SOME ASPECTS OF ICE PROBLEMS CONNECTED WITH HYDRO-ELECTRIC DEVELOPMENTS

By

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The harnessing of streams located in a cold climate cannot be fully taken advantage of if curtailments of power generation result from adverse ice conditions. It is a known fact that the rivers of Canada are exposed to a severe climate during the winter season. In the Province of Quebec, the St. Lawrence River and its numerous tributaries forming the southern network of streams now undergoing intense hydro-electric development, present their quota of difficulties incurred because of ice conditions. This paper deals with some of the aspects of the various ice problems pertaining to some existing and proposed developments within this network.

Streams often differ considerably in their characteristics, among others, the temperature of the water has a great effect upon the ice formation and the seriousness of ice problems. The formation of ice or the presence of an ice cover over a stream is not necessarily an indication that the mass of water is at the freezing point. Some rivers are cooled down to the freezing point whereas others retain a good part of their heat content throughout the winter period. Streams that are cooled down to the freezing point are most favourable to the formation of the three main types of ice namely: surface or sheet ice, frazil ice and anchor ice. Hence, water temperature measurements are of utmost importance and should be the key move in tackling all ice problems.

Firstly, the behaviour of a river whose mass of water is actually cooled down to the freezing point at the approach of winter will be discussed. Then, briefly I will talk about the behaviour of a stream that does not cool down to the freezing point.

The freezing of the St. Lawrence River from Lake St. Peter to the foot of the Lachine Rapids (see Map of the St. Lawrence River), which occurs in very much the same way each year and offers a wide variety of phenomena, has been described by several authors and is a well known fact to many. I will now review it in the light of my own observations which have been carried on during the past ten years.

With the advent of cold weather, the water temperature in this stretch of the river gradually falls to the freezing point and drift-ice appears over the surface. Sheet ice appears over areas of slack water, frazil forms in the more turbulent sections and anchor ice grows in rather shallow but fast water. Slush-ice may also enter into the picture depending on weather conditions. Owing to the somewhat fast current of the river, these ice floes are carried down-stream into Lake St. Peter and there come to rest at a section near the lower end where the average velocity of water is from 1.0 to 1.25 feet per second. The converging shores at the outlet of the lake and the low velocity of water together with the water at the freezing point as well as the favourable weather conditions combine to form an ice bridge from which the ice-pack starts its travel up-stream. A packed ice cover then extends all the way up to the foot of Lachine Rapids covering the entire water surface.

The cover which forms over gently flowing sections, as in the case of Lake St. Peter, is relatively smooth; that is to say, only slight telescoping takes place as the drifts of ice pack up-stream. Thence, the cover becomes more and more rugged as it extends over a faster current. When the pack reaches a section of the river where the velocity becomes so high that the drift-ice is carried under the cover a "hanging dam" forms. Such sections are found in the narrows at the head of Lake St. Peter also opposite Lanoraie as well as in the Harbour of Montreal and at the foot of the Lachine Rapids (Diagram No. 1). While a hanging dam is in the process of formation back water is created in front of the pack the effects of which are a raising of the water level up-stream as well as an increase of the cross-sectional area of the river and a corresponding decrease of the average water velocity. According to this process the pack has been observed building upstream in sections of the river flowing at a rather high velocity. Even the Lachine Rapids were nearly surmounted on two occasions by the pack in the course of the past three winters which is a phenomenon of recent occurrence.

Thus, from the outlet of Lake St. Peter to the foot of Lachine Rapids, smooth ice covers, rugged packed ice covers and hanging dams alternate with one another. The passing of the pack at a certain point is characterized by a raising of the water level as the pack approaches the point and then a lowering of the water surface after the pack has passed the point. When a series of shoves occurs, that is to say when the pack advances and recedes, passing the same point many times during the formation and consolidation of a hanging dam to its full size, the water-level at that point fluctuates giving the hydrograph a saw toothed form. It is possible to determine the time at which the pack has passed a point by examining the hydrograph for that point. The size to which a hanging dam will grow is dependent on the average velocity that the pack must overcome to travel up-stream without ice being carried under the cover and this velocity is influenced by the weather conditions.

The maximum average velocity against which an ice cover will pack up-stream without ice being carried underneath has been established, for all practical purposes, at 2.25 feet per second. It must be emphasized that the term maximum average velocity infers the existence of ideal conditions which may be defined as follows: the temperature of water must be at the freezing point and the atmospheric temperature down to at least zero degree Farenheit or better still sub-zero weather prevailing. Any departure from such ideal conditions must be associated with a lower average velocity. Therefore, the travel of the pack upstream without ice being carried underneath is not governed by the average velocity of water alone; although the latter may well be under 2.25 feet per second, nevertheless a hanging dam will form. The more remote the departure is from ideal conditions, the lower the average velocity will be that the pack can overcome and the larger the hanging dam required to provide the lower velocity. As a matter of fact, the largest hanging dams and the highest water elevations in this stretch of the St. Lawrence River are associated with the milder winters and not with the colder ones. As evidence, diagrams 2 and 3 show the advance of the pack along the same stretch of the St. Lawrence River extending from the head of Lake St. Peter upstream past Lanoraie but under different conditions. In the first instance, namely under ideal conditions, the pack advanced a distance of 25 miles in one day i.e. from December 29th to the 30th of the 1947-48 winter freeze-up period: the temperature of water was at the freezing point and sub-zero weather prevailed. Under such circumstances the pack made fast progress and the ice cover that formed consolidated rapidly. Although ice forms more rapidly under ideal conditions, it must be realized that once a cover is formed, the latter acts as an insulator in preventing further formation of ice save for the growth of the cover itself. The result is that less ice will form and the slopes will be smoother if the freeze-up occurs under ideal conditions. In the second instance, namely under the most adverse conditions, the pack advanced along the same stretch of 25 miles but this time the journey took 21 days i.e. from December the 30th to January the 20th of the 1948-49 winter freeze-up period: the temperature of water was at or very close to the freezing point but the atmospheric temperature was well above the zero mark most of the time. Large quantities of ice formed and packed but as the cover could not consolidate on account of a marked departure from ideal conditions, a series of shoves occured. The pack advanced and receded many times; the hanging dam grew larger and the slope became steeper than it did in the first case.

