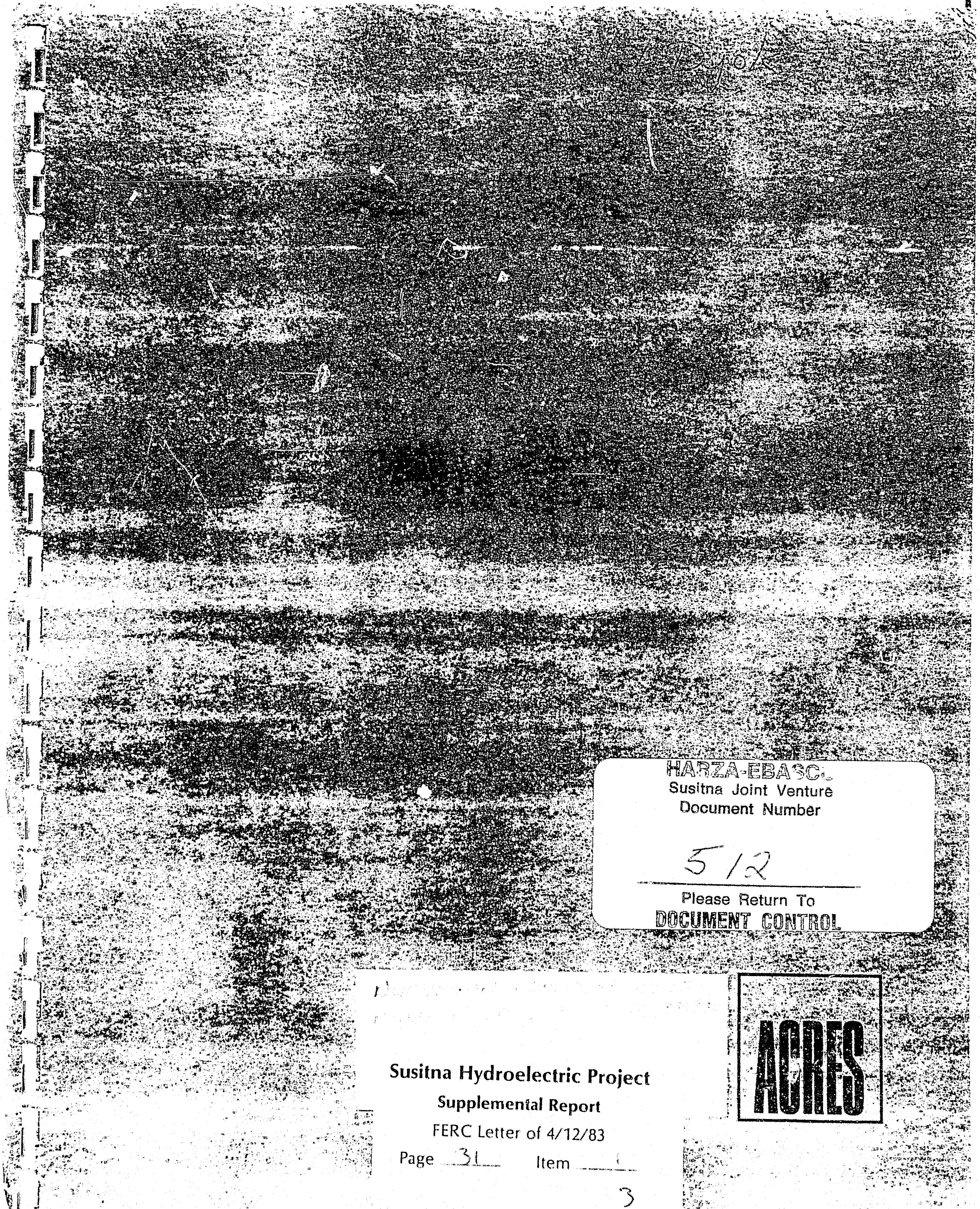

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Supplemental Report

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July 30, 1980
P5645.00

Mr J Yu
Energy Resources Conservation Board
603 - 6th Avenue SW
Calgary, Alberta
T2P 0T4

Dear Mr Yu

Dunvegan Power Project
Peace River Ice Study

It is with pleasure that we present the above report to the Energy Resources Conservation Board.

We found this study to be particularly interesting and challenging. The results of the study have indicated that for all intents and purposes the Dunvegan Project will be able to operate at any time at its full 1000 MW capacity. However, for a one to two week period in some years, the plant will be limited to a maximum of 920 MW while the ice cover forms and strengthens at the town of Peace River. It is not anticipated that any major impacts related to ice will be realized along the river below the project other than the loss of the ice bridge at the Shaftesbury Ferry site.

We would like to take this opportunity to thank you and Mr J Cockroft for the valuable cooperation given Acres during the course of the study and in particular during the preparation of this final report. If we can be of any further assistance, please do not hesitate to contact us.

Yours sincerely

R Bruce Elson, P Eng

RBE:BS
Encs

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ACKNOWLEDGEMENT

Acres wishes to acknowledge the cooperation and assistance of the staff of the Energy Resources Conservation Board, Alberta Environment, Water Survey of Canada, the Alberta Research Council, and the British Columbia Hydro and Power Authority in the execution of this study.

GLOSSARY OF ABBREVIATIONS

m	metres
m^3/s	cubic metres per second
km	kilometres
km^2	square kilometres
MW	megawatts
GW.h	millions of kilowatt-hours
el	elevation

SUMMARY

This study was done to determine whether unrestricted operation of a 1000 MW Dunvegan hydroelectric development in the winter period would cause ice-induced flooding problems downstream, particularly at the town of Peace River.

To conservatively assess this matter, a "worst" case for plant operations has been used throughout the study. This case assumes that only 100 MW or 10 percent of the installed capacity would be operated continuously (base loaded) to provide riparian river flows with the remaining 90 percent meeting daily peaking demands. This mode of operation provides the largest daily variation in winter flows and, consequently, the greatest potential for flooding problems due to ice.

The results of the analyses indicate that there will be little or no need to restrict the operation of the Dunvegan development as summarized below:

- In "drier" years, or years of relatively low mean winter flows, the plant will be able to operate all winter at 100 percent plant capacity without any restrictions.

- In the case of a "normal" winter flow year, the plant will be able to operate at 100 percen capacity except for a very short period of 5 to 15 days during formation of the ice cover at the town of Peace River. During this period, it may be necessary to limit plant operation to 96 percent of full capacity to allow the ice cover to develop and stabilize at the town. Once the ice cover has progressed upstream of the town (above the Smoky River confluence) and consolidation and freezing of the cover has taken place, the full capacity of the plant can again be safely used.

- In "wet" years, which occur less than 20 percent of the time, it may be necessary to limit the plant operation to 92 percent of full capacity for 5 to 15 days for the same reasons as explained above.

- More than 1000 MW could be operated at Dunvegan at all times except during the 5 to 15 day critical period.

- To eliminate the restriction on the last 4 to 8 percent of capacity for 5 to 15 days, some remedial measures such as minor dyke heightening through the town of Peace River would be required.

In the study reach from Dunvegan to 20 km downstream of the town of Peace River, the only other problem would be the probable elimination of the use of an ice bridge at the Shaftesbury ferry crossing.

The study has also found that the ice cover can be expected to occur later in the year and more slowly than at present. Under normal climatic and hydrologic conditions, the river downstream of the Dunvegan project can be expected to be completely ice-covered before winter's end. High mean river flows and warm air temperatures would result in open water all winter for some distance downstream of Dunvegan, although the river in the vicinity of the town of Peace River can be expected to be ice covered. Quite unusual combinations of high mean winter flows and warm temperatures would result in open water at the town of Peace River all winter.

1 - INTRODUCTION

Concern has been expressed about the impact of a hydroelectric development at Dunvegan on the ice regime of the Peace River. In the January, 1977, report entitled "Feasibility Study, Dunvegan Hydro Power Site", the Alberta Hydro Committee concluded that ice observation and evaluation programs should be continued since insufficient data had been gathered to confidently predict the impact of plant operations on the ice regime. In the past, spring ice jams have caused flooding in portions of the town of Peace River located approximately 105 km downstream of the proposed damsite.

Concerns also exist that any potential ice problems could lead to the curtailment of plant operations. Consequently the Energy Resources Conservation Board commissioned Acres Consulting Services in November, 1979, to carry out this study to evaluate the impact of the proposed low dam development at Dunvegan on the ice regime of the Peace River.

1.1 - Scope of Study

The specific objectives of this study, as set out by the Energy Resources Conservation Board, were to:
- Review all available reports, information, and data pertinent to the study.
- Conduct a field program over the 1979-80 winter period designed to provide information and data with which to carry out necessary analyses and assessments.
- Perform analyses of the thermal and hydraulic regimes of the Peace River, taking into consideration the effects of Williston Reservoir, Peace Canyon (formerly Site 1), Site C, and Dunvegan.
- Using the analyses, determine the effect of various modes of operation of a Dunvegan power plant on the Peace River ice cover under a range of winter weather conditions and identify those conditions, if any, which would aggravate existing ice problems or create new problems.

- If the studies indicate ice problems will be created by unrestricted operation of a power plant, determine the amount and duration of curtailments of power plant operation necessary to eliminate such problems.
- As an alternative to power plant curtailment, if any, identify and determine approximate costs of the most practical means of eliminating such problems.

1.2 - Hydroelectric Development of the Peace River

1.2.1 - Existing Developments

Figure 1 outlines the course of the Peace River from its origin in north-central British Columbia to the Peace-Athabasca delta. Plate A shows the locations of the existing and potential hydro-electric sites considered in this study.

At present, the only completed hydroelectric development on the Peace River consists of the W.A.C. Bennett Dam and the G.M. Shrum Generating Station some 29 km upstream of Hudson Hope, British Columbia. This plant began operations in 1968 and will ultimately have a total installed capacity of 2730 MW. The reservoir formed by the W.A.C. Bennett Dam, called Williston Lake, contains approximately 42 billion cubic metres of live storage which provides for substantial multiyear regulation of the Peace River.

The Peace Canyon Development, located about 22 km downstream of the W.A.C. Bennett Dam, is currently under construction and will provide an additional installed capacity of 700 MW. The reservoir at this site has been impounded and first energy has been produced.

1.2.2 - Proposed Developments

Additional hydroelectric sites exist on the Peace River in British Columbia below the Peace Canyon Development. However, for the purposes of this study, only the site identified as Site C by the British Columbia Hydro and Power Authority has been incorporated in this work. Site C is about 84 km below Peace Canyon as shown on Plate A.

The proposed Dunvegan Development is located about 127 km downstream of the provincial boundary and 105 km upstream of the town of Peace River. The feasibility studies completed in 1976 proposed that the low dam power development would consist of 8 units having a totalled installed capacity of 1000 MW at a full supply level of 381 m. The reservoir formed by the dam would extend as far as the provincial boundary and have a total storage volume of 16 billion cubic metres. With reservoir drawdowns of 5 m to 10 m, the live storage volume would be in the order of about 0.40 to 0.75 billion cubic metres respectively. This corresponds to about 3 to 6 days of storage for a long term average outflow of 1469 m^3/s and no reservoir inflow.

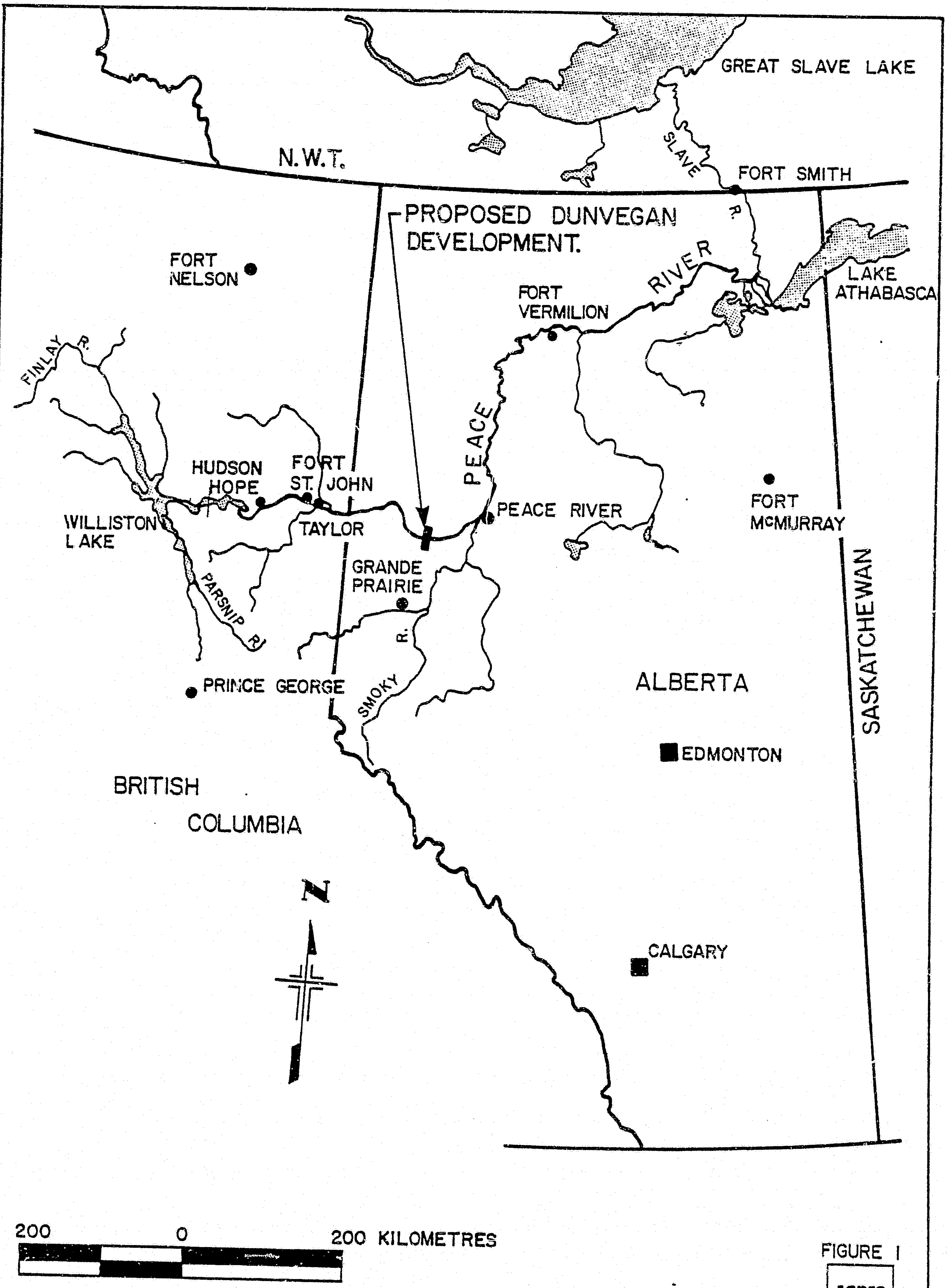

FIGURE 1

LOCATION PLAN

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2 - FIELD RECONNAISSANCE PROGRAM

2.1 - General

A reconnaissance program was undertaken during the winter of 1979-1980 to augment existing information on ice conditions in the Peace River. The study reach extended from a point about 20 km downstream of the town of Peace River to the W.A.C. Bennett Dam in British Columbia.

Aerial observations were made from the beginning of frazil ice production and shore ice growth to the formation of a stable ice cover throughout most of the Alberta portion of the study reach. A total of four reconnaissance flights were undertaken, the details of which are summarized in Table 2.1. It should be noted that the ice front did not advance significantly beyond the location observed on February 7, 1980. No reconnaissance flights were made during spring break-up largely because it was one of the mildest events in recent years.

Ground observations between the town of Peace River and the Shaftesbury ferry crossing were also made during the field trips as well as on April 21, 1980, approximately two days after break-up at the town of Peace River.

In addition to the field trips, various local residents and Water Survey of Canada personnel in the Peace River area were contacted during the ice formation period in order to monitor the location of the ice front between reconnaissance flights.

Discussions were also held with British Columbia Hydro and Power Authority (BCHPA) personnel to exchange observation information as the BCHPA have been observing ice conditions in the Peace River since the winter of 1973-1974.

TABLE 2.1

SUMMARY OF 1979/80 AERIAL RECONNAISSANCE PROGRAM

Survey Date	River Conditions	Extent of Reconnaissance
November 30, 1979	Open water with some border ice growth and slush ice	20 km downstream of the town of Peace River to the W.A.C. Bennett Dam
December 28, 1979	Ice front located 44 km upstream of the town of Peace River	20 km downstream of the town of Peace River to the British Columbia/Alberta border
January 15, 1980	Ice front located 162 km upstream of the town of Peace River	20 km downstream of the town of Peace River to the British Columbia/Alberta border
February 7, 1980	Ice front located 217 km upstream of the town of Peace River	20 km downstream of the town of Peace River to the British Columbia/Alberta border

2.2 - Ice Observations

The events observed during the development of the ice cover on the Peace River in the winter of 1979-1980 are summarized in Table 2.2 and on Plate B.

The most significant of the observed events, are outlined below:

(a) Ice cover formation in this reach of the Peace River can be described as a juxtaposition process in which incoming frazil slush and ice pans accumulate against the leading edge of the advancing ice front. Some thickening of the ice cover was observed immediately above the Highway 2 bridge crossing in the town of Peace River.

(b) Telescoping or "shoving" of the unconsolidated upstream portion of the cover above the Shaftesbury ferry crossing (located 27 kilometres above the town of Peace River) took place following an abrupt three-fold increase in discharge at the W.A.C. Bennett Dam on December 29 and 30, 1979. It is estimated that the 1 metre thick cover formed initially at the Shaftesbury ferry increased to about 2.4 metres during this period.

The consolidated portion of the cover further downstream in the town of Peace River did not collapse despite a corresponding increase in stage of about 1.25 metres.

(c) The "effective" channel bank along the river was generally formed by ice accumulations on the sloping banks. Shearing took place in these accumulations during the course of cover development, resulting in a vertical plane between the grounded bank accumulations and the floating central portion of the cover. After initial cover formation, some smoothing of the underside of the ice occurred, as evidenced by the decrease in recorded water levels at Water Survey of Canada station 07HA001 at the town of Peace River. The ice cover, confined within the vertical ice banks, followed the water level change without breaking up.

(d) The average rate of advance of the ice cover decreased markedly as the ice front progressed upstream. Whereas reductions were due in part to air temperature and discharge increases, the reduction in ice generation area upstream of the advancing front appeared to be more significant, as evidenced by the reduced rate of advance from January 3 to 15, in spite of very low air temperatures.

