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OPTIMUM OPERATION OF HYDRO-ELECTRIC PLANTS DURING THE ICE REGIME OF RIVERS

A CANADIAN EXPERIENCE

NATIONAL RESEARCH COUNCIL OF CANADA
ASSOCIATE COMMITTEE ON HYDROLOGY
SUBCOMMITTEE ON HYDRAULICS OF ICE COVERED RIVERS

Canada

NRCC 31107

R. CARSON

Foreword

Hydro energy production is a major component of total energy production in most regions of Canada. The hydro-plants are generally located in areas subject to intense winter conditions, during which ice related problems can adversely influence river management and power system operations. These difficulties when converted into equivalent economic disbenefits can amount to very sizeable monetary losses for the power production systems.

This background led to NRC Subcommittee on Hydraulics of Ice Covered Rivers to strike the Task Force on Optimum Operation of Hydro Plants during the Ice Regime of Rivers, chaired by Mr. Thomas Wigle of Ontario Hydro. Their mandate was to produce a state-of-the-art report presenting an overview of the major problems, case histories of successful management techniques and make recommendations for continuing improvements.

The production of this excellent monograph has been possible largely due to the dedicated chairmanship of Mr. Wigle, financial assistance from Ontario Hydro, a superb coordinating effort by Mr. Derek Foulds and fine efforts by the contribution authors, with the approval of their agencies as acknowledged in the text.

It is hoped that this excellent volume will be a valuable guide and reference for winter operation of hydro plants in Canada and other parts of the world where similar conditions prevail, and that concerted efforts will continue through research to mitigate the problems identified in the report.

K.S. Davar
NRC Subcommittee on Hydraulics of
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Optimum Operation of Hydro-Electric Plants During the Ice Regime of Rivers

A Canadian Experience

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Authors' Preface

The goal of this Task Group was to provide a state of the art monograph on the "Optimum Operation of (Canadian) Hydro-Electric Plants During the Ice Regime of Rivers." At the outset, we had also hoped, by pooling our experiences, to produce a document with definite solutions to the various problems. We were able to note some similarities in ice management techniques, outlined in Section 7 on "Solutions to Ice Problems," but definitive solutions for all the problems were not possible because many were "site specific," most lacked necessary field data for analysis, and some seemed to contradict the others. It was our feeling that the 25 examples in the appendix covered most of the possible types of problems inherent in winter operation and that the reader could select those which most nearly coincided with his situation, and contact the respective author for further details.

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1.0 INTRODUCTION

Generation of power by hydro-electric means began in Canada about the beginning of this century. Generating stations were relatively small, serving a single, nearby load centre. The results were so popular and the demands so great, that there was a rapid increase in the size and number of generating stations and entire watersheds were harnessed. In addition, transmission lines were added to carry the power to load centres several hundred miles from the source. Today, the various load centres are interconnected, both provincially and internationally, so that troubles on one power system may be alleviated by help from the neighbours.

Our climate causes the highest electrical demands in the winter months when river flows and hence, hydro-power outputs are decreased. At the same time, ice is created in such quantities as to completely shut off the water flow to some generating stations unless expensive preventative measures are taken. Power outputs can be maintained by adding water storage reservoirs, but the resulting winter flows are then higher than under natural conditions. Higher flows tend to aggravate ice problems until the surface of the river becomes ice covered, and again whenever the cover breaks into pieces. The problem then is one of balancing power needs against ice management requirements.

Since 1950, thermally generated sources of electricity have become necessary to meet loads in some of the provinces, and these now supply 30 percent of the total capacity in the country. However, the thermal sources are very much more costly to operate, so any existing hydro-electric source which can offset the use of a thermal one has a value today up to 40 times higher than it did when the plant was designed. Because of this greater replacement value, the tendency now is to design plants for the highest flows the river can pass in winter without creating ice-related flooding problems. Energy production may have to be curtailed during ice cover formation, but may be increased substantially thereafter, and be curtailed again during the break-up period. The objectives are to minimize the degree and extent of the curtailment periods, and to make the greatest amount of hydro-generated power available for peak and system emergencies.

This monograph describes Canadian experiences in solving the problems which have occurred (to 1988) in operating hydro-electric plants in winter to obtain optimum outputs.

2.0 BENEFITS TO THE POWER SYSTEM

Canada has three kinds of power systems, the near total hydraulic systems of British Columbia, Manitoba, Quebec, and Newfoundland, the "hydro-thermal" systems of Alberta, Saskatchewan, Ontario and New Brunswick, and the thermal systems of Prince Edward Island and Nova Scotia. Hydro plants operate at the lowest cost, followed by nuclear, coal and oil-generated sources at respective costs of up to six, twenty and forty times greater than hydro.

When it comes to cold start up, hydro generating units can be "on line" in 5 minutes or less, compared to 6 hours for a thermal unit.

In spite of its advantages, only about one-third of the total hydro capability in the country has been developed. The remaining two-thirds tends to be far from centres of load and transmission costs are high. In Ontario there has been a trend to adding units to existing power plants, and to schedule operations to meet peak demands. In all provinces water has been diverted from other watersheds to supply peak outputs. What limits these trends is the ability of the river system to pass substantially higher flows without causing an ice jam or causing flooding problems (see Section 3.0).

2.1 Need for Operating Flexibility

Demands for power vary considerably within each day, and from day to day during the week. Each power system must provide for its own peak load, even though its duration may be less than one hour. The size of the peak (1987-88 winter) ranges widely as may be seen from the following table:

British Columbia	6 800	megawatts
Trans Alta	4 900	megawatts
Manitoba	3 350	megawatts
Ontario	22 600	megawatts
Quebec	24 900	megawatts

(1 megawatt is 1 000 kilowatts)

Systems must also provide an operating reserve in case of a failure of a generating unit, or the loss of a transmission line, and in Manitoba, the loss of a DC valve group or synchronous condenser. The size of this reserve increases as the system expands and today utilities commonly carry 10-12% reserve capacity, or an amount equal to the single largest contingency in the smaller systems. A source of energy is required which can be started quickly, and reliably, and hydro-electric sources are particularly suited to these tasks. Large amounts of electricity are required at such times, thus ruling out mini-hydro as a supply option. In some provinces, the task of coping with these problems may be assigned to one or more river systems or to a pump-storage development.

Generally, the need for operating flexibility is ever-increasing and each river system is only limited by its ability to accept the changes in level and velocity without breaking enough of the ice cover to cause a jam and create flooding.

2.2 Value of Peak and Operating Reserve

Because of the interconnections, it is possible to provide peak and emergency power to other systems at very favourable rates. For example, peak power can be worth $500 to $1,000 per megawatt per week. This amount is payable whether it is used or not, and if used the cost of the actual energy source required to meet the demand is added on, be it nuclear, coal or oil. For "all hydraulic" systems, the cost of the energy is based on the cost of whatever power is being replaced. Thus, the benefits of having hydro-electric sources available are both large, and similar in magnitude, regardless of the type of system.

In both the "primarily hydraulic" and "hydro-thermal," the value of hydraulic energy is many times greater than was expected at the time that the original run-of-the river plants were designed.

While these requirements may occur at any time in the year, they tend to be larger and more frequent during the winter months when natural river flows tend to be low, and demand is greatest. Essentially, the problem boils down to how high a winter flow will a river withstand without causing ice-related flooding.

3.0 RIVER REGIME CHARACTERISTICS

The construction of hydro-dams on a river changes considerably its thermal regime in winter. Large reservoirs change the time of freeze up and breakup and even the properties of the ice sheet. Fluctuating flows break up the ice in the tailwater, the spring ice becomes smoother, hanging dams and ice jams occur less frequently, and are less dangerous to the structures (Korzhavin 1982).

A dam essentially induces a jam at the upper end of its reservoir, so its final effect is to displace the site of jam formation to one where the jam can be controlled (Michel 1971).

Locations of the twelve rivers where ice has limited hydro operations range in latitude from 42°N to almost 59°N. Some rivers had several problem areas so each problem was described separately and these will be found in the Appendix.

This section presents a summary of the river regimes described in the examples.

3.1 River slopes varied from 0.0025 in the mountains to 0.00004 in Ontario.

3.2 Channel widths generally ranged from 100 to 1 600 m except for one headrace canal where it was only 13 m.

3.3 Depths ranged from shallow (considered to be 3 m or less) to 10 m or more.

3.4 Velocities ranged from 0.6 up to 4.0 m/s.

3.5 Winter temperature ranged from -40°C to +10°C.

3.6 Heavy snowfalls in open water (30 cms or more in 24 hours), and strong winds (30 kmh or greater) were important factors.

3.7 Water temperatures at generating stations were generally 1°C or lower, with the extremes ranging from +2°C for a deep reservoir, to super-cooled in shallow headraces or river channels.

3.8 Rises in level due to jamming ranged from a few meters up to 20 m.

3.9 Ice problems were most prevelent during freeze-up (60%), then during the ice-covered period (25%), and finally during break-up (15%).

4.0 ICE LIMITATIONS DURING FREEZE-UP

All rivers in Canada generate ice and try to form an ice cover each winter. This is a good feature as the ice cover insulates the water from the air and limits the total quantity of ice which the river can produce over the winter season. Ice decreases the water carrying capability of river channels in a number of ways and as a result reduces the rivers power production capacity.

4.1 Climate and Weather

Each river varies in its ability to create an ice cover depending on the climate. The climate may be characterized by weather that fluctuates erratically within a period of a few days, as in the south, to that where it is more constantly cold as in the north. Variations from well below to well above freezing temperatures cause the problems. A sudden freeze converts the potential energy source - the water - from a liquid to a solid. Power outputs must be adjusted to use only the amount of water reaching the generating station at the time. In the early 1900's, the water in some mountainous streams was entirely converted to ice, and the problem was solved by adding water from nearby streams. On the other hand, a sudden thaw melts snow and a lot of the ice, and there is a rapid increase in flow, velocity and water level. The result may be too much ice and water trying to get through too small an opening causing an ice jam and flooding. Both situations influence the reliability of hydro-electric power, and it is desirable to eliminate these restrictions or at least keep them as small as possible.

Ice cover formation under natural conditions may take from a few days to a few months so ice management techniques have been devised to speed up the process. In some climates weather effects are so erratic and so severe that ice cover formation is discouraged (0-16)*. The start of ice cover formation may range from October through January depending on the latitude of the watershed and its climate.

4.2 Restrictions to Flow

All open water surfaces are potential ice producers when the water temperature is close to 0°C, but the types produced and their effects vary widely, with the only common feature being that the flow is restricted. Some ice forms on the river surface, some in the fast-moving flow, and some on the river channel bottom. In every case, the flow is restricted and

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* This exception represents a typical difficulty in trying to form general rules about ice management.

often the head on the generating station is reduced, both factors reducing the power output. The various ice forms are briefly described in the following sections.

4.2.1 Aufeis - Cold temperatures and low flows cause ice to form on the bottom of a river and gradually fill the channel to overflow its banks. The already low flow is decreased further by the continual conversion of water to ice.
See TA-11.

4.2.2 Frazil - Small flat disc-shaped ice crystals several millimeters in diameter. The frazil crystals form in water which is super-cooled (chilled below the freezing point), and where there is enough turbulence to cause mixing of surface and sub-surface waters. Frazil sticks to itself and virtually everything it touches forming massive amounts of semi-porous ice in suspension which rise and float on the river surface forming larger pans as they collide and freeze together. Frazil that coats the channel bottom is called anchor ice.
See TA-5; M-13, 14, 15; O-16 and 23, Q-24.

4.2.3 Anchor Ice - Forms on the bottom of some river sections, as the water becomes more and more super-cooled. The increased roughness factor impedes the river flow and raises the water level, especially when it forms on hydraulic control sections. Decreases in flow of as much as 30% in a few hours have been experienced. During daytime, this ice may lift off the bottom bringing rocks, etc, with it and both are then transported downstream.
See TA-11; O-16.

4.2.4 Snow - Snow falling into open water creates slush, and/or frazil depending on the temperature and turbulence. Huge quantities may be produced, but having buoyancy so low that it tends to float in suspension rather than on the surface. Also, snow falling on top of a thin layer of ice will stop the ice from thickening. This may prevent the formation of a strong ice cover and its weight may cause the ice to break and cause jamming.
See O 19; Q-24.

4.2.5 Pans - Both frazil and anchor ice come to the surface and form "flocs" which freeze together to form a 'pan'. If the velocity is 0.7 m/sec or less the pans will continue to grow in width and thickness. They move with

the current until they meet some surface obstruction such as an island, dam, ice boom or an ice cover. If the current is slow enough they will form a cover, but if too high they will slide over and under the cover forming a restriction to flow.
See M-12, 15; O-18.

4.2.6 Hanging Dams - This term applies to a mass of ice which hangs downwards from the water surface and impedes the flow by its presence. It may be made up of frazil, anchor, slush or pancakes, and its location is dependent on the velocity in the river, usually in a region where the velocity changes from high to low. Velocity is a function of the slope of the river and may be combined with depth to form the Froude number. Hanging dams may be expected wherever the Froude number exceeds about 0.08 provided there is an ice generating reach upstream. See BC-1 and 3; TA-5 to 8; M-13 to 15; O-17, 18, 23; Q-24 and Q-25.

4.3 Ice Cover Formation

Water is subjected to a progressive chilling process as it moves down river. Even when the source is several degrees above freezing the water can start to form ice crystals on the surface in a relatively short travel time. The time until ice starts forming depends on the rate of chilling, which is very much affected by wind velocity, air temperature, snow, and turbulence. As a result, the time until ice starts forming can vary from a number of days to a few hours.

Ice cover formation is the critical period for hydro-electric operation as a jam once formed will usually last all winter, restricting the flow and the output for months.

As a general rule, the sooner an ice cover can be formed the better, so as to insulate the open water from the air and restrict the total quantity of ice which the open water can produce. Depending on the weather, one square meter of open water will produce from four to 10 times as much ice over the winter as it would if there was an ice cover over the area. In every river, there are areas where the cover can form readily and other areas where the velocity is too fast. There may be a whole series of fast water reaches interspersed along the river's length, which will continue to produce ice throughout the winter.

4.3.1 Assisting Factors For Ice Cover Formation

If the velocity can be reduced by flow reductions, then ice cover formation can be assisted through the critical areas.

Ice may be prevented from entering a critical area by restricting its movement using ice booms, or islands (either natural or man-made).

By encouraging ice cover formation, the size of open water areas are reduced and, therefore, the total quantity of ice which the river can generate is also reduced.

An ice cover made from pans that pack together is a good cover, but it needs time to develop sufficient strength. The time varies with the climate, and the slope of the river. (About eight hours is usually adequate at -10°C where the slope is <u>0.00004</u>).

4.3.2 Preventing Factors in Ice Cover Formation

An ice cover will not stabilize at velocities greater than 1 m/sec.

High flows raise stream levels, gradients, and velocities. The increase in turbulence makes pan ice formation difficult.

Rising levels reduce the restraining effect of the shore, permitting the cover to move downstream.

Heavy snow produces slush, which does not make good cover. Snow on top of this ice may cause the cover to break.

Waves interfere with ice cover progression by breaking the pans and helping them slide over and under any existing cover.

4.4 Effects on Power System During Freeze-up

Energy losses were expressed by the various authors in different terms and have been converted, either to megawatt hours per day (MWh/day), or to 1987 dollar values. Peak or capacity losses are in MW.

4.4.1 British Columbia

Energy losses to date have been negligible because the reservoir is large and can absorb any reductions in flow required to accommodate the ice problems (BC-1).

Operating flexibility was reduced and peak requirements must be met by other plants on the system (BC-1).

Occasionally, in very cold winters, the ice cover extends upstream of the town of Taylor (Figure 2) and to prevent flooding, outputs are limited to approximately 50 to 60% for 2 to 3 weeks, resulting in a potential loss of output, of the order of 1 200 - 1 500 MW (BC-3).

4.4.2 Alberta

Energy losses varied from 70 MWh/day to 2 160 MWh/day depending on the size of the plant. Restrictions varied in duration from 2 weeks (TA-7) to 4 months (TA-5).

Peak restrictions varied from reduced operating flexibility (TA-6 and TA-11) to as much as 85 MW (TA-8).

4.4.3 Manitoba

Annual energy losses in excess of $1,000,000 occur as a result of spillage required to ensure that ice staging and associated involuntary storage does not endanger the water supply to the town of Churchill (M-12).

Additional annual energy production in the amount of 500,000 MWh was made possible through use of groins and an ice boom, to control ice movement and reduce ice production capacity (M-13).

Energy losses due to ice accumulation on the trash racks may vary from 50,000 to 100,000 MWh/year (M-14).

Energy losses reduced by two thirds by flow control to promote ice cover formation (M-15).

4.4.4 Ontario

Energy losses due to flow reductions to meet frazil and anchor ice problems were in the 5 000 to 24 000 MWh/day range (O-16).

Energy losses due to rising tailwater levels have varied from a complete shutdown of a 120 MW plant on three occasions, over 80 years, to 5 000 MWh/day for several weeks (0-17).

Improper ice cover formation and a hanging dam curtailed power production by 6 300 MWh/day for 30 days. No loss of energy ensued as the stored water was used later during the year (0-18). Ice booms and flow control have virtually eliminated this problem.

Depending on the quality of the ice cover, winter outputs of energy may vary from the mean by ±1%, depending on the smoothness or roughness of ice cover, ie, about 300 MWh/day (0-19).

Thirty centimeters of snow during ice cover formation resulted in three times the normal thickness for ice. The resulting loss of head on the plant decreased outputs by 1 600 MWh/day for 60 days (0-19).

Occasional flooding of a provincial highway was limiting the plant peak capacity of 164 MW to 82 MW. Scheduling plant operation to provide 5 hour shutdowns in advance of peak load periods eliminated this potential restriction (0-23).