It is obvious that under ideal conditions, a packed ice cover will form and consolidate more readily and that the pack will advance against a higher average velocity. The departure from ideal conditions may be brought about chiefly by a rise in atmospheric temperature or by a rise in water temperature or by both at the same time. In a stream where the mass of water is actually cooled down to the freezing point at the freeze-up period, it is almost invariably the rise in atmospheric temperature that brings about the departure from ideal conditions, the temperature of water remaining at the freezing point. Hence, the rate of formation and consolidation of the ice cover is dependent on the daily degree-days below the freezing point. Likewise, the average velocity against which the pack can travel up-stream, forming a relatively smooth ice cover is subjected to the degrees of frost. Hence it is that during freeze-up period a hanging dam may form at a section where the average velocity of water is well under 2.25 feet per second.

I have made an analysis of the data obtained on ice conditions of the St. Lawrence River over the 9 winter-periods previous to 1952 and have endeavoured to show that an atmospheric temperature of 20°F. is very close to that at which the formation of ice or the growth of the ice cover is at a standstill and consequently, that at least 12 degrees of frost are required at all times during the winter to ensure the stability of the ice sheet.

The amount of ice formation depends on the amount of heat liberated by the water. Therefore, the temperature gradient between the water surface and the atmosphere is by far the most important factor in producing ice. Hence,the number of degree-days below the freezing point in any period will be the measure of the quantity of ice formed. When the temperature of air is above the freezing point, heat passes from the air to the water. Heat is then absorbed by the water with a reduction in the proportion of ice. The amount of ice thus lost is also measurable by the degree-days above freezing.

Once an ice cover has formed and has consolidated to some extent, it is often advisable that pertinent information be made available with regard to its stability especially at the beginning of the winter period. For such purpose I have devised a graph that can easily be prepared from day to day showing at a glance the stability of the cover (diagram No. 4). According to the way the graph is prepared, it is of best value during the early stage of the winter season.

The graph shows the accumulated average of the degree-days from the date the ice cover formed. The only data required are the daily degree-days with reference to the freezing point with which the cumulative degree-days are obtained and the accumulated average worked out daily from the date the cover is formed. The diagram indicates along the X-axis the period from the day the ice cover formed until the day the break-up occured and along the Y-axis the accumulated average of the degree days. The horizontal lines limit the regions of ice cover conditions. When the accumulated average of the degree-days is above 15 the stability of the cover is good; when the average falls between 15 and 12 the ice cover conditions become fair; when the accumulated average drops to and below 12 shoves and even a break-up are most likely to occur. Hence, open water conditions are back when the average is down to 10. The application of this formula will give reliable indications provided that the average velocity of water at freeze-up was low enough to allow the cover to form quickly and without ice being carried underneath under prevailing conditions and that the velocity after consolidation of the cover does not exceed 2.5 feet per second.

On streams that are cooled down to the freezing point at freeze-up period, baseload hydro plants located so that they must use the flow as it comes without being able to store any of it must be provided with a forebay of sufficient cross-sectional areas to ensure a flow unhindered by adverse ice conditions, thereby averting the possibility of floods up-stream and a loss of head at the plant.

Of course, there may exist some natural or artificial features to safeguard a run-of-river plant against flooding up-stream when a loss of head occurs at the plant due to a hanging dam forming in the forebay. Such features may consist of a very large lake, say, the size of Lake Ontario, on the St. Lawrence River or a proportionally smaller lake on a smaller stream, near the forebay and at the same elevation. In this instance, the reduction in flow due to the formation of a hanging dam would not suffice to raise the lake by an appreciable quantity before the winter period is over. Also a diversion channel, similar to that which by-passes the Beauharnois Canal, could provide an effective safety-valve.

On the other hand in the Lachine Section of the St. Lawrence River a baseload run-of-river plant would not be provided with a sea-like lake capable of cushioning a rise in water level but could be provided with a by-pass. Here the flow must pass as it comes and consequently ice conditions obviously would be a big problem unless sufficient cross sectional area could be provided in the forebay to permit the formation of a smooth packed ice cover.

As previously stated, a stream whose mass of water is actually cooled down to the freezing point is most likely to accelerate the formation of all types of ice. The Lachine section is typical of such a stream. Ice could not be disposed of simply by letting it run through the plant as an operation of this sort would soon clog the openings. Besides, a good ice cover must be formed and held up-stream to prevent further ice formation and avoid the recurrence of ice jams downstream in the Laprairie Basin that would flood the tailrace and drown out the units. This danger will always be present as long as the St. Lawrence river is allowed to freeze over below Montreal Harbour.

