ICE CONTROL MEASURES ON THE ST. LAWRENCE RIVER

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Introduction

Within the 160 mile reach of the lower St. Lawrence River between Montreal and Quebec City (see Fig. 1) flooding of low lying areas and damage to shore property used to always be hazards associated with winter. The primary reason for such flooding lay in the fact that the ice still had a firm grip on the river at the time of the spring freshet. Flooding also occurred during the early and mid-winter months due to ice jams caused by shoving and telescoping of the ice cover before final consolidation. Marks on buildings along the Montreal waterfront attest to the heights to which the most disastrous of these floods reached; the worst being that of 1886 when Notre Dame Street virtually became a river. The municipalities around and downstream shared with Montreal the distress associated with the annual spring run-off and ice break-up in the St. Lawrence. It is recorded, for example, that 50 people lost their lives during the spring flood of 1865, and that in the Sorel-Berthierville region miles of low lying areas were innundated.

From earliest times, a particularly vexatious problem has been the formation of an ice bridge at Cap Rouge, some five miles west of Quebec City. Here, at the site of the impressive Quebec Bridge, the St. Lawrence is about 175 feet deep, but its width is reduced to less than half a mile. Under conditions of extremely cold weather and a heavy run of drift and sheet ice, this narrow passage was often spanned by a bridge of ice during slack water at high tide. If this bridge was not dislodged by the following ebb tide, a solid barrier would form and generally remain in place until spring. Not only did this lead to considerable flooding upstream, but when the bridge finally let go, the effects in Quebec Harbour were often disastrous. The break-up of the Cap Rouge ice bridge on May 9, 1874 is reported to have resulted in waterfront damage, including sunken ships, to the extent of one million dollars.

The first organized attempt at ice control was made in 1906 when two federal government icebreakers made their presence felt on the St. Lawrence. In the early spring of that year the brand new Lady Grey* and Montcalm, working together, successfully broke up the ice bridge at Cap Rouge before flood dangers developed. Although this was a modest beginning, it was literally a "breakthrough". The Lady Grey is shown at work in Fig. 2.

It soon became evident that the formation of an ice bridge could be prevented by continual icebreaker patrol throughout the winter, and with this barrier removed, it was a relatively easy matter to maintain an open channel as far upstream as Trois-Rivières. With the addition to the icebreaker fleet of the Saurel in 1929 and the N.B. McLean a year later, it was generally possible to open a channel to Montreal in time to provide an escape route for the heavy run of ice and freshet waters in the spring. There still remained, however, the problem of early and mid-winter floods.

* The Lady Grey sank dramatically after a collision while assisting the Quebec ferry in 1955.

It was not until the acquisition of more powerful and modern ice-breakers in the early 1950's and the inauguration of continuous icebreaking operations through the winter that the situation was controlled and the incidence of flooding drastically reduced. Due to this flood prevention program, improved icebreaking techniques, and recently installed control works, the disasters of former years are now all but forgotten. Although we must accept the fact that we are as yet unable to prevent the formation of ice jams, they are now removed by the icebreakers long before there is danger of flooding. As a matter of interest, the maximum level at Montreal last winter occurred on February 5, when an ice jam at Montreal East raised the water level to about 13 feet above normal for a short period, as compared with levels 25 feet above normal which frequently occurred in the past.

Problem Areas

As already mentioned, a major problem area is the Quebec Narrows section at Cap Rouge. The tidal range at Quebec is in the order of twenty feet and effective icebreaking operations can only be carried out on the ebb tide which flushes the broken ice downstream. These operations may have to be curtailed or even suspended under conditions of poor visibility. During critical periods of winter, at least one icebreaker is on standby at Quebec to prevent the formation of jams. The winter of 1967-68 is illustrative of the very serious conditions which can arise in this section. During the extremely cold weather in the first two weeks of January 1968, the ice bridged over in the Quebec Narrows and with continuing extreme temperatures a very severe ice jam quickly formed upriver as far as Trois-Rivières. It took the combined efforts of nine Coast Guard icebreakers (including the three "heavies") about three weeks to finally clear the channel to Montreal. The conditions which faced the icebreakers are well illustrated in Fig. 3.

Between Quebec and Trois-Rivières tidal action and ice-breaker patrol generally keep the channel open throughout the winter. From Trois-Rivières to Montreal, however, the situation is much more complex, and in this reach there are two key areas for controlling the ice problem - the Lake St. Peter-Lanoraie section and the LaPrairie Basin.

Ice Cover Formation - Trois-Rivières to Montreal

The ice cover in the St.Lawrence River from Trois-Rivières to the foot of the Lachine Rapids develops in much the same way every year. With the advent of cold weather, water temperature gradually falls to the freezing point, drift ice begins to appear over the surface, and sheet ice forms in the bays and in areas of slack water. This newly formed ice tends to break off under the action of wind and waves and together with a mixture of "frazil" and slush, drifts downstream into Lake St. Peter where the average current velocity is less than 1.5 feet per second, and at times of strong northeasterly winds there may be no surface movement at all. This condition allows border ice to form and bridge across the narrow outlet of the lake. The mass of drifting ice accumulates against the bridge and a cover soon forms. This usually happens toward the end of December. Thereafter, the ice cover packs upstream to Montreal at a rate dependent on the meteorological conditions and in a manner governed by the hydraulic characteristics of the river.

The mechanics of ice cover growth by packing are not yet fully understood. In the past, the process was based on simple current velocity criteria, with the limiting velocity for advance of the cover by packing being taken as 2.25 feet per second. It is now generally accepted that progression of an ice cover is related to the Froude number, the value of which determines whether ice floes will pack against the leading edge of the advancing cover, or be drawn under it. The actual value of this number for a particular section is probably dependent on various factors, including the hydraulic conditions and the characteristics of the ice at the section. From observations made by Kivisild[1], it appears that the average critical Froude number is about:

$$F = \frac{V}{\sqrt{gD}} = 0.08$$

where V = velocity of the current at the section.

D = mean depth of water at the section.

g = acceleration due to gravity.

According to Kivisild, when the Froude number is less than 0.08, ice accumulates against the edge of the cover and the pack grows upstream becoming more massive as the Froude number approaches the critical value. At higher Froude numbers ice is drawn under the cover and is deposited on the underside to form a "hanging dam" at sections where the shear stress against the cover is below a certain value. This process creates a backwater effect upstream and makes hydraulic conditions favourable for ice to accumulate against the cover, thus allowing the pack to continue its growth upstream. This is the manner in which the ice cover advances from Lake St. Peter to Montreal. A typical ice cover formation is illustrated in Figs. 4 and 5. If the weather remains very cold the ice cover will be relatively strong. A period of mild weather, however, can weaken the cover sufficiently that it cannot withstand the thrust on it. At this point the cover may buckle or telescope and compress to form a heavy ice jam, with subsequent sharp increases in upstream water levels. Serious jamming frequently occurs in the narrows at the head of Lake St. Peter, in the Lanoraie section and in Montreal Harbour.

A key factor governing the ice problem at Montreal and downstream is the continuous generation of ice throughout the winter in the seven mile open water reach of the Lachine Rapids and lower end of Lake St. Louis. The vast quantities of ice generated in this section continue to flow downstream until the increase in water levels in upper Montreal Harbour caused by the advancing ice cover is sufficient to reduce current velocities and permit an ice cover to form in LaPrairie Basin up to the foot of the rapids. Thereafter, with continuing cold weather, the cover in the basin consolidates and the bulk of the ice generated in the rapids area is stored under it. This marks the end of a critical stage in the winter's operations and normally there is little further trouble. A typical ice cover in Montreal Harbour during the fifties is shown in Fig. 6.

In Lake St. Peter a further complication arises after the channel has been opened by the icebreakers in early winter. The lake is some 8 miles wide and 20 miles long with an average depth of about 10 feet. The Ship Channel, which passes through the middle of the lake, is 800 feet wide and dredged to a depth of 35 feet.

The problem here is that from time to time large pieces of the cover break off through the action of wind and the waves of passing ships. These large masses move into the shipping lane and effectively block it. One of the most troublesome areas is the northeast section of the lake, and an example of what can happen is illustrated in Fig.7.