4.4.5 Quebec

Plant output restricted by 15-20%, due to a combination of frazil problems on the trash racks and ice cover formation limiting flows (and velocities). Both problems were aggravated by winter navigation in the headrace canal. Ice booms, ice breakers, and velocity control resulted in an increase of 250 MW over a period of several months (Q-24).

Ice booms installed upstream of the plant reduced the risk of ice jams upstream and downstream of the powerhouse which in the past tended to flood with a loss of 50 MW (Q-25).

5.0 ICE LIMITATIONS DURING THE ICE SEASON

Once an ice cover has formed, most generating stations can increase their output considerably because the river can accept much higher flows without causing the cover to break. Many rivers do not form a complete cover, but have open water areas which are normally small enough that their ice producing capacity is not serious. In some cases, ice controlling measures must be provided to reduce these open water, ice producing areas.

5.1 Weather Influences on Flows

Where temperatures were consistently below freezing, there were few problems, but where they changed markedly between sudden thaws and extreme cold there were difficulties. For example, a chinook, or a mid-winter thaw lasting four days or more, could cause ice covers to disintegrate. The sudden increase in temperature converts ice and snow to water, raising water levels and velocities, and these natural forces can sometimes overcome the man-made controls.

On the other hand, very cold periods, accompanied by wind and snow could cause a rapid decrease in flow available and a considerable reduction in the operating head on a generating station. This was due to ice cover thickening downstream of the open water areas, or to anchor ice, or both.

Weather influences may last from one day to one week, but may recur several times in a winter depending on the climate and latitude where the watershed is located.

5.2 Effects on Power System During Ice Season

Comments in this section apply only during the ice-covered operating period, and relate to problems caused by extremes of change either sudden warmth or severe cold.

Energy losses were expressed by the various authors in different terms and have been converted, wherever possible to megawatt hours per day (MWh/day). Peak or capacity losses are in MW. Dollar figures were based on the cost of replacing the energy or peak capacity on the individual systems (1987 values).

5.2.1 British Columbia

Peak production may be curtailed by 500-600 MW during ice cover formation, but this is eliminated once the ice cover has formed over the critical area (BC-2).

5.2.2 Alberta

Plant capacity limited by downstream ice conditions which vary with temperatures and ice volumes. Peaking capacity limited to 20 minutes duration (TA-9).

5.2.3 Manitoba

A flow of 10,000 cfs months is required to maintain a domestic water supply and an environmentally sound regime. This water is unavailable for diversion to the powerhouses, causing a reduction in power production worth in excess of 1 million dollars/year (M-12).

Flow restriction due to hanging dams caused energy losses ranging from 150,000 to 300,000 MWh. These amounts were reduced to one third by cutting back flows during the ice cover formation period (M-15).

5.2.4 Ontario

Frazil has reduced energy outputs by 4 800 MWh/day and anchor ice or wind effects have amounted to 24 000 MWh/day. Their combined effect has reached as high as 29,000 MWh/day (O-16).

Ice cover formation reduced output by 5% compared to the open water situation, equivalent to 70 MW. However, flows may be increased substantially (30%) after the ice cover has formed and power outputs increase by 400 MW or more. The head loss was more than offset by the flow increase (O-20).

Tests to determine ice cover stability at 7 1/2 times the dependable December flow, verified that an existing plant could be enlarged by 175%, equivalent to 111 MW, and offset the need to build equivalent thermal operating capacity (O-21).

An air bubbler system to reduce ice cover thickness, plus headrace enlargement and trash rack removal allowed a 320% increase in plant capacity, equivalent to 136 MW, and offset the need to build equivalent thermal operating capacity (O-22).

Highway flooding was eliminated and peak output was increased from 82 to 164 MW as outlined in 4.4.4 last paragraph (O-23).

5.2.5 Quebec

Flow control to assist in smoothing the ice cover to reduce head losses may increase plant output by 250 MW (Q-24).

6.0 ICE LIMITATIONS DUE TO BREAK-UP

Break-up occurs when longer days and rising temperatures cause snow and ice to melt and river flow to increase. Rain occurs instead of snow and again the flow increases. As flows increase so do the levels, the ice cover loses shore restraint and begins to move down river with the current. Under normal conditions, this process may take three to four weeks and the river channel gets rid of the ice before the space it occupied is required for passing the spring flood. On the other hand, the entire process may take place in one week or less, and then there is not enough space for both water and ice to pass through constrictions simultaneously, and jams and flooding occur. It is the rate of change in the weather which governs the rates of change of levels and flows.

6.1 Weather Indicators of Break-Up

Problems may be expected in Ontario when the following events take place:

(a) There is a sudden thaw of 20°C days or more.

(b) One or more centimeters of rain occur in 12 hours or less.

(c) In wide rivers when winds exceed 30 km/h and there are open water sections where waves can develop.

In other provinces, these factors may vary considerably. Factors such as the steepness of the river channel, the rate of increase in flows and hence levels, and the ice thickness all play their parts in the severity of any break-up problems.

6.2 Effects on Power System During Break-Up

At break-up there may be a large impact on peak capacity ranging from 55 MW (TA-10) to 1 000 MW (O-17), depending on the severity of the problem.

Generally, there is a decrease in head due to rising tailwater levels and lowered headwater levels. The energy output may/or may not decrease depending on whether the increase in flow is enough to offset the loss in head. In some instances flows must be curtailed by storages to prevent flooding. Where storages are not available and the water is spilled the power losses may reach 4 300 MWh/day (O-20; Q-24).

Generally, the more southerly latitudes are affected first and there is a gradual trend northwards so the impact is spread out. However, in the mountains a chinook can affect many watersheds simultaneously, and its effects may be transmitted from west to east and from one system to another.

7.0 SUMMARY OF SOLUTIONS TO ICE PROBLEMS

Ice Cover Formation

Freeze-up problems were eliminated once a stable ice cover was in place. Some rivers never reach this state and remain at the mercy of unusual weather conditions (BC-3; TA-11; M-13; O-16). Reducing flows for a few days during ice cover formation can prevent many weeks of reduced output.

Flow or Velocity Control

Ice cover formation may be assisted by reducing velocities, either by plant operation or by installing weirs. Alternatively, ice cover may be prevented by increasing flows depending on weather conditions (TA-6, 7, 8; M-13, 14, 15; O-17, 18, 19; Q-24). After ice cover formation, flows may be increased up to 30% to meet power peaks and energy emergencies (O-20).

The Peace River is operated differently with ice cover formation at higher than natural winter flows (BC-1 and 2).

Flow Augmentation

Adding flow from other tributaries overcame a problem (TA-6) caused by conversion of river flow to ice which resulted in a 75% shutdown. Winter flows up to seven times higher than the dependable December flow have been passed successfully (O-21, 22). Flows up to 12 times have been tried with some difficulties (M-13).

Ice Control

Keeping ice out of critical areas may be achieved by ice booms which help an ice cover to form and reduce the ice manufacturing capacity of the open water reaches of the river (M-13, 15; O-17, 18; Q-24, 25). Power losses have been reduced by millions of dollars by ice booms.

Remove Racks

Frazil/slush problems may be reduced greatly by removing the top section or two of the trash racks (O-16, 22; Q-24).

Ice Breaking

Boats operating "around the clock" when needed have kept ice moving out of critical areas and greatly reduced power losses by hundreds of thousands of dollars annually (O-16, Q-24, 25). May also be used to break out heavy ice covers, or hanging dams to reduce head losses and increase plant outputs (O-17).

Channel Enlargement

Enlarging critical areas (depths 3 m or less) may increase ice storage capacity and/or water carrying capacity to cope with the ice/water mix required to pass through (TA-5; O-18; Q-24).

Cyclical Flow Management

When steady state flows are too high to pass through critically jammed sections, plant flows may be decreased for several hours in advance of daily load demands. When peaked later as required, the space provided by the cutback is filled up again but not to the flooding levels (TA-7, 8, 9; O-23).

8.0 MITIGATION

This word is used in the general sense of "reducing the impact of winter" on the various rivers. There are two sides to this impact, one being the benefits which hydro stations provided, the other being the costs of the mitigating works and/or of compensating payments.

8.1 Benefits of Hydro Stations During the Ice Season

Former flood-prone sites were eliminated by the ice covered headponds of the generating stations. The amount of ice and water mixture required to pass through constricted areas was greatly reduced and flooding was reduced or eliminated (O-18; Q-24). Dollar figures of damages sustained tend to be unavailable.

The value of peak power increased by as much as five times over the last 25 years because the operating costs of other sources of electricity were escalating rapidly. Reliable and rapid startup capabilities make hydro particularly valuable for peak purposes and entire river systems were enlarged to make use of this resource. The ability of many river systems to withstand substantially higher flows once an ice cover has formed makes both peak and energy available during the high demand months.

8.2 Costs of Reducing Impacts of Winter

This section covers costs added to generating stations, either in the design stage or afterwards in operation, and were incurred because of the impacts of hydro operations on other users of the rivers in winter, or on riverside properties. Over the 90-year period under discussion, there was a large increase in the uses of the river ice for ice roads, ice fishing, ski-dooing, etc, and a gradual change in the priorities attached to these uses. At the same time, the benefits were rising, and there was a demand for greater variation in flows, levels and power outputs.

To date compensation payments have taken the form of lump sum payments for changes in lifestyle, and payments to flooded property owners even though many of these had settled on the flood plain after the generating station was constructed. Payments may run into millions of dollars for providing bridges, roads, dykes or relocation of homes.

Many problems can be reduced by providing features such as ice breaking by boat or hovercraft. In other instances, ice movements into critical areas may be reduced or prevented by ice booms, artificial islands, groins and even additional hydro plants. Again, these costs may run into millions of dollars and it becomes a problem of balancing the benefits against the costs.

In general, the value of the benefits was considerably greater than the costs of mitigation which in many cases have been several millions of dollars.

9.0 CONCLUSION

For the first 50 years of hydro-electric development (to 1950), generating stations were generally designed to operate at a capacity based on the dependable December flow of the river, and operating techniques were developed to overcome any ice problems which had not been anticipated in the design.

During the next 20 years, a rapidly increasing demand for peak capacity to meet system needs lead to a desire for much higher flows in the winter months. For example, in the St. Lawrence river, the International Rapids power development at Cornwall - Massena came into operation in 1958 and was designed to form an ice cover at flows well above the dependable December value, and in addition was required to pass substantially higher flows after the ice cover was formed.

Kivisld in 1959, and Michel in 1971, published information which explained in a general way what had been found to work successfully in the particular case of the International Rapids power development. This information has been used extensively for designing suitable river systems for ice management in the post 1971 period, and has helped to explain many problems which were formerly considered to be "Acts of God."

Operating experience has shown that design criteria based on steady state flows and normal weather conditions may require modification for unusual weather sequences. Little has been published heretofore on the successful operating solutions, and these do not appear in text books, so it was concluded that reports of this kind represent a useful vehicle for information transmission.

Dependable December flows are no longer a sensible design limit for generating stations because these have been exceeded from 4 to 12 times for peaking purposes with a considerable degree of success.

Reliable remote indicators of levels, flows, and weather conditions can be helpful operating aids but expensive to obtain, calibrate, and maintain.

Flow control was widely practiced but ice movement control and controlling ice manufacturing capability was not so general and could be used to more advantage (see O-18 vs BC-1).

APPENDIX TO REPORT

ON

OPTIMUM OPERATION OF HYDRO-ELECTRIC PLANTS DURING THE ICE REGIME OF RIVERS

This appendix contains 25 examples of locations in Canada where ice limits the operation of hydro plants at some time during the winter season. The examples come from 12 river systems beginning in British Columbia and proceeding eastward to Quebec. As a result, river slopes vary from mountainous through all the variations to quite flat, ie, from 0.002 to 0.00004.

In the main report, ice limitations were divided into three sections as follows:

Section 4.0 During Freeze-Up
Section 5.0 During the Ice-Covered Season
Section 6.0 During Break-Up

Examples are identified by province of origin, by number, and by period of ice limitation. River locations are shown approximately on Figure 1 and in detail on maps following the first example of each river system. Problems and their causes have been included in the index using a few key words.

Index of Examples of
Ice Problems and Causes

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APPENDIX

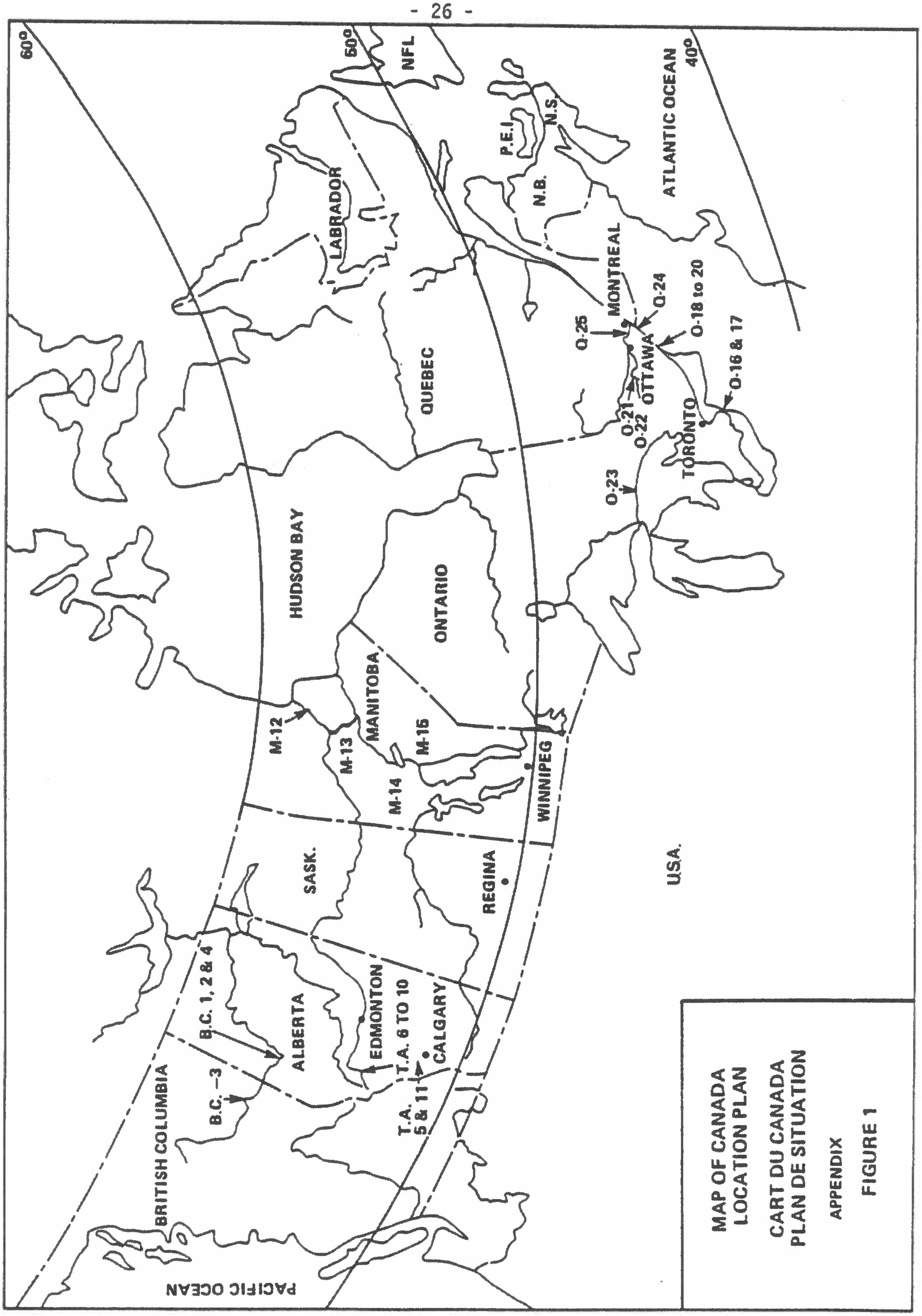

60°
60°
NFL
40°
ATLANTIC OCEAN
P.E.I.
N.S.
N.B.
LABRADOR
QUEBEC
MONTREAL
O-25
O-24
O-18 to 20
O-16 & 17
OTTAWA
O-21
O-22
TORONTO
O-23
HUDSON BAY
ONTARIO
MANITOBA
M-12
M-13
M-14
M-15
WINNIPEG
SASK.
REGINA
U.S.A.
ALBERTA
EDMONTON
CALGARY
B.C. 1, 2 & 4
B.C. -3
T.A. 6 TO 10
T.A. 5 & 11
BRITISH COLUMBIA
PACIFIC OCEAN
MAP OF CANADA
LOCATION PLAN
CART DU CANADA
PLAN DE SITUATION
APPENDIX
FIGURE 1

FIGURE 1

APPENDIX BC-1

EXAMPLES OF ICE PROBLEMS ON THE PEACE RIVER

Example 1 - 1981/82 Freeze-up at Town of Peace River, Alberta.

Reach Characteristics

Slope 0.0003
Channel Width 500 m
Flow Velocity 0.7 m/s
Discharge 1 000 to 2 000 m^3/s

Problem

The initial ice cover formed on the Peace River between the Town of Peace River (TPR) and Dunvegan 100 km upstream, broke up under increased flow conditions (Figure 2). An ice jam formed just downstream of TPR and the ice cover reformed resulting in freeze-up levels just below the crest of the dykes protecting the town.

Causes

Freeze-up on the Peace River at TPR occurred on January 2, 1982. Over the New Year weekend (January 1 to 3, 1982) mean daily flow releases from the upstream G.M. Shrum and Peace Canyon hydroelectric plants were reduced from approximately 1 700 to 1 000 m^3/s due to low load demand. This low flow combined with extremely cold weather (mean daily air temperatures of -30 to -35°C) resulted in the rapid upstream advance of the ice front, and by January 7 the ice front was upstream of the town of Dunvegan, approximately 100 km upstream of TPR.