(e) Significant attenuation of peak outflows from the G.M. Shrum Plant was observed at the town of Peace River.

TABLE 2.2

SUMMARY OF 1979-1980 FREEZE-UP EVENTS

Period or Date	Event	Mean Daily Discharge at Peace River m^3/s ($\pm$%)	Mean Daily* Discharge at Hudson Hope m^3/s ($\pm$%)	Mean Daily Air Temperature at Peace River °C (std. dev.)	Comments
Nov 19 - Dec 4	Pre-ice condition with relatively constant discharges	1479 $\pm$8%	1389 $\pm$5%	-3.9 (4.4)	Inflow between Hudson Hope and Peace River averages about 90 m^3/s
Dec 5 - Dec 11	Ice front at La Crete Ferry crossing; 300 km downstream of Peace River; Discharge from Williston Lake decreasing	1370 $\pm$16%	1048 $\pm$56%	-9.2 (6.4)	Peace River discharges decreasing more slowly than Hudson Hope due to channel storage between stations
Dec 12	First ice on river at Peace River reported by Water Survey of Canada			-23.4	
Dec 3 - Dec 21	Ice front advances to downstream of Peace River; discharges continue to be decreased from Williston	901 $\pm$72%	725 $\pm$60%	-16.4 (12.0)	Difference between Peace River and Hudson Hope discharges decreases as channel storage is depleted
Dec 21 - Dec 23	Stage at Peace River rises about 0.9 m; discharge continues to decrease	-**	535 $\pm$9%	-9.9 (3.7)	Stage rise at Peace River is due to backwater effect of advancing ice front. Discharge measurements at Peace River are no longer reliable
Dec 24	Complete freeze-over at Peace River occurs	-	453	-11.7	Total stage increase of about 1.0 over open water level experienced. Average rate of ice front advance from La Crete = 23 km/day
Dec 25 - Dec 28	Ice front advances to km 44 upstream of Peace River. Discharge is nearly constant during period	-	400 $\pm$5%	-3.3 (5.9)	Average rate of ice front advance is 11 km/day. Decreasing ratio due in part to warmer temperatures, but also to reducing ice generation area upstream of advancing ice front
Dec 29	Williston discharges increase abruptly to 1200 m^3/s on Dec 30	-	823	-6.5	
Dec 30 - Jan 2	Ice front retreats to km 32 upstream of Peace River. Cover shove from leading edge to Shaftesbury Ferry (km 18), thickening from about 1 m to 2.4 m at km 18	-	1191 $\pm$12%	-12.1 (2.5)	Twenty-six kilometres of unconsolidated ice front thickened due to three-fold increase in discharge. Consolidated cover in Peace River remained intact with stage increase of about 1.25 metres due to discharge increase.
Jan 3 - Jan 9	Ice front advances to Dunvegan (km 100) as discharges continue to increase and air temperatures decrease markedly	-	1276 $^{+23\%}_{-87\%}$	-28.7 (8.1)	Average rate of ice front advance is 8.5 km/day. Large range of daily discharges from 800 m^3/s to 1570 m^3/s at Williston reflected in stage changes of $\pm$0.25 m at Peace River; i.e. attenuation of short duration changes is appreciable due to channel storage effects. Lag time also appears to be increased.
Jan 10 - Jan 15	Ice front advances to km 175. Discharge increases slightly but varies little. Low temperatures continue, but with warming trend	-	1464 $\pm$6%	-26.1 (7.5)	Average rate of ice front advance is 11 km/day. This rate is no doubt sustained by prevailing low temperatures.
Jan 16 - Feb 7	Ice front advances to km 215. Mean daily discharge decreases slightly, but variability increases. Temperatures rise and fall appreciably in period.	-	1111 $^{+35\%}_{-60\%}$	-10.9 (8.6)	Average rate of ice front advance is 1.7 km/day. Reduction is due to both warmer temperatures and much reduced ice generation area upstream of ice front. An approximate inverse relationship between discharge and air temperature is noted during January and February (due probably to power demands increasing with decreasing air temperatures).

*Hudson Hope discharges lagged two days to account in some measure for travel time between Hudson Hope and Peace River.

**Discharge measurements at Peace River after this date unreliable due to ice effects.

3 - IMPACT OF THE OPERATIONS OF WILLISTON LAKE ON THE PEACE RIVER ICE REGIME

At present, the flow in the Peace River is influenced greatly by the operations of the G.M. Shrum Generating Station at Williston Lake. Hourly flow releases have varied by as much as 1000 m^3/s in order to meet the needs for electric power in British Columbia on any given day.

To assess the influence regulation of flows has had on the development of an ice cover in the Peace River, a comparison of freeze-up data before and after the construction of Williston Lake was made as presented in Table 3.1. Clearly, the marked increase in daily discharges during the month of freeze-up due to flow regulation has had a great influence on the timing and duration of freeze-up in the Peace River. In view of the similarity of the air temperatures, the differences in climatic regimes between the two periods can be ruled out as a major causative factor for the observed differences.

Further evidence of the capability of Williston Lake to control the winter flows in the Peace River is seen by the comparison of daily discharge on the date of complete freeze-up at the town of Peace River. Since the construction of Williston Lake, the mean discharge has increased from 464 to 1275 m^3/s.

It is evident that regulation has on average extended the open water season at the town of Peace River appreciably and has reduced the average duration of freeze-up. This is largely due to the freeze-up period being delayed from November to December. December, as shown by the temperature data in Table 3.1, is significantly colder on average than November. and thus the volume of ice required to produce a complete cover on the river can be produced in less time.

Of further interest is the greater variability in the dates of first ice and freeze-up resulting from the increase in variability of the discharge with regulation by the G.M. Shrum Generating Station. The date of first ice in this case is the date on which ice conditions, frazil and slush ice, were initially reported by Water Survey of Canada.

It is also interesting to note that the variability of the unregulated Smoky River flows has decreased over the comparison period.

Flow regulation has also had a significant effect on the timing and extent of ice conditions in the Fort St. John and Taylor area in British Columbia. Historical records show that since 1968, the mean date of first ice at Taylor has been delayed by about 50 days, from November 24 to January 11. The variability of the date of first ice has also increased from about 8.5 to 15.7 days. It should be noted that with the exception of the winter of 1978-1979, ice effects have not been reported by Water Survey of Canada for the Taylor gauge since 1974.

Prior to the winter of 1968-1969, complete freeze-over in the Fort St. John and Taylor area often occurred before freeze-over in the town of Peace River. Under natural flow conditions the date of ice cover formation at Fort St. John and Taylor was therefore largely dependent on whether or not an ice bridging point had developed at some location upstream of the town of Peace River. A reduction in the volume of ice available in the river due to thermal effects and considerably higher discharges during the winter months has since eliminated any significant ice bridging formations upstream of the town of Peace River. At present, initial lodgement of the ice is believed to occur between Carcajou and Fort Vermilion, some 340 to 440 km below the town of Peace River.

TABLE 3.1

EFFECT OF REGULATION ON FREEZE-UP

Period		Date of First Ice at Town of Peace River**	Date of Complete Freeze-Over	Duration of Freeze-Up Period	Mean Discharge During Month of Freeze-Up: Peace River	Mean Discharge During Month of Freeze-Up: Smoky River*	Mean Daily Discharge on Date of Complete Freeze-Over	Mean Nov-Dec Air Temperature at Fort St. John	Mean Nov-Dec Air Temperature at Peace River
Pre-Williston Reservoir Period									
1957/58	n	12	11	11	12	11	11	12	10
to	m	Nov. 7	Dec. 4	27 days	885 m^3/s	110 m^3/s	464 m^3/s	-10.0°C	-11.7°C
1968/69	s	6.1 days	9.7 days	9.1 days	271 m^3/s	57 m^3/s	193 m^3/s	5.6°C	5.2°C
Post-Williston Reservoir Period									
1969/70	n	11	11	10	11	10	11	12	10
to	m	Dec. 5	Dec. 19	17 days	1340 m^3/s	82 m^3/s	1275 m^3/s	-9.8°C	-12.3°C
1979/80	s	17.8 days	15.5 days	11.2 days	336 m^3/s	35 m^3/s	333 m^3/s	5.6°C	5.9°C
Change	m	+28 days	+15 days	-10 days	+51%	-25%	+175%	+0.2°C	-0.6°C
	s	+11.7 days	+5.8 days	+2.1 days	+24%	-39%	+73%	0	+0.7°C

n = number of years observed
m = mean value for n years
s = std. deviation
* Smoky River flows presented to provide indication of differences in natural (unregulated) hydrology between the pre- and post-Williston Reservoir periods.
** The date of first ice is defined as the date on which ice conditions were initially reported by Water Survey of Canada personnel.

Mean Air Temperature		Fort St. John	Peace River
	Nov.	-6.5°C	-8.5°C
	Dec.	-13.3°C	-15.5°C
	n	29 yrs.	20 yrs.

4 – DUNVEGAN PLANT OPERATIONS AND HYDROLOGIC REGIME

4 - DUNVEGAN PLANT OPERATIONS AND HYDROLOGIC REGIME

4.1 - Operating Policy for the Dunvegan Project

The daily winter flow regime at the town of Peace River will be determined principally by power operations at the Dunvegan Hydro-electric Project some 105 km upstream and, to a lesser extent, by inflows from the Smoky River. For the purposes of this study it was assumed that the Dunvegan Project would be used to the fullest extent possible for meeting peak daily power demands in the Alberta interconnected power system. That is, large daily fluctuations of power flow from a minimum riparian flow to the maximum installed capacity can be expected to occur on a daily basis as Dunvegan follows the daily system load pattern. One generating unit at the power plant operating at 2/3 to 3/4 of full gate discharge was assumed as the minimum practicable operating discharge, resulting in a riparian flow of 300 m^3/s (i.e. approx. 100 MW).

The daily flow pattern at Dunvegan will occur at the town of Peace River and points further downstream, although some modifications to the timing and magnitude of the peak discharges can be expected. The amount of modification will be dependent upon the effects of channel storage and friction in the intervening channel and, to a great extent, upon the daily operating capacity factor at Dunvegan. The daily capacity factor in this case is defined as the ratio of the mean daily discharge to the full capacity discharge at the plant.

With the foregoing operating policy for Dunvegan, and the thorough regulation of the Peace River winter flows provided by the Williston Lake storage reservoir, the operating capacity factor in the winter for the Dunvegan Project over moderate to long time periods will be determined almost exclusively by power releases from the G.M. Shrum Development upstream. Slightly higher operating capacity factors could be sustained by drawing water from storage. However, drawing the reservoir down to gain any appreciable increase in regulated flow would result in a large percentage loss of generating head at the plant with a corresponding reduction in power peaking capability. This is contrary to the assumed role for the Dunvegan Project. Thus, it has been presumed herein that the Dunvegan reservoir would be used with only minor weekly variations in level to balance differences in both daily load demands and daily inflows throughout the week.

The existing and proposed upstream power developments at Peace Canyon and Site C, respectively, will not influence the capacity factor as their operating policies would be similar to that assumed for Dunvegan for the same reasons. Inflows to Dunvegan are unlikely to coincide with the desired flow release pattern from Dunvegan because of both the travel time of flows between plants and the fact that the upstream plants will be following the British Columbia power system load pattern.

However, this is not problematical, as a storage volume of about 80 million cubic metres per metre of drawdown in the Dunvegan reservoir will provide ample capacity for daily re-regulation of upstream power releases to suit the Alberta power system requirements. This daily drawdown will not significantly affect the available generating head at Dunvegan.

Based on the foregoing assumptions for the operation of the Dunvegan Project, the range of possible flow patterns that might reasonably be expected in the town of Peace River was estimated as outlined in the following sections.

4.2 - Winter Monthly Inflows to Dunvegan

Winter month inflows to Dunvegan were determined from the 1976 report on the feasibility of the Dunvegan Project by Monenco (Table 3-25). The range of monthly power flow patterns provided in that report were derived by river basin runoff/regulation studies of Williston Lake for various scenarios of power generation development for the British Columbia System and based on 40 years of hydrologic data. For the purpose of this study, the results of the simulations are summarized as follows:

WINTER MONTHLY INFLOWS TO DUNVEGAN

	Extreme Dry Year		Normal Year		Extreme Wet Year	
Month	Mean Discharge	Equivalent Dunvegan Energy	Mean Discharge	Equivalent Dunvegan Energy	Mean Discharge	Equivalent Dunvegan Energy
	m^3/s	GW.h	m^3/s	GW.h	m^3/s	GW.h
December	439	118	1115	274	1854	456
January	338	83	1105	271	1700	418
February	328	80	1111	279	1694	416

The extreme conditions shown above are based on hydrologic events that could occur about once in 40 years combined with the most severe of nine British Columbia development scenarios studied by the BCHPA. These numbers are subject to revision in view of developments since the BCHPA analysis; however, the data provides a reasonable basis for defining the mean and low and high extremes for the possible winter inflows to the Dunvegan Development.

4.3 - Future Power and Energy Demands

A forecast of the energy demand for the Alberta interconnected power system was obtained from the September, 1978 ERCB Report entitled, "Energy Requirements in Alberta 1977-2006". These are summarized in the following table. The annual load factors shown were obtained from the June 1978 Electric Utility Planning Council report entitled "Alberta Electrical Energy Requirements, Total Energy and Total Demand Forecast, 1978-2007". These load factors were used to calculate the annual peak day power demands shown in the table.

FORECAST OF POWER AND ENERGY DEMANDS FOR ALBERTA INTERCONNECTED POWER SYSTEM

Year	Annual Peak Day Power MW	Annual Load Factor %	Annual Energy GW.h
1985	5550	66.2	32180
1990	7450	67.5	44040
1995	9460	68.6	56830
2000	11855	69.6	72270
2005	14480	70.4	89290

4.4 - Dunvegan Discharge Patterns

To obtain a representative sample of the wide variety of power flow patterns that might reasonably be expected in the future, a variety of combinations of hydrologic conditions discussed in the foregoing sections was considered with the energy requirements for the years 1990 and 2005. For each of the selected combinations, the energy available from the Dunvegan Project was "stacked" in the system for a typical weekly load pattern such that the total installed capacity of 1000 MW (2940 m^3/s) or as much of it as possible, was utilized in the system each day. The typical weekly load pattern, in conjunction with the range of hydrologies, provided a variety of daily operating capacity factors for the plant. In each case, 100 MW was assumed to be base loaded in the system to provide the riparian flow of 300 m^3/s. Also, the weekly energy was balanced to match the available inflow in dry, normal, and wet years so that large changes in operating head would not occur, as previously discussed. Typical results of the stacking analysis are illustrated on Plate C for the 1990 power demand. This indicates that in low flow years, the full capacity of the plant may not be used for peaking operations on a regular basis. In later years, as the load grows, the full capacity can be used even in these years as shown on Plate D for the year 2005.

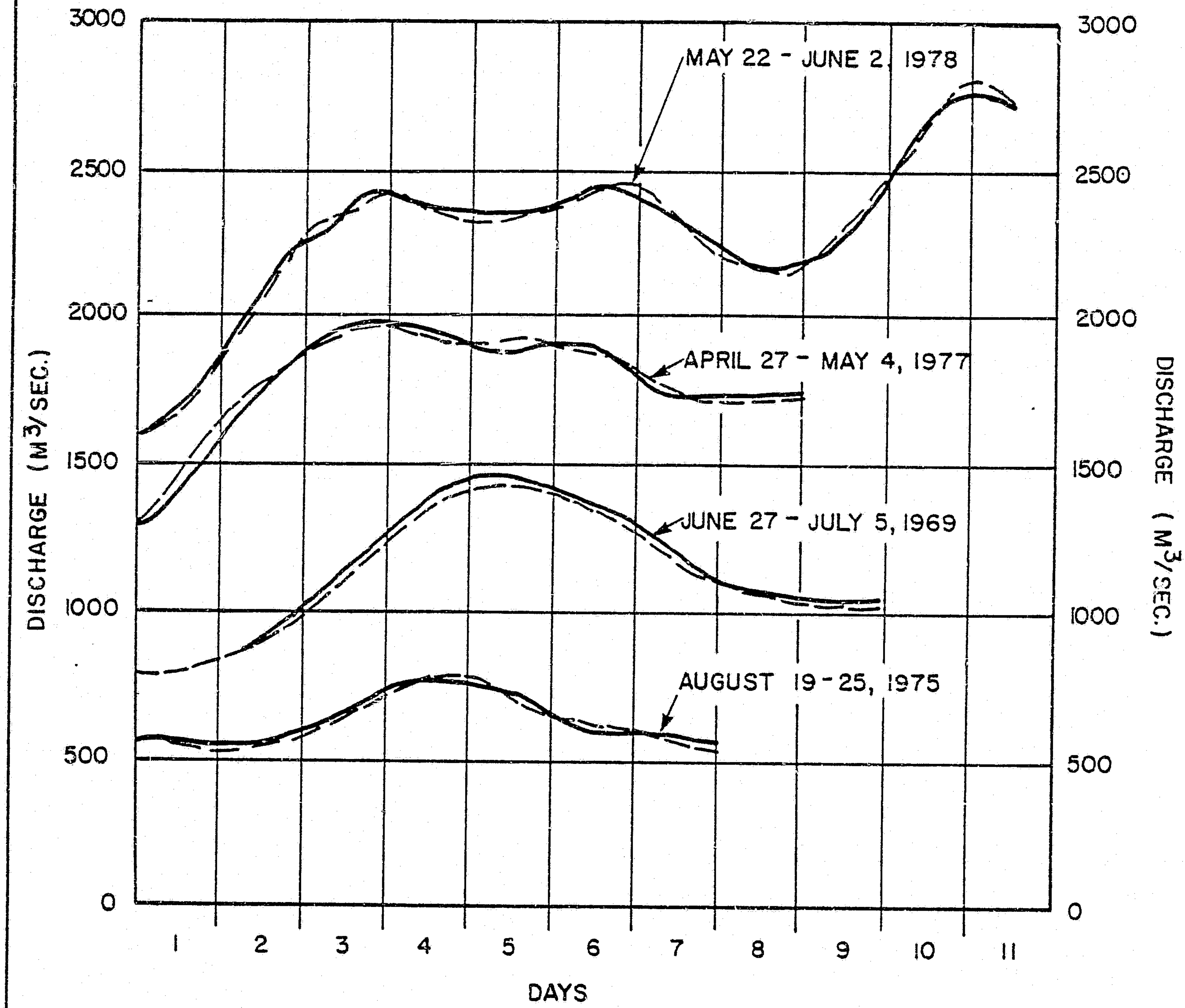
Hourly power discharge patterns from Dunvegan for the example weekly load pattern were derived from the foregoing power generating patterns. Typical examples are illustrated on Plate D for the load year 2005.