Icebreaking and Winter Navigation

Until a few years ago icebreaking between Quebec City and Montreal was traditionally carried out only for flood control, and the maintenance of an ice-free track for ferry crossings at Quebec, Trois-Rivières and Sorel. Officially no direct assistance was given to ships navigating in this reach of the river except in emergencies. During the last decade, however, there has been a growing trend of ships taking advantage of these icebreaking operations to reach Montreal in the winter months. The closed season, i.e. the time between last departures and first arrivals at Montreal has been progressively shortened from about five months at the beginning of the century until today the port is virtually open to year-round navigation. Most of the ships sailing to Montreal in winter have specially reinforced hulls to combat ice conditions in the Gulf and the St. Lawrence River. Fig. 8 shows the trend and growth in the number of vessels sailing to Montreal during the winter months, January through March.

Although the major role of the icebreakers in this reach of the St. Lawrence is still flood control, they have now taken on the additional responsibility of maintaining an open channel in support of the developing winter traffic through the area. The annual cost of icebreaking between Quebec and Montreal is at present about $750,000 with the following ships of the Coast Guard fleet usually assigned to these operations:

N.M. Rogers	-	13,000 Horsepower
N.B. McLean	-	6,500 Horsepower
Montcalm	-	4,000 Horsepower
Ernest Lapointe	-	2,000 Horsepower

An important factor in icebreaking operations is the width of channel opened. The aim is to open a lane wide enough to permit safe navigation and adequate ice evacuation. This policy leads to less ice being produced in the system, and the slightly higher velocities in the restricted channel favour better ice evacuation. Fig.9 shows an historic representation of the ice cover formation and icebreaking operations between Quebec and Montreal for the winter of 1967-68. The influence of these operations on water levels in Montreal Harbour is further illustrated in Fig. 10.

At times bad weather can reduce visibility and seriously hinder the work of maintaining an open channel. The Ministry of Transport, recognizing the need to get the most effective use of its icebreaking fleet, is actively evaluating and experimenting with a number of accurate vessel location systems which would allow the icebreakers to work under conditions of extremely poor visibility. One Radar Positioning System now under extensive testing on the Norman McLeod Rogers has indicated that an accuracy of about 3 meters can be obtained in vessel location. When this equipment has been fully proved and becomes operational, downtime dueto poor visibility should be practically zero.

Ice Control Structures

To enhance its ice control program to meet the dual challenge of reducing the danger of flooding and of assisting winter navigation, the Ministry has also installed a number of additional features in this reach of the river.

The construction of EXPO'67 involved the narrowing of St. Lawrence River channels in the Montreal area, resulting in a potential danger of more severe jams from a run of ice out of LaPrairie Basin, and hence possible flooding of not only EXPO itself, but of the low lying areas along the Montreal waterfront. To minimize this danger, a permanent ice control structure was constructed across the river at the lower end of the basin. The location and details of the structure are shown in Figs. 11, 12 and 13. Built in 1964-65, at a cost of $18,000,000, the LaPrairie Basin ice control structure was taken over by Transport in October of 1966 and came into full operation during the subsequent winter.

The structure, which is essentially an elaborate system of floating stoplogs set between piers, was designed to help form a stable ice cover on the basin earlier than would normally be the case. Once formed, this cover provides a large storage area for the ice continually generated in the Lachine Rapids section upstream. Thus, the large volume of ice which normally flows out of the basin in early winter is arrested and prevented from causing severe ice jams and consequent flooding in the Montreal area.

Successful operation of the control structure is dependent upon an increase in water level at the structure due to backwater effects of the ice cover advancing upstream into Montreal Harbour. Development of recommended operating procedures was based on extensive model studies. The two main factors investigated were the water levels at which the stoplogs should be placed to promote an ice cover, and the capacity of LaPrairie Basin to store ice under the cover thus formed. It was established from the model tests that if operated under certain stage discharge relationships created by ice jams downstream, the structure would initiate an ice cover on the basin. The operation is illustrated schematically in Fig. 14.

One method of estimating the volume of ice formed from a given area of water exposed to the cooling action of air is by establishing the rate of heat loss as the water is cooled to the freezing point and applying the rate found to later exposures. MacLachlin[2] determined this rate to be about 95 British Thermal Units transferred per day per square foot per degree difference between air and water temperatures, and went on to establish the equation:

$$V = \frac{95.T.A}{144 \times 57.4} \qquad \text{(Simplified to } V = \frac{T.A}{87}\text{)}$$

where V = Vol. of ice formed per day in cu. ft.

T = Av. Diff. between air and water temp. in ^{o}F.

A = Area of open water in $ft.^2$

This relationship was used to establish for various mean temperatures the cumulative production of ice in the open reach of the Lachine Rapids and Lake St. Louis, the area of which was taken to be 270 x 10^6 square feet. The storage capacity of the basin related to water elevation and rate of ice production in the Lachine Rapids, as obtained from model tests, is shown in the composite diagram in Fig. 15.

Because of the success icebreakers have had in recent years in maintaining an open channel, the high water conditions necessary for operation of the structure as described no longer occur, and usually the ice covers only about two-thirds of the width of the basin. Experimental work is now in hand to improve the efficiency of the ice retention capacity of the structure by converting some stoplogs to booms and floating them downstream. Tests are also being made with a boom made out of large diameter nylon rope.

Another feature of the Ministry's ice control program is the installation of a system of floating ice booms. Established initially on an experimental basis, the ice booms are now considered to be an integral part of the control works of the Ship Channel. The booms, which are constructed in 500 feet sections, consist of B.C. fir timbers 14 inches by 22 inches in section and 30 feet long, linked together with 2 inch diameter galvanized steel cable. A typical arrangement is illustrated in Fig. 16.

The booms in the Ship Channel have been designed and located to:

(a) Form a stable ice cover outside the shipping lanes as early as possible, thereby closing large areas of ice producing open water.

(b) Control the movement of this ice cover during its formation and retain it throughout the winter.

(c) Minimize erosion of the ice field caused by waves from passing ships and thus reduce the number of floes breaking off into the channel, presenting a hazard to shipping and creating serious ice jams.

The first booms were installed in Lake St. Peter five winters ago in the location shown on Fig. 17. This installation consists of four booms, each 2,000 feet in length. In the light of experience gained during the first two winters certain design modifications have been carried out to strengthen the booms and improve their performance. This installation has proved to be extremely efficient in preventing the ice cover from breaking up and has considerably eased the workload of the icebreakers in this area.

In conjunction with these booms artificial islands were created in Lake St. Peter to assist in control of ice. These islands (see Fig. 17), constructed of glacial till from dredging operations and topped with rock, measure 40 feet by 40 feet at the top (8 feet above low water datum), and were completed in 1968.

Ice booms have also been installed at two other locations, viz at Lavaltrie, near the lower end of the Verchères Islands and at Ile St. Ours, a little further downstream (see Fig. 17). This is the second winter of operation for the Lavaltrie boom which has been very successful in controlling the ice in the channel north of the Verchères Islands. The boom at St. Ours was installed this winter and its performance is being carefully observed.

Ice Studies

Complementary to, and in conjunction with the ice control measures described, an extensive program of research and development is continuing into all aspects of ice problems related to the St. Lawrence River. The work includes aerial photography, collection of data, field measurements, laboratory analyses, hydraulic model studies and icebreaker design. With regard to icebreakers, perhaps Fig. 18 gives an indication of things to come in the not too distant future.

References

1. Kivisild, H.R. - "Hanging Ice Dams" - IAHR 8th Congress, Montreal, 1959.

2. Report of Joint Board of Engineers - 1926 "St. Lawrence Waterway Project" APPENDIX E - "Ice Formation on the St. Lawrence and Other Rivers".