In this connection I fully concur with the opinion of Mr. Herbert L. Land, Chief Engineer of the St. Lawrence Ship Channel, who told a meeting of the World Ship Society held on February the 27th 1958 that "Winter navigation in the St. Lawrence River inasmuch as the ice has to run all the way to tidewater will not be possible for a long time to come with existing methods of combatting the ice menace".

A smooth packed ice cover is unquestionably the best protection with which a plant can be provided against ice troubles. A good ice cover on a forebay puts an end to the formation of ice of all types save of course for the growth of the cover itself; it acts as an insulator. In the light of my observations carried on the St. Lawrence River in the Soulanges and Lachine Sections and also below the Lachine Rapids downstream to the head of tide-water, the cross-sectional area of the forebay at Lachine should be such that the average velocity of water would not exceed 1.5 feet per second at freeze-up period and 2.5 feet per second after the cover is well consolidated and until Spring break-up.

Such velocities may seem low but it must be borne in mind that in this particular section of the river,

<u>firstly,</u> the temperature of water actually drops to the freezing point;

<u>secondly,</u> ideal conditions seldom exist at freeze-up time, however, if this is the case at the beginning, such conditions rarely prevail throughout the freeze-up period.

When conditions are such that even under a velocity of 1.5 feet per second the ice cover will not advance nor consolidate, then the chances are that the drifts of ice may run freely through the plant. But when a cover will form readily under a velocity of 1.5 feet per second or higher, then the disposal of ice through the plant becomes more and more hazardous as the velocity increases. In my opinion, the use of heat and compressed air to prevent trouble from ice cannot be relied upon in so mighty a river as the St. Lawrence.

In contrast with the St. Lawrence River the Bersimis River, (see map of the

Bersimis River) a tributary of the St. Lawrence flowing into it between Forestville and Baie Comeau on the North Shore, is to a great extent never cooled down to the freezing point.

Under natural conditions, the Bersimis river appeared in winter like any other stream covered with an ice sheet save for a few open rapid stretches. Its development called for the establishment of two power plants Bersimis No. 1 and No. 2. The design of Bersimis No. 1 required an eight-mile supply tunnel by-passing a nine-mile gorge plus an eight-mile stretch of the river, whose intake was located on a tributary stream the Desroches river. The valley of the latter forming the approach to the tunnel provided a restricted section for the flow. At first sight velocities were found unduly high and consequently a certain volume of excavation was deemed necessary for the following reasons:

a) to reduce the loss of head;
b) to prevent erosion of the banks and ensuing pitting of turbines;

As regards the formation and maintenance of a probable ice cover, precise water temperature measurements were the key move. They were taken during the winter period 1952-53 when the river was still under natural conditions and brought to light the fact that at the head of the gorge the temperature of water of the Bersimis River never dropped to the freezing point, but averaged during the coldest winter months from 0.10 to 0.37 of a degree Centigrade above the freezing point. Nevertheless, an ice cover formed from the head of the gorge up-stream. The ice cover was tested and found to be very poor, hardly strong enough to support a man and dotted with small air holes. It is noteworthy that this river lying between the 49th and 50th parallels of latitude, where the winters are without doubt must longer and colder, was never cooled down to the freezing point. This is indeed one special feature that accounts for the large difference in ice problems encountered from one river to another.

Furthermore, No. 1 development called for the creation of a reservoir from the head of the gorge up-stream which meant raising the level of the river by 160 feet (from elevation 1,145 to elevation 1,305 above Mean Sea level) .The mass of water would then lose its turbulence and also its uniform temperature to assume the water temperature gradient characterizing deep quiet waters. That is to say the upper layer of water would undoubtedly be cooled down to the freezing point and then the temperature of water would be warmer with depth tending towards a temperature of 4°C. near the bottom at which temperature water attains its maximum density. As the reservoir was to be created along a river and lakes having rather steep banks, the resulting storage was relatively deep in proportion to the area. These conditions were most favourable to the conservation of a good part of the heat content in the mass of water. As a matter of fact, subsequent water temperature measurements effected at various reservoir elevation have indicated that the higher the water elevation, the higher the temperature of water (diagram No. 5).

At a reservoir elevation of 1,275, the upper layers of water entering the approach to the tunnel averaged 2.35^{o} Centigrade while at full reservoir elevation of 1,305 it averaged 2.70 degrees as measured during the winters of 1956-57 and 1957-58 respectively. Excavation of the narrows therefore was carried out only to the extent required to reduce head loss and prevent erosion as no ice problem was anticipated and consequently there was no necessity to provide velocities to form and consolidate an ice cover, which meant considerable saving. Actually, whatever the velocity, no ice cover can form as long as a little turbulence is maintained. Should neverthless the flow be completely stopped then a cover would form to be melted as soon as operation of the plant is resumed.

The temperature of water at the foot of the gorge, under natural conditions, was sometimes very close to the freezing point and from there downstream a solid ice sheet formed to the mouth of the river except at the rapid sections. To-day the water in the Bersimis No. 1 tailrace is at a temperature of 2.8 degrees C. when the reservoir is full. This temperature should never drop lower than 2.5 degrees C. above the freezing point at low reservoir level under normal operating conditions. Thence, the water flows to Bersimis No. 2 presently under development where it arrives at a temperature of 0.6^{o}C. after a turbulent 23-mile journey under obviously open water conditions.