Flow releases at the upstream plants were increased to 1 750 m^3/s by January 5, 1982. These plants are more than 370 km upstream and flow travel time from the plants to TPR is approximately 2 days. On January 7 as a result of these increased flows, break-up of the ice cover occurred at Dunvegan and a temporary ice jam 15 km downstream was formed. After several hours the jam released and the resulting flow surge estimated at 2 500 m^3/s cause the ice cover as far downstream as TPR to break-up. The broken ice debris moved downstream and packed against the upstream edge of the unbroken cover 20 km downstream of TPR. Approximately 155 km of ice cover had broken and consolidated into a distance of 60 km. Water levels on January 8 at TPR increased to El 318.2, 3.5 m above the prebreak-up level on January 7 and only 1.6 m below the top of the dykes protecting the town.

Solution

To avoid a re-occurance of this problem, once the ice front has advanced to within about 15 km of TPR, mean daily releases at the upstream plants are held constant at about 1 500 m^3/s until the ice front has advanced well upstream of TPR and the ice cover has had a chance to consolidate. Freeze-up and consolidation usually takes from 1 to 2 weeks. Although short term flow increases for daily load factoring are usually limited, due to the distance between the plants and TPR minor flow changes throughout the day are almost completely attenuated by the time they reach TPR. Maintaining relatively high river flows during the freeze-up period at TPR, results in the formation of a thick ice cover at a high river stage which is stable under a wide range of river flows. This permits maximum operating flexibility at the upstream plants during the rest of the winter period.

Loss of Output

During the freeze-up period, there is very little operating flexibility and peak system loads must be met by plants on other river systems. To date because of the large upstream reservoirs on both the Peace and Columbia River systems no net energy loss has been experienced.

Mitigation Costs

None.

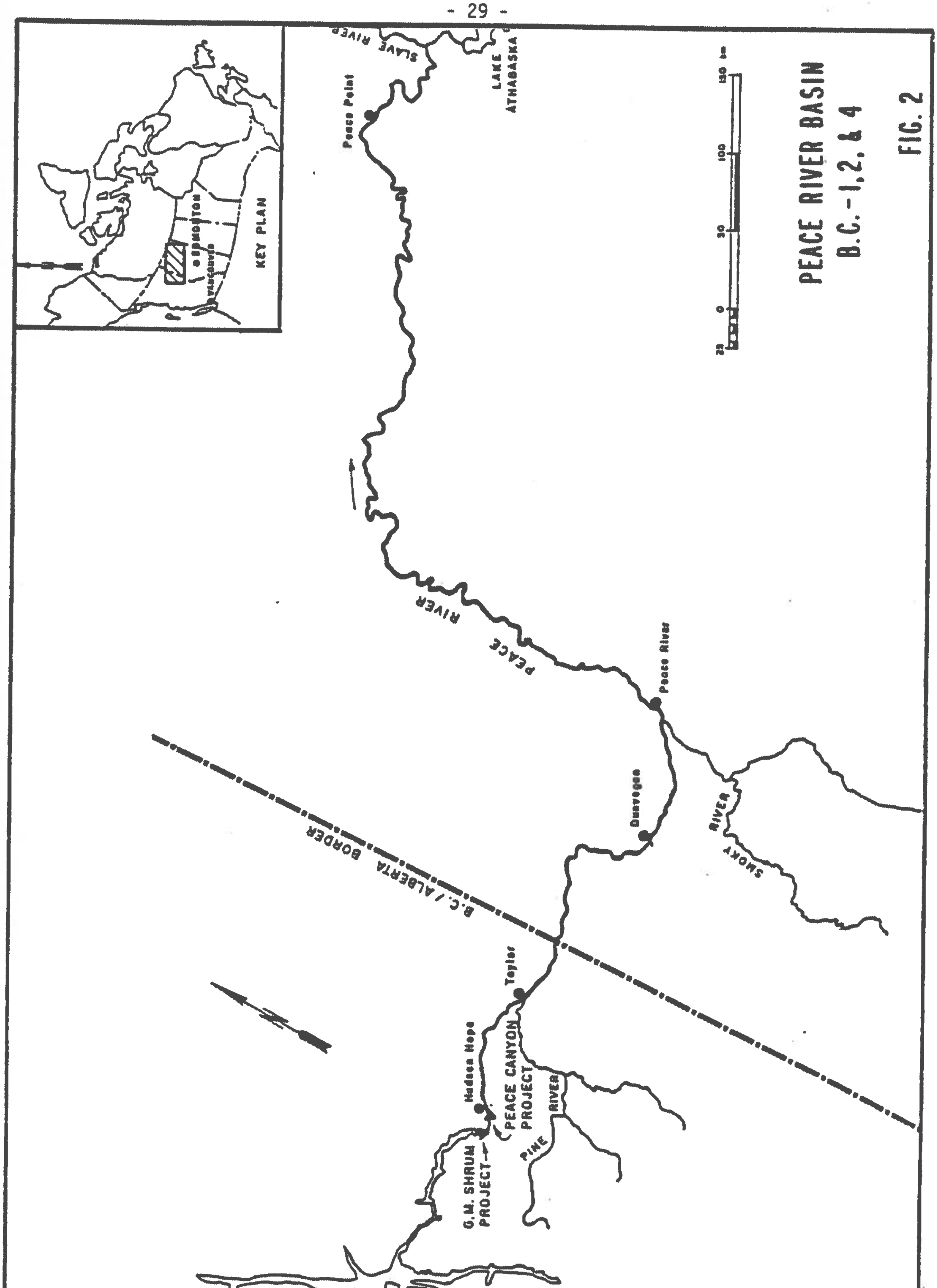


FIG. 2

FIGURE 2

APPENDIX BC-2

Example 2 - 1981/82 Ice Season at Town of Peace River, Alberta.

Reach Characteristics

Slope 0.0003
Channel Width 500 m
Flow Velocity 0.7 m/s
Discharge 1 000 to 2 000 m^3/s

Problem

As a result of high river stages at the Town of Peace River (TPR) following the collapse and subsequent reformation of the ice cover in early January 1982 (see Example 1), ground water levels in the subdivision of West Peace River were raised, and residents complained of basement flooding due to ground water seepage (Figure 2).

Causes

The West Peace subdivision of TPR is located on the flood plain along the left bank of the Peace River. Although the subdivision is protected by a dyke, the alluvial gravels of the floodplain are quite pervious and groundwater levels respond within a week or so to changes in river stage.

As explained in Example 1, the initial ice cover on the Peace River formed very rapidly during early January 1982 under relatively low flows and very cold weather conditions. Increased flow releases from the upstream hydroelectric plants in response to higher load demands resulted in the break-up and subsequent consolidation and reformation of the ice cover. River stages at TPR increase dramatically.

To ensure the formation of a competent ice cover which would be stable under a large range of power releases, flows were held relatively constant at about 1 700 m^3/s throughout January and the first half of February 1982. River stages during this period, although substantially lower than the peak stage (El 318.2) during the reformation of the ice cover, were still relatively high at about El 316.5. As a result, the groundwater levels in the West Peace subdivision increased to near river levels causing basement flooding in some 60 residences.

In mid-February 1982, releases from the upstream hydroelectric plants were reduced to about 1 000 m^3/s and river stages at TPR decreased to El 315.2 by the end of February. This temporarily solved the groundwater seepage problem but more complaints were received in March when power releases were increased to approximately 1 300 m^3/s. The problem of groundwater seepage and basement flooding persisted until river stages and groundwater levels were lowered following break-up of the Peace River in late April.

Solution

The persistence of the basement seepage problem at West Peace River and the substantial reduction in plant output necessary to correct the problem emphasis the importance of maintaining constant, relatively high river discharges during the freeze-up period at TPR as outlined in Example 1. This produces a competent ice cover which is stable under a large range of flow releases from the upstream hydroelectric plants.

Since river stages at TPR above El 315.3 for prolonged periods result in groundwater seepage and basement flooding, the temporary peak river stage during freeze-up should not exceed El 315.3 by more than approximately 0.5 m. Subsequent smoothing of the underside of the ice cover and gradual erosion of accumulated slush ice, results in a reduction of at least 0.5 m in river stage for the same discharge 3 to 5 days after freeze-up. During this brief period when river stages are above El 315.3, the groundwater table is not charged sufficiently to cause basement seepage problems. Experience has indicated that releases from the upstream hydroelectric plants of up to 1 600 m^3/s can be sustained during freeze-up at TPR without problem.

Loss of Output

During the 1981/82 winter output from G.M. Shrun and Peace Canyon hydroelectric plants on the Peace River was reduced to minimize basement flooding due to groundwater seepage as system load demand permitted. Because of the large storage capacity of the upstream Williston Lake reservoir no net loss in energy production resulted.

Mitigation Costs

BC Hydro compensated residents of West Peace River whose basements were flooded.

APPENDIX BC-3

Example 3 - 1981/82 Freeze-up at Taylor, BC.

Reach Characteristics

Slope 0.0004 - 0.0006
Channel Width 400 m
Flow Velocity 0.75 m/s
Discharge 1 200 to 1 750 m^3/s

Problem

The weather during the month of February 1979 was extremely cold and the ice cover on the Peace River advanced upstream past Taylor, BC (Figure 3). River stages at Taylor increased dramatically as a result of ice jamming and relatively high power flow releases, causing local flooding. Outbuildings were damaged, cattle were drowned, and moose were trapped on bars and islands in the river channel.

Causes

The temperature of water released from the upstream Williston Lake reservoir during the winter varies from 1 to 4°C. As a result of this above 0°C water temperature and high winter flows on the Peace River under the regulated regime, a long reach of open water downstream of the hydroelectric plants persist throughout the winter and the ice front usually does not advance as far upstream as Taylor. However, air temperatures during February 1979 averaged -27°C and despite relatively high power flow releases the ice front progressed upstream from the BC/Alberta border at an average rate of 6 km/day, reaching its maximum point of advance (19 km upstream of Taylor) on March 1, 1979.

For the ice cover to progress through the relatively steep Taylor reach, a series of ice jams or accumulation cover sections must form to raise the river stage and decrease flow velocities. Since Taylor is only 100 km downstream of the Peace Canyon plant only minor attenuation of short term flow fluctuations occurs. The collapsing and shoving of the leading edge of the ice cover is aggravated by flow fluctuations and combined with relatively high flow releases, results in high river stages during freeze up. Despite flow reductions to less than 1 500 m^3/s and load factoring restrictions at the upstream plants, peak river stages at Taylor during February 1987 reach El 407.2, more than 5 m above normal open-water levels.

Solution

When it is evident that the ice front will advance as far as Taylor, local residents along the river are advised that high river stages could occur and farm animals, machinery, etc, should be moved to high ground. To prevent local flooding when the ice front approaches Taylor, flow releases from the upstream hydroelectric plants are reduced to less than 1 200 m^3/s and kept as constant as possible. Flood zone limits prohibiting development in areas subject to flood damage have recently been established along the Peace River downstream from Taylor.

Fortunately, the ice front does not usually progress as far upstream as Taylor, and when it does the ice cover usually only lasts for a period of 2 to 3 weeks. The ice front usually moves downstream without incident as a result of thermal erosion caused by warmer air temperatures and the above 0°C temperature of the water released from the upstream plants.

Loss of Output

During the period that the ice front is upstream of Taylor, output at the upstream plants must be severely restricted (50%) if flooding is to be avoided. Although, the probabilities of energy loss is low because of the large upstream reservoir, the curtailment of generation may result in a significant loss of revenue from the sale of secondary energy.

Mitigation Costs

BC Hydro compensated residents for property damage as a result of flooding.

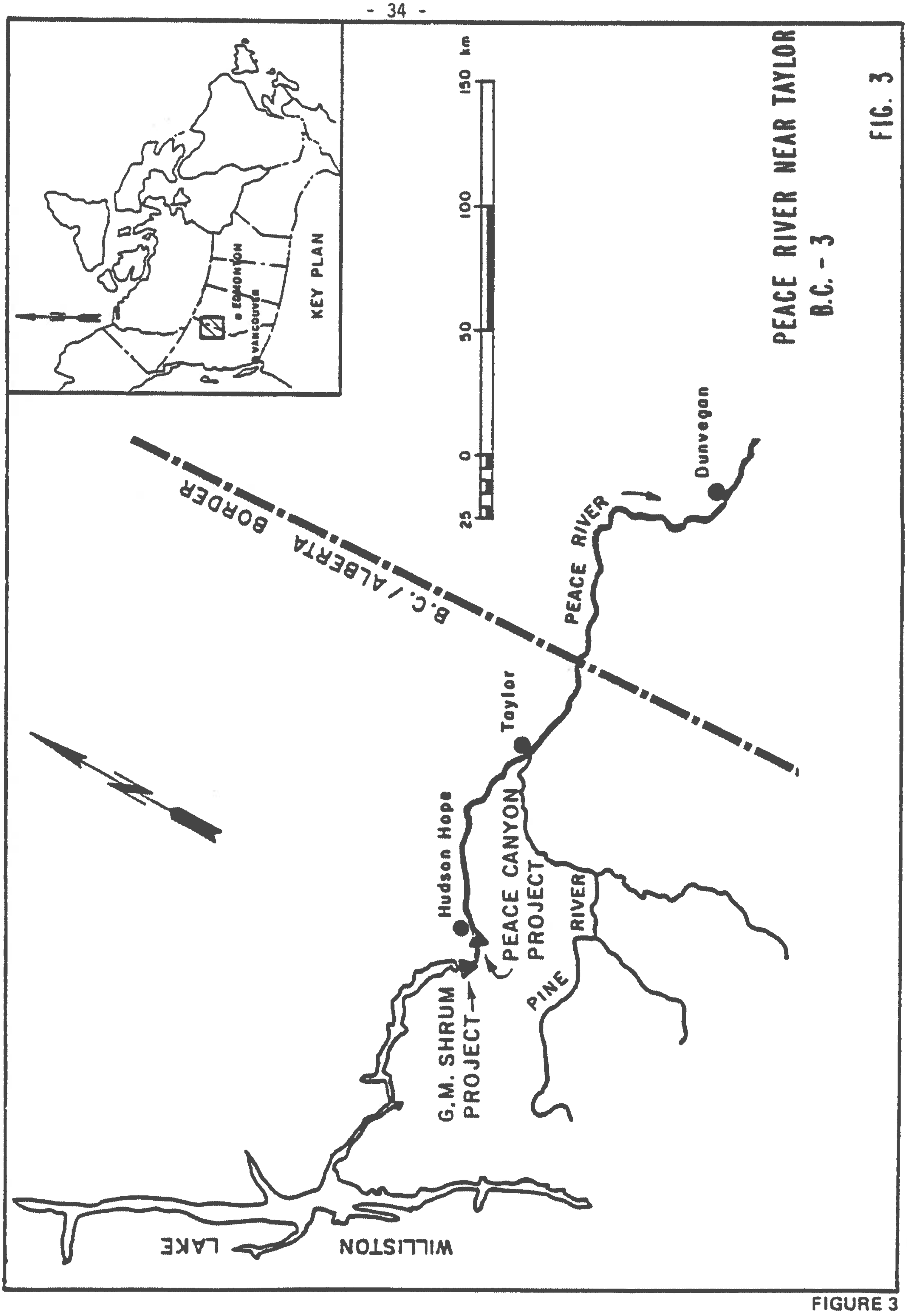

PEACE RIVER NEAR TAYLOR
B.C. - 3
FIG. 3
KEY PLAN
EDMONTON
VANCOUVER
0
25
50
100
150 km
B.C. / ALBERTA BORDER
PEACE RIVER
Dunvegan
Taylor
Hudson Hope
PEACE CANYON PROJECT
G.M. SHRUM PROJECT
PINE RIVER
WILLISTON LAKE

FIGURE 3

APPENDIX BC-4

Example 4 - 1978/79 Break-Up at Town of Peace River, Alberta

Reach Characteristics

Slope 0.0003
Channel Width 500 m
Flow Velocity 0.8 m/s
Discharge 2 500 m^3/s

Problem

On April 30, 1979, a massive ice jam at the mouth of the Smoky River broke, releasing large volumes of water and ice into the Peace River (Figure 2). This caused the break-up of the Peace River ice cover between the Smoky confluence and the town of Peace River (TPR), a distance of about 5 km. The river stage at TPR increased approximately 2 m to El 318.7, less than 1 m below the dyke crests, the highest level ever recorded. Dykes in the Springfield subdivision were overtopped and residents of the West Peace subdivision were evacuated as a safety measure. Some flooding as a result of storm sewers backing occurred in TPR.

Causes

Large winter snowpacks and warm (10°C) weather in April resulted in high spring runoffs on the Smoky River and other Peace River tributaries. Break-up on the upper reaches of the Smoky River occurred on April 26 and a massive ice jam was formed at the Peace/Smoky River confluence. The Peace River ice front was 20 km downstream of Dunvegan (80 km upstream of TPR) and was moving slowly downstream as a result of thermal erosion. Flow releases at the upstream hydroelectric plants during April were relatively low, averaging less than 1 000 m^3/s, and because of the high flood potential the releases were further reduced to about 500 m^3/s prior to break-up at TPR.

When the ice jam at the mouth of the Smoky River broke on April 30, 1979, the resulting surge of ice and water triggered break-up of the Peace River ice downstream of the Peace/Smoky River confluence as far as TPR. The high spring runoff produced peak flows during break-up of 1 590 m^3/s on the Smoky River and 2 520 m^3/s on the Peace River upstream of the Smoky confluence despite flow reductions at the upstream plants. These high flows together with the broken ice debris which jammed just downstream of TPR resulted in record high river stages. The Peace River ice cover upstream of the Smoky confluence broke-up on May 2, 1979, and moved downstream without incident.