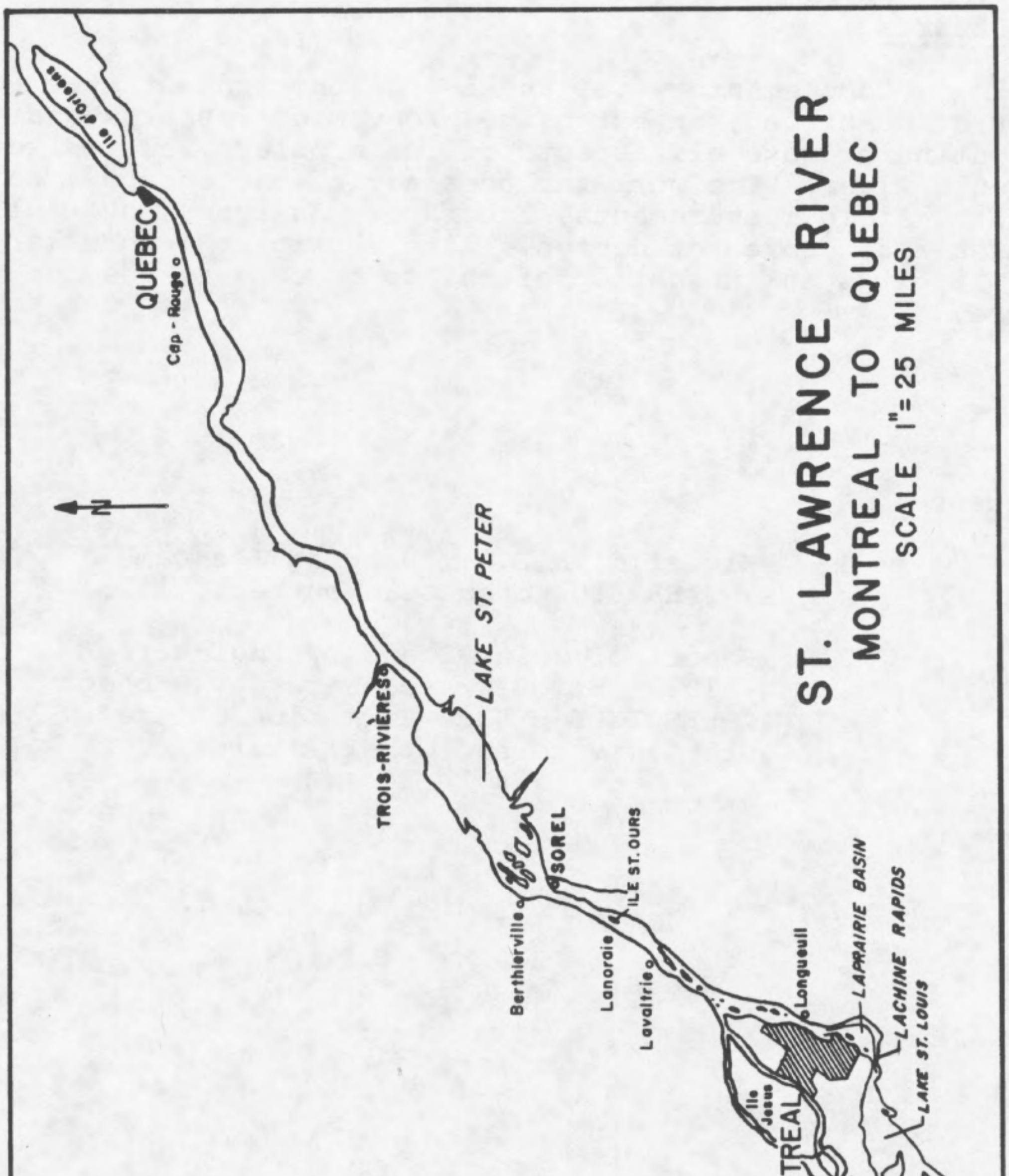

ST. LAWRENCE RIVER
MONTREAL TO QUEBEC
SCALE 1" = 25 MILES
N
Ile d'Orleans
QUEBEC
Cap - Rouge
LAKE ST. PETER
TROIS-RIVIÈRES
SOREL
ILE ST. OURS
Berthierville
Lanoraie
Lavaltrie
Longueuil
LAPRAIRIE BASIN
LACHINE RAPIDS
LAKE ST. LOUIS
MONTREAL
Ile Jesus
Ile Perrot

FIG. No. 1

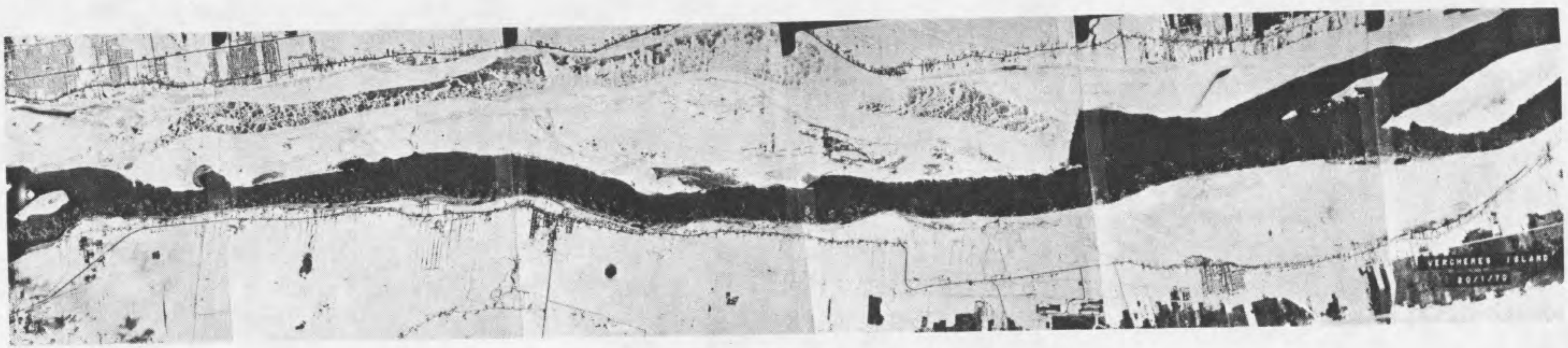
THE "LADY GREY" AT WORK ON THE ST. LAWRENCE RIVER