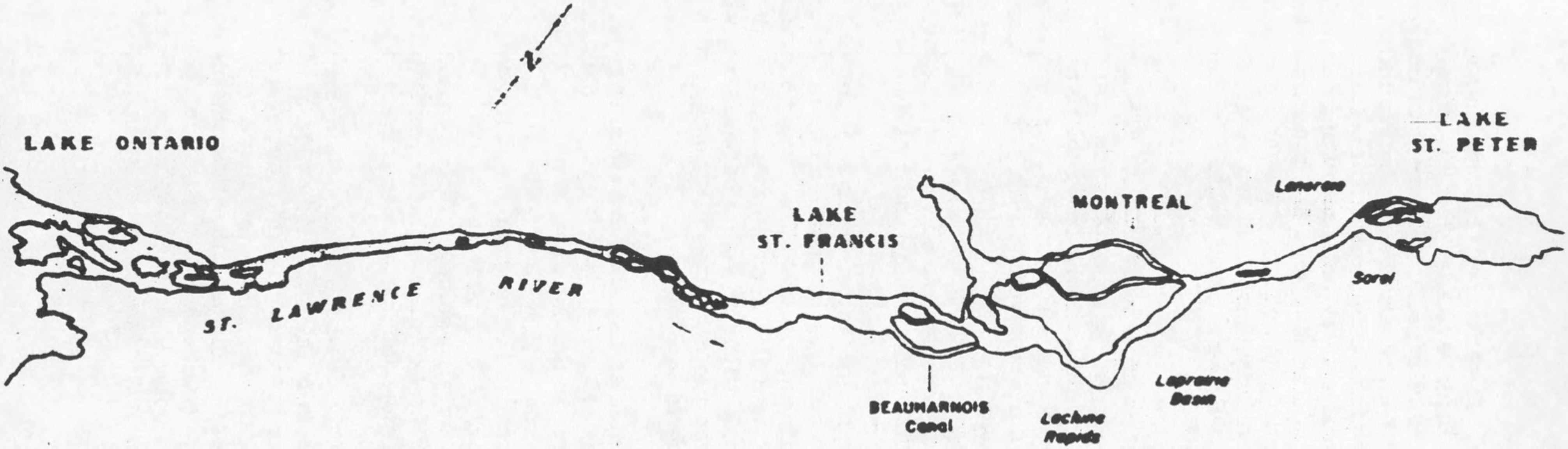
Upon completion of Bersimis No. 2 the forebay will become a deeply embanked body of water flowing gently under an ice cover preserving its heat content. Under these new conditions water should reach the No. 2 plant at a temperature somewhat lower than that found at the outlet of No. 1 plant on account of the cold tributary waters between the two developments. In brief, ice will never interfere with the operation of the two plants due to the high temperature of water in winter.

Another example of an intake canal using "warm" water and flowing open the year round as at Bersimis No. 1, is the Shipshaw canal diverting the Saguenay river waters to the Shipshaw plant No. 2. It is 1 1/2 miles long and the flow ranges from 36,000 to 46,000 c.f.s. under an average velocity of 4 to 5 feet per second. The temperature of its water, as I was able to observe during the coldest part of the winter of 1954-55, was 0.15 of a degree Centigrade above the freezing point at the entrance of the canal. Therefore, no ice problem is to be expected at the Shipshaw plant providing ice from the gently flowing head-pond upstream is prevented from entering the canal.

The sum up, rivers whose waters are cooled down to the freezing point are most favourable to the formation of ice of all kinds and the best means of preventing ice from interfering with plant operation, especially if an important stream is concerned, is by providing a forebay with sufficient cross-sectional area to meet conditions other than the ideal. As regards streams whose waters are never cooled down to the freezing point, their ice problems are usually very easily solved. In resume, the solution of the ice problem on one stream cannot be applied to any other stream.