4.5 - Flows at the Town of Peace River

Hourly flow patterns at the town of Peace River were derived from the Dunvegan patterns by means of the Muskingum hydrologic flow routing technique, which accounts for the effects of channel storage and friction. Limited river cross-section data did not permit the use of more detailed hydraulic flow routing techniques. Plate D shows the resulting flow pattern at the town of Peace River for the previously noted Dunvegan hourly power flow pattern for open water conditions.

To carry out the flow routing, a channel storage coefficient of 0.4 was adopted from an analysis of recorded flood hydrographs at Dunvegan and the town of Peace River for open water conditons. The travel time for flow between the points as a function of discharge was adopted from an earlier analysis by Andres (1978). It was found that this method and associated assumptions were suitable for open water conditions as demonstrated by the results shown in Figure 2.

In this analysis, it was found that the recorded conditions could be simulated satisfactorily with a range of values for the storage coefficient (from about 0.3 to 0.4). The upper value was selected for the power flow routing computations in order to provide a modestly conservative estimate of the attenuation of hourly flows from Dunvegan at the town of Peace River.



———— OBSERVED, RECORDED FLOWS AT PEACE RIVER (STATION 07HA001) LESS THE SMOKY RIVER DISCHARGE AT WATINO (STATION 07GJ001).

– – – – COMPUTED, RECORDED FLOWS AT THE DUNVEGAN BRIDGE (STATION 07FD003) ROUTED TO THE SMOKY RIVER CONFLUENCE (STORAGE COEFFICIENT = 0·4).

FIGURE 2

COMPARISON OF OBSERVED AND COMPUTED DISCHARGE HYDROGRAPHS.

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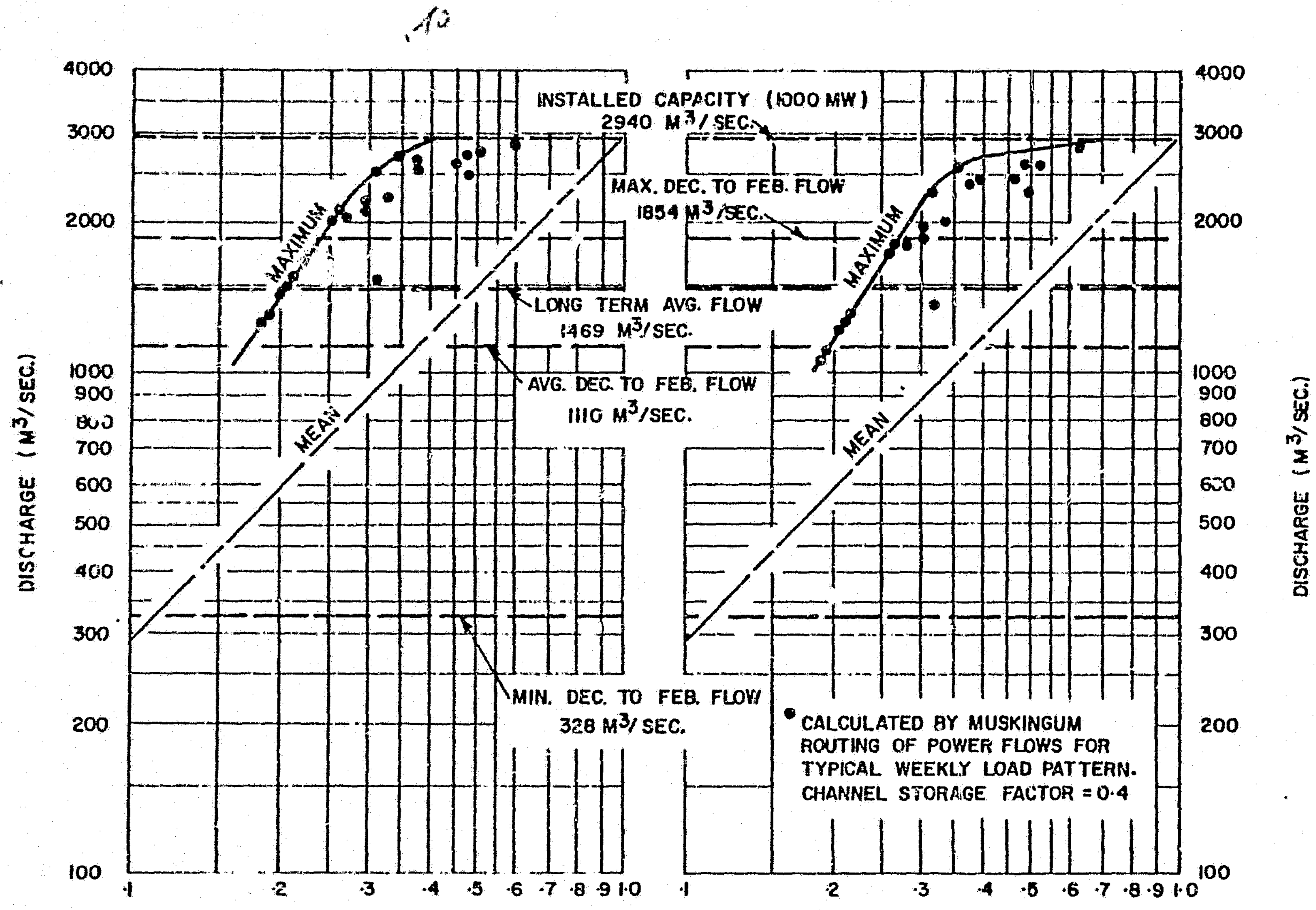
As the presence of an ice cover increases the time of travel in the river, the load flow patterns derived for Dunvegan were routed a second time with a modified lag-time/discharge relationship. As no hydrographic data is available from Dunvegan for the winter months, the modification was made with theoretical justification using approximate summer and winter lag-times observed for flows between Hudson Hope and the town of Peace River. The adopted adjustment factor was 1.6. Typical effects of an ice cover are illustrated on Plate D for a normal year. The results of this additional routing analysis were later used to estimate mid-winter water level fluctuations.

The results of the power flow routings from Dunvegan to the town of Peace River have been summarized in Figure 3 for both open water and ice cover conditions. These diagrams show the maximum hourly discharge that would occur at the town of Peace River for the maximum likely range of operating capacity factors at Dunvegan (i.e. 0.18 to 0.58). It is evident that with Dunvegan operating at higher capacity factors, peak discharges at the town of Peace River will, for all practical purposes, be equal to the peak power releases. Attenuation of peak discharges is seen to increase appreciably for factors below 0.35. The estimated capacity factor for normal winter hydrology is about 0.38.

It should be noted that if a higher riparian flow were assumed, the effect would be to increase the attenuation for operation at a given capacity factor.



OPEN WATER CONDITIONS

(NO ICE EFFECT)

ICE COVERED CONDITIONS

(ICE COVER TO THE VICINITY OF THE DUNVEGAN TAILRACE)

NOTES

1. MAXIMUM HOURLY DISCHARGE RELATIONSHIPS ARE ONLY APPLICABLE FOR AN ASSUMED MINIMUM POWER FLOW OF 300 M^3/SEC.
2. MAXIMUM HOURLY DISCHARGES AT THE TOWN OF PEACE RIVER DEPEND ON THE FLOW RELEASE PATTERN AT DUNVEGAN.

FIGURE 3

RANGE OF HOURLY DISCHARGES AT THE TOWN OF PEACE RIVER, WITH DUNVEGAN POWER PEAKING (1000 MW).

ACRES

5 - PEACE RIVER ICE REGIME

5.1 - Development of an Ice Cover

The development of an ice cover on the Peace River is typical of moderately steep and wide rivers. When the river water surface has cooled to the freezing point, frazil and slush ice form, being accumulated in a downstream direction until a moving blanket of ice pans and slush filling the river has been obtained. This blanket lodges at some constricted point in the channel to begin forming a solid, stationary ice cover (this point is currently near Fort Vermilion). The upstream or leading edge of the ice cover advances in an upstream direction as more ice is supplied to it from the inflowing blanket. However, typically the front soon reaches a section where the velocity of flow at the leading edge is too great for the slush to remain there, and it is instead carried under the established solid cover to be deposited on its underside at the first location where the velocity permits.

As deposition occurs, it restricts the channel flow section, thereby increasing the water depth at the leading edge until the velocities are low enough to permit slush accumulation and continued advancement of the leading edge. The maximum winter water levels in the Peace River for a given discharge are observed to be determined by this process of cover development.

Subsequent to its initial formation, the internal stresses in the cover may become too great for it to remain in place as the front continues to advance further upstream. Consequently, the cover compresses, or telescopes, to increase to a thickness which can resist the developing stresses. Any further increases in thickness that occur are then due to either the depositions previously described or significant increases in discharge. Once the cover has consolidated in this manner and gained strength by further freezing, rather large

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Subsequent to its formation and consolidation, the under surface of the ice cover becomes smoother due to the flow under it, and the water level decreases slightly for a given discharge. This process has been reported by a number of investigators (see Michel, 1971). Typically, the discharge capacity of the ice covered channel for a given water level might increase by 25 percent.

The observed hydraulic characteristics of the Peace River channel and experience with increased mean winter flows due to regulation by Williston Lake suggest that the prevailing processes will not be altered by further increases in the instantaneous flow at the time of cover formation. This suggestion has been born out by subsequent analysis. However, with the increased instantaneous or short duration discharges, due to power peaking operations at Dunvegan, the process will occur at increased water levels, with resulting increased ice cover thicknesses.

5.1.1 - Leading Edge Stability

As noted above, the maximum water levels in the town of Peace River occur as a consequence of the requirement for water depths which will yield a stable leading edge as it passes through the town. The minimum required depth for stability is defined by a dimensionless ratio called the critical Froude number which is defined as follows:

$$Fr = \frac{V}{\sqrt{gH}} = 0.154\sqrt{1-e}$$

where V = velocity at leading edge
H = depth of flow at leading edge
g = gravitational constant
and e = porosity of ice blanket, normally between 0 and 0.73.

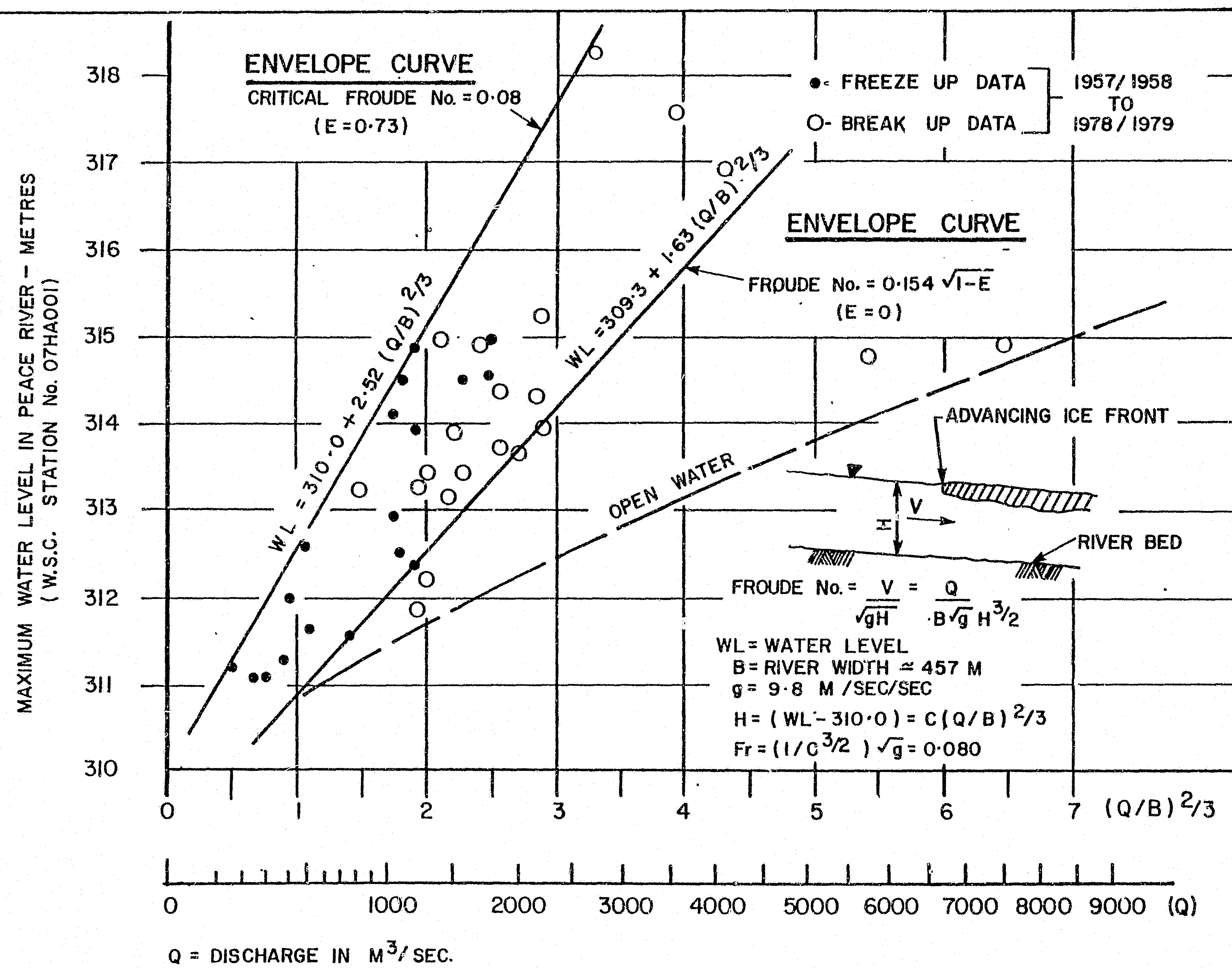
This relationship has been derived from theoretical considerations which have been amply supported by laboratory experiments and observations in other rivers and channels. If the Froude number at a given river section is less than the value indicated by the foregoing equation, the ice front can progress. If it is not, then the water depth will increase as described until the Froude number is equal to the indicated critical value. With porosity normally varying between 0 and 0.73, the normal range of critical Froude numbers is 0.154 to 0.08.

Froude numbers at the Water Survey of Canada gauge (NO. 07HA001) in the town of Peace River have been determined under winter conditions for a period of 22 years, as shown in Figure 4. Data obtained at time of spring break-up is included, as the same staging phenomena prevails at that time as well. Clearly, the range of critical Froude numbers typical of experience elsewhere envelopes the Peace River data with the exception of four break-up points. These points lie closer to the open water rating curve for the gauging station, probably because of the volume of ice at break-up in these years being too small to achieve the necessary staging. There is, however, no way of confirming this. In any case, it is not of concern for the purpose of this study as the upper boundary condition of the data corresponding to a Froude number of 0.08 is the more critical envelope. This must be conservatively adopted for assessing the critical ice condition discharge value for the town of Peace River.

Based on observations made during the field reconnaissance program and on subsequent analysis using available river cross-section data, the critical section for leading edge stability was determined to be near the bridge crossing section some 800 m upstream of the Water Survey of Canada gauge. Hence, the use of the channel width at that section in the analysis rather than the gauge location section width.

5.1.2 - Internal Stability

Analysis of the internal stability of the ice cover at the town of Peace River was undertaken to:



MAXIMUM WATER LEVELS DURING FREEZE - UP AND BREAK-UP.

FIGURE 4

AGRES

- confirm that the governing ice process would not change with increases in peak discharge that might be realized with the Dunvegan Project.
- obtain water surface/ice cover gradients for the river reach through the town of Peace River.

The latter information was required to determine water levels within the existing flood protection dykes along both banks of the river. The West Peace River dyke is approximately 2.2 km long and is currently constructed to a level of about 320.5 m as shown on Plate F. It is understood that the 4.5 km long dyke along the east bank will be raised this year to a crest elevation of 320.3 m at the mouth of the Heart River.*

The analysis was carried out by means of a mathematical model which simulates the thermal generation, upstream progression, packing and thickening of frazil ice at formation as well as the accumulation and jamming of ice. The associated backwater effects along the ice-covered and open water reaches of the river are calculated in the mathematical model using the standard step method. Application of the model to a wide range of hydraulic conditions has proven its capability to simulate fragmented ice cover behaviour.

Typical results obtained from the analysis are illustrated for a discharge of 2500 m^3/s on Plate F.

5.2 - Winter Water Levels and Critical Discharges

From the water surface and ice cover profiles calculated for discharges of 500 m^3/s to 3500 m^3/s, it is possible to construct water level/discharge relationships at various points through the Town, both downstream and upstream of the Water Survey of Canada gauge. Figure 5 shows these relationships for the cross-section adjacent to the West Peace River dyke and the Heart River confluence. Included in Figure 5 is a corresponding envelope curve for the mean ice surface elevation.