Solution

The potential for high tributary inflows during break-up exists when large snow packs have accumulated during the winter, and a dynamic break-up of the ice cover and high river stages can be expected. If the ice cover on the Peace River has not progresses too far upstream and the onset of warm (10°C) spring weather is not too rapid, high flow releases of above 0°C water from the upstream hydroelectric plants (load demand permitting) can induce a gradual (thermal) break-up and clearing of the Peace River ice downstream past TPR before break-up occurs on the Smoky River. This greatly reduces the chance of high river stage on the Peace River during the Smoky River break-up. Because of the 2 days flow travel time from the upstream plants to TPR, care must be taken to ensure that large power flows are commited to the river system only when there is little chance of a sudden break-up on the Smoky River.

If the Peace River channel cannot be cleared of ice prior to break-up on the Smoky River, the only recourse is to reduce flows at the upstream plants. A joint "BC/Alberta Peace River Ice Task Force," comprised of representatives from the Alberta Department of Environment, the BC Ministry of Environment and BC Hydro, was formed in 1974 to coordinate ice observations on the Peace River in general, and in particular to observe, study, and make recommendations with respect to ice related flood hazards at TPR.

Loss of Output

Because of large upstream reservoirs on both the Columbia and Peace River systems, no net energy losses have been experienced to date. However as the system load demand increases, maintaining reduced Peace River flows during break-up will become more difficult, and costs in terms of lost revenue could be high.

Mitigation Costs

None.

APPENDIX TA-5 (F/U)

FREEZE-UP - Bow River - Freeze-Up Series

Problem

High stages on the Bow River through Calgary (Figures 4 to 6) resulting from ice jams would overtop river banks and inundate adjacent roads. For detailed description of problems see 1952 Royal Commission Report on Bow River flooding due to ice.

Causes

Ice jamming (packing) as a result of flow augmentation from upstream storage and peaking type operation of upstream hydro plants (16 hours on - 8 hours off). The 30 river miles above Calgary (average gradient 10+ feet per mile) allowed a vast quantity of slush ice to form and be brought into the city.

Solutions

Construct storage reservoir (Bearspaw Development) immediately upstream of Calgary to limit ice flowing into city. The Hydro plant on the reservoir runs as a baseload type operation and is restricted in maximum flow during ice formation periods.

Dyke river through city in areas of low river banks to contain ice within river channel.

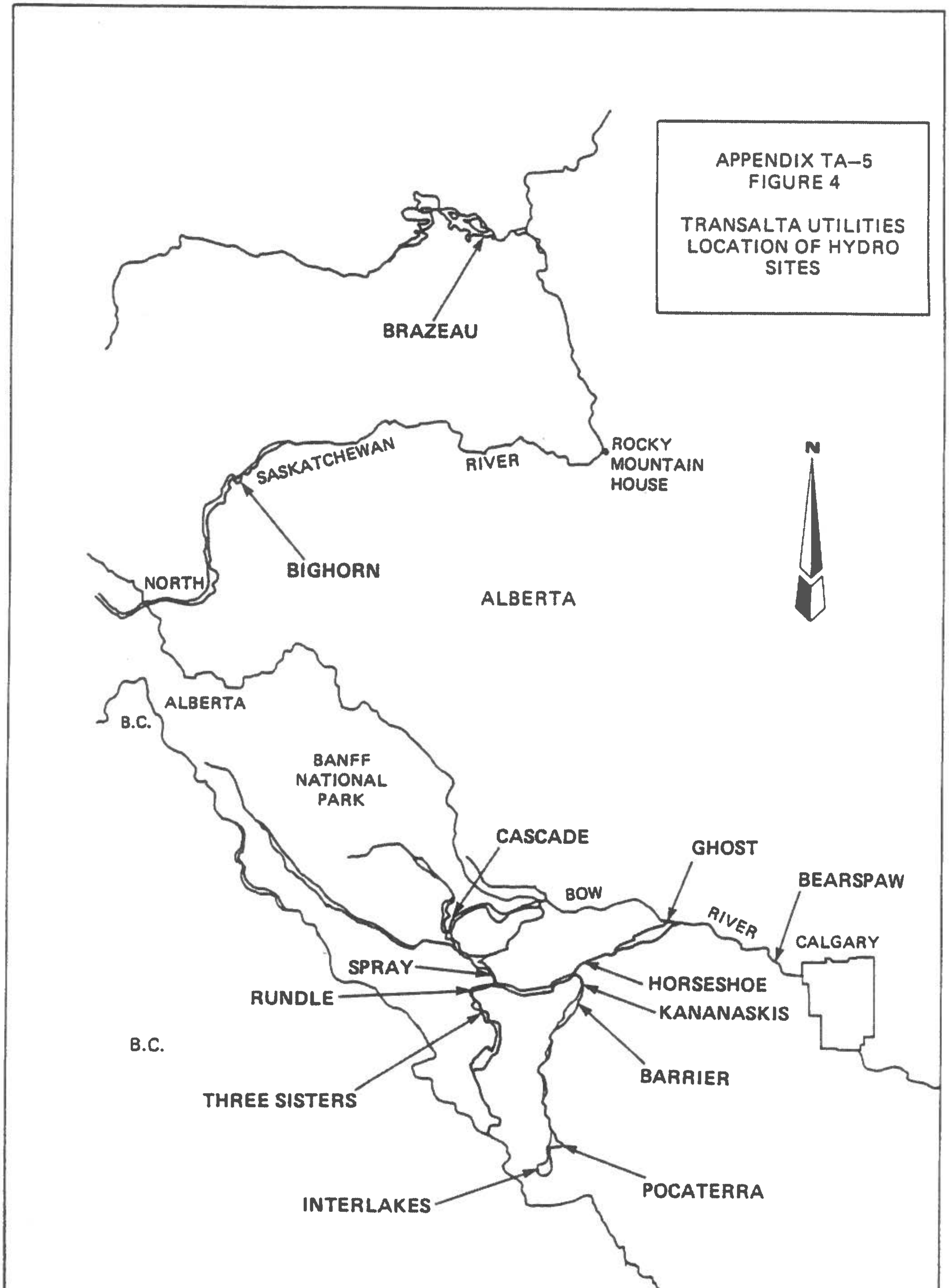
Excavate "Ice Pack Anchorage" in river to encourage early formation of an ice bridge with hanging dam and upstream progression of an ice cover. This limits inflowing ice to critical downstream reaches with resultant lower stages when an ice cover does form.

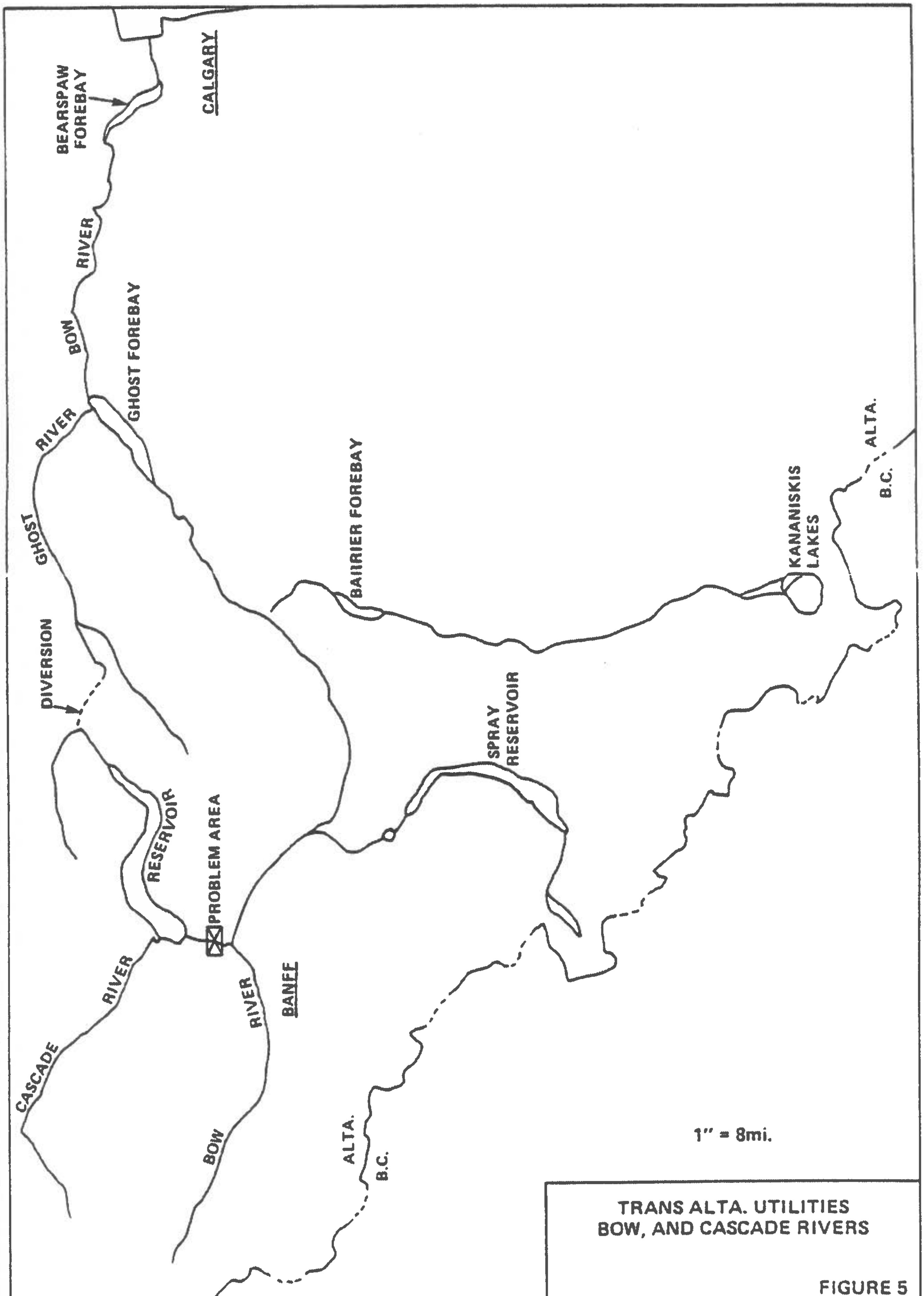
Loss of Output

Plant is restricted to 80% of maximum capacity while ice cover exists through the city. This is a loss of 3 MW for approximately 4 months.

Mitigation

Place limits on plant operation during winter.


APPENDIX TA–5
FIGURE 4
TRANSALTA UTILITIES
LOCATION OF HYDRO
SITES
BRAZEAU
ROCKY
MOUNTAIN
HOUSE
SASKATCHEWAN
RIVER
N
NORTH
BIGHORN
ALBERTA
ALBERTA
B.C.
BANFF
NATIONAL
PARK
CASCADE
GHOST
BEARSPAW
BOW
RIVER
CALGARY
SPRAY
RUNDLE
HORSESHOE
KANANASKIS
B.C.
THREE SISTERS
BARRIER
INTERLAKES
POCATERRA



TRANS ALTA. UTILITIES
BOW, AND CASCADE RIVERS

FIGURE 5

APPENDIX TA-5

Bow River at Calgary

Reach Characteristics:

Slope - 0.00178*
December Average Flow - 45.3 cms@

Channel Geometry for discharge of 44 cms:

Area	- 71.6	m^2
Width	- 78	m
Depth	- 0.92	m
Velocity	- 0.615	m/s

---

* from "Hydraulic and Geomorphic Characteristics of Rivers in Alberta" by Kellerhals, Neill and Bray, 1972.
@ includes regulation on river since 1913.

Figure 6

APPENDIX TA-6

FREEZE-UP - North Saskatchewan River - Freeze-Up

Problem

Inadequate flow augmentation at Edmonton if freeze-up occurs suddenly in -40°C temperatures (Figure 7).

Causes

Augmentation is provided from Bighorn and Brazeau reservoirs, 140 and 270 river miles respectively upstream of Edmonton. During sudden very cold incursions of Arctic Air over the river basin, before appreciable ice cover has formed, up to 75% of released water can be lost in ice production before reaching Edmonton.

Normal operation of hydro plants is for Bighorn to provide bulk of flow augmentation in 24-hour operation while Brazeau provides 16-hour peaking type operation.

Solutions

Increase Brazeau operation to 24 hours daily. Transfer load from Bighorn to Brazeau to perform bulk of augmentation requirements.

Loss of Output

No loss of output, some loss of scheduling flexibility.

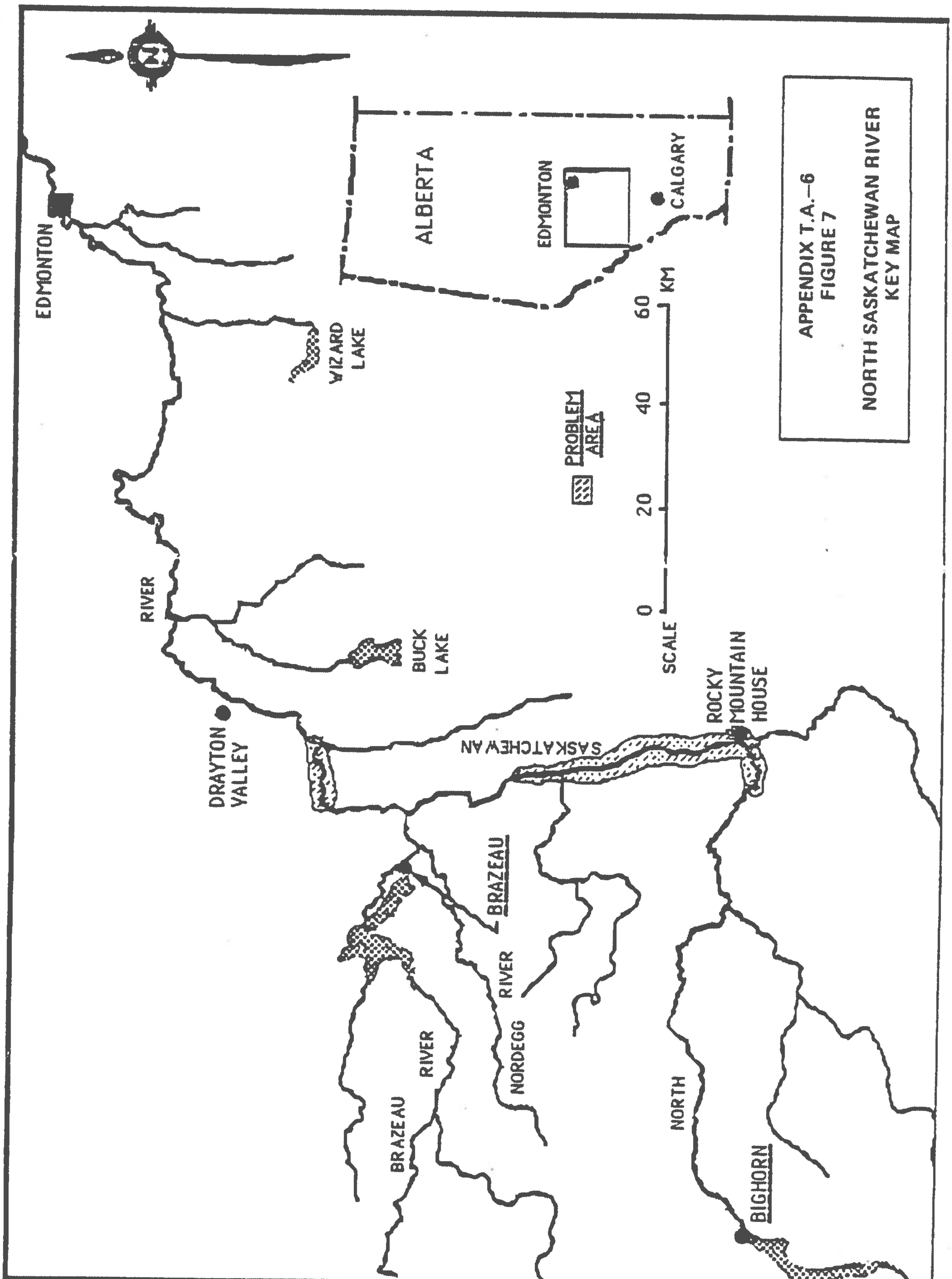

N
ALBERTA
EDMONTON
CALGARY
EDMONTON
WIZARD LAKE
RIVER
BUCK LAKE
DRAYTON VALLEY
PROBLEM AREA
SCALE 0 20 40 60 KM
ROCKY MOUNTAIN HOUSE
SASKATCHEWAN
BRAZEAU
RIVER
NORDEGG
BRAZEAU
RIVER
NORTH
BIGHORN
APPENDIX T.A.—6
FIGURE 7
NORTH SASKATCHEWAN RIVER
KEY MAP

FIGURE 7

APPENDIX TA-7

FREEZE-UP - North Saskatchewan River - Freeze-Up Series

Problem

High stages during ice cover formation can inundate oil wells and approach roads in an oil field along the North Saskatchewan River (Figure 7).

Causes

Sustained high peak discharges from Brazeau hydro plant can create high backwater levels in an ice pack as it is forming.

Solutions

Limit time period Brazeau can run at full load while ice cover is building in the critical reach. Following a period of full load Brazeau generation must be decreased to give a flowby which will not create unacceptable high stages in the critical downstream reach.

Loss of Output

Full plant capacity available for approximately 20 minutes then plant reduced to 75% of capacity (loss of 90 MW). This restriction may last for up to 2 weeks.

Mitigation

Monitor formation of ice and restrict plant operation when ice is forming in critical reaches.