April 21, 1958

MAP OF THE ST. LAWRENCE RIVER



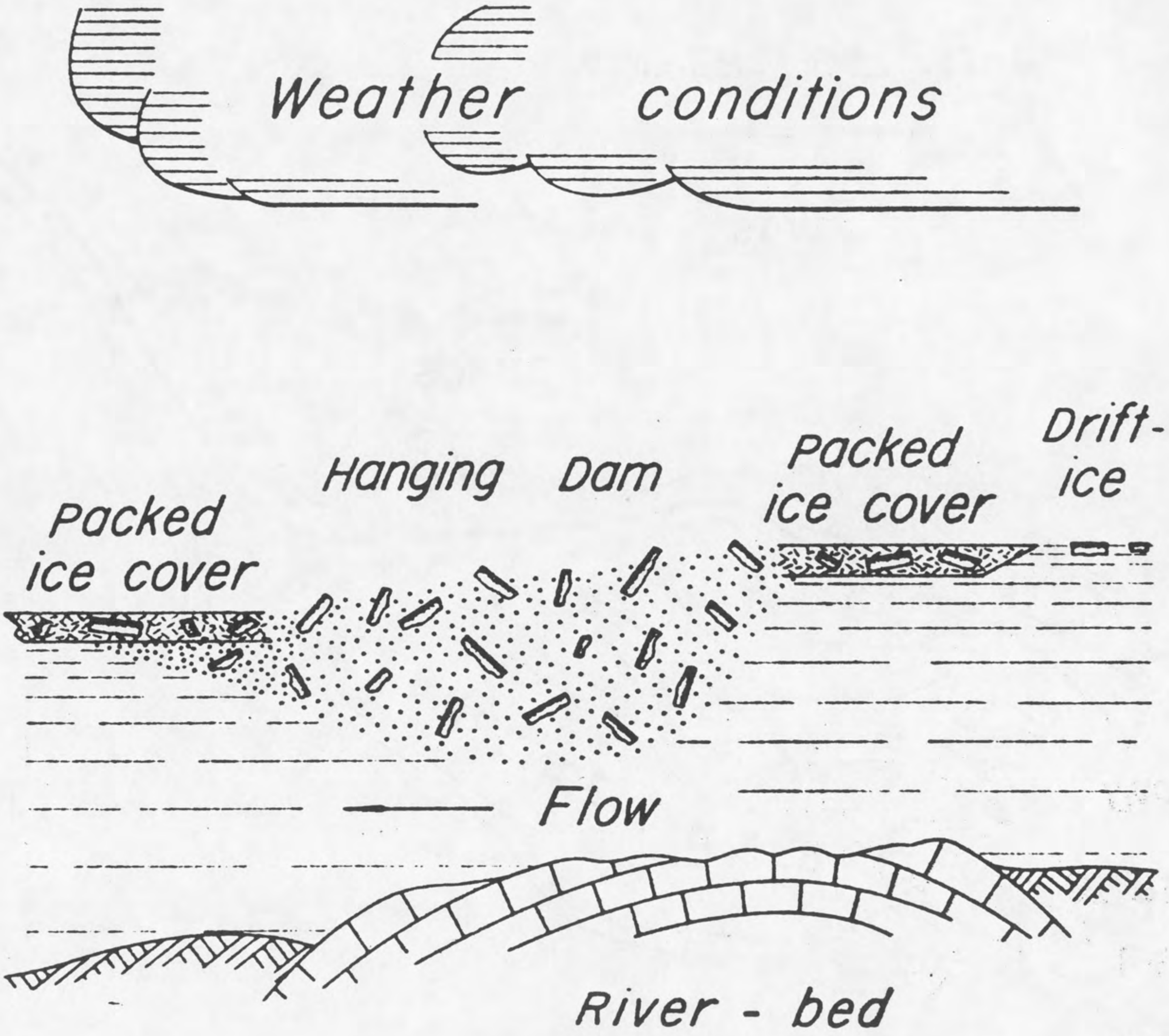