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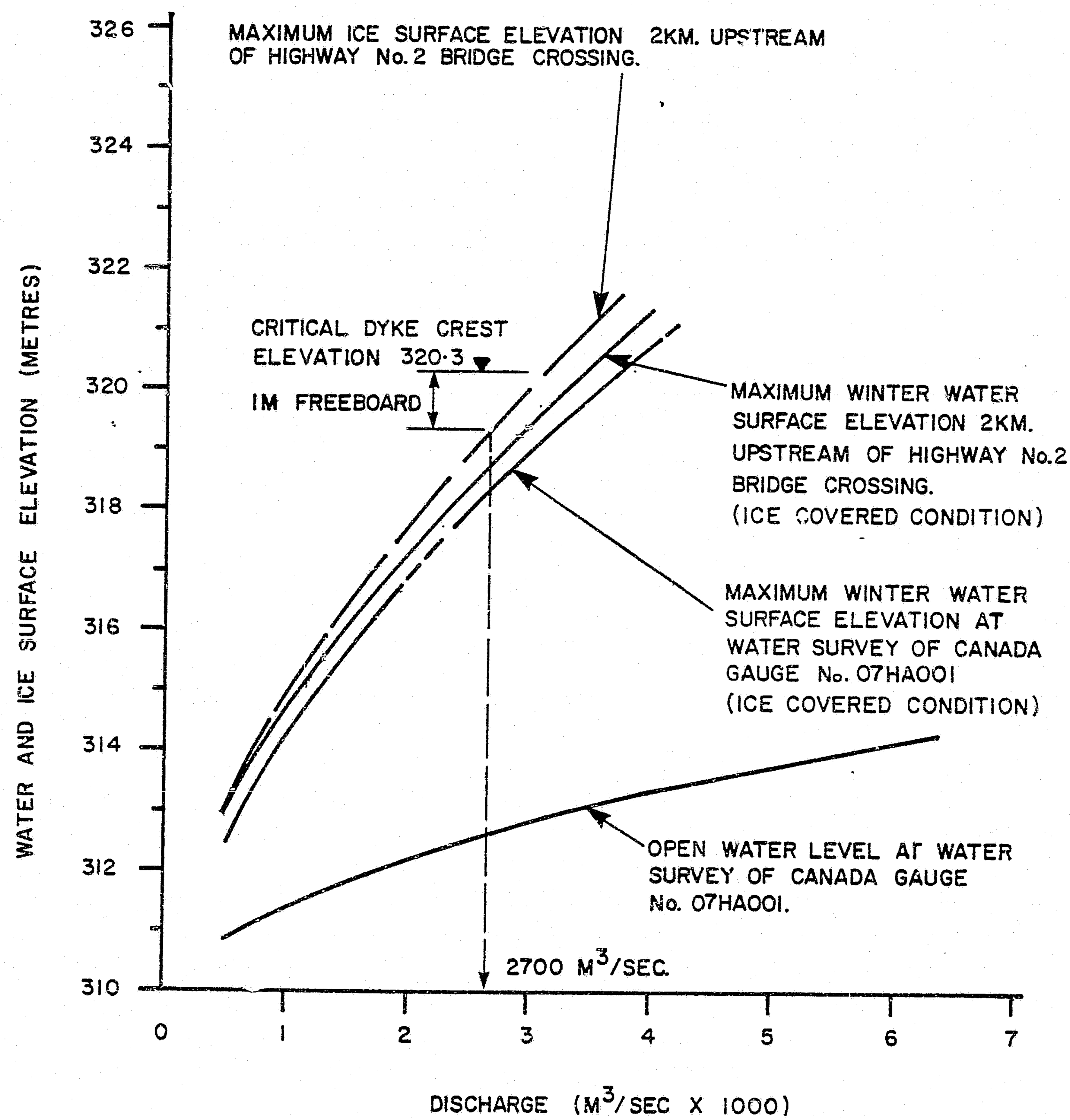
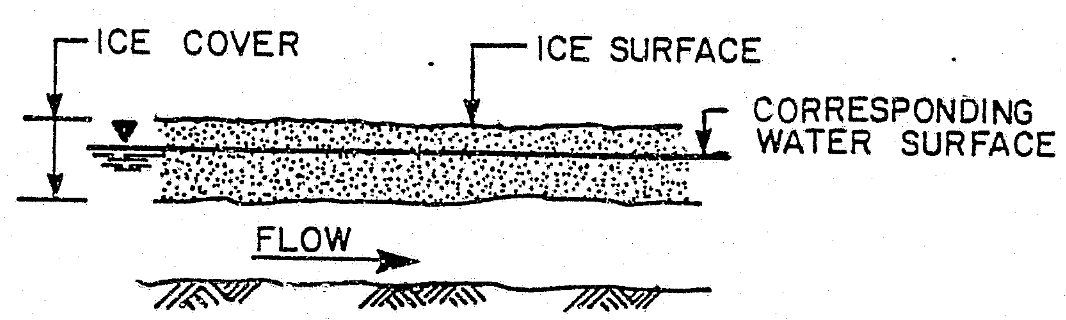
* This information was obtained from discussions with representatives of the town of Peace River.





DEFINITION SKETCH

FIGURE 5

MAXIMUM WATER AND ICE LEVELS IN THE TOWN OF PEACE RIVER

ACRES

At this location, the critical dyke crest elevation will be 320.3 m upon completion of the flood dyke along the east bank.

A criterion of a minimum of 1.0 m of freeboard between the mean ice surface and the critical dyke crest elevation has been adopted. This will provide a minimum freeboard allowance on the water surface of 1.5 m. The critical winter discharge for the town of Peace River on the basis of these criteria is seen from Figure 5 to be about 2700 m^3/s. If the dyke crest elevations were to be increased while maintaining the same freeboard criterion, the magnitude of the critical discharge would also increase as shown in the following table.

The cost of raising the dykes or of other means of flood protection would be part of a subsequent phase of the work if required and as such has not been estimated for this report.

CRITICAL WINTER DISCHARGE
IN THE TOWN OF PEACE RIVER

Critical Dyke Crest Elevation	Increment of Dyke Height	Critical Winter Discharge
m	m	m^3/s
320.3 (existing)	0	2700
320.5	0.2	2800
321.0	0.7	3000
321.5	1.2	3235
322.0	1.7	3455

5.3 - Critical Power Peak at Dunvegan

By combining the foregoing critical discharges with the results of the power flow routing in Figure 3 in Section 4.5, the maximum peak power discharges that can be released at Dunvegan without risking flooding in the town of Peace River at the critical time of ice cover formation there, have been derived. The results of this analysis are summarized in Table 5.1.

As outlined in Section 5.1, the critical discharge at the town of Peace River is governed by the requirement for leading edge stability of the ice front as it passes through the Town. Upstream of the ice front, the river will be partially covered by a thin drifting blanket of slush and pan ice accumulations. These accumulations will decrease in surface area density in an upstream direction. The overall effect of this loose ice blanket on peak power flow attenuation between Dunvegan and the town of Peace River cannot be precisely determined.

Consequently, it has been assumed for the purposes of this study that attenuation of peak power discharges between the leading edge of the ice cover and Dunvegan will be similar to that of an open water condition. Figure 3 indicates that there is less attenuation of peak flows for the open water case than for the case of complete ice cover. The critical discharges and power peaks for the Dunvegan development have been assessed on the basis of this assumption and the ice front located at the critical river section in the town of Peace River.

Very large installed capacities could be safely used if the Dunvegan power plant was to be operated at low capacity factors. However, with the previously described "normal" hydrology, the operating capacity factor would be in the range of 0.35 to 0.40 for an installed capacity of 1000 MW with 100 MW base loaded. In the "wet" hydrology years, values in the range of 0.40 to 0.50 will occur. Consequently, a capacity factor as high as 0.50 has been assumed in defining the critical peak power release at Dunvegan. This does not preclude higher installed capacities at Dunvegan which could be used to good advantage for peaking in normal or drier years. The optimum installed capacity for the project is a matter of project and power system economics, being dependent upon the flow frequency and is beyond the scope of this study.

TABLE 5.1

CRITICAL DISCHARGE (Q) AND POWER PEAK (P) AT DUNVEGAN

Critical Dyke Crest Elevation	Critical Discharge at The Town of Peace River	DUNVEGAN OPERATING CAPACITY FACTORS									
		0.2		0.3		0.4		0.5		0.6	
		Q	P	Q	P	Q	P	Q	P	Q	P
m	m^3/s	m^3/s	MW	m^3/s	MW	m^3/s	MW	m^3/s	MW	m^3/s	MW
320.3 (existing)	2700	5290	1800	3050	1040	2785	950	2700	920	2700	920
320.5	2800	5490	1870	3170	1080	2890	985	2800	950	2800	950
321.0	3000	5880	2000	3390	1155	3095	1055	3000	1020	3000	1020
321.5	3235	6340	2160	3660	1245	3340	1135	3235	1100	3235	1100
322.0	3455	6770	2300	3910	1330	3565	1215	3455	1175	3455	1175

Note:

1. Based on a minimum of 1.0 m of freeboard above mean ice cover surface.
2. Based on assumption of most severe possible ice conditions in the town of Peace River.
3. Permissible peak power limits are based on preliminary analyses with limited river section data and are subject to refinement when more detailed river surveys have been completed.
4. Existing dyke crest elevation taken as 320.3 m at the Heart River confluence (east bank) on the basis of discussions with the Town Engineer for the town of Peace River.
5. Based on 100 MW base loaded and 900 MW available for peaking operations.

It is evident from Table 5.1 that a minimum winter power peaking capability of 920 MW or 92 percent of the installed capacity is feasible in "wet" hydrology years with capacity factors in the order of about 0.50. For "normal" hydrology years with a corresponding capacity factor of 0.38, the critical power peak at Dunvegan would be about 960 MW. It should be noted that this assessment is based on the somewhat conservative criteria perviously discussed such as the 100 MW base load assumptions, the peak power flows occurring when the ice front is at the Town, the leading edge stability being controlled by the upper boundary condition corresponding to a Froude number of0.08, a river channel storage coefficient assumed to be 0.4 and the attenuation of peak flows corresponding to open water conditions.

5.4 - Mid-Winter Power Peaks

As noted in the earlier brief description of ice cover development on the Peace River, a decrease or "set-back" in water levels for a given discharge occurs with smoothing of the underside of the cover once internal equilibrium has been achieved. This results in a corresponding increase in the dyke freeboard and gives rise to a possible ice formation operating strategy which would limit power peaking capability to the previously tabulated minimums for a relatively brief period some years. Increases in peak power discharges could be permitted after the decrease in water levels has occurred. The application of the strategy is described below.

With open water conditions from Dunvegan to downstream of the town of Peace River, there is no limit, for all practical purposes, to the peak power that can be used at Dunvegan. However, as the ice front approaches the Town from downstream, increasing water level stages are realized in the Town as previously noted. Peak power releases could then be reduced to the critical values appropriate to the prevailing hydrology. These reduced power releases would be maintained until the ice front had advanced upstream of the Smoky River confluence, consolidation and freezing of the cover had taken place and "set-back" of the water level had occurred. It has been observed that this smoothing of the ice undersurface and corresponding decrease in water level (for a given discharge) occurs within about a one week period.

On the basis of the thermal calculations and assessment of the effects of Site C and Dunvegan reservoirs on the rate of cover development as described later, it is estimated that the reduced peaking policy would be required for 5 to 15 days. (The shorter duration corresponds to cold climate/low mean flow combinations at the time of ice front advance through the Town; the longer duration to warm climate/high mean flow combinations.) Peak power releases could then safely be increased appreciably, with the limiting peak discharge being determined by the minimum desirable dyke freeboard and the amount of "set-back". This phenomenon occurred during the reconnaissance program as described in Section 2. Typically, the "set-back" phenomenon will permit an increase in flow for given level of about 25 percent.

As in the case for the ice formation period, the mid-winter power peaks could be substantially larger for small values of operating capacity factor at Dunvegan, due to the increased attenuation of peak flows between Dunvegan and the town of Peace River.

On the basis of a minimum freeboard of 1.5 m on the water surface and an increase of 25 percent in discharge for a given stage at the upstream end of Town, the mid-winter power peaks were determined for capacity factors in excess of 50 percent. These are summarized in Table 5.2.

5.5 - Daily Water Level Fluctuations

The water level fluctuations to be expected in the town of Peace River due to daily power peaking operations at Dunvegan have been estimated. The maximum range of levels would occur for the higher operating capacity factors for which little attenuation of peak discharges is realized, but for which the daily minimum power flow also occurs at the Town.

Table 5.3 summarizes the maximum daily ranges that might be expected for mid-winter conditions with both an ice cover in place between Dunvegan and the town of Peace River including the "set-back" allowance, and for open water conditions.

TABLE 5.2

MID-WINTER DISCHARGE AND POWER PEAK AT DUNVEGAN*

Critical Dyke Crest Elevation m	Critical Discharge m^3/s	Corresponding Power Peak MW
320.3 (existing)	3300	1120
320.5	3490	1190
321.0	3800	1295
321.5	4150	1410
322.0	4400	1495

* for capacity factors in excess of 50%

TABLE 5.3

MAXIMUM POTENTIAL DAILY WATER LEVEL RANGES IN PEACE RIVER

Critical Dyke Elevation	Power Peak	Dunvegan Operating Capacity Factor 0.2 Open Water	0.2 Ice Covered	0.4 Open Water	0.4 Ice Covered	0.6 Open Water	0.6 Ice Covered	Time of Year
m	MW	m	m	m	m	m	m	
320.3 (existing)	1000	1.1	1.9	2.1	3.6	2.2	3.7	Ice Formation Period
320.3 (existing)	1120	1.2	2.0	2.2	3.7	2.3	3.9	Mid-Winter With "Set-Back" of ice Cover
320.5	1190	1.2	2.1	2.3	3.9	2.4	4.1	
321.0	1295	1.3	2.2	2.4	4.1	2.6	4.4	
321.5	1410	1.4	2.4	2.6	4.4	2.7	4.6	
322.0	1495	1.5	2.6	2.7	4.6	2.8	4.8	

Notes:

1. Range at Water Survey of Canada gauge No. 07HA001, 800 m downstream of Highway 2 Bridge in the town of Peace River.

2. Minimum power flow from Dunvegan assumed to be 300 m^3/s (100 MW base loaded)

3. Water level fluctuations for ice covered conditions are based on preliminary analyses and are subject to further refinement when more detailed hydraulic data becomes available.

5.6 - Effect of Water Level Fluctuations on Ice Covers

The three stages of typical ice cover development described in Section 5.1 are illustrated schematically in Figure 6. Of particular note in the second stage of development is the grounding of ice on the shoreline and the subsequent development of shear lines more or less parallel to the riverbanks. This process is the key to the response of ice covers in most reaches of the Peace River to large variations in water level.

With decreases in flow subsequent to cover formation, the floating, central portions of the cover follows the falling water level. If freezing at the shear lines has taken place, the central portion will simply sag until the strength of the bond between the floating and grounded portions is exceeded by the increasing weight of cover supported by it. Since the shear line is a very significant plane of weakness at the point of greatest stress in the cover, the cover will always refracture close to this point.

If the decrease in water level is sufficient, the extremities of the floating cover will come to rest on the channel bed, with sagging again occurring with continuing decreases in level. Ultimately, the cover could assume a position as illustrated in Figure 6 for a low flow stage. Fracturing as shown will occur depending upon the local channel configuration and the initial cover rigidity, to permit the cover to conform to the channel bed.

As the discharge and stage increase from a low value, the sections of central cover will simply float back into place, or develop a "hinge" mechanism, depending upon the rigidity of the cover. Unless the cover is maintained in the low position for prolonged periods of time, it would be expected to maintain its flexibility and would not need to form the hinge mechanism. In fact, observation of the Peace River has shown that increases in the position of the cover to elevations in excess of the initial formation level are possible, as illustrated for a high flow stage in Figure 6. As long as the central cover is restrained laterally by the vertical shear walls of the grounded ice, the hydrodynamic stresses in the cover can be transferred

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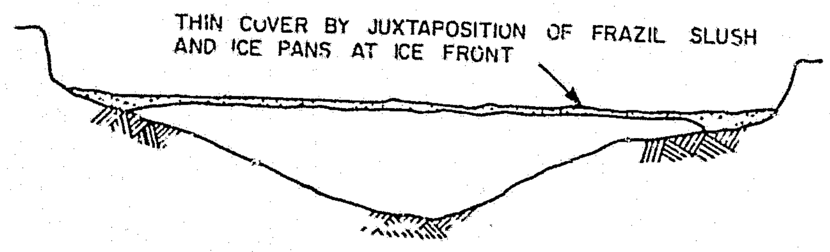
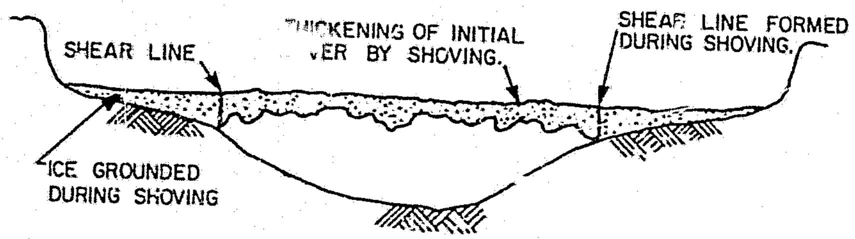


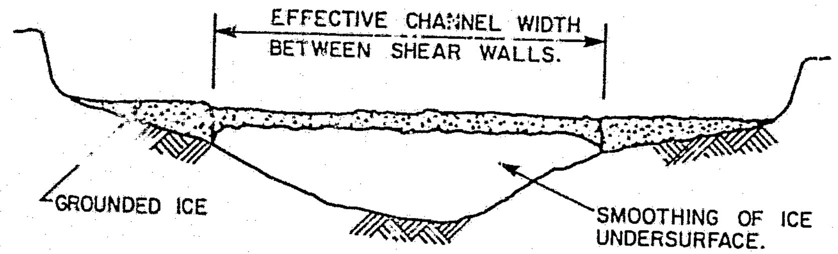
STAGE I DEVELOPMENT

LEADING EDGE STABILITY DETERMINES COVER THICKNESS INITIALLY AS ICE FRONT ADVANCES THROUGH SECTION.



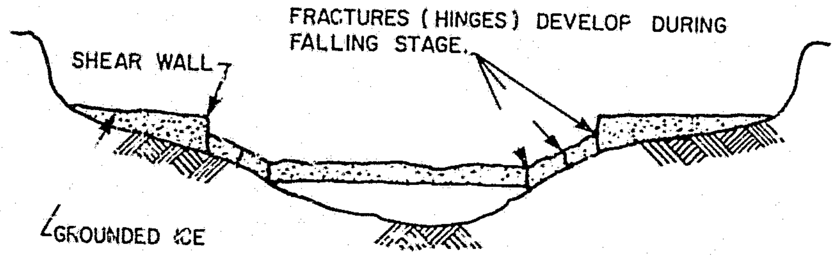
STAGE 2 DEVELOPMENT

COVER THICKNESS INCREASES SUBSEQUENT TO PASSAGE OF ICE FRONT AS STRESSES INCREASE IN COVER AT SECTION DUE TO BODY AND DRAG FORCES ACTING ON COVER UPSTREAM OF SECTION. COVER MAY ALSO THICKEN BY DEPOSITION IF ADDITIONAL ENERGY LOSS REQUIRED TO CREATE SUFFICIENT STAGE FOR STABLE ICE FRONT AT SOME UPSTREAM SECTION SHEAR LINES FORM AS COVER TELESCOPES TO INTERNAL EQUILIBRIUM THICKNESS.



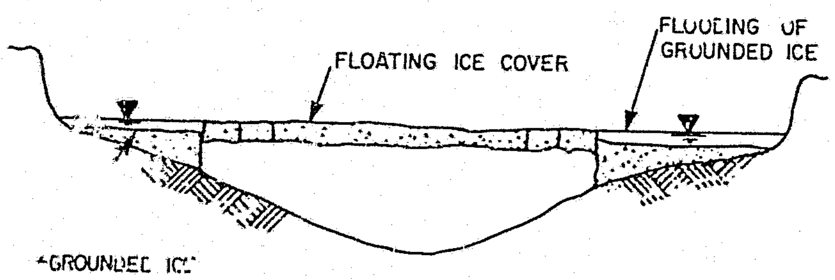
STAGE 3 DEVELOPMENT

FLOW UNDER COVER OR SLUSH/FRAZIL DEPOSITS SMOOTH UNDER SURFACE OF ICE COVER, WITH CONSEQUENT DROP IN STAGE FOR A GIVEN FLOW.



