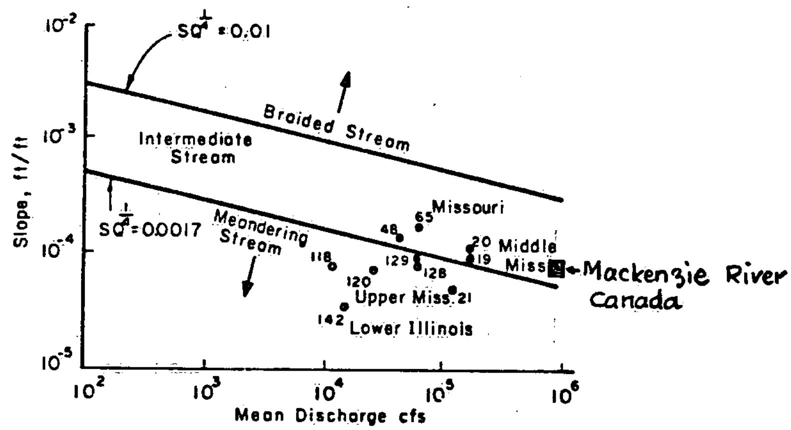
* Lane, E. W., "A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material", Missouri River Division Sediments Series No. 9, U.S. Army Engineer Division, Missouri River Corps of Engineers, Omaha, Nebraska, 1957.

** Leopold, L. B. and Wolman, M. G., "River Channel Patterns: Braided, Meandering and Straight", U.S.G.S. Prof. Paper 282-B, 85 p. 1957.

With respect to bed forms, the report under the section 4.1 or channel roughness states that the development of the bed form is not extreme. This statement is only partially true. Indeed, if one computes the ratio of the Shield's parameter to the critical Shield's parameter, one gets a values of 42.5. This high value suggests, according to Yalin's graph shown in Fig. B, that the bed-form steepness is on the descending side of the graph implying that the river is in the stage of washing out of the bed forms with high sediment transport rate in the vicinity of the bed and in the bulk of the flow.

In conclusion, it can be stated that report A has dealt with the problem of the long term effects of the proposed artificial islands in the Mackenzie River near Norman Wells in an adequate manner. However, it is possible that the effects of the islands could be more severe than that suggested in the report, considering the present regime of the river and the high values of the excess capacity to transport sediment. It should be pointed out that at the present state of knowledge on the river morphological behaviour, it is not possible to make quantitative predictions of the long term changes. It is possible only to make some qualitative judgement as to which way the regime could change. Considering this, the 4 km stretch for the cross section and bed-level modification to occur as a result of the artificial islands should not be considered as the upper bound.



Identification of Reaches Plotted

19	St. Louis to Chester	Middle Mississippi	118	St. Paul to Redwing	Upper Mississippi
20	Chester to Cape Girardeau	Middle Mississippi	120	La Crosse to Lansing	Upper Mississippi
21	Ohio River		128	Hannibal to Louisiana	Upper Mississippi
48	Lower Arkansas River		129	Louisiana to Grafton	Upper Mississippi
65	Missouri River		142	Lower Illinois River	

Fig. A. Slope-Discharge Relation for Braiding or Meandering in Sand Bed Streams (after Lane (1957))

