SUS. 489

# SUSITNA HYDROELECTRIC PROJECT

# SURVEY OF EXPERIENCE IN OPERATING HYDROELECTRIC PROJECTS IN COLD REGIONS

## VOLUME 4 - APPENDIX E

## FIELD MEMORANDUM OF VISIT BY H.W. COLEMAN BRITISH COLUMBIA HYDRO (VANCOUVER) AND PEACE RIVER TOWN AND SUPPLEMENTARY MATERIAL

Prepared by
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Prepared for
Alaska Power Authority

Draft Report
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**HARZA-EBASCO** *SUSITNA JOINT VENTURE*

**MEMORANDUM**

LOCATION Chicago Office

DATE April 20, 1984

TO FGD, AEA, MPS, HHC, WEL

NUMBER

FROM H.W. Coleman

SUBJECT Winter Power Operations
B.C. Hydro-Peace River Experience

Introduction

During the week of April 2, 1984, HWC and Wayne Dyok attented the Third International Specialty Conference on Cold Regions Engineering in Edmonton, Alberta to add to background design information for Susitna. My comments regarding the conference papers are included in a separate memo. In addition to the conference, we gathered additional information regarding B.C. Hydro's winter power operation, particularly the Portage Mountain Development (PMD), and its effect on downstream river ice in the vicinity of Peace River Town (PRT), Alberta. Reference 1 gives a good summary description of the freeze-up event of January, 1982, which has focused attention on the flooding potential of fluctuating power flows with an ice covered river.

Conclusions

My conclusions regarding the effect of Portage Mountain Development on Peace River ice conditions, based on discussions with B.C. Hydro and Alberta Environment personnel, and other are as follows:

1. Freeze-up staging of the order of several meters can result from consolidation of an ice front following flow fluctuations from a load following power plant.

2. This consolidation and associated staging can extend over a range of 100-150 km.

3. Such consolidations occur naturally to some extent, but are considerably more frequent and of greater magnitude with the higher winter power flows, and particularly if flow is fluctuated.

4. The most important aspect of the freeze-up staging is flow surge from water released from storage under a backwater profile following consolidation of an ice front, resulting in unsteady flows which may be 1.5-2.0 times the steady flow.

5. The generally accepted procedure for operation in the vicinity of a sensitive area, is to maintain steady, high power discharge while the ice front is passing thru the area. Once the front is well upstream, and a competent cover has developed, which period

may be 1-2 weeks depending on the air temperatures, load following operations can resume. The ice front is always subject to consolidation, but the sensitive area will be safe if the front is far enough upstream.

6. Break-up consolidation and jamming is much less controllable. Factors other than power releases can be more important, such as development of intervening flow from snowmelt, effect of tributaries, and rate of warming of air temperatures.

7. On the Peace River, the procedure on break-up seems to be to provide high, fluctuating flows as far as possible in non-sensitive areas. When approaching a sensitive area, it is desirable to reduce flow and hold steady until the front is downstream of the sensitive area.

8. For Sustina, our basic problem is that we don't have a specific sensitive area, but rather the entire river more or less, since the fishery is the primary environmental concern.

## Visit to Peace River Town

I visited PRT on April 3, 1984 in order to see the river ice conditions first-hand and talk to Alberta Environment personnel in PRT, who monitor the river ice conditions on a daily basis. Reference 2 shows photos of the river ice conditions in PRT and for a distance of about 25 km upstream on April 3, 1984. The ice front on this day was near Dunvegan Bridge, about 100 km upstream of PRT. The front was retreating gradually with warm air temperatures and little intervening flow. I talked briefly with Jim Amirault of Alberta Enviroment in PRT. His staff monitors ice front location and ice conditions in general. When the ice front is advancing or retreating thru town, the central office in Edmonton takes over the monitoring effort. Gordon Fonstad of the Edmonton office has been in charge of this program in recent years. Amirault emphasized the importance of the Smoky River, which enters the Peace about 6 km upstream of town. If the Smoky breaks up prior to the Peace, jamming will occur in town. (Reference 3, p. 15). This occurred in 1979 and raised ice levels within 0.3 meters of the top of dikes at that time. The dikes were subsequently raised about 1 meter. High break-up stages occurred in 1973 and 1974 also (Reference 3, p. 17), but dikes were not overtopped since they had been raised following a very large summer flood in 1972.