LOW FLOW STAGE

LARGE DECREASES IN FLOW RESULT IN SAGGING AND FRACTURING OF COVER. HINGE MECHANISM MAY FORM, DEPENDING ON HOW RIGIDLY COVER HAS FROZEN BEFORE LARGE DROP IN WATER LEVEL. COVER WILL FLOAT BACK UP WITH FLOW INCREASE, EITHER WITH HINGE MECHANISM OR AS SHOWN FOR HIGH FLOW STAGE, DEPENDING ON RIGIDITY OF COVER.



HIGH FLOW STAGE

LARGE INCREASES IN FLOW WILL FLOAT COVER. COVER WILL NOT FAIL PROVIDED ITS INITIAL INTERNAL EQUILIBRIUM THICKNESS WAS DETERMINED AT HIGH FLOW AND FLOW DOES NOT REACH STAGE WHICH FLOATS COVER OUT OF CONFINES OF GROUNDED ICE SHEAR WALLS.

FIGURE 6

TYPICAL ICE PROCESSES OBSERVED ON THE PEACE RIVER.

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to the shore across the shear lines. If this contact is lost, the internal stresses cumulating in the cover in the downstream direction can disrupt its equilibrium.

In the event that the cover develops at a low flow and is later subjected to a large flow, it could be expected to fail because of the loss of shoreline contact, or because it is too thin and weak internally to resist the large stresses resulting from the large flows. This is, of course, what happens at spring break-up as ice covers thin and weaken due to warming at the same time as spring melt increases run-off. However, this is not critical if it happens in mid-winter due to variations in power peaking patterns, provided that the critical discharge as previously defined is not exceeded. All that would be expected is a dynamic restructuring of the ice cover to a greater thickness at a higher elevation as occurs at spring break-up. As noted in Section 5.1 on leading edge stability, both formation and break-up data conform in determining maximum water levels. As long as the critical discharge is not exceeded, water levels will be acceptable.

From the foregoing insight evolves an operating strategy for the proposed Dunvegan Project at the time of cover formation which will preclude dynamic mid-winter cover disruptions. The strategy is quite simply to operate the plant in the mode in which it is expected to operate throughout the winter, up to the limiting critical discharge (or peak power) value. Under these conditions, the maximum desirable water levels under ice conditions will not be exceeded,but the ice cover will be able to develop with grounded ice,elevations and internal strengths appropriate to the planned winter peaking operations. Continued "exercising" of the cover on a daily basis will maintain its flexibility.

5.7 - Date of First Ice

Using the thermal regime mathematical model and the ranges of input parameters described in Appendix A, calculations were undertaken to determine the length of open water reach downstream of the Dunvegan site, with both Site C and Dunvegan reservoirs in place. These calculations provided the basis for estimating the effect of the two proposed reservoirs on the date at which ice can be first expected to appear in the river at various locations.

In general, delays of from 1/2 to 3-1/2 weeks in appearance of first ice can be expected, depending greatly on the severity of early winter temperatures experienced. Similarly, the prevailing hydrology was found to have considerable effect with higher flows delaying date of first ice by up to one month. Tables 5.4 and 5.5 summarize these effects for the reach of the river in the town of Peace River.

5.8 - Ice Front Location and Rate of Advance

The location of the ice front as the ice cover develops on the Peace River has been observed for the past 7 years, since the G.M. Shrum Plant began operating. The results of these observations are summarized on graph no. 5 on Plate G. Evidently, the position of the front on a given calender date depends markedly on the prevailing climate. The 1973/74 and 1976/77 winter seasons were the coldest and warmest of the record, respectively, and are seen to provide upper and lower bounds to the observed data. The more normal climatic years are seen to be clustered in the middle area of the plot.

The three curves shown on graph no. 5 on Plate G have been adopted to represent typical years in which the climate is extremely cold, normal, and warm. The three curves are felt to be representative of the prevailing situation. Although there has been some variability in the hydrology in the period of the record, it has been "near" normal, and the curves are thus regarded as being appropriate to the normal hydrology of the river.

TABLE 5.4

EFFECTS OF SITE C AND DUNVEGAN HYDROELECTRIC POWER PROJECTS ON THE DATE OF FIRST ICE IN TOWN OF PEACE RIVER
(Normal Discharge)

	Date of First Ice		
	Climate		
Reservoir Combinations	Cold	Normal	Warm
Williston Lake and Site 1	Early-November	Late-November to Early-December	Early-December
Williston Lake, Site 1 Site C and Dunvegan	Late-November to Early-December	Mid to Late-December	Late-December
Difference in timing	2-1/2 to 3 weeks	2-1/2 to 3 weeks	3 to 3-1/2 weeks

TABLE 5.5

EFFECT OF HYDROLOGY ON DATE OF FIRST ICE AT THE TOWN OF PEACE RIVER
(Williston Lake, Peace Canyon, Site C and Dunvegan Reservoirs in Operation)

	Date of First Ice		
	Climate		
Peace River Discharge	Cold	Normal	Warm
High (1854 m^3/s)	Early to Mid-January	Early to Mid-January	Early to Mid-January*
Normal (1110 m^3/s)	Late-November to Early-December	Mid to Late-December	Late-December
Low (328 m^3/s)	Early to Mid-November	Mid-November to Early-December	Early-December

* Computations indicated that for this case, ice would appear in the river for only a very short period.

With completion of the Site C and Dunvegan projects, the observed pattern of cover advance will change considerably. Obviously, the front will no longer be able to advance past the Dunvegan Site. Also, the loss of ice generating area both upstream of Dunvegan and downstream due to the thermal effects of the storage may reduce the rate at which ice is supplied to the advancing ice front on any given day in any climatic year. In turn, the rate of advance of the ice front will be correspondingly reduced, with its position on any given date being very much altered. An assessment of these potential changes has been made as described briefly in the following paragraphs.

The length of the open water or ice-free reach in the river on any given day due to the thermal effects of upstream storages was determined for each of the three typical climatic regimes by means of the mathematical model described in Appendix A. This was done both for the existing situation with only the W.A.C. Bennett and Peace Canyon dams in place and also with both Site C and Dunvegan dams assumed to be in place. With this information, the length of ice generating reach was calculated from the known position of the ice front on corresponding days. This is of course readily done for the existing situations where the ice front location has been defined from observations for the three typical climatic regimes as previously discussed.

For the case where the proposed developments are in place, it was necessary to assume the ice front started at Fort Vermilion and to carry out the analysis from this point using an approximate step-by-step integration procedure. Historic dates of freeze-up at Fort Vermilion were used to estimate the initial starting dates for the calculations to determine the modified rates of advance of the ice front.

The results of this analysis are presented on Plate G and summarized in Tables 5.6 and 5.7. Examination of these results provide some insight into a few of the potential effects of the proposed power developments. In general, ice cover development can be expected to occur

TABLE 5.6

SUMMARY OF ESTIMATED EFFECTS OF SITE C AND DUNVEGAN HYDROELECTRIC POWER PROJECTS ON THE DEVELOPMENT OF AN ICE COVER ON THE PEACE RIVER

(with Normal Hydrology)

Point of Comparison	Climate	Reservoir Combinations: Williston Lake and Site 1	Reservoir Combinations: Williston Lake, Site 1, Site C and Dunvegan
1. Time of ice front arrival at the town of Peace River (rate of advance through town).	Cold	Mid-December (20 km/day)	Mid to Late-December (14 km/day)
	Normal	Late-December (11 km/day)	Early to Mid-January (6 km/day)
	Warm	Mid-January (8 km/day)	Late-January (4 km/day)
2. Time of ice front arrival at Dunvegan Bridge (rate of advance).	Cold	Mid to late-December (12 km/day)	Early-January (less than 1 km/day)
	Normal	Early to Mid-January (7 km/day)	Early-February (less than 1 km/day)
	Warm	Ice front does not reach Dunvegan	Ice front does not reach Dunvegan
3. Furthest advance of ice front upstream of the town of Peace River (time of arrival).	Cold	310 km (Early-March)	100 km; Dunvegan project (Early-January)
	Normal	235 km, near Alberta/B.C. border (Late-February)	100 km; Dunvegan Project (Early-February)
	Warm	65 km; 35 km downstream of Dunvegan (Early-February)	30 km; 70 km downstream of Dunvegan (Early to Mid-February)

Note: 1. Ice front rate of advance varies markedly with air temperature on specific dates; indicated values should be regarded as approximate norms.
2. Cold and warm year types can be regarded as moderately rare events.

TABLE 5.7

SUMMARY OF ESTIMATED EFFECTS OF SITE C AND DUNVEGAN HYDROELECTRIC POWER PROJECTS ON THE DEVELOPMENT OF AN ICE COVER ON THE PEACE RIVER

(with Combinations of Extreme Temperature and Hydrology)

Point of Comparison	Climate	Reservoir Combinations	
		Williston Lake and Site 1	Williston Lake, Site 1, Site C and Dunvegan
1. Time of ice front arrival at the town of Peace River (rate of advance through town).	Cold with high discharge	Mid to late-December (13 km/day)	Early to mid-January (4 km/day)
	Warm with low discharge	Early-January (11 km/day)	Mid to late-January (7 km/day)
2. Time of ice front arrival at Dunvegan (rate of advance).	Cold with high discharge	Late December (8 km/day)	Ice front does not reach Dunvegan
	Warm with low discharge	Mid-January (8 km/day)	Ice front does not reach Dunvegan
3. Furthest advance of ice front upstream of the town of Peace River (time of arrival).	Cold with high discharge	260 km (Late-February)	65 km; 35 km downstream of Dunvegan (Late-February)
	Warm with low discharge	200 km (Early to mid-February)	55 km; 45 km downstream Dunvegan (Early to mid-February)

Note: 1. Ice front rate of advance varies markedly with air temperature on specific dates; indicated values should be regarded as approximate norms.

2. Combinations of climate and hydrology can be regarded as rare. The two combinations of temperature and hydrology considered were chosen on the basis of a trend towards an inverse relation between temperature and power demand. That is with lowering temperatures, power releases from storage (Williston Lake) tend to increase.

later in the year and more slowly than currently occurs with the existing power installations at Portage Mountain and Peace Canyon in British Columbia. For normal climatic and hydrologic conditions, the ice front can be expected to reach Dunvegan shortly before winter's end, subsequent to Site C and Dunvegan power developments.

Although moderately rare combinations of high mean river flows and warm air temperature may prevent the ice front from reaching Dunvegan in some years, it can be expected to advance to a point upstream of the town of Peace River in most years. Quite unusual combinations of high mean winter flows and warm temperatures may prevent the ice front from reaching even the town of Peace River.

It should be noted that the net reductions identified for the rate of advance of the ice front as a result of Site C and Dunvegan will be somewhat smaller if the Site C project is not undertaken due to its minimal thermal storage. Most of the reduction will be directly attributable to the Dunvegan Development by reason of its proximity to the town of Peace River.

5.9 - Upstream Effects of the Dunvegan Development

The proposed Dunvegan Development is not expected to have a significant effect on winter tailwater levels at Site C. Thermal calculations indicate that there will be insufficient ice generated in this reach to allow the thermal cover formed in the Dunvegan reservoir to progress much beyond the Alberta/British Columbia border. Except for a combination of extremely cold climatic conditions and low flows in the river, (a relatively rare event), most of the reach will remain open all winter.

Under the extreme conditions, the ice front may progress far enough upstream to cause a backwater effect. Maximum tailwater levels at Site C would have to be determined by a detailed analysis which is beyond the scope of this study. However it is anticipated that these levels would be no greater than those that would be experienced in the area without the Dunvegan Development in place.

5.10 - Winter Road Crossings

Other than the town of Peace River, there does not appear to be any other areas within the study reach that will be significantly affected by changes in the ice regime as a result of Dunvegan power operations. However, it is expected that the present utilization of winter ice roads to cross the river will not be possible in most years. There were several such crossings located in the vicinity of the town of Peace River in 1979-1980; the most notable being the Shaftesbury ferry crossing.

5.11 - Spring Break-Up Regime

The town of Peace River has been occasionally subjected to flooding during spring break-up. The primary cause of this flooding has been the accumulation of large masses of ice in the Peace River channel downstream of the Town.

Although the Peace River itself tends to dissipate its ice cover quietly, the Smoky River has been known to break up in a very sudden and forceful manner, particularly during years in which there is a significant amount of runoff. When this happens, a glut of ice is pushed into the Peace River channel. Spring flooding has not occurred as long as break-up in the Smoky River has been relatively mild.

The potential for spring break-up flooding at the town of Peace River will be unaltered by the Dunvegan Development provided that power operations are modified as required from the time that break-up on the Smoky River is imminent until its ice has safely dissipated or been transported well downstream of the town of Peace River. Since dissipation normally occurs within a period of about one week and as break-up occurs well after the period of winter peak power demands, any modifications would likely be a negligible detriment to development of the Dunvegan site.

With a live reservoir storage of 0.75 billion cubic metres, the Dunvegan Development will in fact have the potential to reduce spring break-up flooding potential. Manipulation of the storage would be required, however, with the reservoir being gradually drawn down during the month of March to create a flood storage reserve. This reserve would have to be held until it became clear whether or not it would be needed. A perfunctory analysis indicates that spring flows would be able to refill the storage in the event it was not needed for flood control.

To operate the development in this manner would result in a loss of head and consequently the ability to meet power system requirements. Nevertheless, flood control benefits may justify the operation of the plant in this mode. This would have to be determined by a detailed analysis which is beyond the scope of this study.

A - THERMAL REGIME - METHOD OF ANALYSIS

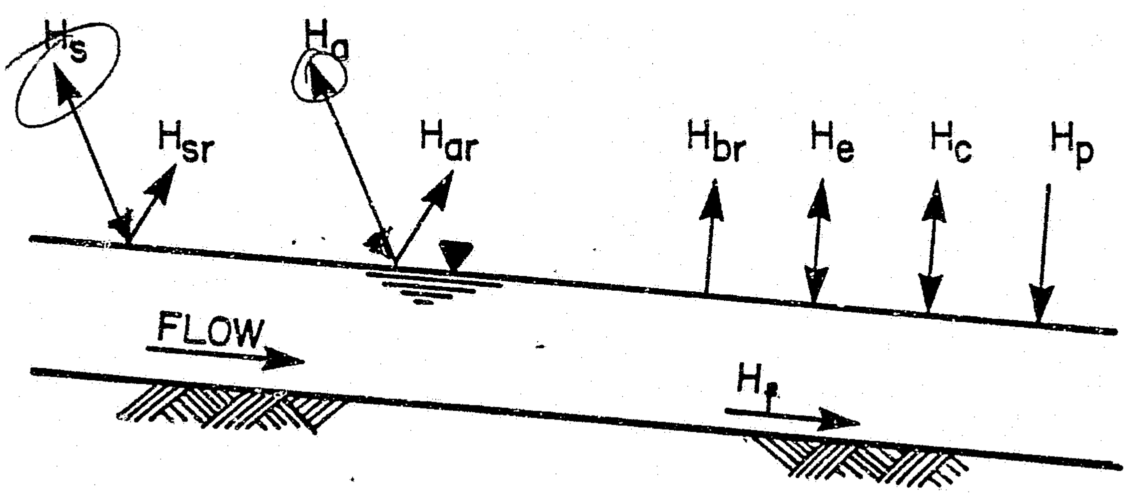
Water released from lower levels in a storage reservoir during the winter months is warmer than the freezing point, and therefore has the effect of removing a reach of the river downstream of it from active frazil ice generation. The length of the reach required for the water to be cooled to the point where ice generation can begin (approximately $0^{o}C$) is essentially a function of three variables, namely, the discharge in the river, the temperature of the water released from the reservoir and climatic conditions (mainly air temperature and wind velocity). Therefore, in order to predict the ice regime of a river, it is necessary to determine the cooling rate of the water.

A.1 - Methodology

Acres has within its library of computer programs, a mathematical model that performs daily heat transfer computations for any combination of reservoirs and/or river reaches. This model was used to evaluate the combined effects of reservoir storage at Site C and Dunvegan on the ice cover development with respect to the date of first ice, the rate of advance of the ice front and its time of arrival at various points along the river. The effects of varying climatic and hydrologic conditions on ice cover development were also considered.

A.2 - Model Description

Computation of the cooling rate from an open water surface is based on the heat budget approach. The heat budget is expressed as the sum of the major components illustrated and described as follows:



$$H_{net} = H_s - H_{sr} + H_a - H_{ar} - H_{br} \pm H_e \pm H_c \pm H_p + H_f$$

where:

H_{net} is the net heat transfer at the water surfaces

H_s is the solar radiation incident to the water surface

H_{sr} is the reflected solar radiation

H_a is the atmospheric radiation incident to the water surface

H_{ar} is the reflected atmospheric radiation

H_{br} is the back radiation or the net energy lost by the body of water through the exchange of long-wave radiation between the body of water and the atmosphere

H_e is the evaporative heat exchange

H_c is the conductive heat exchange

H_p is the heat required to supply the latent heat of fusion of snow falling into the water <u>or</u> the heat gain from rainfall

H_f is the heat gain from flow friction losses in a river reach

Each of the above components is determined using the empirical relationships presented in Raphael (1962) and Michel (1971). Several other possible sources of heat such as the conduction of heat from within the earth and heat gain from groundwater inflows have been neglected because of their relatively small magnitude.

Heat transfer computations for a reservoir also take into account the formation and growth of an ice cover once the reservoir temperature becomes uniform at about 4°C. The ice cover growth is represented by a simple relationship originally derived by Stefan and simplified by others (see Michel, 1971).

$$t_i = a\sqrt{D}$$

where: t_i = thickness of solid ice

a = a form of local heat transfer coefficient

D = accumulated degree-days of freezing

The coefficient "a" is obtained from experience to represent the time average values of the various physical and thermal properties of the ice and water, as well as the highly variable and complex heat transfer between the ice and the atmosphere. Heat transfer at the ice/water interface is also considered in the selection of "a". Values of the coefficient, derived from field experience are:

windy lakes with no snow	$a = 0.8$
average lake with snow	$a = 0.5$ to 0.7

A value of $a = 0.6$ was adopted for this analysis.

Although heat transfer from the lower ice surface to the atmosphere actually occurs in two stages, the model assumes that the upper ice surface is at air temperature and therefore heat transfer occurs from conduction alone. Experience has shown this approximation to be acceptable.