APPENDIX TA-8

FREEZE-UP - North Saskatchewan River - Freeze-Up Series

Problem

There is a 53 mile reach centred on Rocky Mountain House (Figures 7 and 8) containing many houses, oil field structures, roads, and agricultural fields subject to inundation caused by high backwater stages due to ice. At Rocky there is the town water supply pumphouse and a National Historic Park which can be affected by high stages.

Causes

Increased winter flows due to augmentation from the Bighorn reservoir have coincided with increased winter ice formation levels. Bighorn is also used for peaking which further increases the maximum flow downstream.

Chinooks (sudden increases in temperature) have been known to cause collapse of the head of an ice cover with subsequent reformation at a higher stage.

Solutions

Use air and land observation to monitor location of the head of pack. As pack builds to a critical reach apply flow restrictions at Bighorn as required. Restrictions may take the form of peak restrictions or maximum daily flow restrictions. Restrictions are based on past experience of flows and high stages in the critical reaches.

Loss of Output

Variable from winter to winter depending on speed with which ice cover builds through the 53 river miles. Bighorn is restricted to 30% of capacity, a loss of 85 MW while the ice pack is building through the most critical reach.

Mitigation

To date, costs have been incurred to remove or protect homes, roads, and oil field installations which were within the Potential winter flood plain.

Monitor formation of ice cover and restrict plant operation when ice is forming in critical reaches.

APPENDIX TA-8

North Saskatchewan River at Rocky Mountain House

Reach Characteristics:

Slope	- 0.0022*
December Average Flow	- 45.3 cms@

Channel Geometry for discharge of 44.5 cms:

Area	- 70.1 m^2
Width	- 106 m
Depth	- 0.58 m
Velocity	- 0.64 m/s

* - from "Hydraulic and Geomorphic Characteristics of Rivers in Alberta" by Kellerhals, Neill and Bray, 1972

@ - includes regulation on the river since 1972

Figure 8

APPENDIX TA-9

MID-WINTER - North Saskatchewan River - Ice Covered Series

Problem

The full installed capacity at Bighorn plant is not useable after growth of an ice pack through Rocky Mountain House due to resulting high stages under the ice cover (Figure 7).

Causes

The ice cover at Rocky is formed on restricted flow to prevent inundating critical structures. After formation backwater effects due to the ice cover are sufficient to inundate the structures if full plant capacity was used.

Solutions

Using telemarks at a water level station installed near the critical structure monitor the stage under ice cover. As backwater decreases, increase the allowable maximum flowby at Bighorn.

Use short daily peak operation pulses from Bighorn to accelerate the rate of decrease of backwater at Rocky. This method of operation also allows increased use of installed capacity over system peaks.

Loss of Output

Variable, depends on rate at which backwater due to ice cover recedes.

Mitigation

Install monitoring and communications equipment at the critical point. Reduce plant restrictions as the backwater effects from the ice cover decrease.

Cost of a water level station installed (stilling well, intake, shelter, and communications) runs $10,000+. Savings can be realized by using existing intakes wherever possible.

APPENDIX TA-10

BREAK-UP - North Saskatchewan River - Break-Up Series

Problem

Sudden intrusions of Arctic Air can cause recession of an ice cover to cease and freeze-up of the river to begin again.

Causes

During break-up Bighorn plant (Figure 7) is normally available to full plant capacity. This flow is too high for ice formation on critical reaches.

Solutions

Monitor ice cover recession using air and ground reconnaissance. As receding ice cover approaches the critical reach monitor the weather forecasts very closely. If temperatures of -20°C or lower are forecast place equivalent restrictions on Bighorn operation as was used during freeze up.

Loss of Output

Variable, may be as high as 60% of plant capacity, or a loss of 55 MW.

Mitigation

Monitor recession of ice cover and restrict plant operation if freeze-up re-occurs.

APPENDIX TA-11

FREEZE-UP - Cascade/Bow River - Freeze-Up Series

Problem

The Cascade River, a tributary of the Bow River, is regulated by the Cascade hydro development. Figure 5.

Anchor (aufeis) formation causes the Cascade River to leave its normal channel and glaciate surrounding areas. Extreme levels of glaciation have caused inundation of a rail line.

Causes

Cascade plant normally is off at night with approximately 2 cfs leakage flow passing. There is no other residual flow into the Cascade River. During very cold periods this low flow results in vast quantities of anchor ice forming in the flow channel. The following days generation flow then overflows the river banks because of the obstructed flow channel.

Solutions

Allow glaciation to occur until the water level reaches the base of the rail line fill. Cascade plant must then run sufficient hours at night at partial load setting to prevent anchor ice formation whenever forecast temperatures are -25°C or lower.

Loss of Output

None, some loss of scheduling flexibility.

Mitigation

Allow as much ice buildup as possible before requiring night time operation to prevent further ice buildup.

APPENDIX M-12

A. LOWER CHURCHILL RIVER - Latitude 58° 45' Freeze-Up and Ice Covered and Series

Ice Regime (Figure 9 and 10)

480 km of northerly flowing extremely shallow, wide, flat bottomed river channel with very little local inflow during the winter months. There are five very large lakes along the upper half of the reach in question.

Problem

Diversion flows for power production are compromised by releases down the natural channel required for security of the Town of Churchill water supply. Additional water must be released each winter to account for temporary storage caused by ice staging along the 480 km route between the diversion reservoir (Southern Indian Lake) and the town. The additional flow thus released at Missi Control cannot be used for diversion and subsequent generation on the Lower Nelson.

Causes

Diversion for power production has removed most of the natural flow from this river. The outlets of a number of large lakes on the natural channel get blocked by ice causing rises in water level which temporarily remove flow from the lower portion of this river system. In addition, the natural channel itself, which is normally in excess of one kilometer in width, stages similarly and puts more water into temporary storage.

Solutions

The solution to date has been to surcharge the Lower Churchill so that even if large amounts of water go into temporary storage, some will make it to the water supply pumphouse. About 10 000 cfs-months of water is required for this purpose. This water becomes unavailable for diversion and subsequent generation.

The incorporation of a weir downstream of the domestic water intake is being considered as an alternate solution. However, the structure would have to be in excess of one kilometer long, there are environmental concerns and there are concerns that the weir will worsen spring flooding and ice staging during break-up.

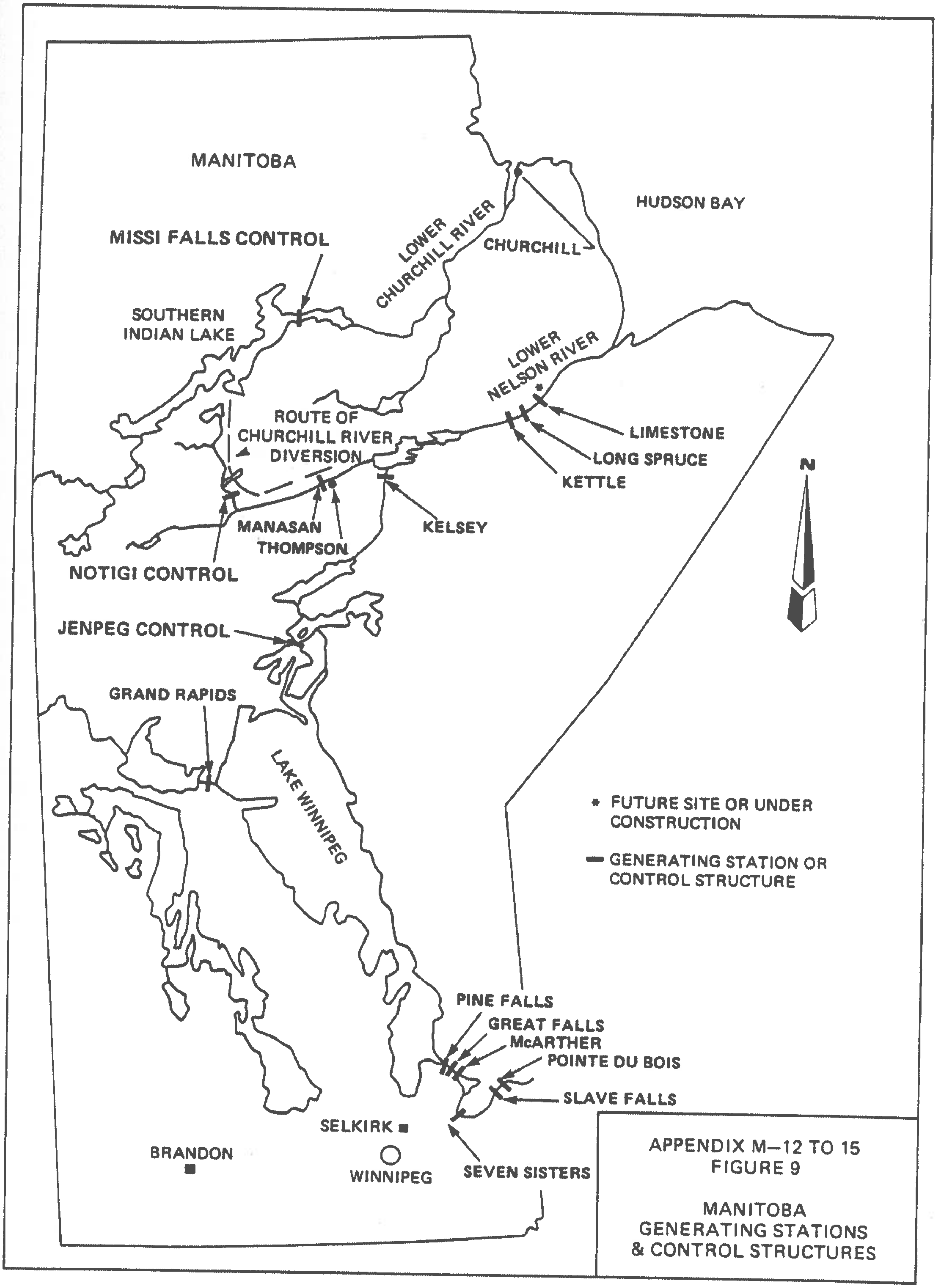
Other solutions that have been considered include regulation of a major tributary to provide the required winter flow, and regulation of one or more of the major lakes on the trunk system to provide adequate winter flows.

Effects on Power Production

The surcharging of the Lower Churchill River system costs Manitoba Hydro in excess of $1,000,000 annually in lost generation.

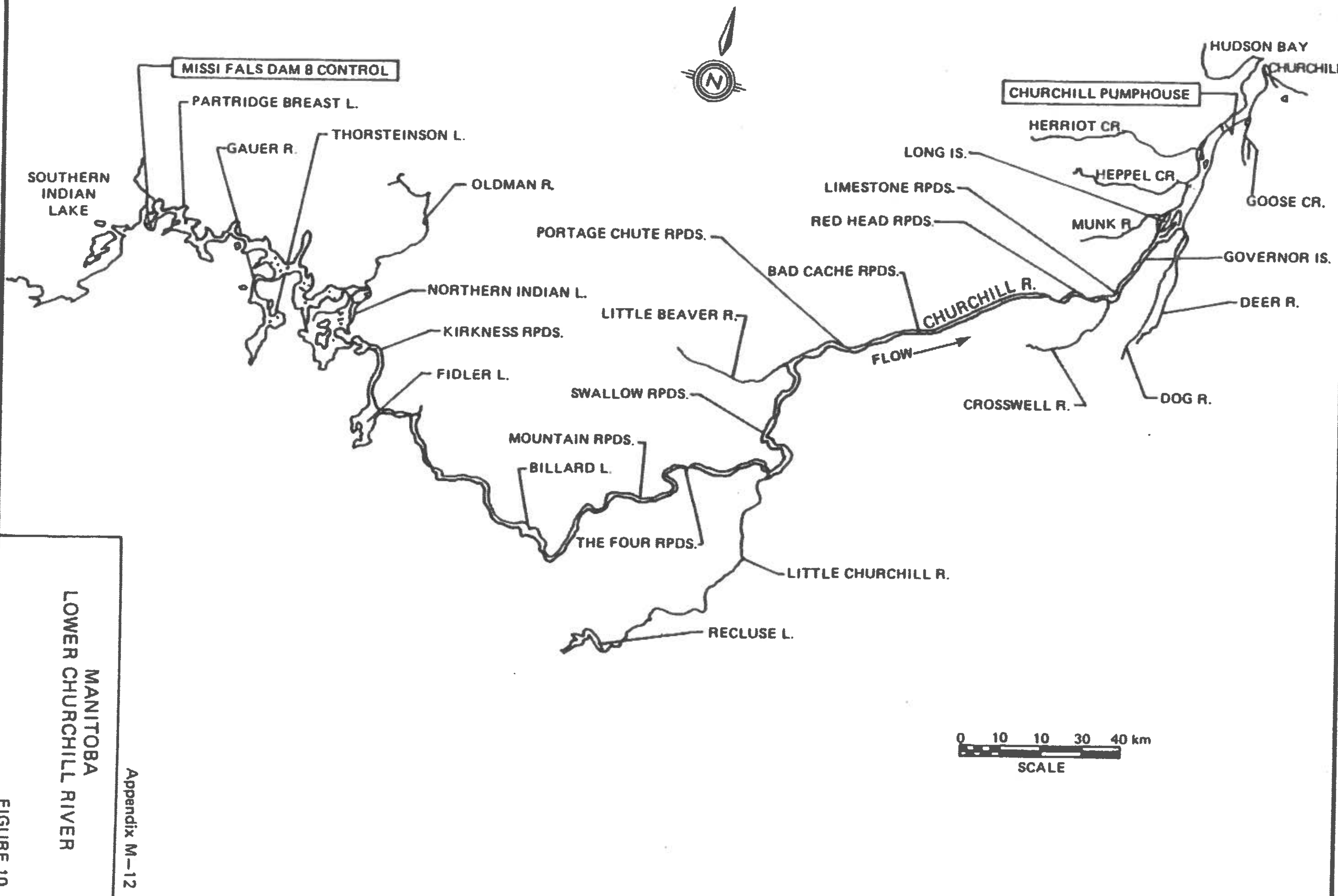
Mitigation Cost/Values

To date, millions of dollars have been spent to relocate the water supply sufficiently upstream that there would be no salt water intrusion from Hudson Bay and that the intake could be located in a natural depression where it would not be affected by ice. There are annual costs related to the additional expense of operating the new pumphouse, intake line, supply line and access road. The works and services provided to date will not function without successful implementation of one of the solutions discussed above.



APPENDIX M–12 TO 15
FIGURE 9

MANITOBA
GENERATING STATIONS
& CONTROL STRUCTURES



Appendix M–12

MANITOBA
LOWER CHURCHILL RIVER

FIGURE 10

APPENDIX M-13

B. **BURNTWOOD RIVER** - Latitude 55° 45' Freeze-Up Series

Ice Regime (Figure 11)

Interbasin diversion has increased flow at freeze-up from 85 cms to about 1 000 cms. River is narrow and, velocities now in excess of 1.0 m per second.

Problem

Ice covers are not able to form over several reaches. Ice accumulations up to 9.0 m thick occur with staging of up to 5 m. This is a problem only at one populated location near the City of Thompson where a bridge, two water supply pumphouses, and several river-based facilities would be endangered if corrective measures were not taken.

Causes

The addition of diversion flows to the waterway has resulted in velocities in excess of those that would allow ice covers to form.

Solution

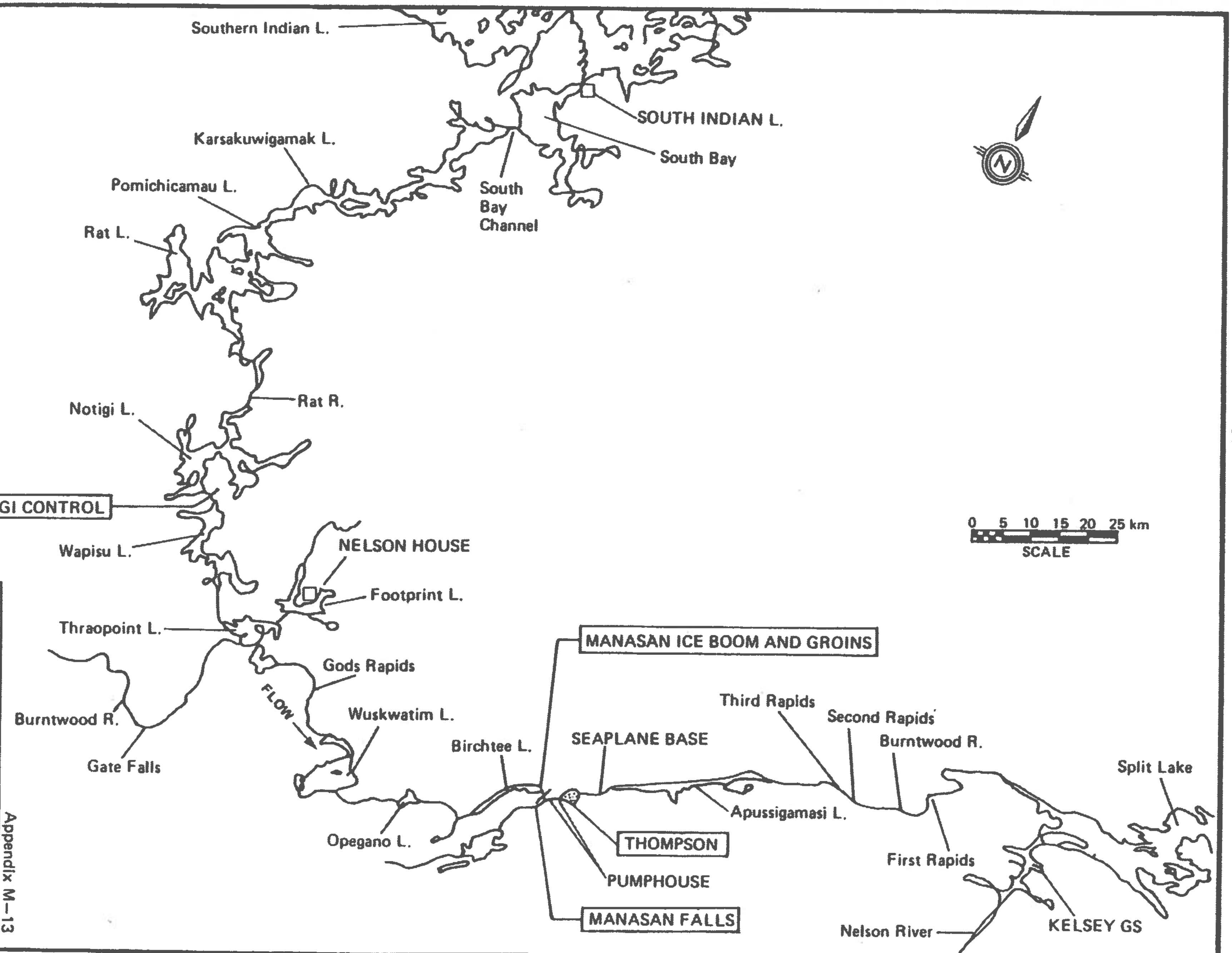
Rock groins were placed above Manasan Falls at the downstream end of the ice generating reach. An ice boom was placed upstream of the rock groins. Velocities at the boom location are reduced by the backwater effect from the groins to the point where the ice boom becomes effective in retaining floating ice and the ice cover progresses upstream.