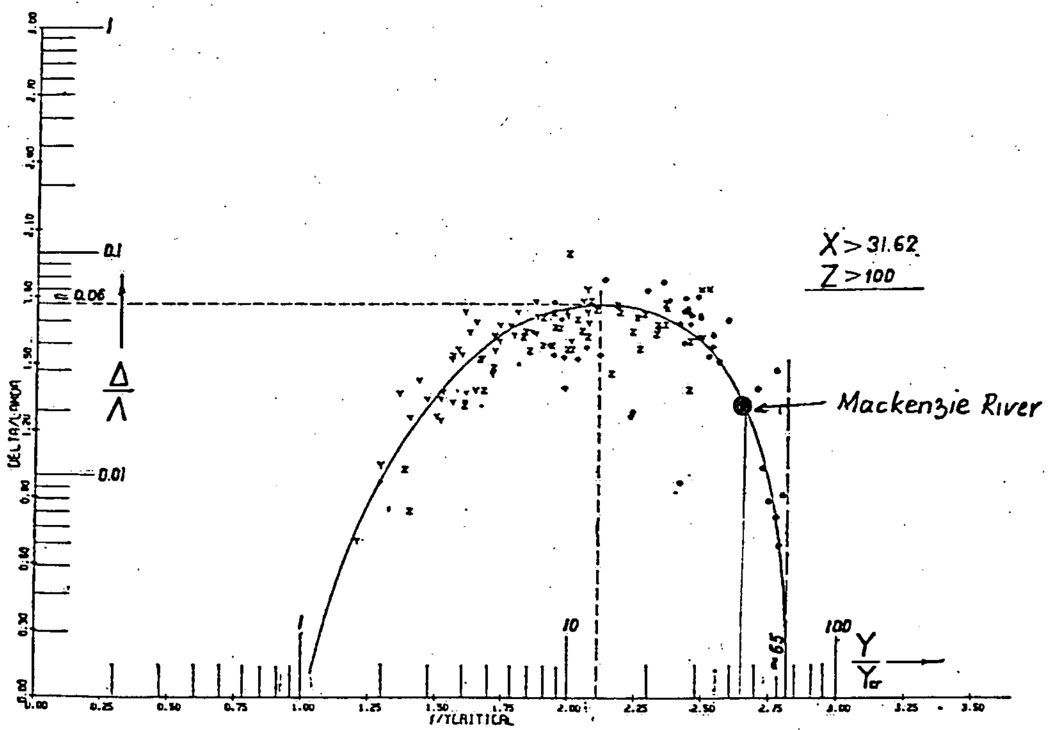


Fig. B. Bed-Form Steepness as a Function of Excess Transport Capacity (after M. S. Yalin, 1972)

5.0 BOTTOM AND SLOPE PROTECTION

The stone sizes for the bottom protection around the proposed artificial islands at Normal Wells in Mackenzie River as recommended by Beaver Dredging Company's report appears to have been calcualted using a value for the "critical velocity" of 3.5 m/s or so. But, in a 'state of the art' report * by IAHR task force on local scour around piers, it is recommended that the rip-rap protection to prevent scour at the bottom has to be designed for a "critical velocity" which is to be at least two times the maximum average velocity in the stream. For Mackenzie River at Norman Wells, according to the Northwest Hydraulic Consultant's report, the average velocity for a flow rate of 28 300 m^3/s (10 yr. flood) is 2.0 m/s. Therefore, the stone size for this stretch of the river has to be calculated using the "critical velocity" of at least 4.0 m/s. When such a calculation was performed, the stone weight becomes 356 kg which is more than twice the weight calculated in this report. The stone size for the slope protection of the islands should also be recalculated using higher value for the critical velocity. It should be noted that a maximum velocity of 6 m/s during ice jam has been quoted.

The horizontal extent of the bottom protection around the proposed islands, recommended by the report also appears to be inadequate. IAHR task force recommend that the horizontal dimensions of the protection be at least two times the width of the pier measured from the face of the pier. In the proposed island design, even though the slope protection would form some part of the bottom protection, perhaps, it would be safer to increase the bottom protection by another 50 percent or so.

In conclusion, the stone sizes for the bottom protection and slope protection should be redesigned using higher values for the "critical velocity". The horizontal extent of the bottom protection should also be increased.

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* H.N.C. Breusers, G. Nicollet and H. W. Shen (IAHR Task Force on Local Scour around Piers), "Local Scour around Cylindrical Piers", Journal of Hydraulic Research, Vol. 15, No. 3, 1977.