Heat conducted to or from the lower ice surface (ice-water interface) is described by the following equation:

$$q_c = \frac{k_c}{t_i} (T_f - T_s)$$

where: q_c = rate of heat transfer

k_c = conduction coefficient

t_i = ice cover thickness

t_f = freezing temperature of water

T_s = upper ice surface temperature

Transfer of heat by convection and radiation from the upper ice surface to the atmosphere is not considered in the model. Baines (1961) notes that this practice is equivalent to assuming an overcast sky condition and a strong wind, whereas the average winter condition is one of moderate sunshine and light wind which tends to produce thinner covers.

The validity of this assumption is supported by data collected on the Nelson River as reported by Newbury (1966). Newbury's analysis of the data showed independence of ice growth from wind conditions and a transfer coefficient very near the generally accepted value for conduction through ice.

After performing daily heat transfer calculations, the model then determines the water temperature at the end of each river reach and also identifies the point at which frazil ice begins to form on the water surface. The criterion adopted to determine the length of the ice generating reach, i.e., frazil ice begins to form at water temperatures less than about 0.1°C, was supported by observations made by the BCHPA during their ongoing field investigation program on the Peace River.

The computations to determine the outflow temperature in a reservoir take into account the additional heating or cooling effect caused by daily inflows. It is assumed that the temperature would be uniform throughout the entire body of water. This approximation is considered reasonable for the reservoirs below Williston Lake because they have relatively small storage volumes and thus relatively short turnover periods.

A.3 - Model Calibration

Calibration of the heat budget model was based on continuous daily water temperature and air temperature data obtained from the BCHPA for two periods - January 1977 to March 1977, and November 1977 to January 1978. Although BCHPA have been recording water temperatures in the Peace River since about 1973, the above periods constitute the most comprehensive data available for the reach between the W.A.C. Bennett Dam and Site C. Water temperatures have not been recorded on a regular basis between Site C and the town of Peace River.

The objective of the calibration was to reproduce the daily record at Site C using the Peace Canyon data and the meteorological records at the Fort St. John Airport (with the exception of air temperature) as input to the model. The air temperature data used were those observed adjacent to the river by the BCHPA.

A comparison of the computed versus measured thermographs at Site C for the two periods is presented on Plate E. It can be seen from the relatively close agreement achieved that the model is suitable for predicting the cooling rate from an open water surface.

A.4 - Model Parameters

The basic input parameters that were used in the model to compare the effects of Site C and Dunvegan storage on the existing ice cover development are outlined as follows:

(a) Meteorologic Data

The typical climatic regimes, designated as cold, normal, and warm, were selected from meteorologic records at the Fort St. John airport for the period 1969 to 1979, which covers the period of operation of the G.M. Shrum Plant. The 1973-1974 and 1976-1977 winter seasons were respectively the coldest and warmest of the record, and were therefore used for these two extremes. The 1972-1973 period was selected as a normal winter season. A comparison of the accumulated degree-days of freezing associated with each climatic regime is shown in Figure A.1.

(b) Channel Hydraulic Data

The river channel between the W.A.C. Bennett Dam and the town of Peace River was subdivided for computation purposes into three hydraulically distinct reaches. Relationships between mean depth versus discharge and mean velocity versus discharge were then derived for each reach using data available from the Water Survey of Canada. These are summarized in the following table.

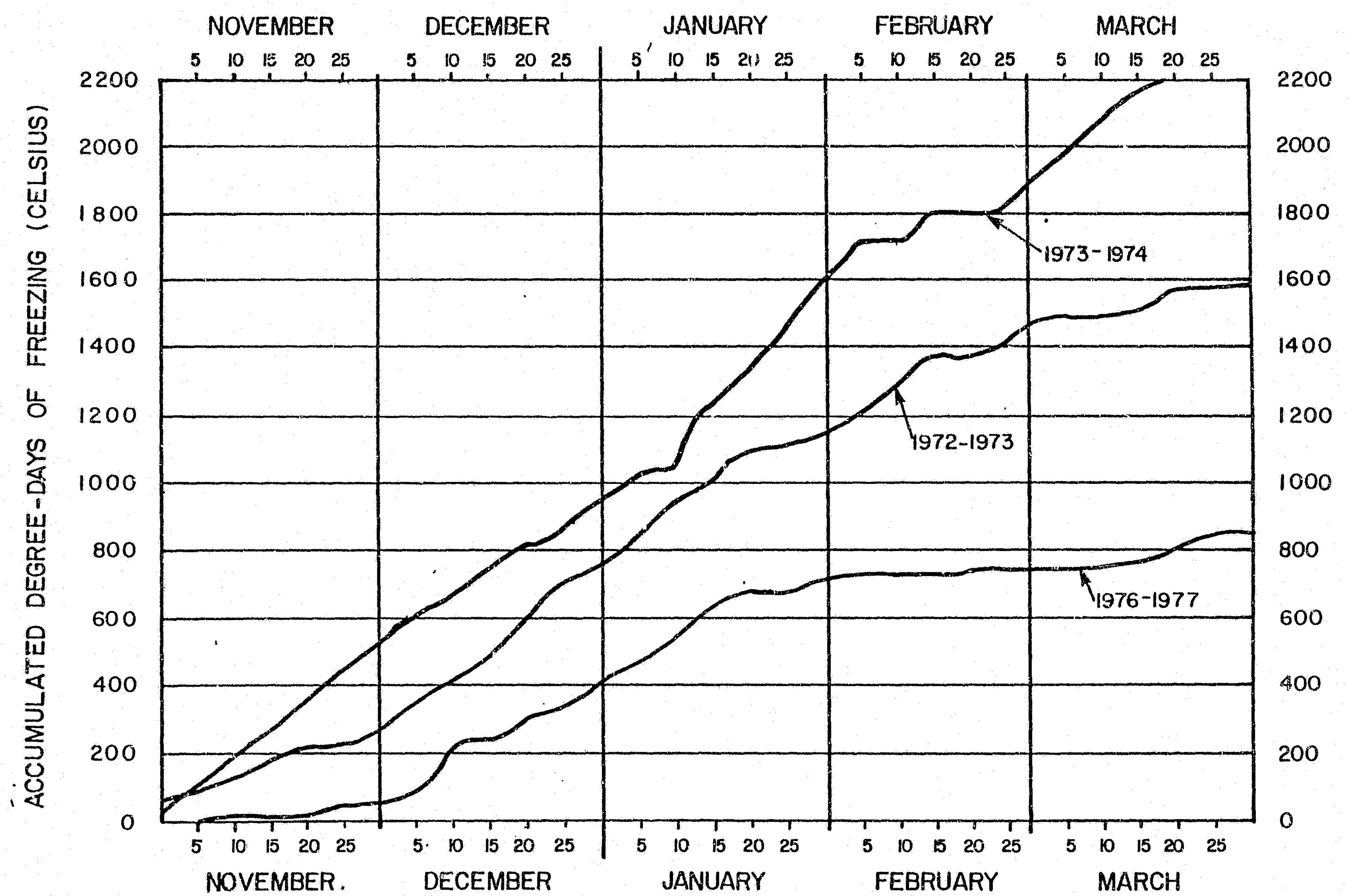


FIGURE A1

DEGREE-DAYS OF FREEZING
FORT ST. JOHN (A)

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MEAN DEPTH/VELOCITY RELATIONSHIPS

Characteristic Reach	Corresponding Water Survey of Canada Gauge	Mean Depth	Mean Velocity
W.A.C. Bennett Dam to Site C	07EF001 Hudson Hope, B.C.	$d = .1162\ Q^{.44}$	$V = .117\ Q^{.35}$
Site C to Dunvegan	07FD002 Taylor, B.C.	$d = .129\ Q^{.44}$	$V = .013\ Q^{.55}$
Dunvegan to Peace River	07FD003 Dunvegan, Alberta	$d = .025\ Q^{.62}$	$V = .188\ Q^{.29}$

where V = mean velocity in metres per second
d = mean depth in metres
Q = discharge in cubic metres per second

(c) Reservoir Data

For the purpose of this analysis each plant was assumed to be operating at full supply level. The reservoir storage volumes and surface areas associated with these levels are summarized as follows:

RESERVOIR DATA SUMMARY

Plant	Full Supply Level (FSL)	Total Storage Volume	Surface Area at FSL
Dunvegan	El 381 m	$1.6 \times 10^9\ m^3$	96 km^2
Site C	El 462 m	$2.2 \times 10^9\ m^3$	97 km^2
Peace Canyon	El 503 m	$0.2 \times 10^9\ m^3$	9 km^2

(d) Water Temperature Data

Water temperatures measured in the G.M. Shrum tailrace in 1976-1977 and 1977-1978 were used to develop a typical thermograph for outflows below the development. This location was the point for all of the calculations undertaken with the heat budget model. Examination of available records shows that because of its great size and depth, temperatures below Williston Lake do not vary significantly from year to year.

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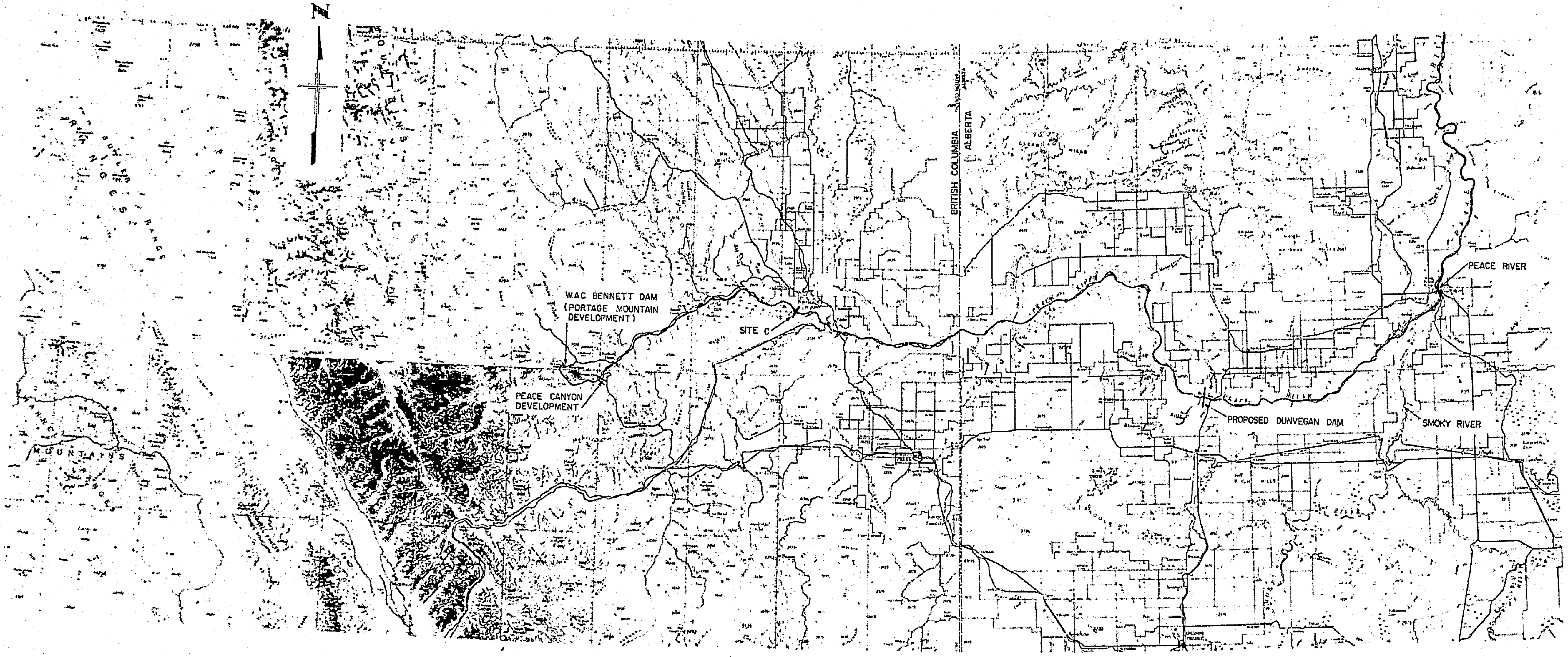
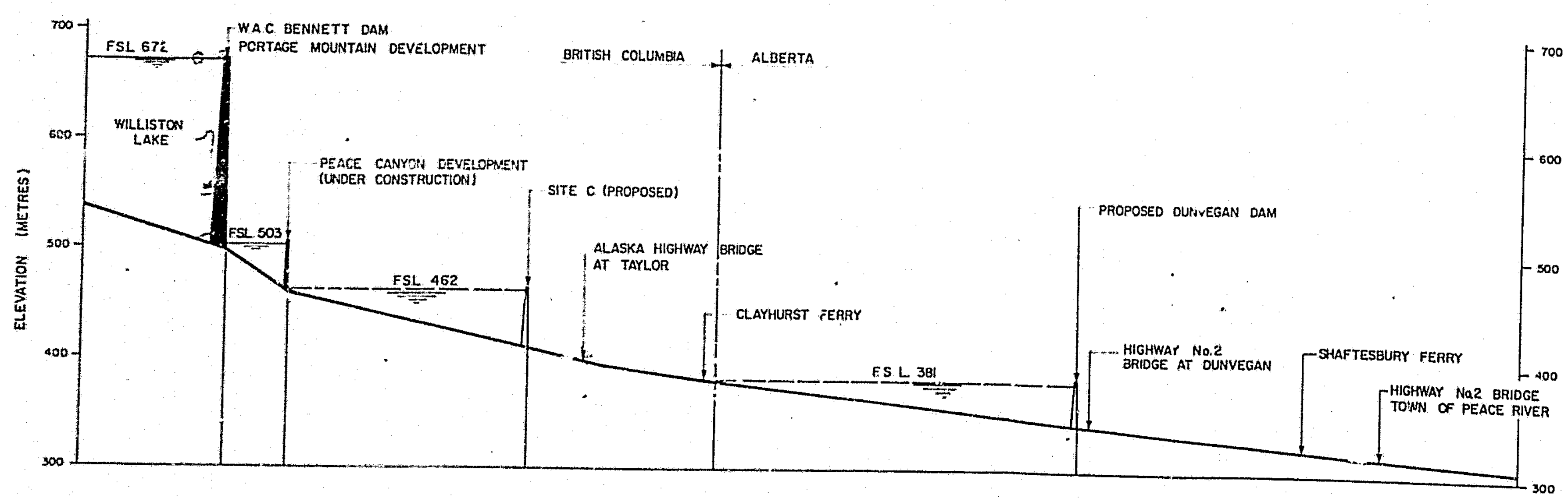


PLAN (SCALE A)



PROFILE (SCALE B)

SCALE A 30 0 30 KILOMETRES

SCALE B 50 KILOMETRES

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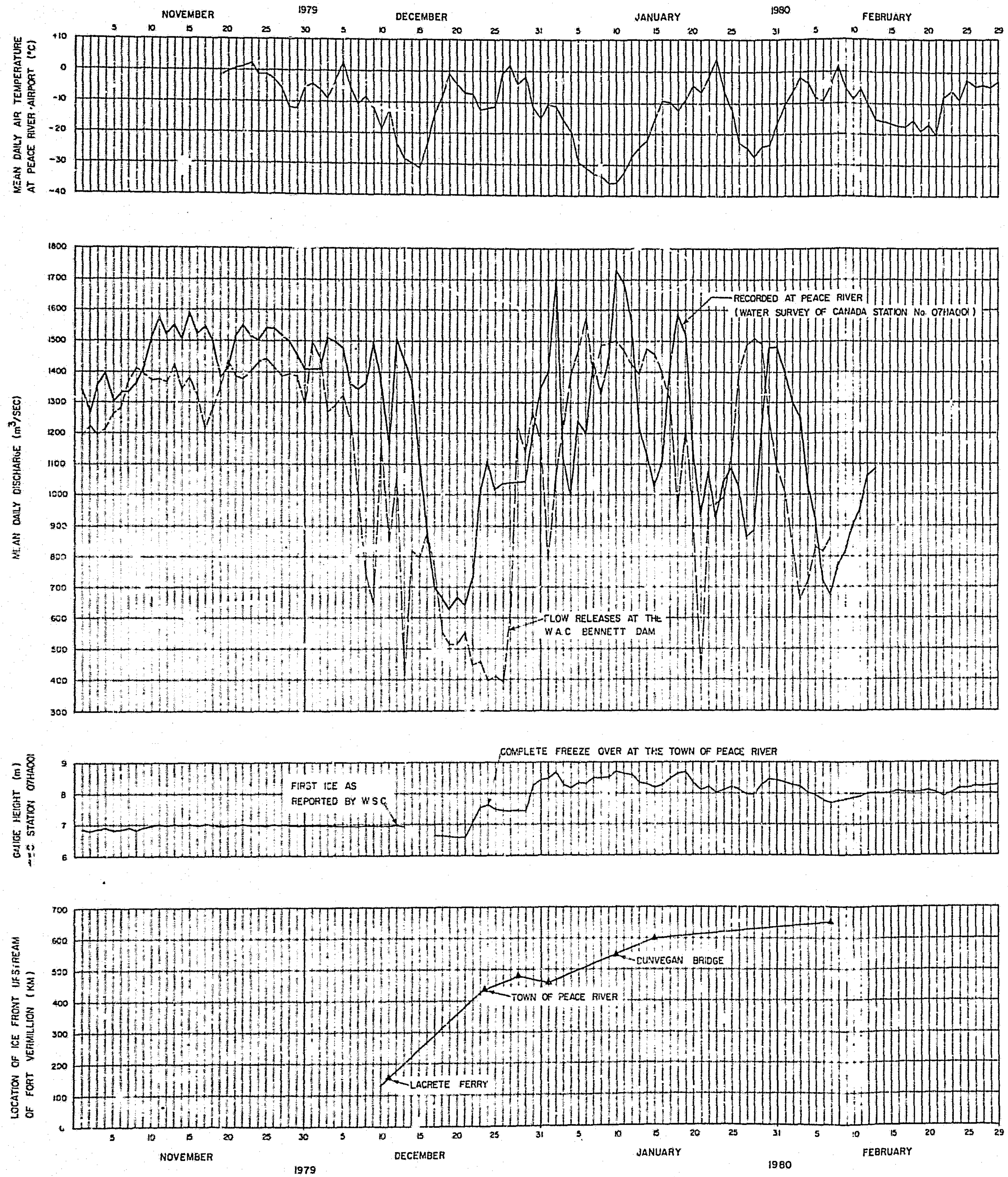
	PEACE RIVER PLAN AND PROFILE
P.B. Ellor (signature) ACRES	JUNE 1980 — PLATE A



NOTE
RECORDED DISCHARGES AT PEACE RIVER ARE PRELIMINARY DATA AND MAY NOT BE ACCURATE DURING THE ICE FORMATION PERIOD DUE TO ICE EFFECTS.