Effects on Power Production

The inclusion of the groins and ice boom enable winter diversion of an additional 500 to 700 cms down the Burntwood without serious ice effects and staging at the City of Thompson. The resulting additional generation is about 500,000 MWh annually. It must be remembered, however, that the cost of the groins and ice boom is still very small compared to the total cost of diversion which enables extra generation of about 3 500 000 MWh annually.

Mitigation Cost/Values

The alternative to solving the ice problem would have been to provide an alternate water supply for the city, relocate the bridge and highway and provide upgraded shoreline services at a cost of tens of millions of dollars more than the cost of the ice control structures.



Appendix M–13

MANITOBA
CHURCHILL RIVER DIVISION

FIGURE 11

APPENDIX M-14

C. NELSON RIVER AT JENPEG - Latitude 54° 30' Freeze-Up Series

Ice Regime (Figure 12)

Short shallow intake channel at low and variable head plant (4 m to 12 m). Velocities in excess of 1.2 m per second. Ice generating reach with velocities of about 0.9 m per second upstream.

Problem

During freeze-up small pieces of floating ice and frazil ice pass through the trashracks and precipitate upward into the intake and tailrace stoplog wells. This ice consolidates in place and in the event of unit outage prevents the placement of stoplogs until it is removed. As freeze-up progresses, the frazil ice in the upstream channel forms pans that accumulate on the trash racks creating head differentials and reducing cooling water pressure. This derates the plant for most of the winter and occasionally causes unit or total plant shutdowns.

Causes

Low head plants, such as Jenpeg, make it easy for floating ice to be drawn into the intakes. Stoplogs were used as a cost saving measure instead of head gates in heated housings.

Solutions

Normally the stoplog wells are heated to unconsolidate the ice, which is then removed by clamming on an "as required" basis. A special clam bucket was designed and built for this purpose.

We have undertaken an ice formation flow cutback operation that effectively reduced the amount of ice accumulation by promoting a complete ice cover on the ice generating reach upstream. This was considered only marginally successful because of the timing of flow reduction and the amount of cutback required.

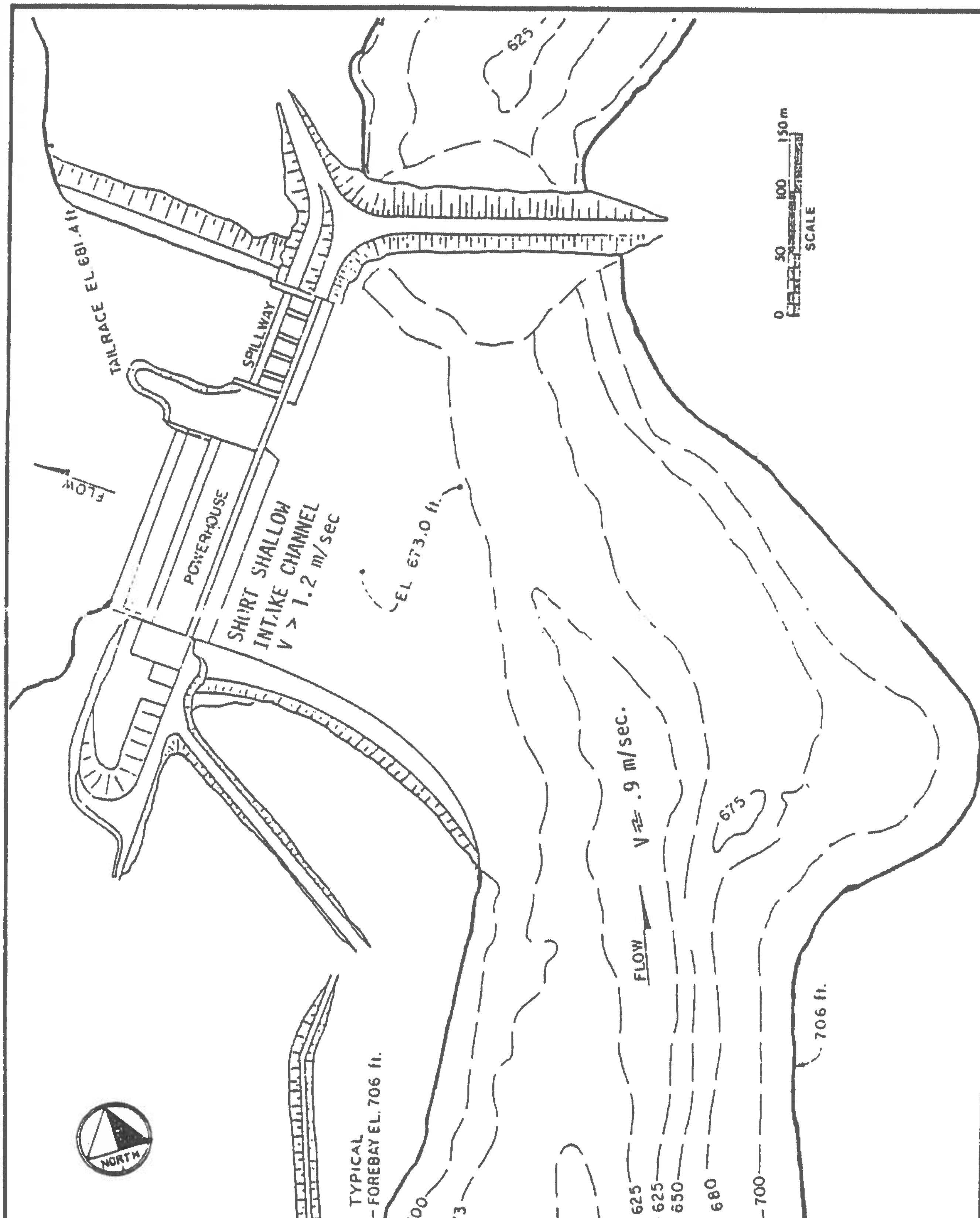
An ice boom is being pursued as a solution to the trashrack blockage and cooling water problem. This may help reduce the ice accumulation in the stoplog wells, although some flow cutback will also be required to assist the ice boom in collecting the "early ice."

Loss of Output

In November of 1986 a unit outage was extended for an additional five days because of the stoplog well ice problem. The loss was about 2 400 MWh. The intake blockage reduces output by 50 000 to 100 000 MWh annually.

Mitigation Costs/Benefits

The ice formation "cutback" solution causes downstream water and ice level fluctuations at a time of year when trappers, fishermen and other residents of downstream communities just begin using the ice. The disruption of the ice cover is a serious problem in some years and settlements are pending.



Appendix M-14

MANITOBA
JENPEG FOREBAY

FIGURE 12

APPENDIX M-15

D. LAKE WINNIPEG OUTLET CHANNELS - Latitude 54° 25' Freeze-Up and Ice Covered Series

Ice Regime (Figure 13)

Natural and man made channels with velocities in excess of 1.1 m per second over long reaches. Complex network of lakes and channels. Control structure is located 130 water km downstream of the reservoir.

Problem

Hanging ice dams form at critical locations. They restrict the winter flow capacity of the Lake Winnipeg Regulation project, the object of which is to store water during the low load summer period and increase winter flows for premium generation at large plants hundreds of kilometers downstream.

Causes

The high outflows required during the winter do not permit ice covers to form over critical reaches.

Solutions

An ice formation flow cutback operation has been implemented on four occasions with varying degrees of success. Unfortunately the "cutback" must be undertaken at a time when maximum flows are required for generation. Strategically located ice booms have been proposed as a measure to reduce the amount of cutback required. The intention is to locate two or more booms upstream of short fast water sections in order to promote ice cover development in the long moderately fast reaches upstream. Some amount of cutback would still be required to assist the booms during the freeze-up period.

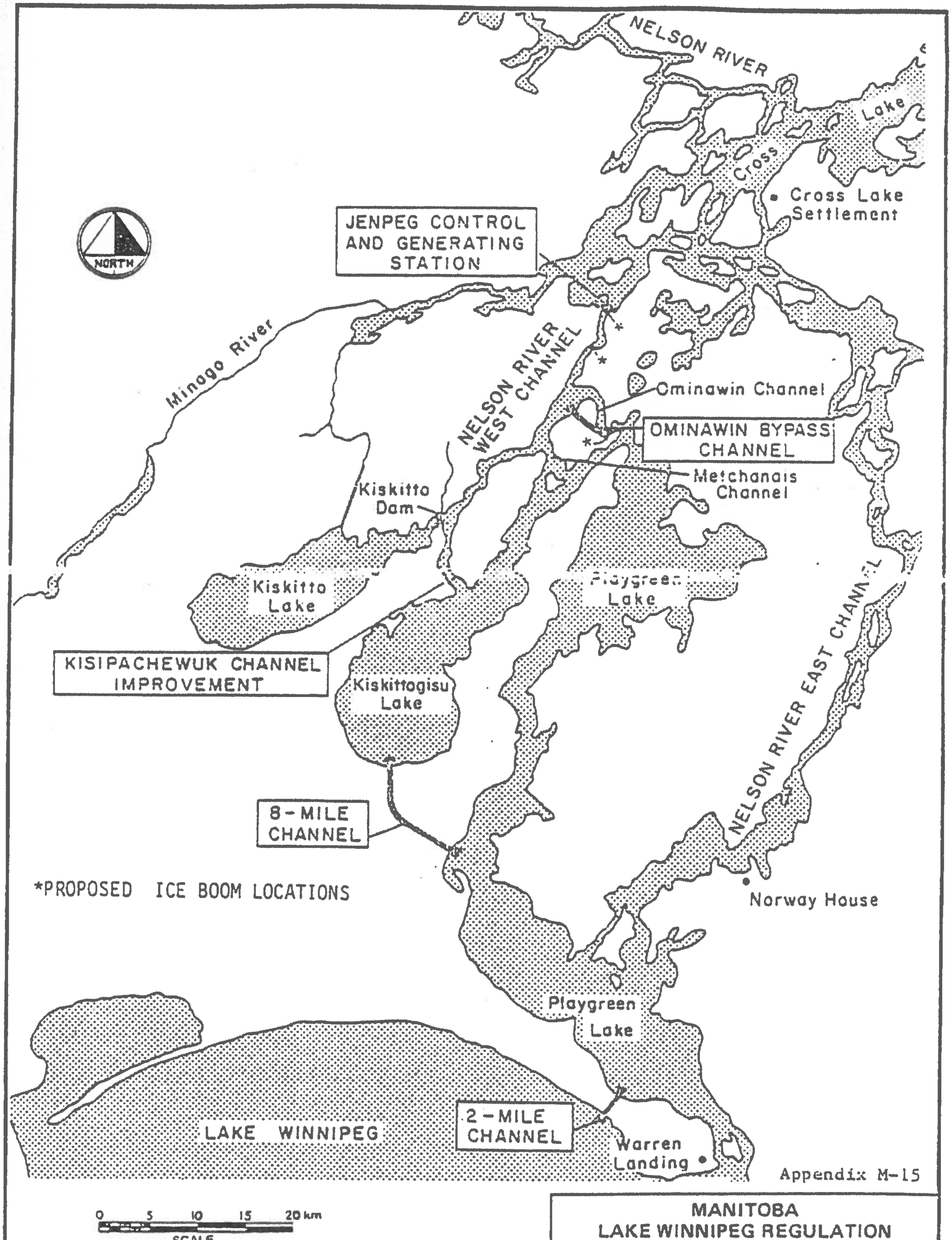
Loss of Output

With no special measures	150 000 to 300 000 MWh
With ice formation cutback	50 000 to 100 000 MWh
With ice booms and minor cutback	Minimum Loss

Mitigation Costs/Benefits

The "cutback" which helps form upstream ice covers causes appreciable fluctuations in level in the downstream areas. The main problem is the disturbance of the ice covers in downstream reaches and the resulting effect on fishing, trapping, transportation on the ice and other ice-related activities in the affected native communities. The implementation of ice booms will minimize the amount of "cutback" required and thereby reduce mitigation costs.

The cost of ice-related mitigation claims has been small to date, but expensive settlements are being sought and relations with the communities are not improving as they should



MANITOBA
LAKE WINNIPEG REGULATION
OUTLET LAKES AND CHANNELS

FIGURE 13

APPENDIX 0-16

NIAGARA - Latitude 42°N Open Water

Problems

Frazil and pan ice, anchor ice and wind effects may each decrease the flows available for power by from 10 to 25 percent and last for eight to 48 hours.

Causes

Weather variability and economics combined their influences to dictate that this system would have to operate with no ice cover. There is an open water area 1.6 km wide by 30 km long with a fast water section about 3 km long at the upstream end. (Figure 14).

Frazil is generated in huge quantities which evolve into pans 4 cm thick by 100 m in diameter as they proceed downstream. To keep all this ice moving downstream without entering the intake to the generation station, diversions for power may have to be reduced by 10 percent, to increase the ice discharge capacity.

Due to the shallow depths and turbulent mixing, large quantities of the frazil attach themselves to the bottom and become anchor ice. The reduction in flow develops in as little as three hours and can amount to 25 percent.

Strong easterly winds may depress the lake level at the entrance to the river by as much as 70 cm and reduce the outflow by up to 25 percent. While this may occur at any time of the year, its effect is most serious in winter.

Effects on Power Production

Based on an average winter flow of 5600 cms the power reductions can amount to 400 MW for frazil, and 1000 MW for anchor ice and wind effects respectively. Fortunately, the combined effects do not all occur simultaneously, but have been as high as 1 200 MW.

Solutions

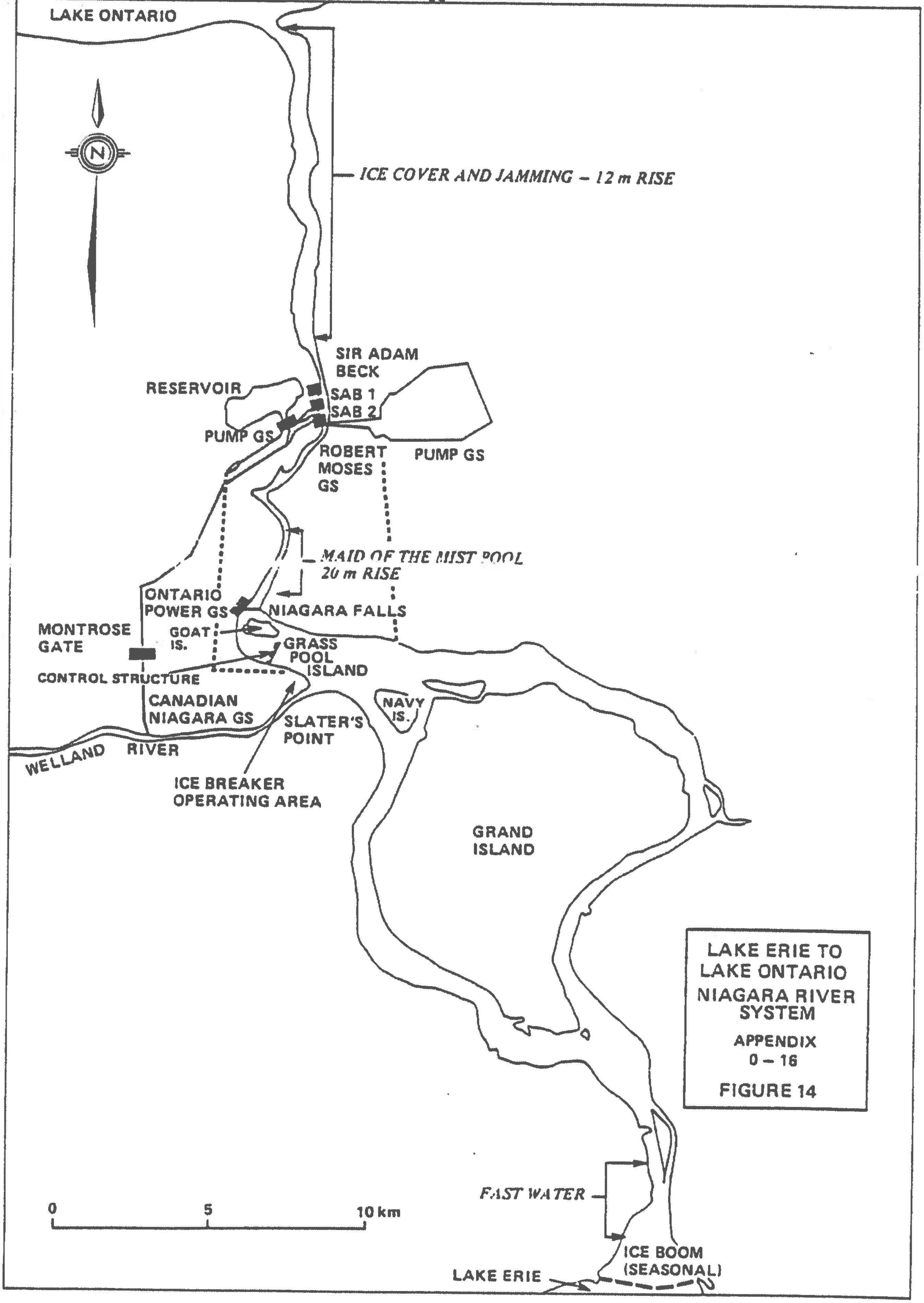
Frazil and pan ice may be kept moving past the intakes using ice breaking boats, thereby decreasing the amount of reduction in diversion. (Figure 14).