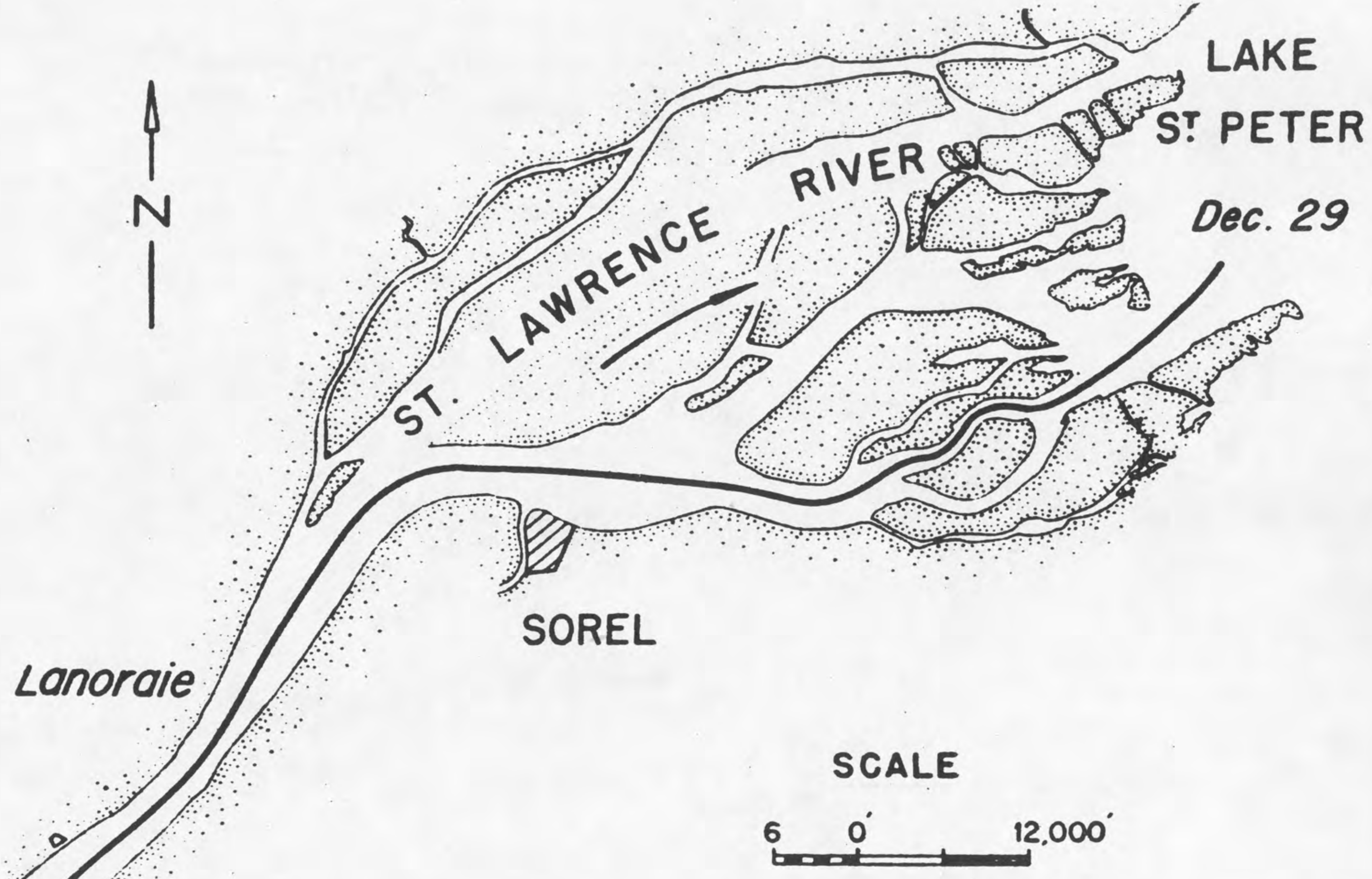
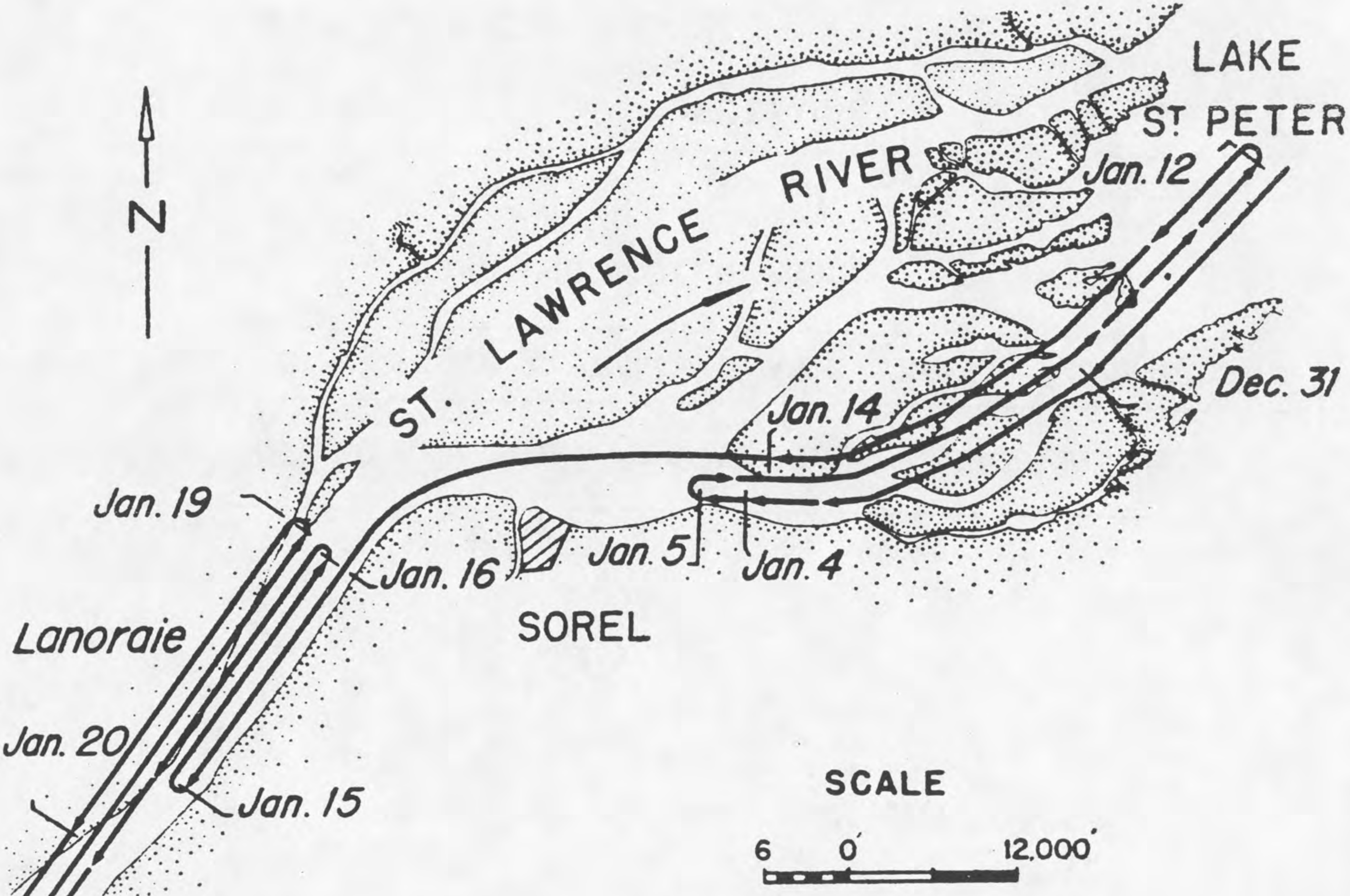