LEGEND
▲ OBSERVED LOCATION OF ICE FRONT.

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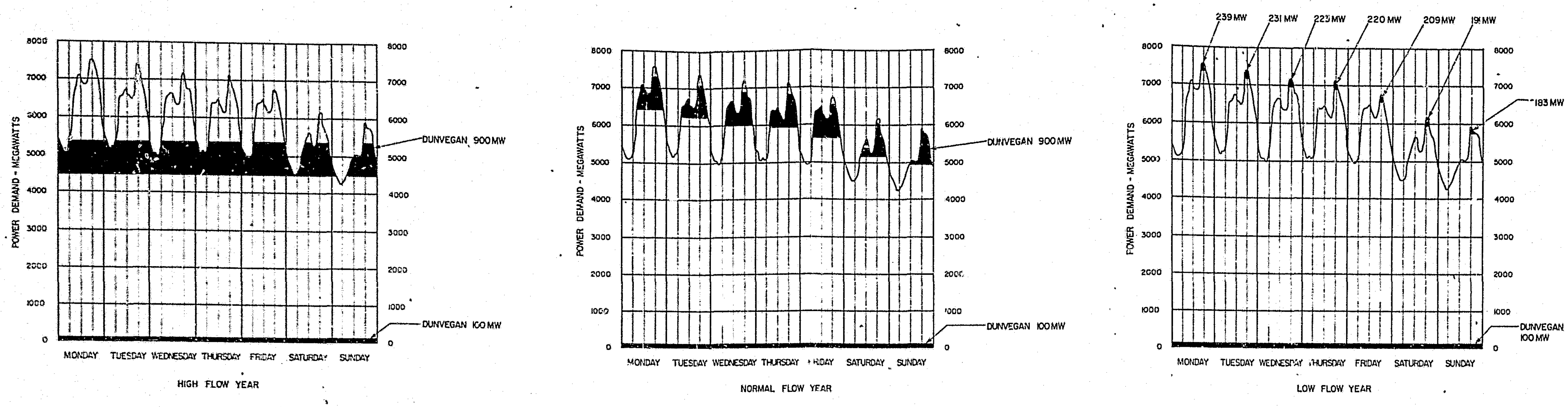
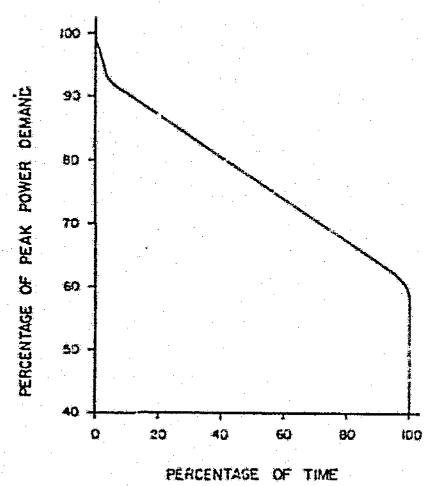
PEACE RIVER HYDROMETRIC DATA FOR THE 1979-1980 ICE FORMATION PERIOD

ACRES | JUNE 1980 | PLATE B



TYPICAL WEEKLY LOAD PATTERN (1990)



HOURLY LOAD DURATION CURVE

NOTE:

1 WEEKLY LOAD PATTERN BASED ON JANUARY 14 TO 20, 1974 LOAD PATTERN.
2 HOURLY LOAD DURATION CURVE OBTAINED FROM 1978 ANNUAL STATISTICS REPORT ELECTRIC UTILITY PLANNING COUNCIL, SYSTEM EVALUATION AND RELIABILITY COMMITTEE.

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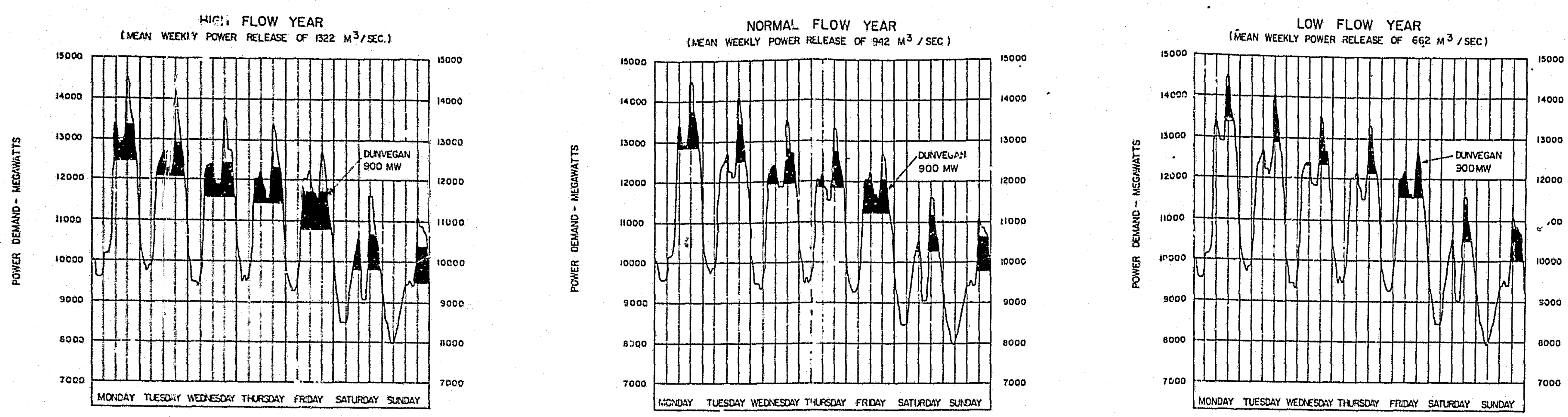
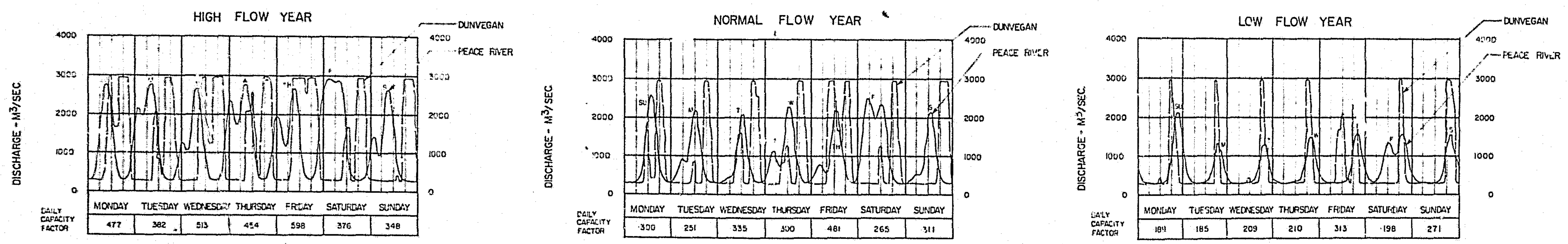
	DUNVEGAN POWER DEVELOPMENT ICE ANALYSIS
	TYPICAL WEEKLY LOAD PATTERN FOR THE ALBERTA INTERCONNECTED POWER SYSTEM IN 1990
ACRES	JUNE 1980 — PLATE C



TYPICAL WEEKLY LOAD PATTERN FOR THE ALBERTA INTECONNECTED POWER SYSTEM IN 2005

(NOTE 100MW AT DUNVEGAN ASSUMED TO BE BASE LOADED IN SYSTEM)



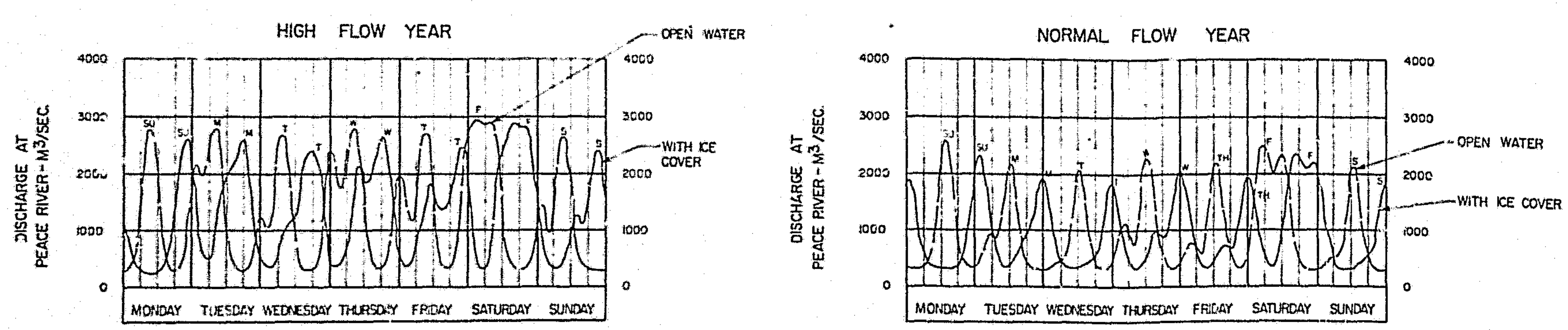
HOURLY FLOW PATTERNS FOR OPEN WATER CONDITIONS

LEGEND

SU SUNDAY
M MONDAY
T TUESDAY
W WEDNESDAY
TH THURSDAY
F FRIDAY
S SATURDAY

NOTE

HOURLY FLOW PATTERNS SHOWN ARE REPRESENTATIVE EXAMPLES OF THE RANGE OF HYDROLOGIC AND OPERATING CONDITIONS CONSIDERED IN THIS STUDY



EFFECT OF AN ICE COVER ON HOURLY FLOW PATTERNS AT THE TOWN OF PEACE RIVER

(PEACE RIVER ASSUMED TO BE ICE COVERED TO THE VICINITY OF THE DUNVEGAN TAILRACE)

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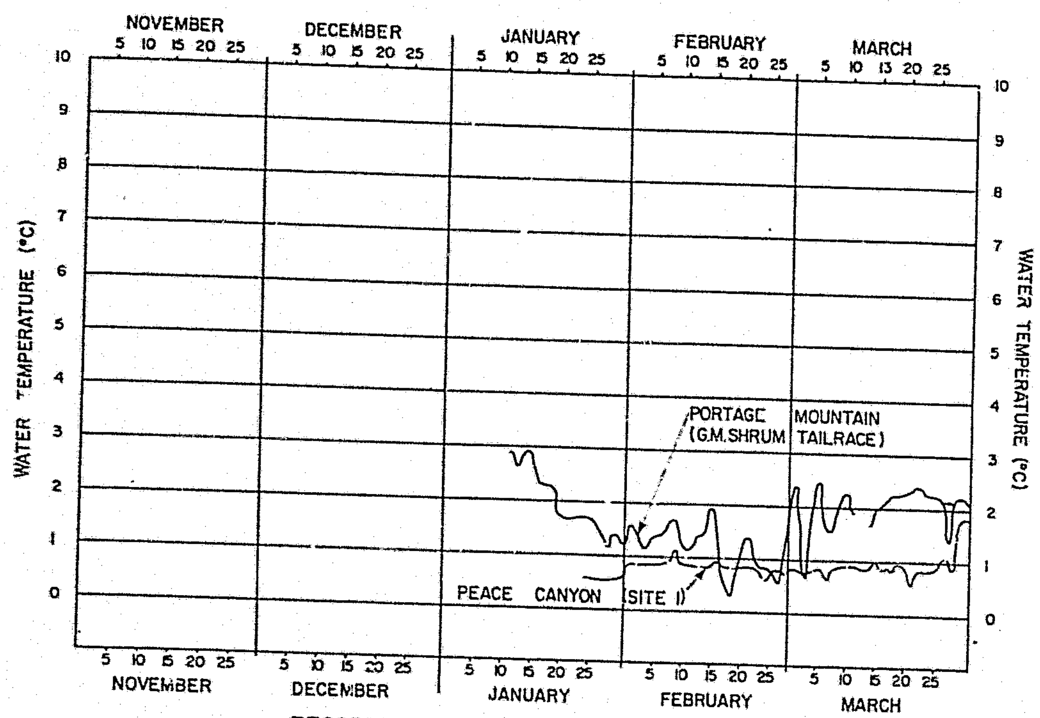
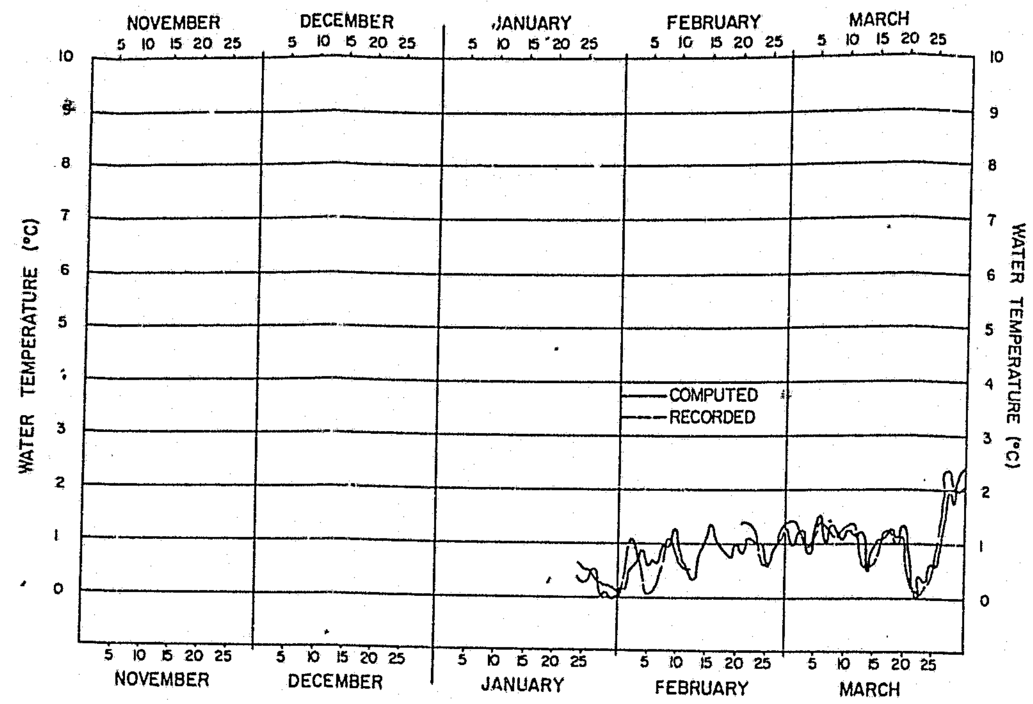
HOURLY FLOWS FOR A TYPICAL WEEKLY LOAD PATTERN IN 2005

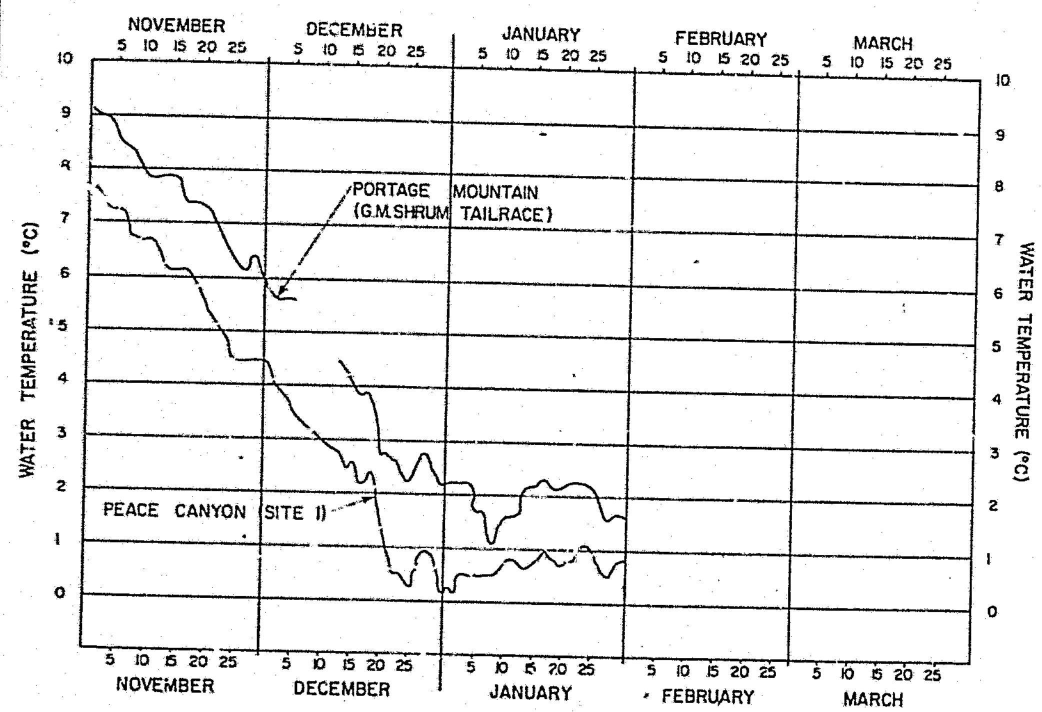
ACRES | JUNE 1980 | PLATE D



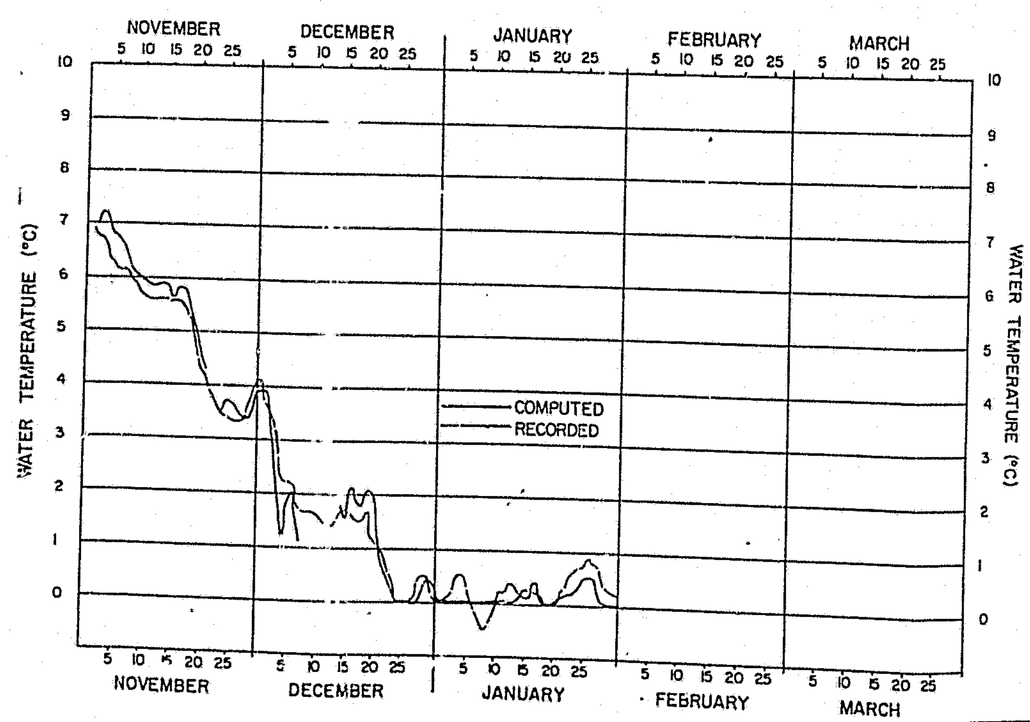
RECORDED WATER TEMPERATURES AT PORTAGE MOUNTAIN AND PEACE CANYON 1977



RECORDED AND COMPUTED WATER TEMPERATURES AT SITE C 1977



RECORDED WATER TEMPERATURES AT PORTAGE MOUNTAIN AND PEACE CANYON 1977/78



RECORDED AND COMPUTED WATER TEMPERATURES AT SITE C 1977/78

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PEACE RIVER WATER TEMPERATURE DATA