Anchor ice and wind effects can be offset by using the pump-storage reservoirs to augment flows and power production while the river flows are reduced.

<u>Mitigation Costs or Values</u>

The value of the power savings is enough to buy two new ice breakers each year.

To offset a 1 200 MW reduction, the replacement energy would cost at least $24,000 per hour and could be double this amount. Over the peak periods the $1,000/MW capacity charge would have to be added.



LAKE ONTARIO
N
ICE COVER AND JAMMING – 12 m RISE
SIR ADAM BECK
RESERVOIR
SAB 1
SAB 2
PUMP GS
ROBERT MOSES GS
PUMP GS
MAID OF THE MIST POOL 20 m RISE
ONTARIO POWER GS
NIAGARA FALLS
MONTROSE GATE
GOAT IS.
GRASS POOL ISLAND
CONTROL STRUCTURE
CANADIAN NIAGARA GS
NAVY IS.
SLATER'S POINT
WELLAND RIVER
ICE BREAKER OPERATING AREA
GRAND ISLAND
LAKE ERIE TO LAKE ONTARIO NIAGARA RIVER SYSTEM
APPENDIX 0 – 16
FIGURE 14
FAST WATER
0
5
10 km
ICE BOOM (SEASONAL)
LAKE ERIE

APPENDIX 0-17

BREAK-UP - NIAGARA RIVER, Lat 42°N, Break-Up Series

Problem

Tailwater levels rise due to ice jams by amounts ranging from 12 to 20 meters, and may occur in any month after Lake Erie reaches freezing temperature, and continue until the lake is clear of ice in the spring.

Causes

Winds of 30 km/h or more from the southwest may break the ice cover in Lake Erie, causing a rapid increase in flow and force large quantities of ice into the river. Ice thickness and quantity, augmented by high flows, may overload the river causing jams in shallow areas or narrow gorges.

Solutions

River channels were widened and deepened, but remain limited in depth to 3 m. The rate of incoming ice has been reduced by an ice boom between Buffalo and Fort Erie which also encourages the formation of an ice arch across the entrance to the river.

Diversions of water reduce flows through the Maid-of-the-Mist Pool below the falls and help reduce the 20 metre rises. (Figure 14).

Ice-breaking boats are used to break jams upstream of the Falls, and between Queenston and Lake Ontario where jams causing a 12 m rise have occurred in the past. (Figure 14).

Loss of Output

Ranges from 500 to 1 000 MW.

Mitigation Costs/Benefits

Power losses may amount to several million dollars. Ice breaking boats and the ice boom have reduced the losses enough to pay for themselves annually.

APPENDIX 0-18

ST. LAWRENCE RIVER - International Rapids Section, Freeze-Up Series
- Latitude 45°N

Ice Regime

Freeze-up takes place in the first week of January, plus or minus 3 weeks depending on the climate. Winter temperatures range from -10° to -20°C and occasionally to -40°C. Water leaving Lake Ontario (Figure 15A) is progressively chilled in its 160 km route to the powerhouses, and large ice pans are created. River widths of 1 to 2 km and depths of 10 m or more are typical. Channels were enlarged (Figure 15B) to form an ice cover with velocities of 0.7 m/s with one exception.

Problem

About 18 km of the river between Prescott and Cardinal needs help in forming and ice cover (see Figure 15C). This area is large enough to create a major hanging dam unless the open water reach can be reduced to 8 km or less. A hanging dam still forms, 10 m deep by 300 m long, but the ice production capacity is limited to that which the river can accommodate.

Causes

Velocities up to 1 m/s occur in the 8 km reach. Frazil generated in the open water, slush from heavy snowfalls, and pan ice during the ice cover formation period all contribute to the hanging dam.

Solutions

Use ice booms to assist in the rapid formation and retention of an ice cover, and to keep ice out of the hanging dam area.

Control velocities by flow reductions when ice forming conditions are unfavourable.

Effects on Power Production

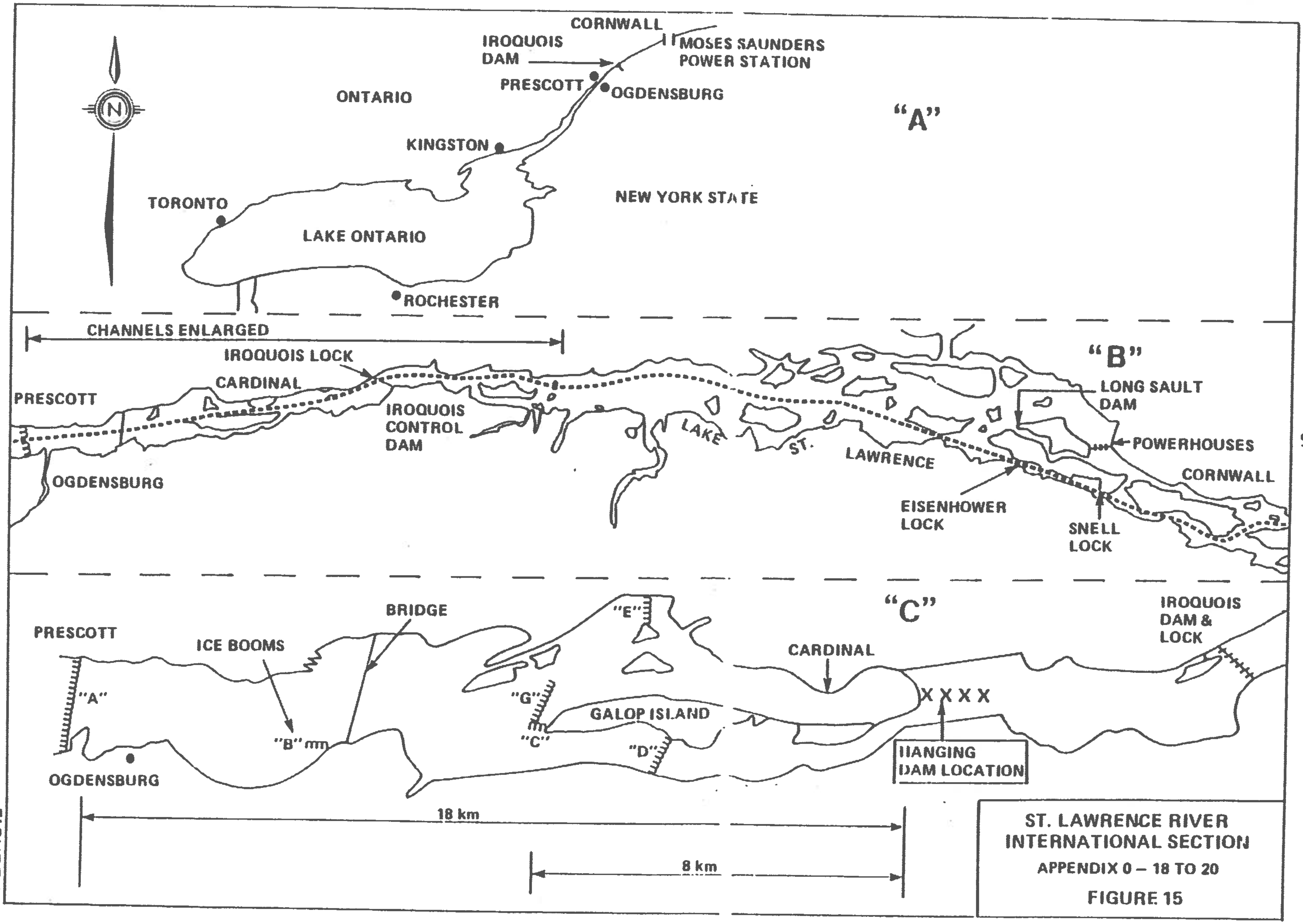
Prior to the ice booms, winter flows were curtailed by up to 44 000 cfs and power production by 6 300 MWh/day for a period of 30 days.

Since the ice booms were installed the adverse effects have been reduced by about 90%.

Mitigation Costs/Benefits

If the ice booms had not been successful the river channel would have required an excavation amounting to about 20 million cubic yards of material to get ice cover forming velocities.

Prior to the power project, the city of Cornwall used to experience flooding due to water level rises of up to 15 m. These events have been eliminated.



ST. LAWRENCE RIVER
INTERNATIONAL SECTION
APPENDIX 0 – 18 TO 20
FIGURE 15

FIGURE 15

APPENDIX 0-19

SNOW - St. Lawrence River, International Section (Latitude 45°N) Freeze-Up Series.

Problem

Thirty kilometres of ice cover over one metre in thickness decreased the water carrying capacity of the river, and the operating head on the plant.

Causes

Thirty centimeters of snow fell at a time when the open water was beginning to freeze due to -10°C temperatures and 30 kph winds. Immense quantities of slush formed, but no pan ice due to the wind and waves. Long areas that normally formed ice cover with thickness of 30 cm had over 100 cm instead, ie, from Prescott to Morrisburg (Figure 15B).

Solution

A flow reduction to assist in ice cover formation is the operating technique available, however, to make slush form a cover the reduction must be much greater than for the packing of pan ice. More than 24 hours are required for a flow reduction to be effective in the problem area necessitating the pre-scheduling of such emergencies.

Loss of Output

About five percent of the output of the generating station was unavailable for over two months because of the loss of head at the plant. This amounted to 79,000 MWh at a cost of at least 1 million dollars.

Mitigation Measures

Until the ice cover has formed, weather forecasts involving heavy snowfall, combined with near freezing water temperatures require flow reductions in advance of the anticipated problem.

APPENDIX 0-20

ST. LAWRENCE RIVER - International Section, Ice Covered Series
- Latitude 45°N

Problem

There is a decrease in the power output of the plant in winter compared to the open water situation (Figure 15B).

Causes

Ice cover causes the tailwater level to rise and the headwater level to fall, thus decreasing the operating head on the plant.

Solutions

After the ice cover has formed, flows may be increased sufficiently that the apparent loss can be eliminated and a benefit obtained.

Effects on Power Production

Ice cover formation reduces the operating head by about 5 percent equivalent to 70 MW. After ice cover formation flows may be increased to suit demands by up to 30% equivalent to 400 MW.

Mitigation Cost/Values

The net gain of 330 MW is worth from $6,500 to $13,000/hour for the energy a $1,000 per MW/ for peak.

APPENDIX 0-21

MADAWASKA RIVER - Latitude 46°N, Ice Covered Series
- Stewartville to Arnprior

Ice Regime

Freeze-up in December with generally stable winter weather in the -10° to -30°C range.

Problem

An existing river system, with three generating stations in series was to have its winter output expanded by adding units for peaking purposes. The problem was to decide how great a flow the ice cover could withstand without causing flooding, or restricting flows for power purposes.

Causes

Fluctuations in water level of up to 2 m were likely and there were signs that the existing operation was creating ice lumps up to 10 m deep, 13 km downstream of Stewartville Generating Station (Figure 16). Ice ridges at the end of a long rapids indicated substantial blockage of incoming flows which might prevent sustained outputs from the plants downstream.

Solutions

Test the existing system, using the spillways to simulate the extra flows from enlarged generating stations. Increase the test flows each day by 50% of the previous winter maximum up to the limit of the hydraulic storage available. Inspect the ice cover by helicopter and shore observations to observe behaviour and any tendency to disintegrate so tests could be stopped. In fact, the ice cover remained essentially intact with water levels of up to 2 m higher, except where the rate of change of water level exceeded 1 metre in less than 1 hour, ie, within 1 km of the generating stations.

Effects on Power Production

Peak capacity of the river system could be expanded by a factor of 3 and could be sustained for 6 hours or more to permit starting of alternative thermal generating sources. Such flows were seven times the dependable December winter flow used for plant design.

Flows from upstream storage took roughly twice as long to refill the forebays compared to open water operations.

Mitigation/Costs

Water level fluctuations during the non-winter season caused bank stability problems (slumping) and another generating station (Arnprior) was constructed downstream of Stewartville to eliminate these problems.

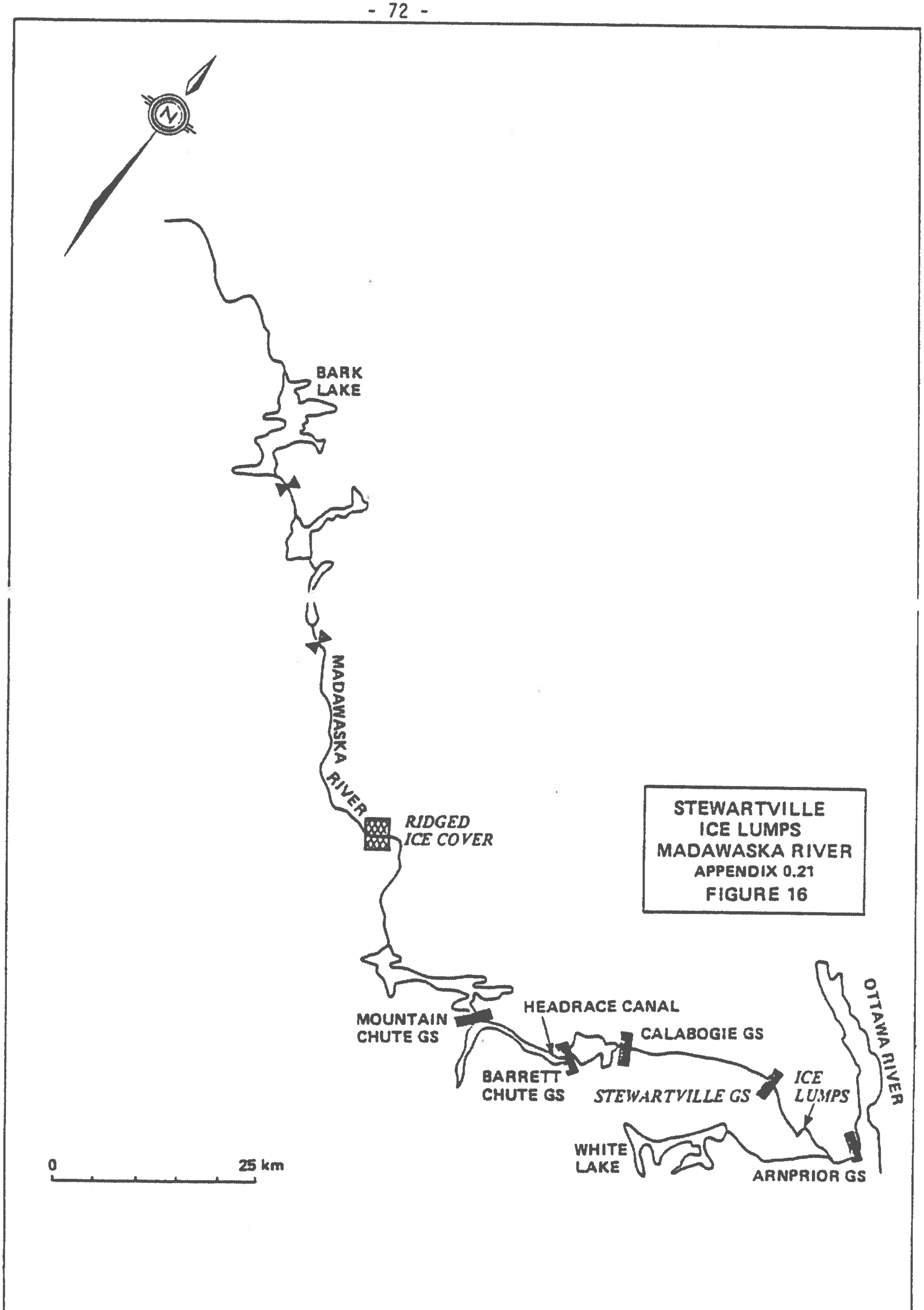

N
BARK LAKE
MADAWASKA RIVER
RIDGED ICE COVER
STEWARTVILLE
ICE LUMPS
MADAWASKA RIVER
APPENDIX 0.21
FIGURE 16
OTTAWA RIVER
HEADRACE CANAL
MOUNTAIN CHUTE GS
CALABOGIE GS
BARRETT CHUTE GS
STEWARTVILLE GS
ICE LUMPS
WHITE LAKE
ARNPRIOR GS
0
25 km

FIGURE 16

APPENDIX O-22

MADAWASKA RIVER - Barrett Chute Generation Station (Figure 16), Ice Covered Series

- Latitude 46°N

Ice Regime

Freeze up in early December with a generally constant winter weather in the -10° to -30°C range.

Problem

Expansion of the existing plant by a factor of 3 times resulted in intermittent plant operations of a few hours per day and generally only 5 days per week. Ice covers up to 10 cm thick would form on the 610 m long by 12 m wide headrace canal after a 2-day shutdown. Total disintegration of the ice cover would occur when the plant started up due to rapid changes in water level and velocity. Up to 720 cubic metres of ice had to be discharged from the headrace canal. (Figure 16).