Weather conditions
Packed ice cover
Hanging Dam
Packed ice cover
Drift-ice
Flow
River - bed

DIAGRAM No. 1



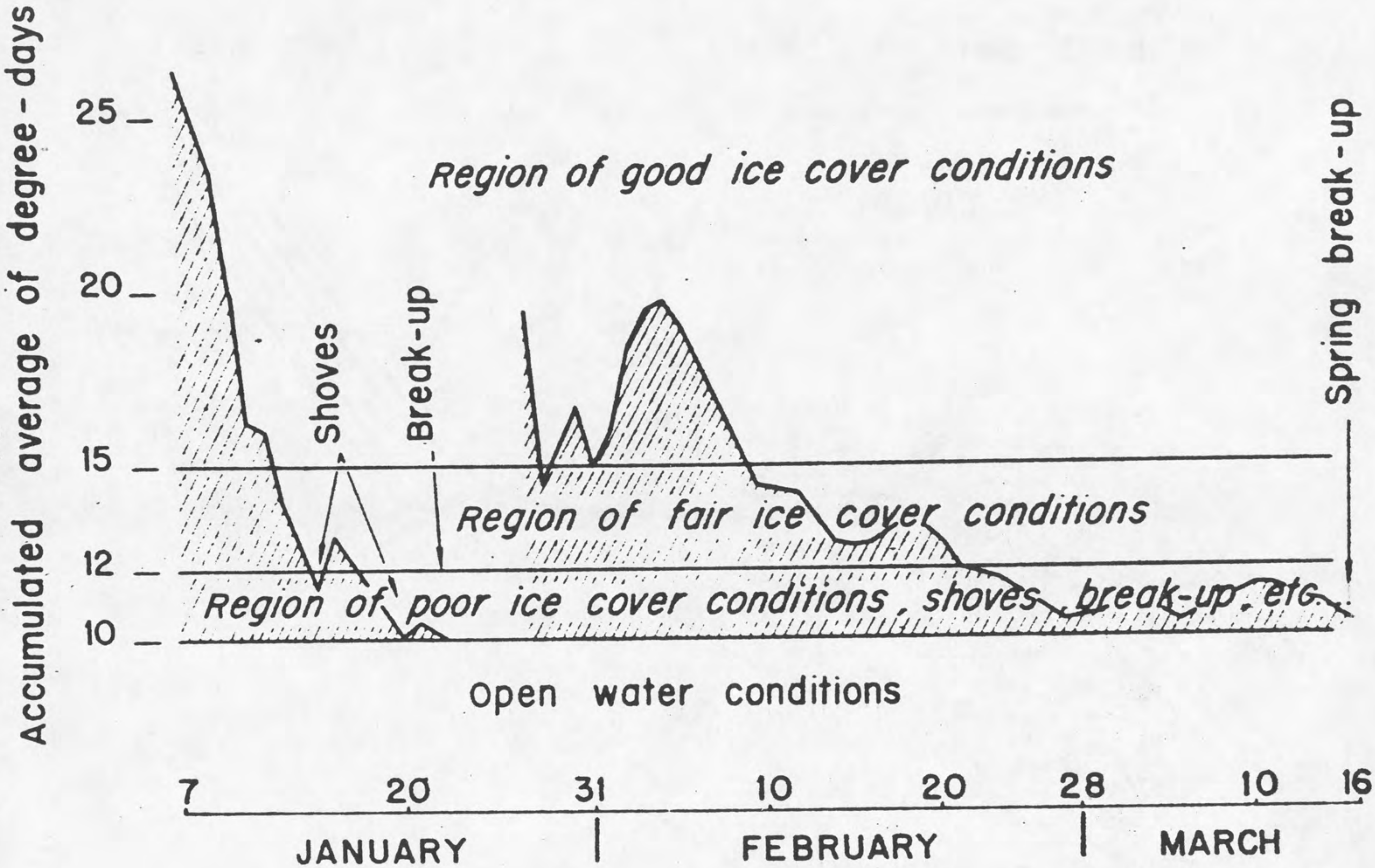
WINTER 1947 - 1948

DIAGRAM No. 2



WINTER 1948 - 1949