FIG. No. 2

ICEBREAKERS BATTLING HEAVY ICE JAMS IN QUEBEC NARROWS - MID JAN. 1968

FIG. No. 3

MONTREAL TO REPENTIGNY

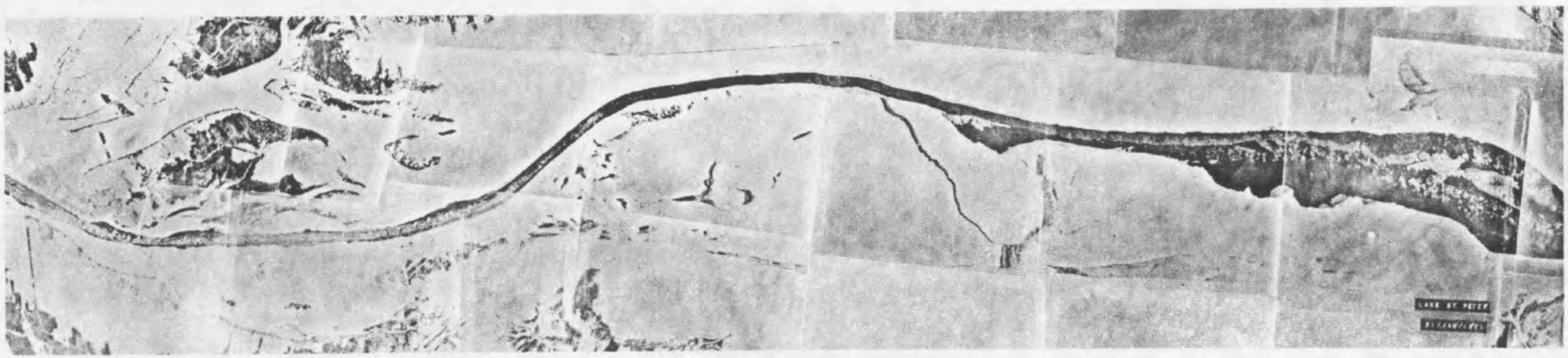


REPENTIGNY TO ILE ST. OURS

FIG. No. 4

TYPICAL ICE COVER

ILE ST. OURS TO ILE MADAME



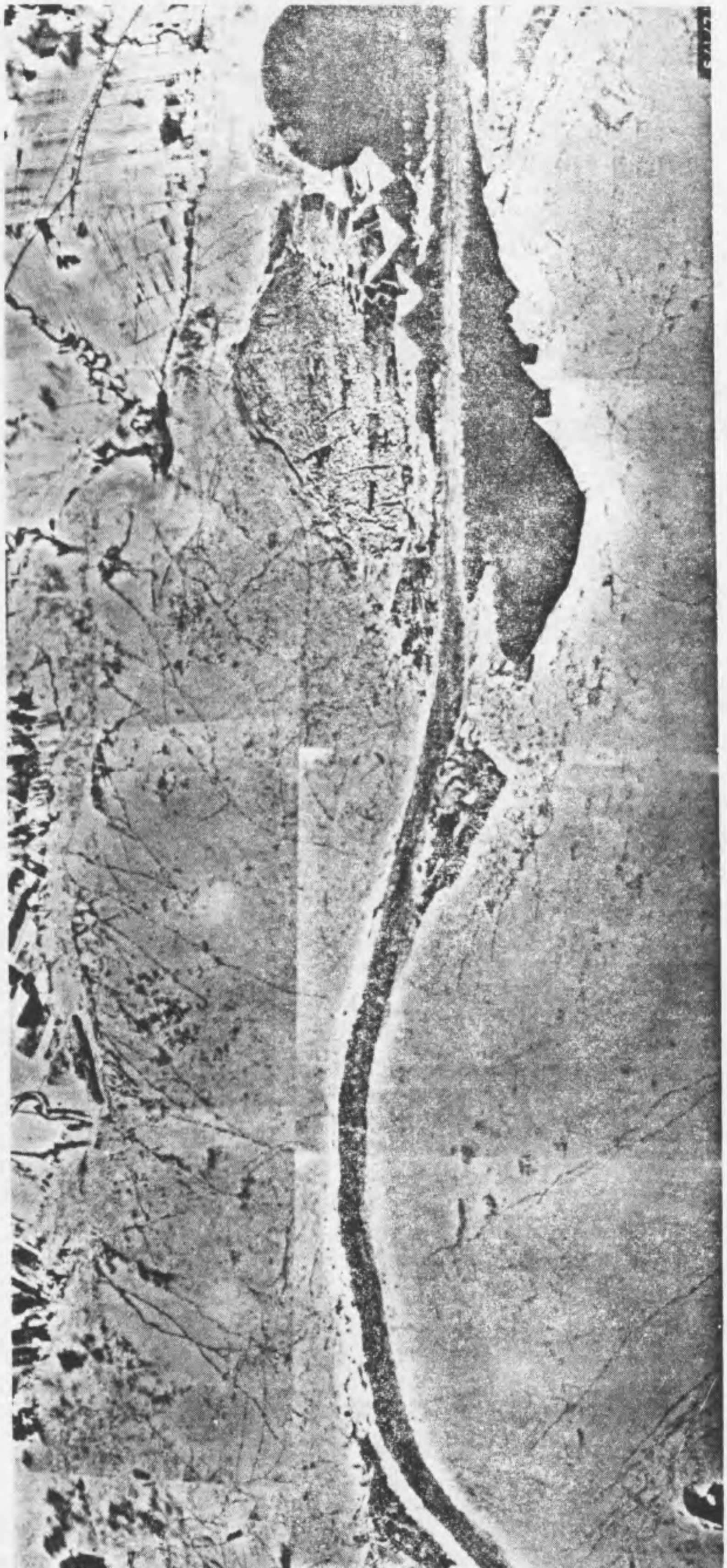
ILE MADAME TO PORT ST. FRANCOIS

FIG. No. 5

TYPICAL ICE COVER

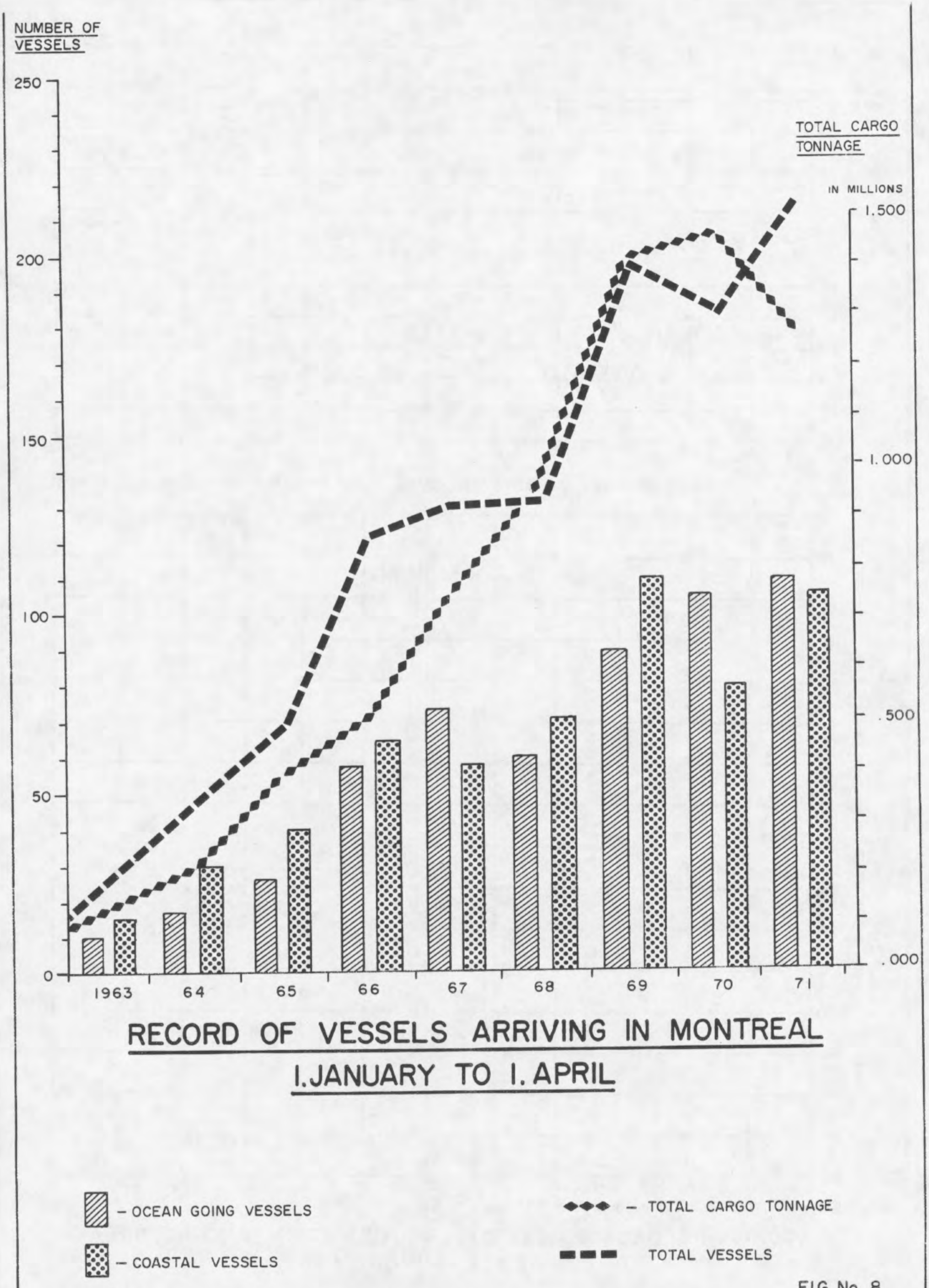
PACKED ICE COVER MONTREAL HARBOUR WINTER 1956