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In fact, all high stages prior to 1982 resulted from break-up. The January 1982 event was the first problem which occurred on freeze-up.

Following the early January, 1982 freeze-up event in PRT, B.C. Hydro releases were held very uniform at about 1700 $m^3/s$ (about 90% of capacity) for the next two weeks, per request of Alberta Environment (Reference 4, p. 5). On January 20, B.C. Hydro returned to its normal load following operation, with discharge varying daily from as high as 1900 $m^3/sec$ to as low as 900 $m^3/sec$ (Reference 4, Figure 1). The gauge reading at Peace River showed almost no response to the daily flow fluctuation.

Basement flooding in PRT was reported as early as January 9, 1982. However, because power demand was high, and an attempt was being made to "set" the ice cover, releases from B.C. Hydro were not decreased (Reference 4, p. 6). Consequently, groundwater levels in West PRT maintained at flood levels until early March, after B.C. Hydro releases were decreased to about 1000 $m^3/s$ in late February. In late March, B.C. Hydro increased flows again and flooding occurred again in PRT until the river ice broke up in late April.

Because of the massive amount of ice in the consolidated cover from the January, 1982 event, break-up was considered a potential problem in PRT. Mitigative measures included plowed lanes in the ice with sand and salt to weaken the ice at desired locations and pre-blasting in jam key areas. The break-up turned out to be very mild, primarily melt-out in place, because of a dry fall and cool spring which prevented a build-up of river flow before break-up. In addition, B.C. Hydro releases were maintained nearly constant for 1 week prior to break-up in PRT.

After talking with Amirault, I toured the river around town, and drove up river about 25 km to Shaftsbury Ferry. The river was ice coverd generally, with a few areas of weak ice and a few small open leads. The ice level in town appeared to be 5-6 meters below the top of dikes. The ice was generally rough and broken up from consolidation. The river at surface level was generally 500-600 meters wide, excluding islands, and of the order of 5 meters deep. The ice was probably up to 2 meters thick. My general impression from looking at the river ice condition and stage, was that break-up flooding this year will be no problem. However, it has been demonstrated many times that break-up predictions are notoriously unreliable.

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B.C. Hydro-Peace River Experience

Visit to B.C. Hydro, Vancouver

On Thursday, April 5, Wayne Dyok and I flew from Edmonton to Vancouver to discuss winter power operation and enviromental aspects common to B.C. projects and Susitna.

We met with C.V. Kartha and Les Parmly of the Hydrology Section. They are in charge of monitoring river conditions at the various B.C. Hydro projects.

Parmly described the Peace River as follows: The river originates in the Rocky Mountains in B.C. and flows easterly to Peace River Town Alberta, a distance of about 500 km. From Peace River Town, it flows north and then east to vicinity of Lake Athabasca in Northeastern Alberta, another 500-600 km. From here it joins other rivers, ultimately the Mackenzie River, and drains to the Beaufort Sea. The river is generally wide and flat sloped, with intermittent narrow canyon sections. In 1972, the Portage Mountain Development (PMD), located about 400 km upstream of PRT, was completed. In 1979, the Peace Canyon Dam, about 20 km downstream of PMD, with much smaller storage and no reregulation capacity, was completed.

The PMD supplies about 35% of the total sytem load and Mica about 25% (Reference 5). PMD is the primarily load following plant because treaty committments to the U.S. preclude Mica from large flow fluctuations. Therefore, it is critically important to the B.C. system for PMD to load follow in the winter.

Under pre-project conditions, the ice cover advanced upriver, and with some intermitttent bridging, eventually covered the entire river length. With PMD, the ice generally bridges well downstream of PRT at Fort Vermillion, and advances upriver to vicinity of the Alberta-B.C. border, about 175 km downstream of PMD. The furthest upstream progression with PMD has been to the town of Taylor, B.C., about 125 km downstream of PMD, in 1974 and 1979.

PMD has a selective withdrawal intake with two levels. Drawdown is up to 100 feet. Release temperatures in winter are generally 2-3°C.

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FROM H.W. Coleman Page Five

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B.C. Hydro has developed a river ice computer model over the years for use on the Peace and other rivers. Their model is the result of work done by LaSalle Lab on the Liard and MacKenzie Rivers, and other improvements based on Syl Petryks work on the Peace. The main concern of B.C. Hydro on the Peace seems to have been the freeze-up jam induced flooding around Taylor, B.C. in 1974 and 1979. The event in 1979 was extensively monitored and modelled by B.C. Hydro (Reference 6).