R. B. Elson
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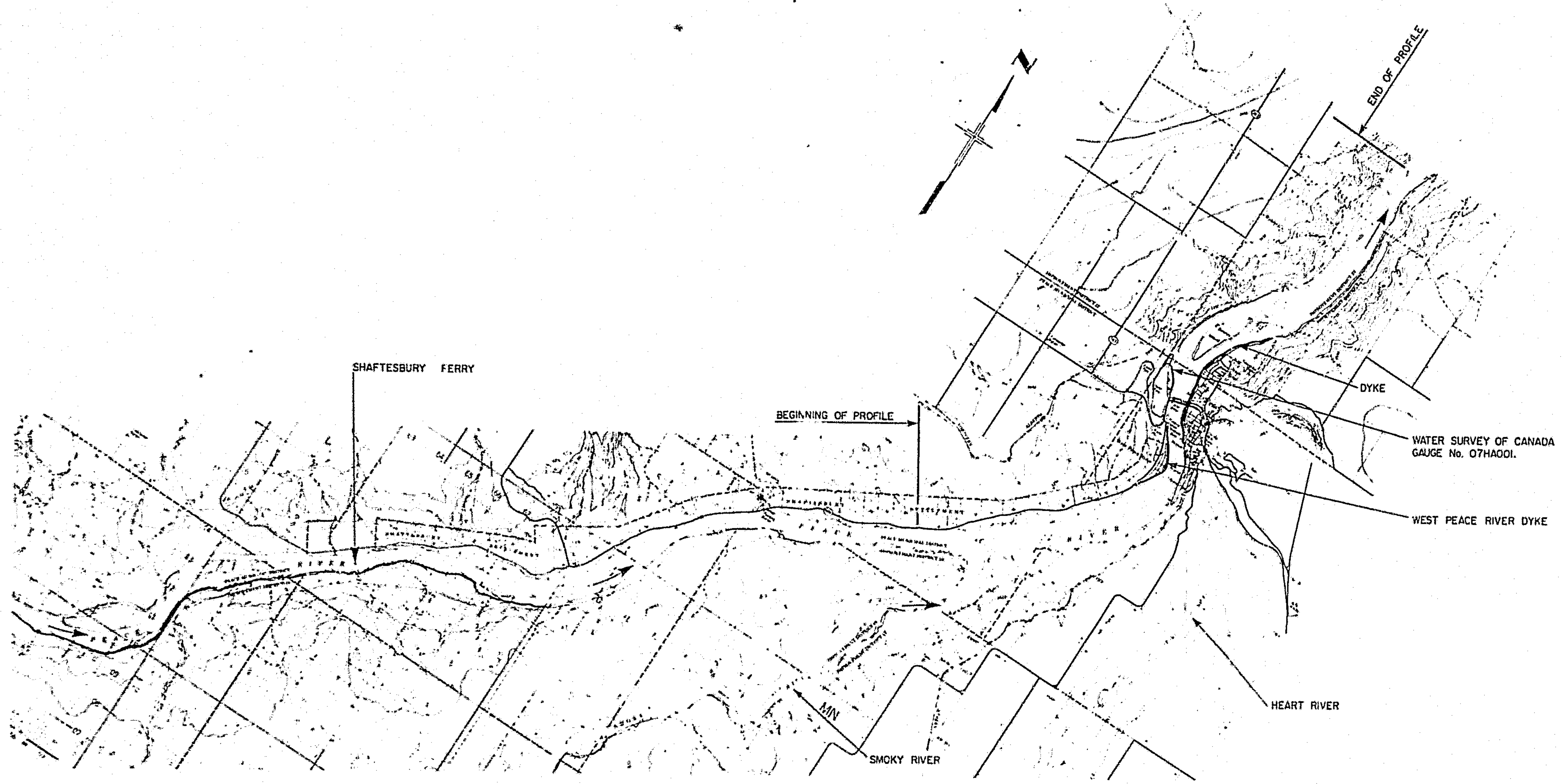
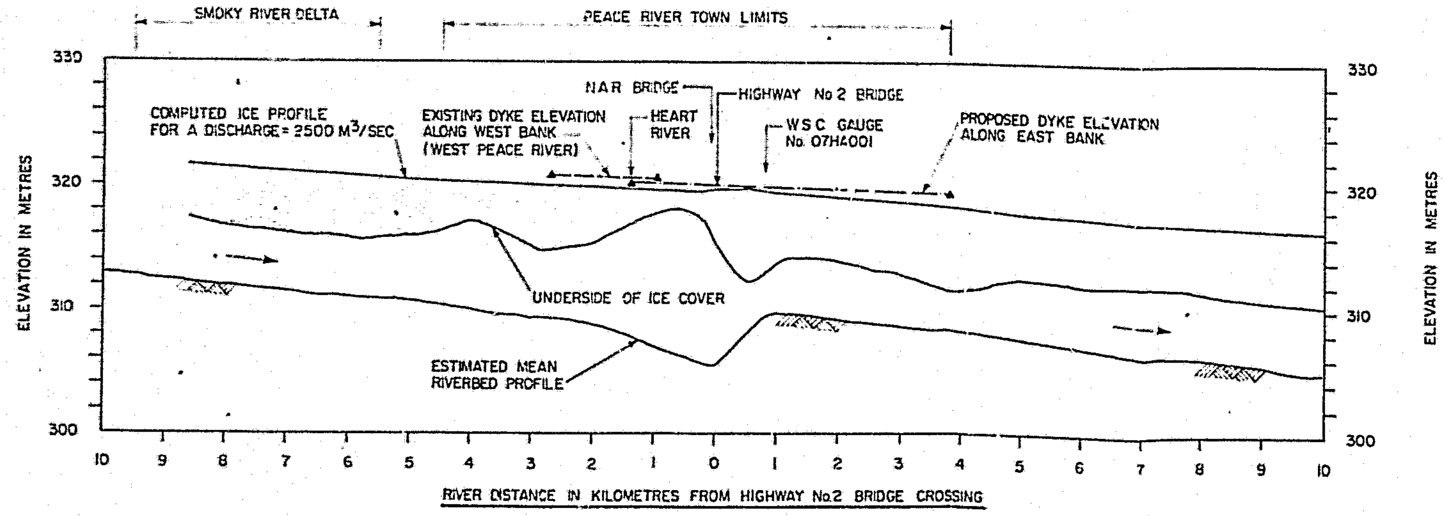
PLATE E



PLAN



PROFILE

30 0 30

SCALE IN KILOMETRES

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DUNVEGAN POWER DEVELOPMENT ICE ANALYSIS

PEACE RIVER PLAN AND PROFILE IN THE VICINITY OF THE TOWN OF PEACE RIVER.

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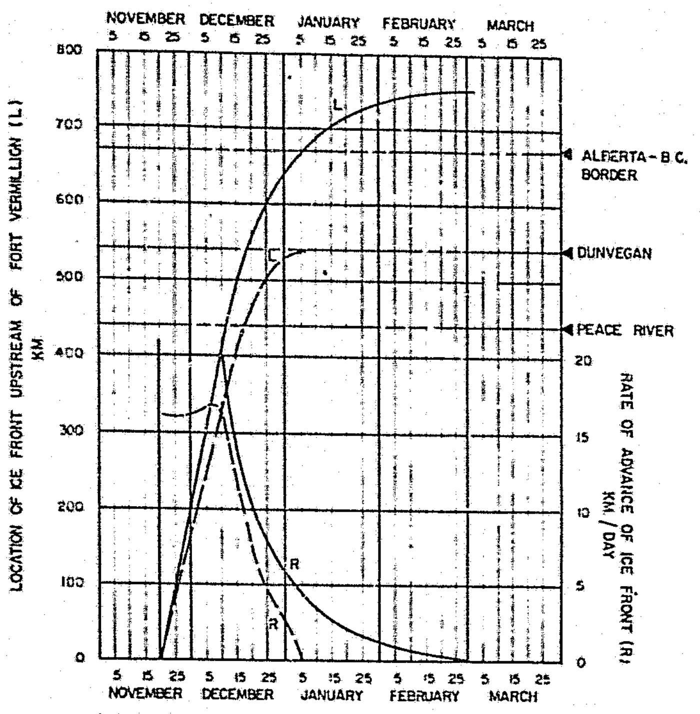
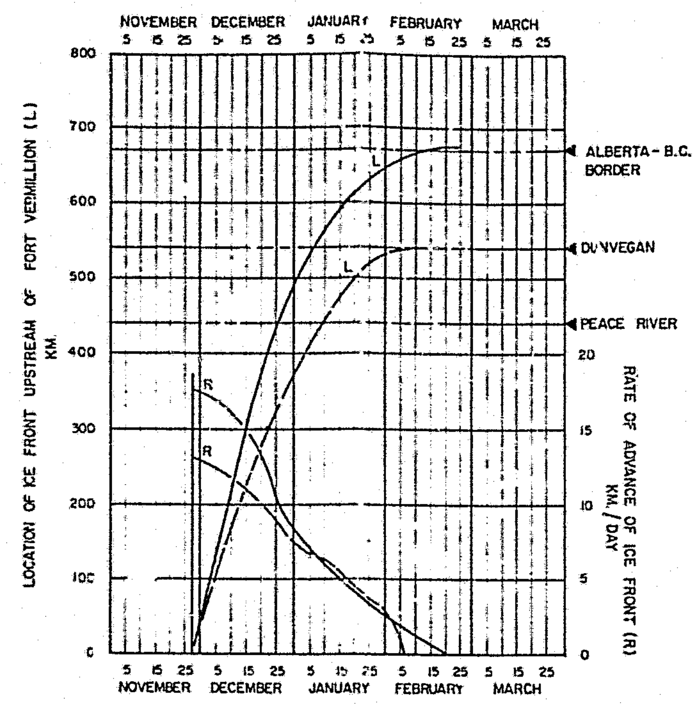
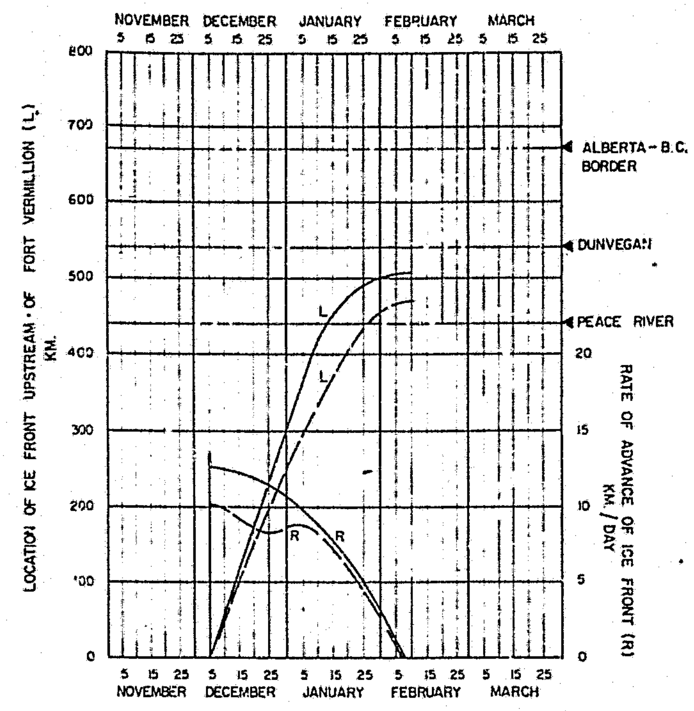
PLATE F



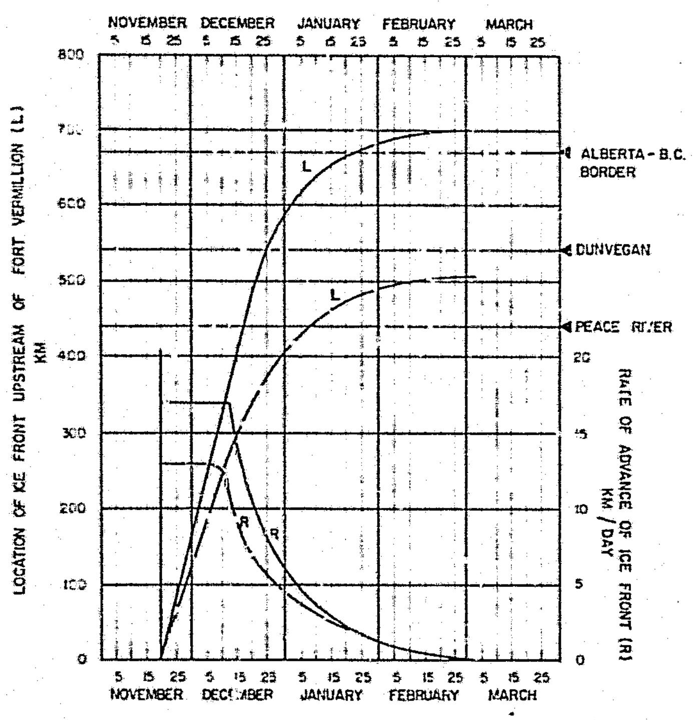
1. NORMAL FLOW — COLD TEMPERATURES



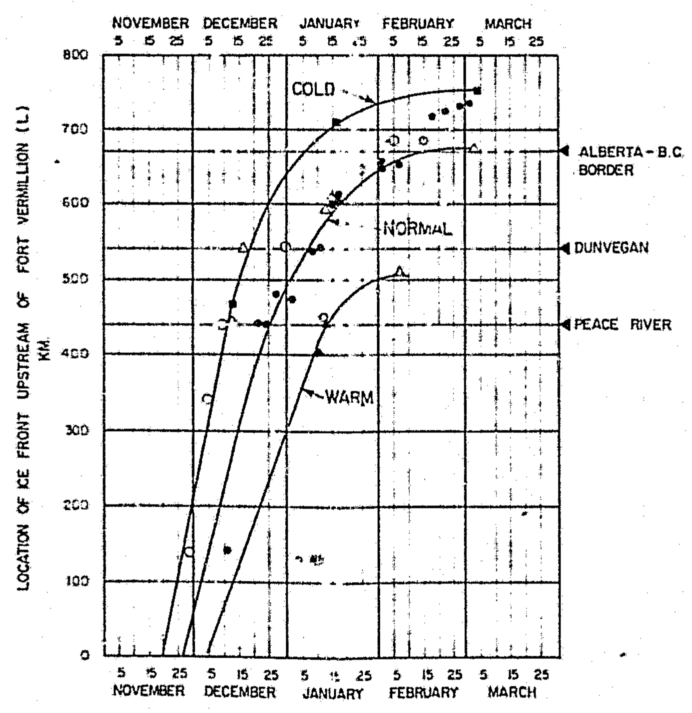
2. NORMAL FLOW — NORMAL TEMPERATURES



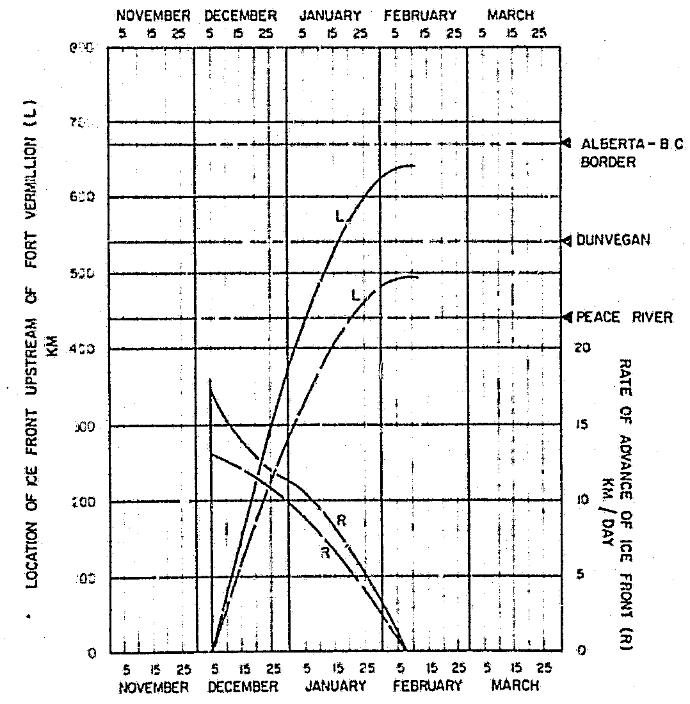
3. NORMAL FLOW — WARM TEMPERATURES



4. HIGH FLOW — COLD TEMPERATURES



5. ENVELOPE CURVES FOR NORMAL FLOW
(OBSERVED DATA)



6. LOW FLOW — WARM TEMPERATURES

LEGEND

- ——— PORTAGE MOUNTAIN AND PEACE CANYON
- – – – PORTAGE MOUNTAIN, PEACE CANYON, SITE C, AND DUNVEGAN
- ■ 1973 TO 1974 OBSERVED DATA
- ○ 1974 " 1975 " "
- △ 1975 " 1976 " "
- ▲ 1976 " 1977 " "
- ○ 1977 " 1978 " "
- ● 1978 " 1979 " "
- ● 1979 " 1980 " "

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ICE COVER DEVELOPMENT ON THE PEACE RIVER

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PLATE G