FIG. No. 6



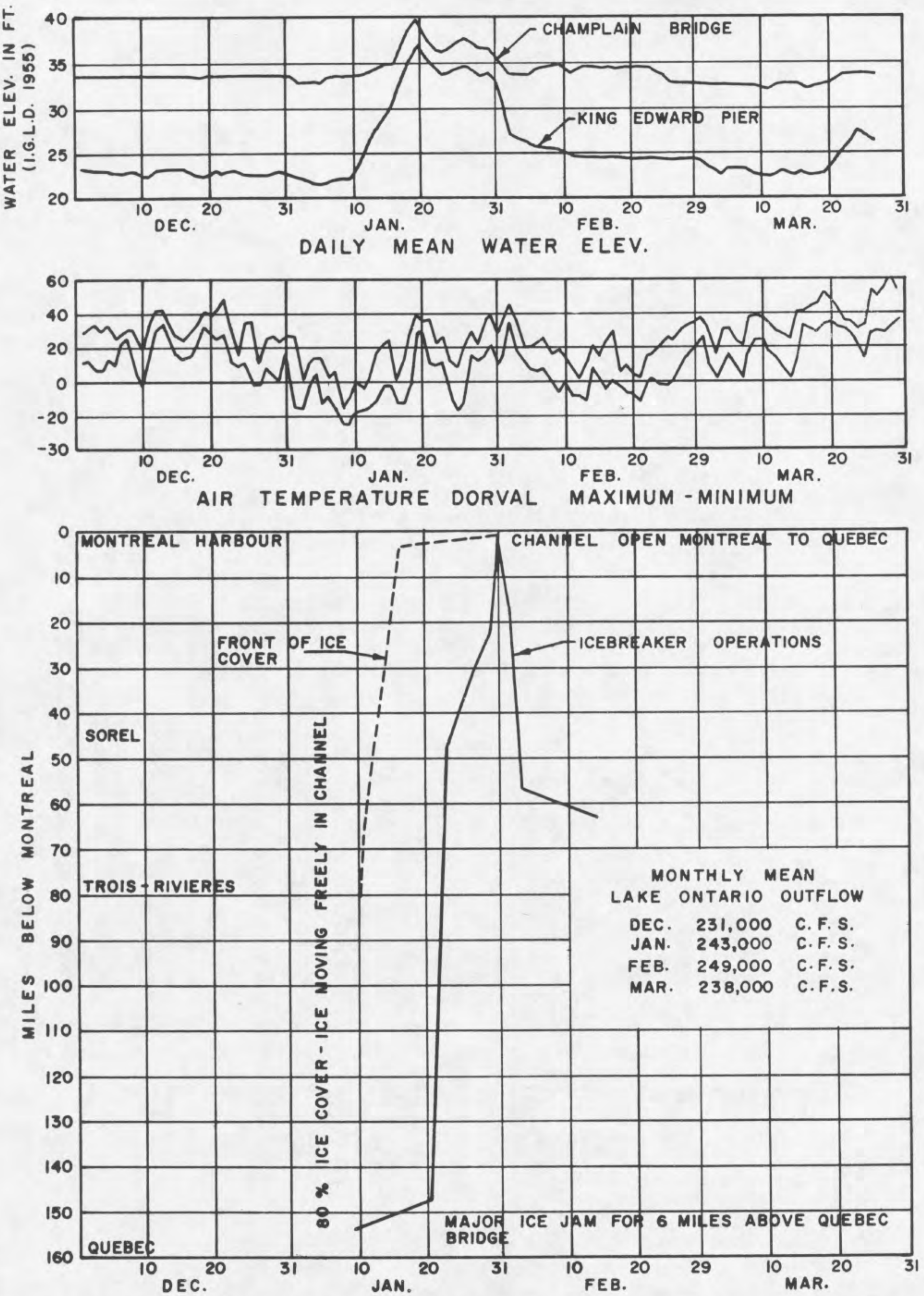
ICE BREAK-OFF IN LAKE ST. PETER

FIG. No. 7



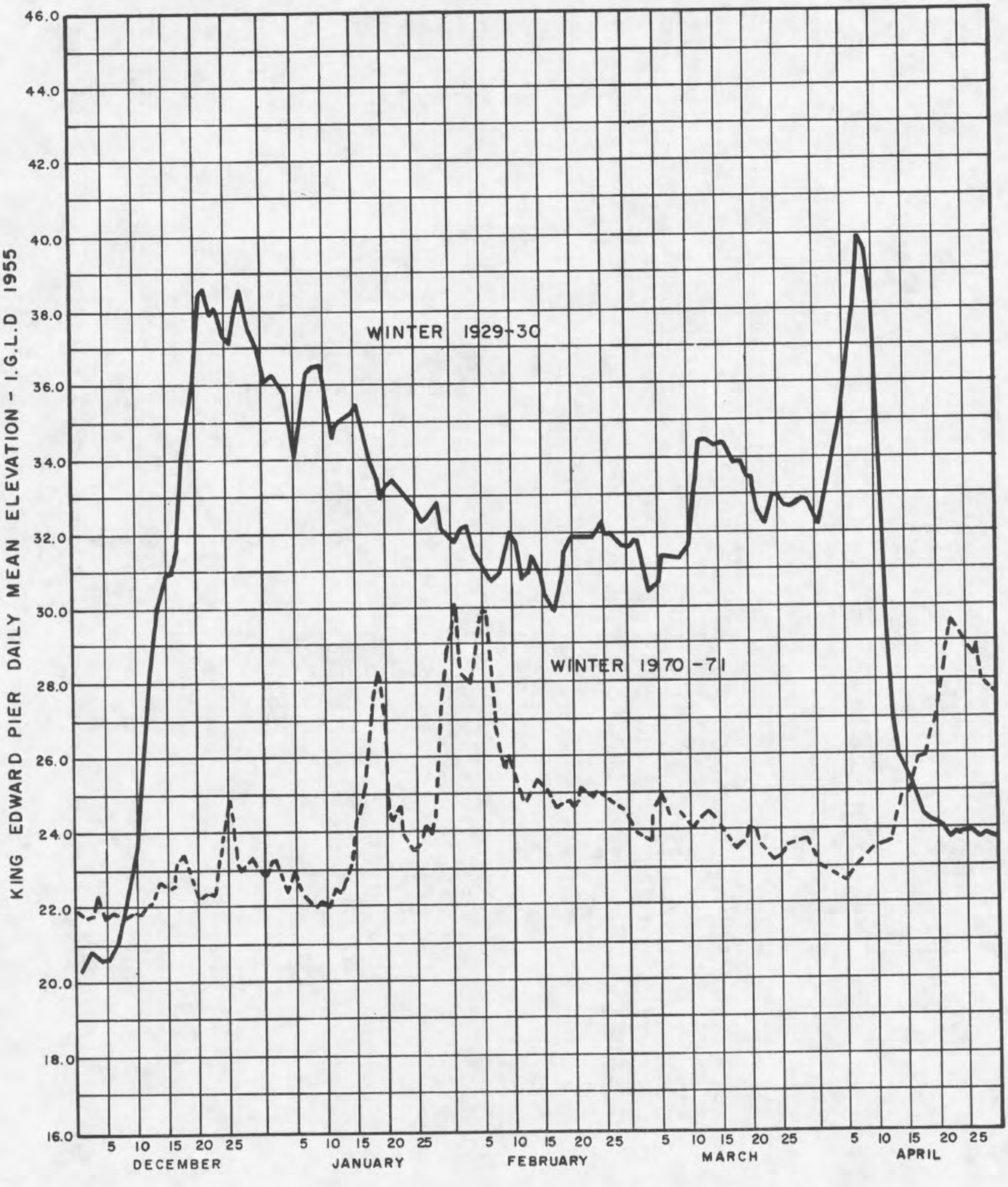
RECORD OF VESSELS ARRIVING IN MONTREAL
1. JANUARY TO 1. APRIL

FIG. No. 8



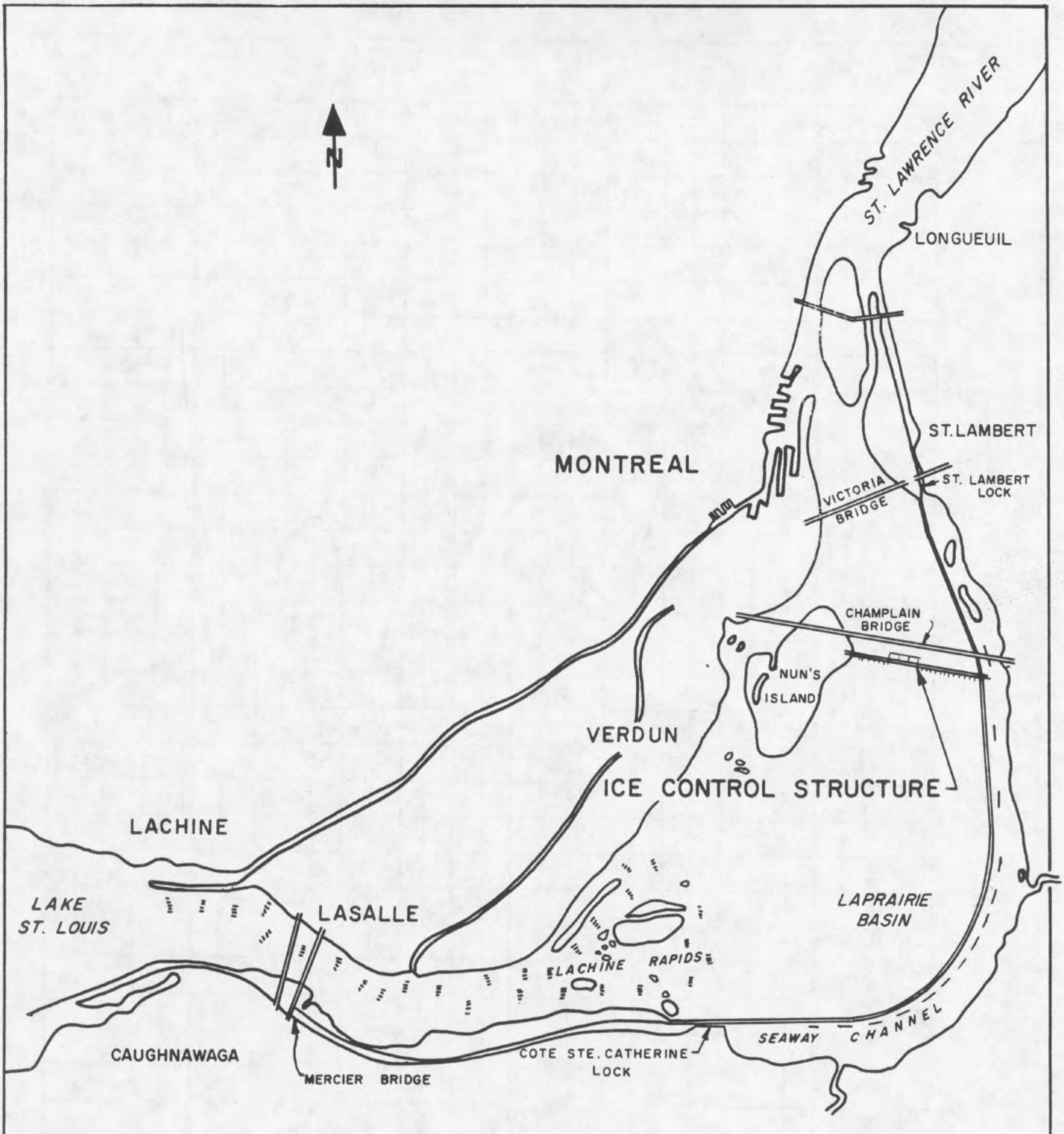
HISTORIC RECORD OF ICE COVER FORMATION AND ICEBREAKING
ST. LAWRENCE RIVER 1967 - 68