6.0 ADDITIONAL DESIGN RELATED INFORMATION THAT SHOULD BE SUBMITTED

1. The report by "...Loran/NHCL, 1979..." referred to on p. 23 of report A should be sumitted.
2. The report by "...Northern Construction, 1979..." referred to on p. 2 of report A should be submitted.
3. On p. 11 of report A, cross-sectional data are given for an open-water discharge of 28 300 m^3/s. Similar data should be given for a range of discharges, preferably in the form of width- and average depth- discharge diagrams.
4. On p. 23 of report A, it is stated that "Efforts were made in previous Esso studies to analyze the hydraulics of Mackenzie River ice-jam sites according to procedures in the literature". The findings of these studies should be submitted, if not already covered in reports B, C and D.
5. Figure 4 of report A is missing; a copy should be submitted.
6. The significance of "LOW WATER" in Table 2.1 (p. 5) of report B should be explained, i.e. provide the open-water discharge at this stage and, if possible, the percentage of time this stage is exceeded.
7. In Fig. 1 of report B, the "instantaneous gauge height for a 9 year period" is shown; exactly which 9 year period does this refer to?
8. On p. 11 of report B it is stated that "The highest recorded water level (back water of downstream jam) is approximately 51.00 m above T.S.C. datum. This water level was reached during a massive ice jam near Patricia Island". This statement should be supplemented by the following information: (i) What is the length of record implied in the words "The highest recorded water level" and which are the years involved in this record; (ii) When was this peak stage recorded (year/date) and what was the river flow at that time; (iii) Exactly where is Patricia Island located relative to Norman Wells (reference to this island is made often in the reports under review but nowhere is its location specified).
9. On p. 12 of report B, it is stated that "The maximum ice free discharge gives ... at Norman Wells...". How is maximum ice free discharge defined and how was it determined?
10. On p. 13 of report B, the river slope is taken as 1.5×10^{-4}; however, in report A, this parameter is given as 0.92×10^{-4} (p. 11). Which is the correct value?

11. In report B, the streamwise ice forces on the islands are computed using the (presumably) normal river slope of 1.5×10^{-4}. However, during ice jammed conditions, the local (vicinity of jam toe) water surface slope may be much larger than the normal slope. Because the ice force is proportional to this slope, it would be prudent to consider the design implications of a total force governed by the strength of the ice sheet.

12. A readable version of Fig. 11 of report B should be provided.

13. On p. 1 of report C, certain statements are made regarding the nature of ice breakup near Norman Wells. The source of this information should be quoted, not only for completeness but also because these statements contradict relevant information provided on p. 23 of report A.

14. On p. 5 of report C it is stated that "Jams downstream of Norman Wells cause back water rises with a maximum of about 13 m". This statement should be supplemented by the following information: (i) source of this finding and an explanation of how it is guaranteed that the quoted maximum cannot be exceeded; (ii) definition of "back water".

15. In report C (Table 1) the river slope is taken as 1.43×10^{-4}. Again this contradicts report A (see item No. 10 above).

16. On p. 9 of report C it is stated that "boundary conditions for these 3 cases have been kept constant Q_1=12,000 m^3/sec., h_{27}=1 m)". This statement should be supplemented by a justification for this choice of parameters, especially the value of h_{27}.

17. In Figs. 3 and 4 of report C, the assumed initial values of depth should be correlated with the T.S.C. datum.

18. Report D should provide a definition for the initials "a.s.l." and a correlation between the quoted elevations and the T.S.C. datum. In its present form, this report is useless for review purposes.

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7.0 MONITORING PROGRAM

Present engineering capabilities for dealing with river ice problems are rather limited. A pertinent monitoring program during and after construction of the islands would be desirable as a means of improving future island designs; in addition, the data gathered under such a program would, when published, be of considerable benefit to Canadian ice engineering in general.

It is not intended to provide here detailed recommendations for an ice observation program; in general, an effort should be made to annually observe and record ice conditions and relevant events during freeze up and breakup within a 50 km long reach roughly centered at Norman Wells.

If a monitoring program is eventually deemed desirable, the Hydraulics Division would be prepared to provide advise on its detailed design.