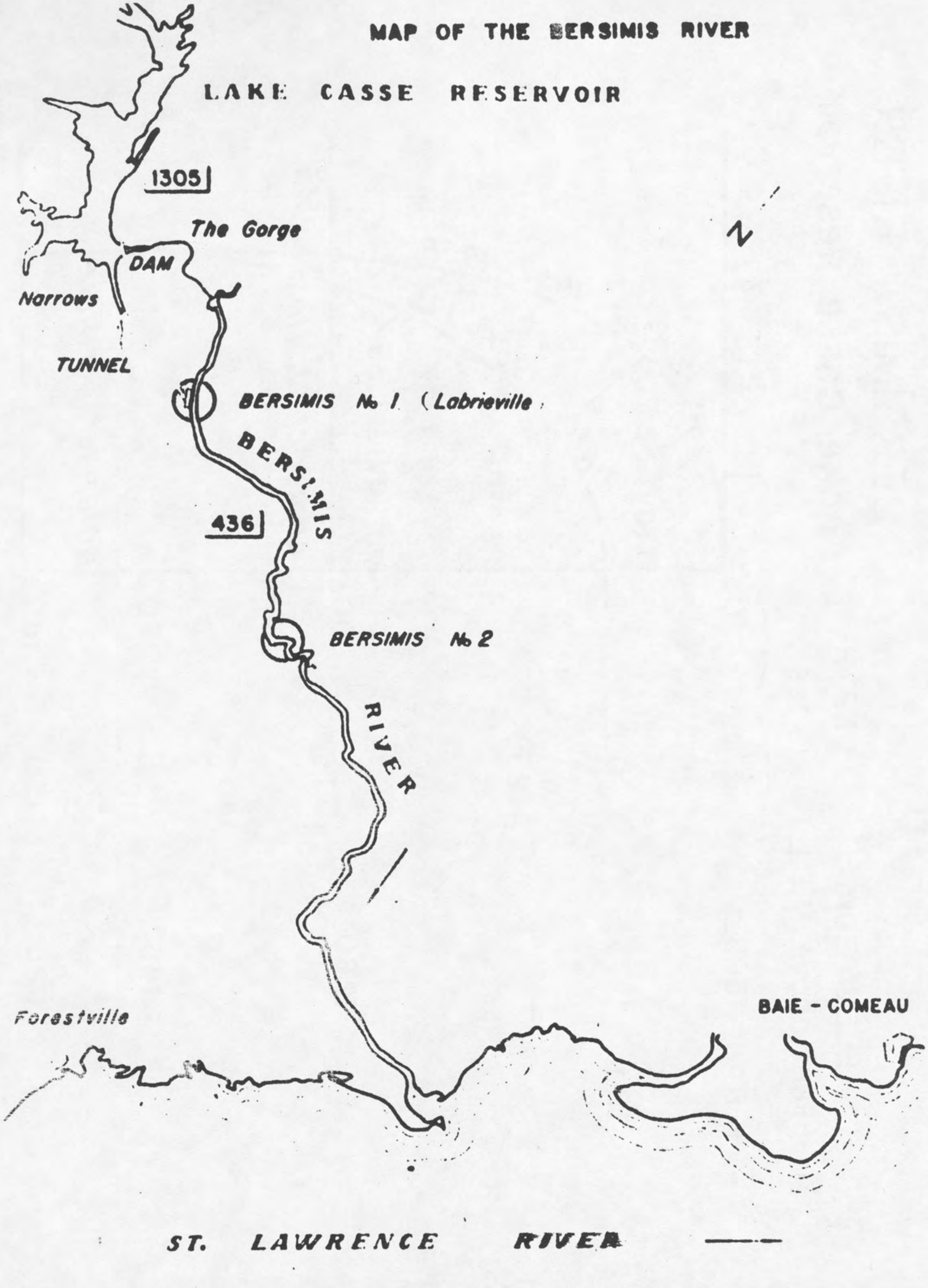
DIAGRAM No. 3

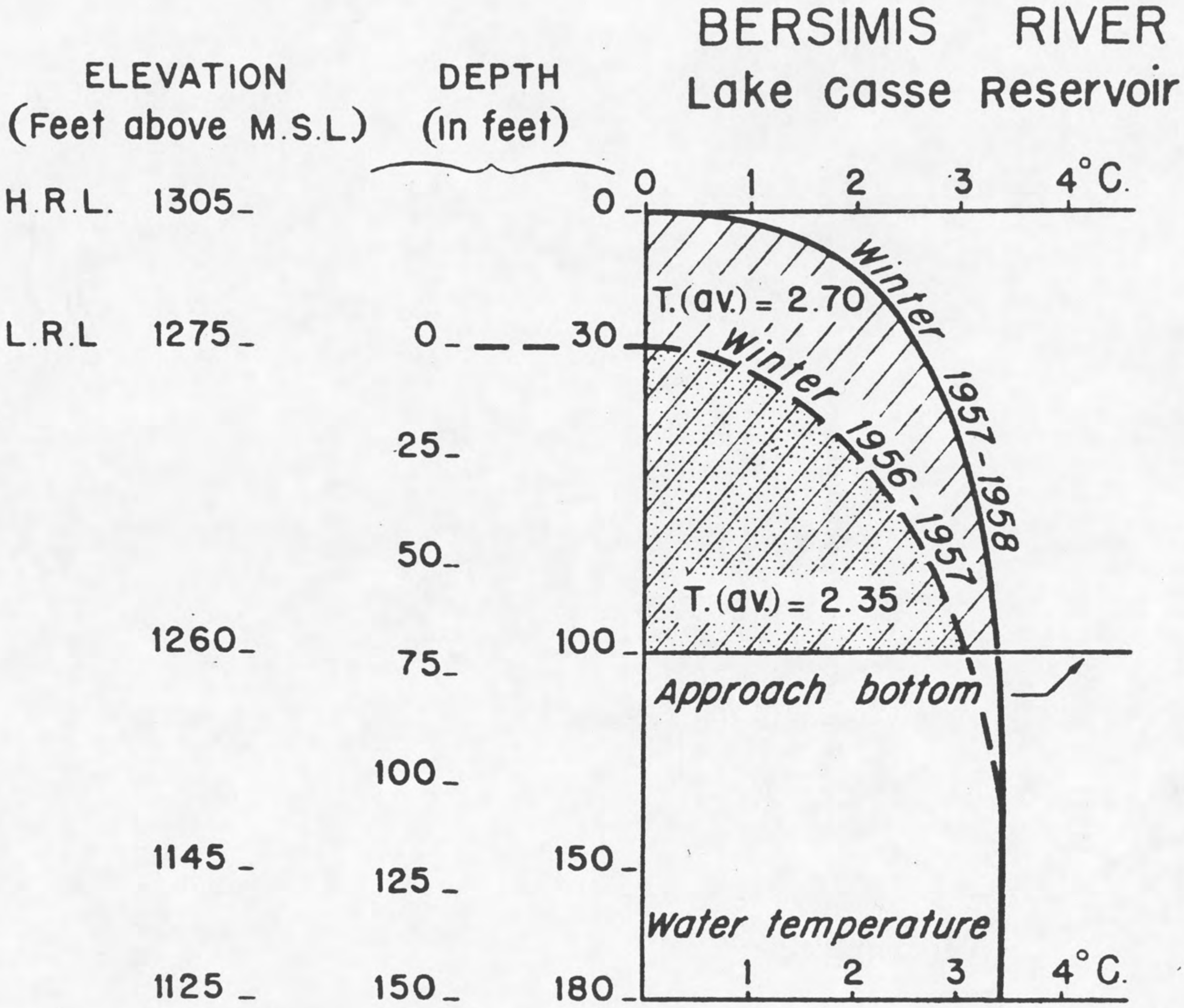


BEAUHARNOIS CANAL (1953)

DIAGRAM No. 4

MAP OF THE BERSIMIS RIVER





BERSIMIS RIVER
Lake Casse Reservoir

DIAGRAM No. 5