FIG. No. 9



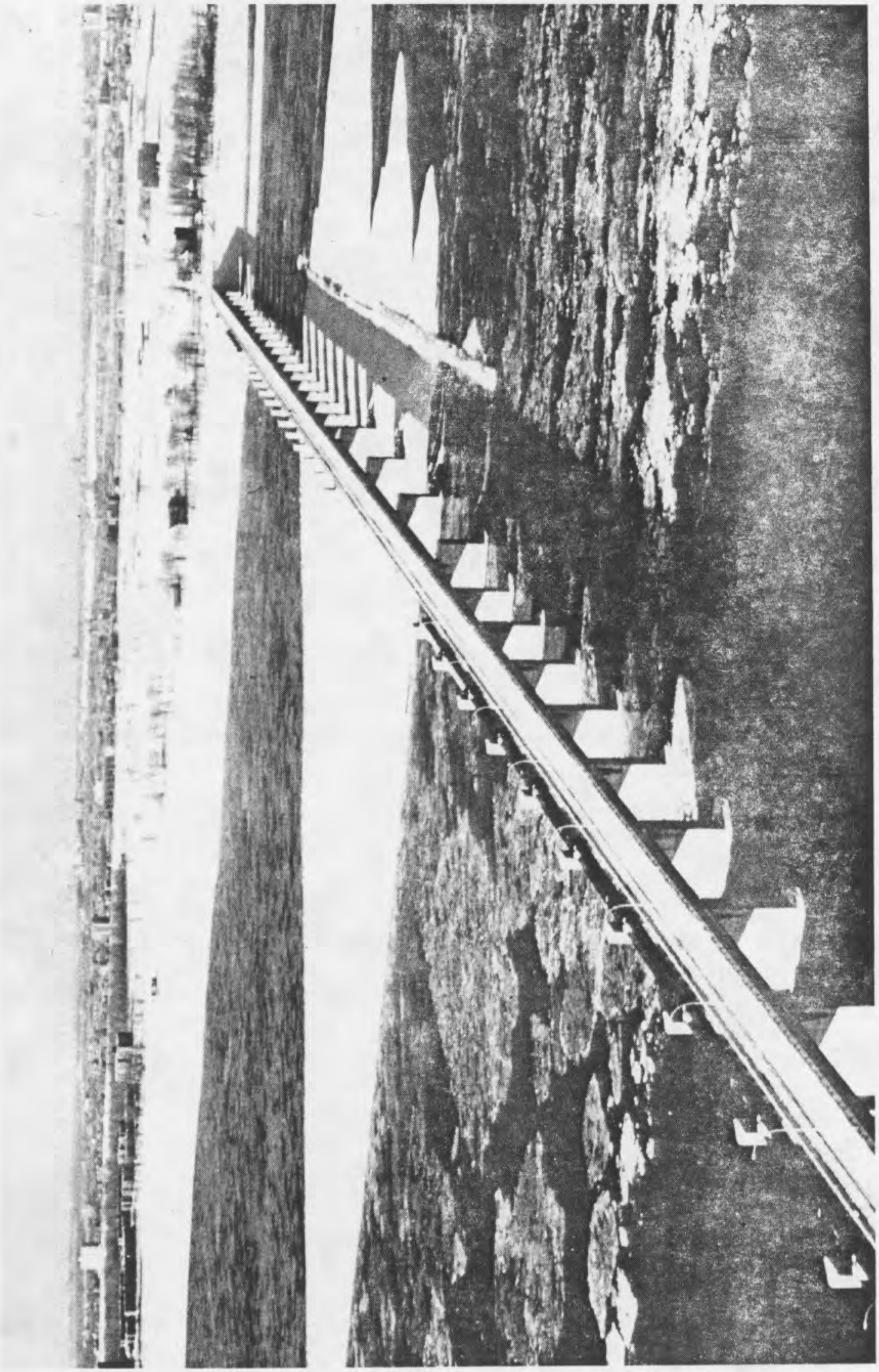
INFLUENCE OF ICEBREAKER OPERATION ON
WATER LEVELS IN MONTREAL HARBOUR

FIG. No. 10



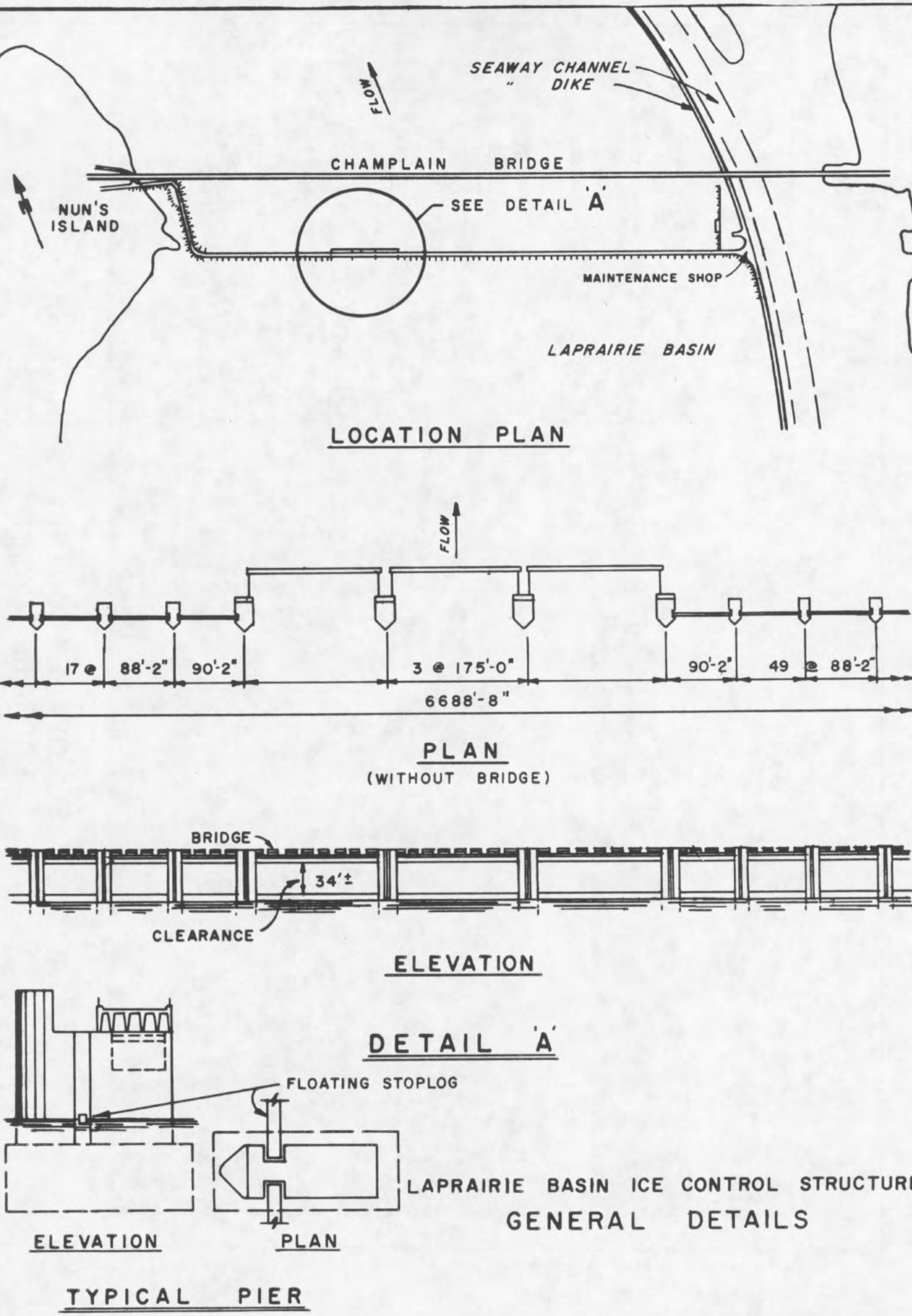
LOCATION OF ICE CONTROL STRUCTURE

FIG. No. 11



AERIAL VIEW OF ICE CONTROL STRUCTURE
LAPRAIRIE BASIN

FIG. No. 12

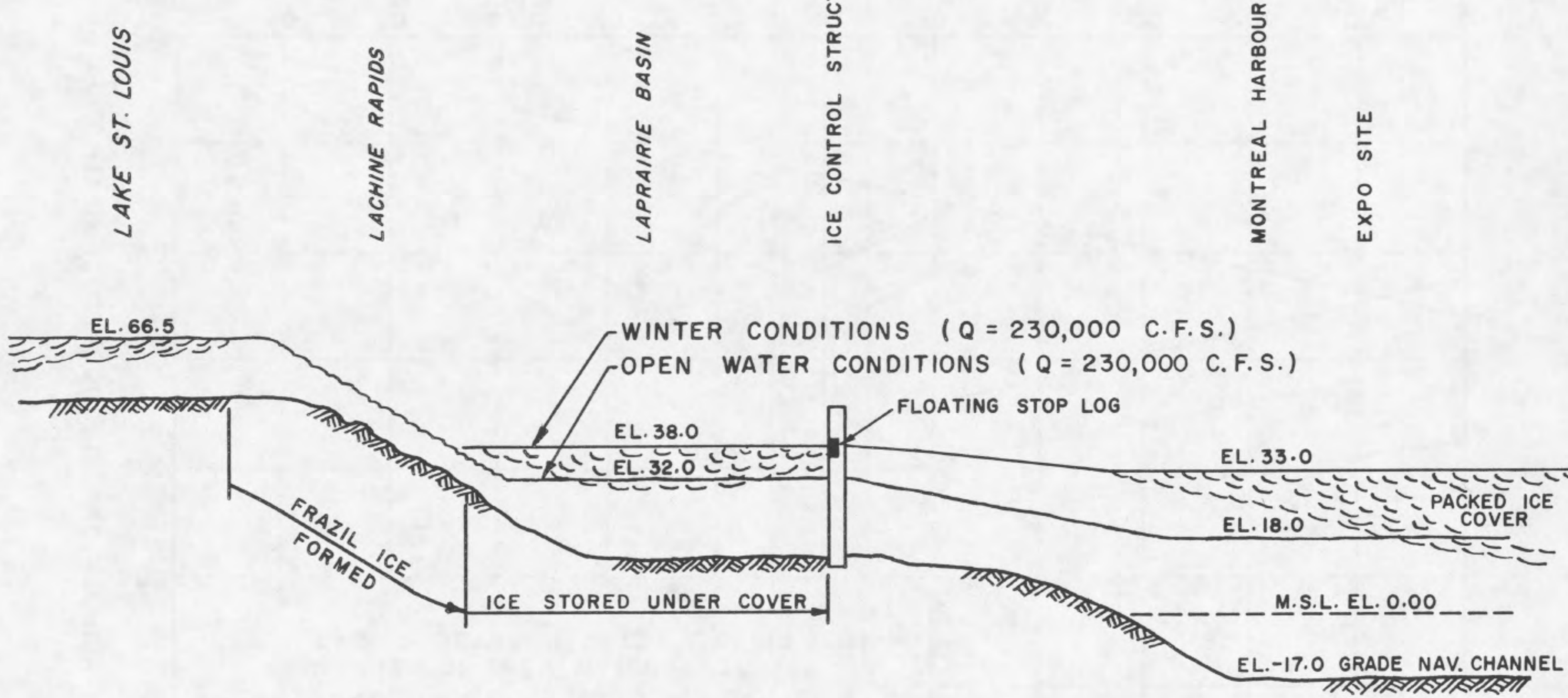


LAPRAIRIE BASIN ICE CONTROL STRUCTURE
GENERAL DETAILS

FIG. No. 13