Solutions

Remove the top sections of the trash racks to pass the ice through the turbines.

Deepen the canal to reduce the headrace velocity.

Install an air bubbler along the centre line of the canal and close to the bottom.

Effects of Power Production

Plant capacity was increased from 42 MW to 178 MW. Water surges in the headrace canal limit the rate at which the plant may be loaded to 20 minutes but this is of course much faster than the 6 hours required for a fossil-fixed thermal unit.

Mitigation/Costs

The air bubbler effectively reduced the amount of ice required to be discharged through the plant by about 80% at very little cost for operation and installation.

APPENDIX O-23

FRAZIL - Mississagi River - Northern Ontario (Latitude 47°N), Freeze-Up Series

Problem

A provincial highway flooded downstream of a generating station (Figure 17). The event occurred about breakfast time when the station was not operating and had been shut down some eight hours earlier.

Causes

Winter temperatures between -15°C and -40°C, and 30 km of almost continuous rapids, combined to create immense quantities of frazil and anchor ice. The frazil was packed against and underneath an ice cover extending upstream from another generating station, and flooded first one rapids and then another, working slowly upstream. The station was designed to produce energy for both peak loads and operating reserves. Periods of high flow and no flow were anticipated. The high flows amounted to five times the dependable winter flow under natural conditions.

Solution

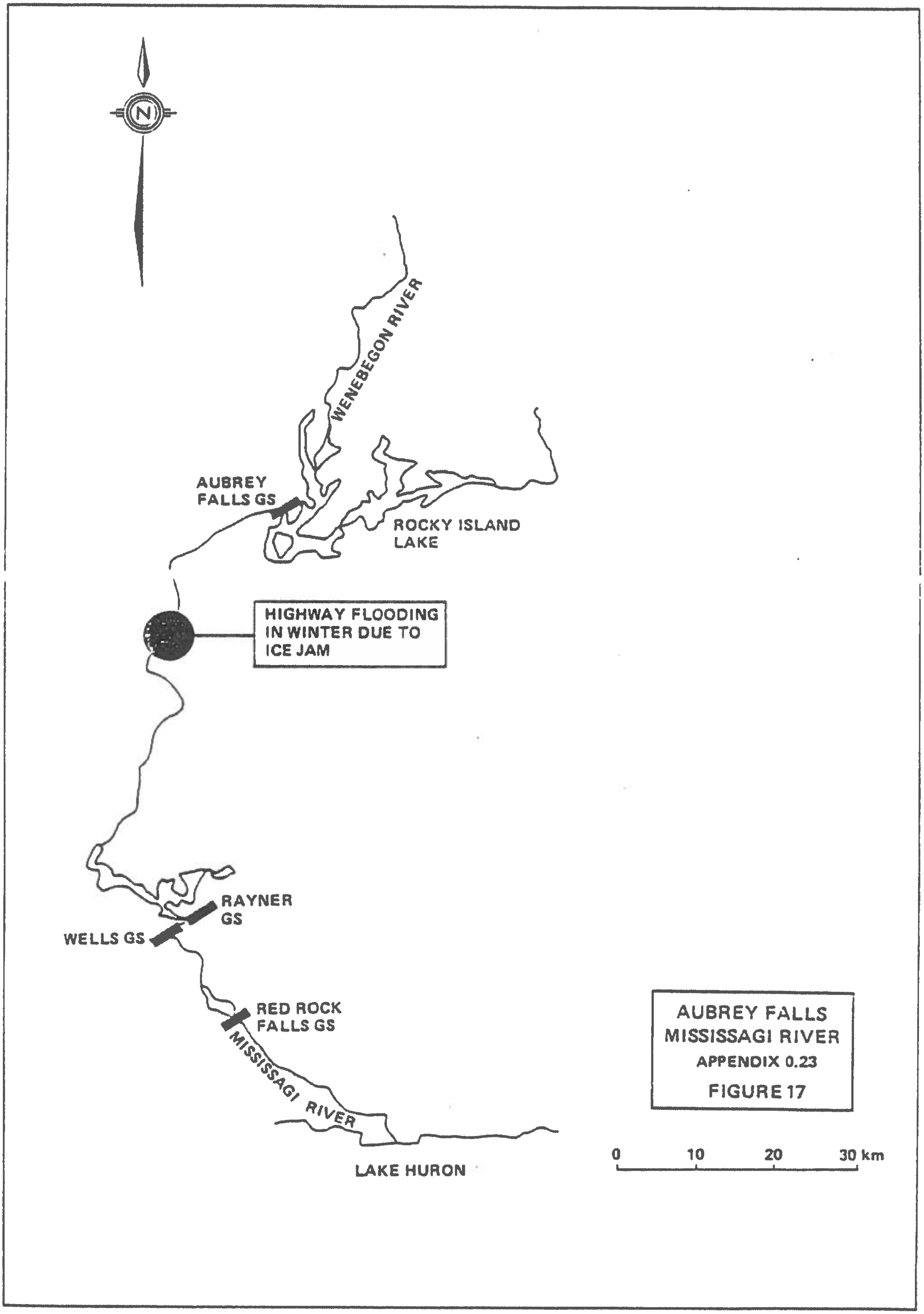
When the station stopped generating, the river level subsided almost to the bottom, well below the flood level. There was then enough space to permit two hours of operation at maximum output without causing flooding. This cycle could be repeated provided the shut down period was at least five hours. It therefore became possible to obtain the benefits of the peak and operating reserve capacity by this "interval operating" technique.

Loss of Output

Potentially, one half the peak output of 160 MW was affected, but in fact became zero due to the operating techniques.

Mitigation

Some of the lowest sections of the highway were raised at a cost of $100,000, however, the operating technique made it unnecessary to do a longer stretch of the highway, at considerably greater cost.



AUBREY FALLS
MISSISSAGI RIVER
APPENDIX 0.23
FIGURE 17

APPENDIX Q-24

ST. LAWRENCE RIVER - Quebec Section, Freeze-Up Series
- Beauharnois Canal (Figure 18)
- Latitude 45°N

Ice Regime

Ice cover formation usually begins about December 21 but may vary by ±3 weeks depending on the climate. The powerhouse is located at the end of a 25 km headrace canal, having a width of 1 km, a depth of 9 m, and a flat bed slope of only 1.3 m in 25 km. Winter temperatures are in the -10° to -30°C range and snowfalls total 3 to 4 metres.

Problems

Vast amounts of frazil, slush ice and thin cake ice are created in the canal which clog trash racks and produce hanging dam conditions as ice cover forms on the headrace canal. Ice cover formation is hindered by bridge piers breaking the thin cake ice, and by shipping passing through the canal which forms a part of the St. Lawrence Seaway.

Solutions

Velocities in the canal were reduced by widening and deepening over a 6 1/2 km length, adding 650 m^2 of area, an increase equivalent to 7 1/2 percent of the total area.

Upper sections of the trash racks were removed in winter to pass frazil and slush through the turbines.

Ice booms were installed at a number of locations (Figure 18) to accelerate the rate at which ice cover forms on the canal, and to stabilize this cover when broken by ship movements. Load measuring devices were installed on the boom nearest the headworks as an indicator of accumulating ice pressures.

Ice breakers are used to clear ice from the immediate powerhouse area, and also at the Lake St. Francis end of the headrace. As much as 2 km^2/day of ice cakes are broken off the lake ice to assist in ice cover formation in the canal. Flow reductions are also required, coordinated with ice breaking, to ensure the formation of a smooth ice cover. One to five days may be required for the process depending on the weather.

Effects on Power Production

Heavy snows coinciding with ice cover formation may require flow reductions of 15 to 20% for a day but are preferable to a thick ice cover lasting several months.

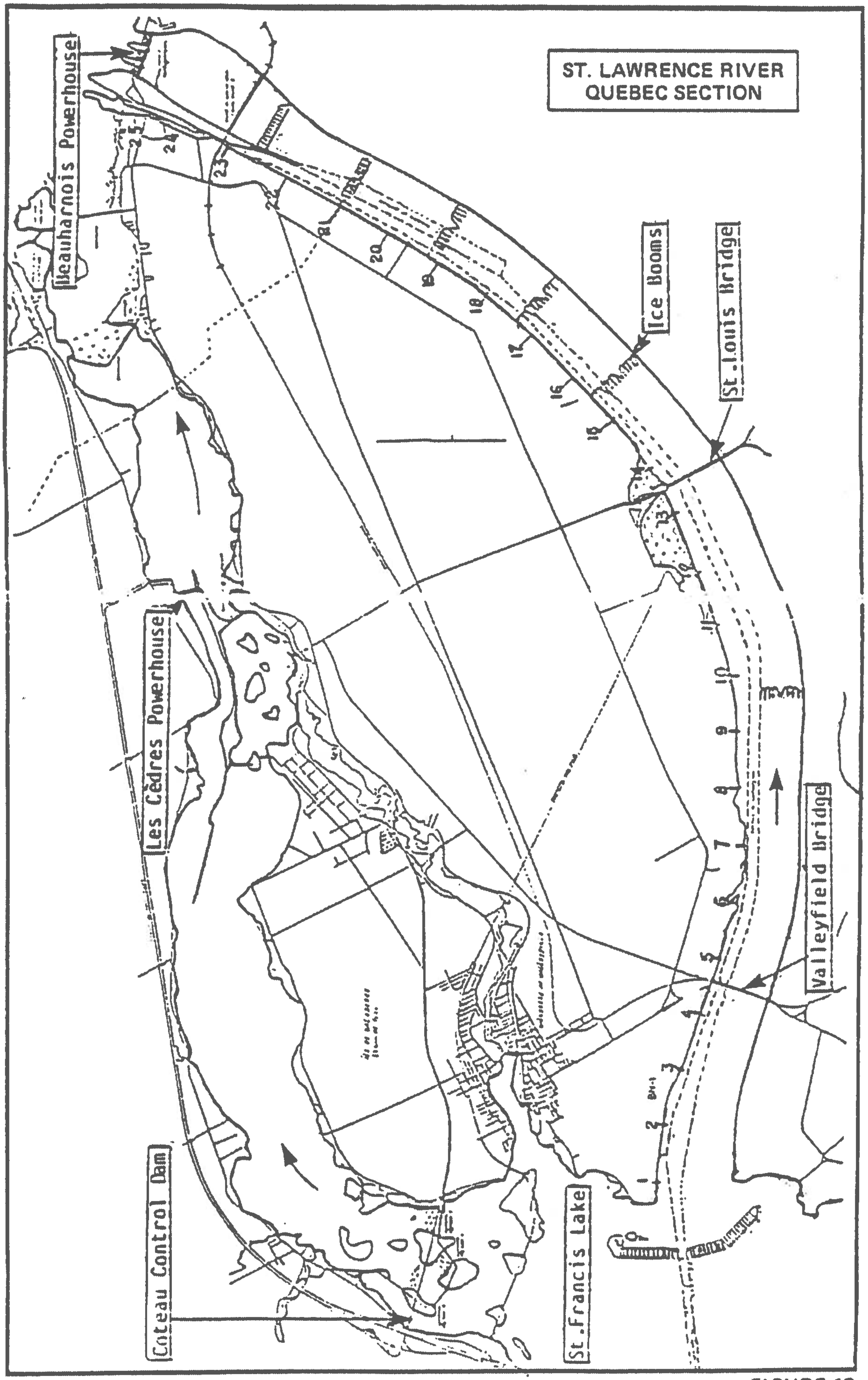
Ships passing through the ice cover as it is forming cause ridging and thickening and flows must be reduced by about 22% to maintain the same load on the ice booms as existed prior to the ship movement. This is equivalent to a power reduction of about 300 MW.

After ice cover formation, the flow is gradually increased as the roughness is eroded, and 250 MW more output is achieved now than was possible 25 years ago.

A short reduction of a few days during ice cover formation is more than offset by substantially higher outputs in the succeeding months.

<u>Mitigation/Costs</u>

Ice booms, ice breaking boats and channel excavations have all been required at considerable expense, however, the benefits were enough to offset these costs.



APPENDIX Q–24
FIGURE 18

FIGURE 18

APPENDIX Q-25

RIVIERE DES PRAIRIES - Montreal Island, North Side, Freeze-Up Series,
- Latitude 45°N

Ice Regime

Fast water areas upstream of the generating station (see (1) on Figure 19) produce frazil and cake ice in quantity, especially during the early winter when flows are high. As winter progresses the flows decline and the cover advances under the influence of temperatures in the -10° to -30°C range. Heavy snows in the open water areas may create large amounts of slush ice.

Problems

Ice cover forms rapidly between the powerhouse and Perry Island ((4) and (10) on Figure 19), but high velocities in this region cause a hanging dam to form, with consequent rising water levels and flooding.

Downstream of the powerhouse ice passed through the ice sluices tends to jam and flood the powerhouse.

Solutions

An ice breaker is used to keep a channel open through the critical area and ice passes downstream and through the ice sluices provided at the generating station.

As river flows decrease a natural ice cover forms over much of the fast water areas between Perry Island and White Horse rapids. This reduces the ice producing open water area and also stores ice coming in from upstream. When this happens the ice sluices are closed and all the flow passes through the powerhouse.

Ice booms are used to help form ice covers sooner, one where the natural ice cover eventually forms, and the other in the south channel around Bizard Island.

Effect on Power Production

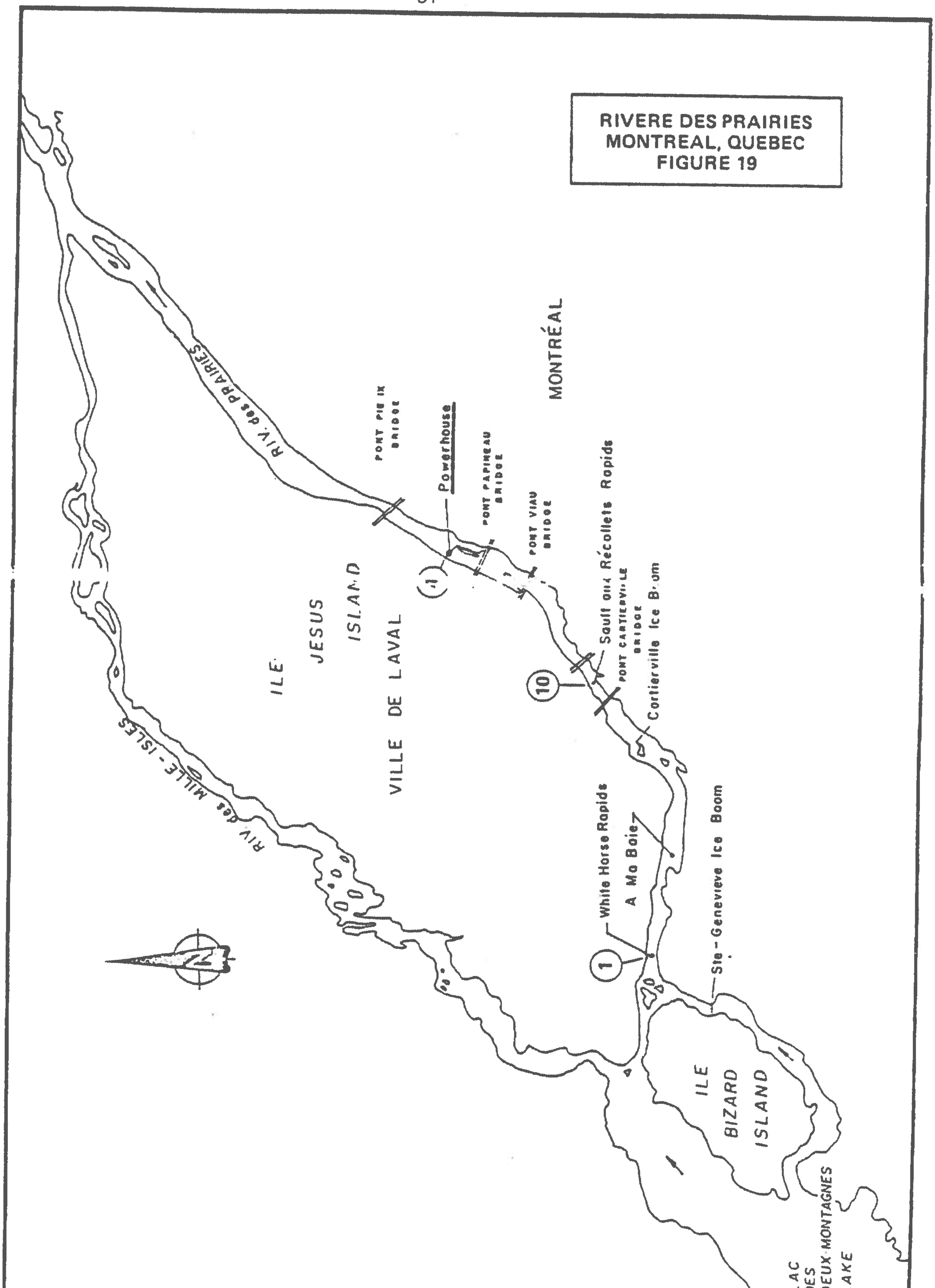
Losses in generation due to head reductions and to spilling have amounted to 50 MW.

Downstream backup of the tailwater levels in the past caused complete loss of generation due to flooding in the powerhouse.

Mitigation/Costs

Powerhouse was flooded and shut down. Costs of rehabiliation were not available.

Ice breaker required to prevent hanging dam, and ice sluices required to pass ice use considerable water which would otherwise be available for power. Ice booms added to reduce the costs.



RIVERE DES PRAIRIES
MONTREAL, QUEBEC
FIGURE 19

FIGURE 19