RECOMMENDED CRITERIA FOR OPERATING STRUCTURE

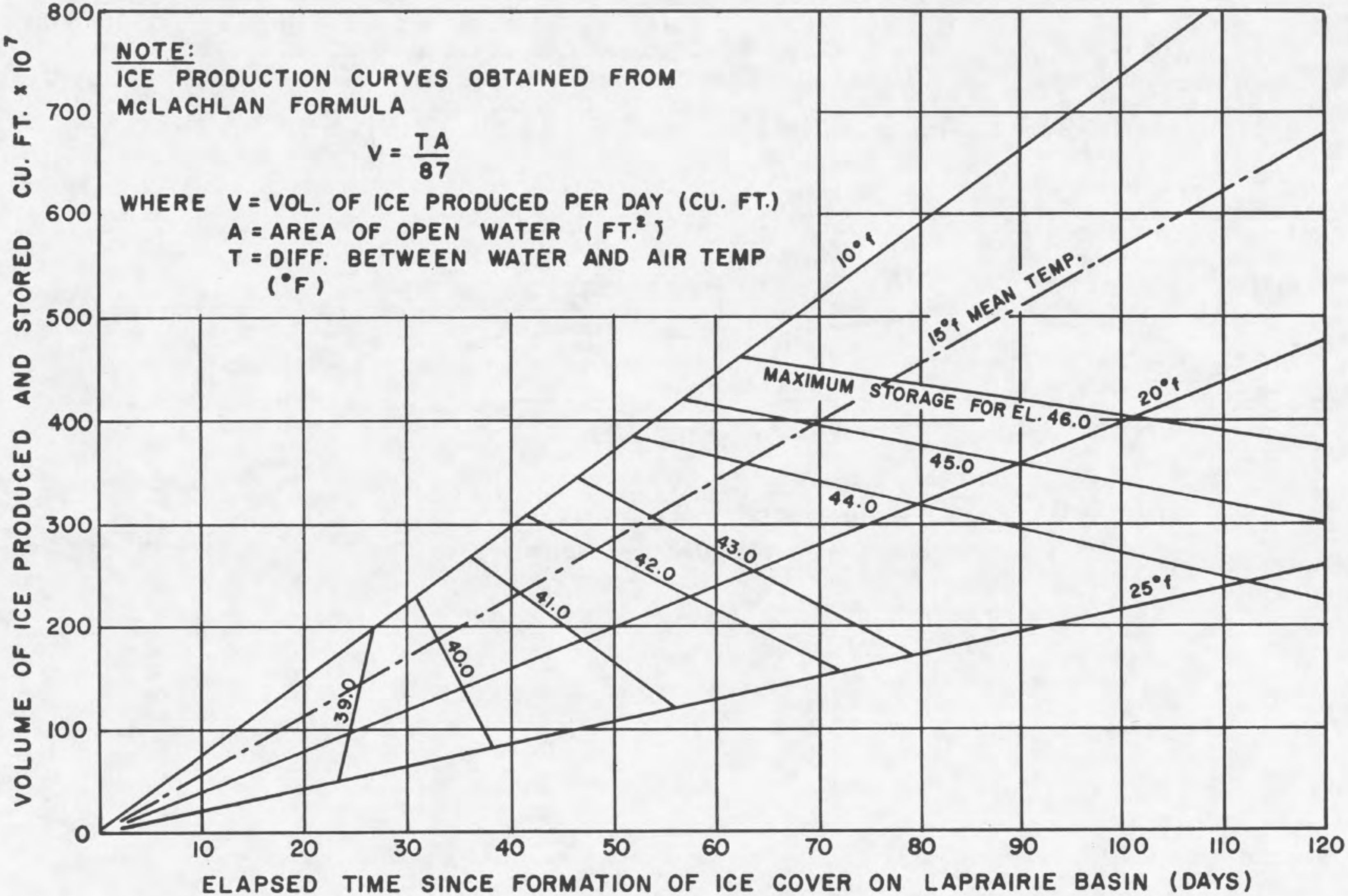
WATER ELEV (I.G.L.D. 1955)	DISCHARGE (C.F.S.)
37.0	200,000
38.0	250,000
40.0	300,000



LAPRAIRIE BASIN ICE CONTROL STRUCTURE

DIAGRAM SHOWING TYPICAL WATER SURFACE PROFILES IN THE ST. LAWRENCE RIVER AT MONTREAL FOR OPEN WATER AND WINTER CONDITIONS - INDICATING EFFECT OF ICE COVER DOWNSTREAM ON WATER LEVELS AT THE STRUCTURE.

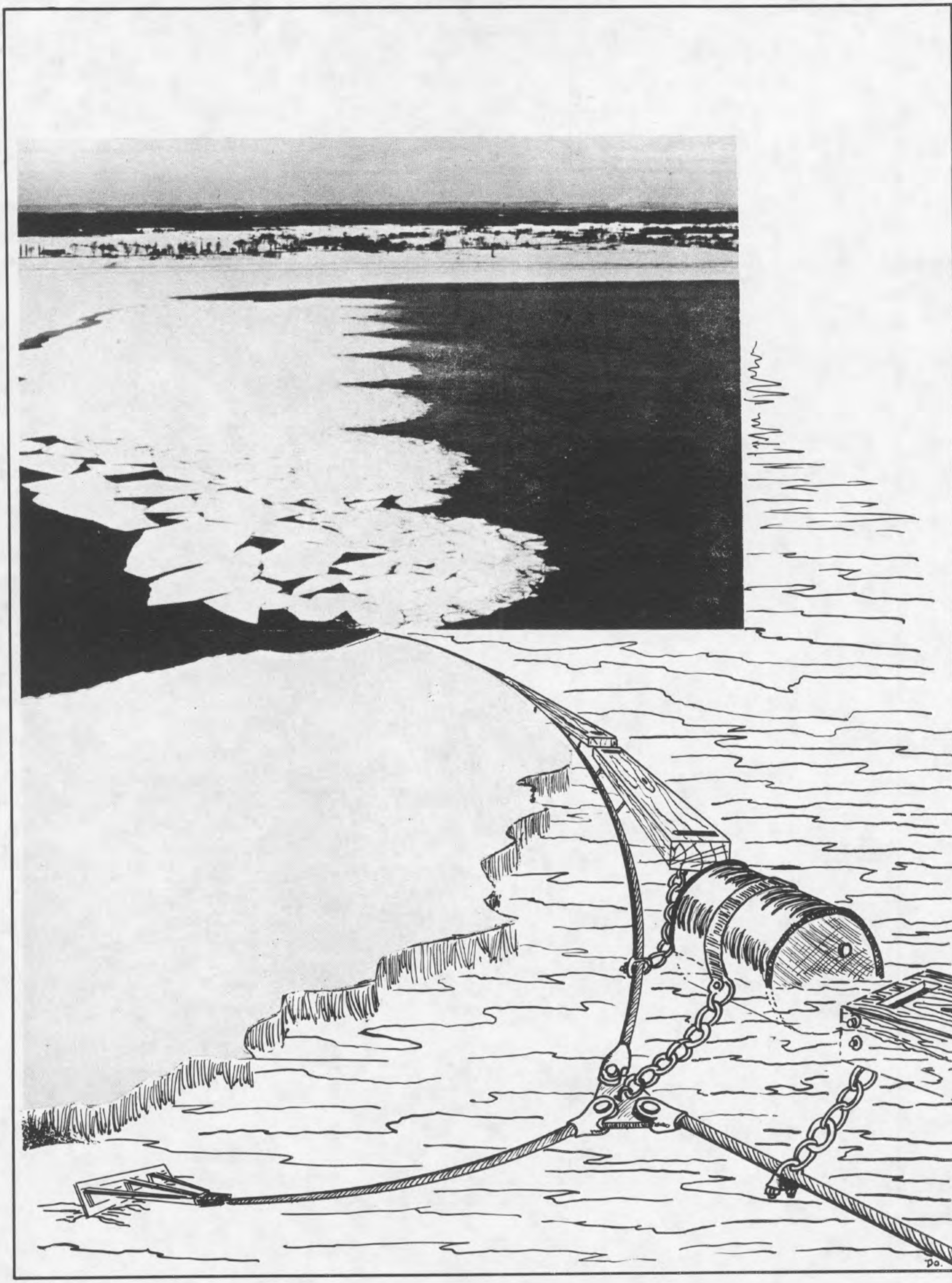
FIG. No. 14



MAXIMUM STORAGE CAPACITY OF LAPRAIRIE BASIN AT VARIOUS WATER ELEVATIONS RELATED TO ICE PRODUCTION IN LACHINE RAPIDS.

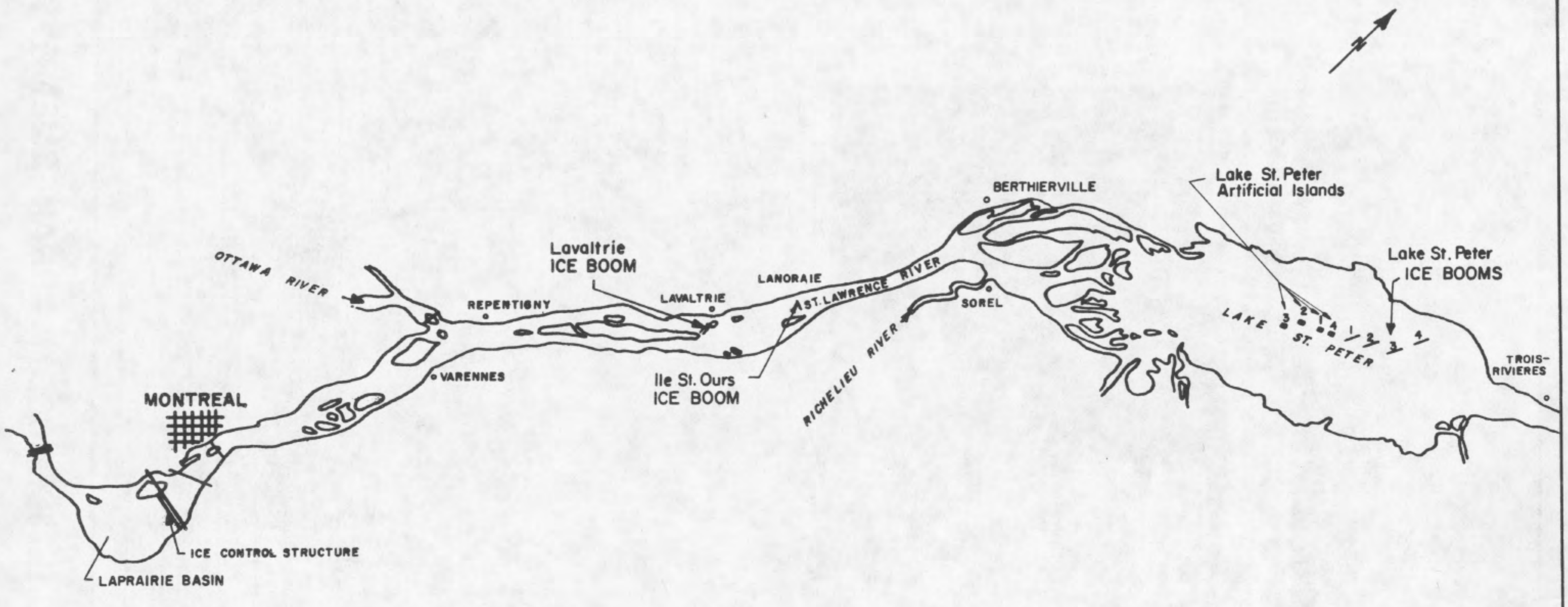
FROM: HYDRAULIC MODEL STUDIES
BY LASALLE HYDRAULIC LABORATORY

FIG. No. 15



TYPICAL ICE BOOM ARRANGEMENT

FIG. No. 16



MINISTRY OF TRANSPORT

ST. LAWRENCE RIVER

LOCATION OF ICE BOOMS LAVALTRIE AND LAKE ST. PETER
AND ARTIFICIAL ISLANDS LAKE ST. PETER

APPROX. SCALE 1" = 10 MILES

FIG. No. 17