The freeze-up jams at Taylor, B.C. are induced by the flow fluctuations at PMD, when the ice front is in the vicinity of Taylor. The situation is similar at Peace River Town (PRT). The difference is that the problem at PRT has generally been during break-up, whereas break-up has not been a problem in B.C.

Parmly and Kartha confirmed the influence of the Smoky River on PRT problems. If the Smoky breaks-up first, jams will develop at the confluence with possible flooding in PRT. B.C. Hydro recognizes that operation control is necessary at PMD during passage of the ice front thru sensitive areas during freeze-up. Their approach is to "set" the cover in place at relatively high uniform flows. After this, they can fluctuate load as required with no negative effects.

On break-up, the preferred procedure is to try to induce the Peace to break-up in PRT prior to the Smoky. To accomplish this, PMD should be fluctuated as much as possible as long as the ice front is well upstream of PRT. When the break-up front nears PRT, PMD flow should be minimized and held steady until the front moves thru PRT. Following this, PMD can resume normal operation.

In March, 1982, Acres conducted ice flexure tests on the Peace River for the Canadian Electrical Association. These test consisted of flow fluctuations at Peace Canyon over a 6 day period, with measurements of open-water stage fluctuations, and under-ice stage fluctuations downstream of the ice front. Results are shown in Reference 7. These studies demonstrate the following:

1. The open-water stage fluctuations propagate downstream without significant attenuation.

2. The ice front retreat (meltout) at Clayhurst Ferry was probably encouraged by the flow fluctuation.

3. The ice-water surface at Dunvegan and PRT responds to the flow fluctuation, but the rapid fluctuations are dampened. The ice cover floats up and down without substantial break-up in these areas, except for shore-fast ice.

We were also shown photo records taken during river ice reconnaissance flights for the past 4-5 years. These records are similar to the R&M documentation for the Susitna. We were supplied with a copy of the 1981-82 and 1982-83 Ice Observation Reports prepared by B.C. Hydro (References 8 and 9). These reports include observers diaries, meteorological data, miscellaneous ice/water levels and ice front progression rates.

Meeting with Alberta Environment, Edmonton

On April 6, 1984, I visited with Gordon Fonstad of Alberta Environment in Edmonton. He supplied me with three reports (References 3, 10 and 11) in addition to the 1981-82 Ice Observation Report he sent previously (Reference 4). We discussed the various ice events on the Peace River since he has been in charge of the Alberta Environment effort for several years. He was responsible for the mitigative efforts in preparation for break-up in 1982. It is interesting that following the severe consolidation event in January 1982, the spring break-up was uneventful. In fact, Fonstad indicated that the ice weakening efforts in PRT probably had little to do with the mild break-up. It was primarily lack of rapid flow build-up from smowmelt.

Fonstad also pointed out that the 1983 break-up was different from previous years. Usually, the Peace breaks-up and moves thru PRT, followed by the Smoky break-up. In a few years, the Smoky broke up first, causing jams in PRT. However, in 1983, a partial meltout occurred in PRT, followed by break-up of the Smoky, and then break-up of the Peace. No significant stage increase occurred in PRT.

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The 1982-83 Alberta Enviroment report includes a summary of break-up stage increases in PRT since 1960. This summary shows a clear increase in high break-up stage frequency with project compared to pre-project (3 events to 1). However, it is interesting that all four events had accompanying high flow rates in the Peace River and 3 out of 4 events had high flow rates in the Smoky during break-up. In other words, the break-up event in PRT is probably related more to snowmelt interflow than to PMD operation.

Fonstad also described other rivers in Alberta where monitoring programs of winter flow conditions are in progress. In particular, the Athabasca River break-up jams cause flooding in the City of Fort McMurray, Alberta (Reference 11). This problem is apparently unrelated to any hydro operation.

Fonstad also mentioned a problem on the North Saskatchewan River, downstream of the Trans Alta Utilities Corporation, Bighorn Dam and on the Red Deer River downstream of Dickson Dam. He gave me a reference in Calgary who can probably supply more information.

Fonstad thought that Manitoba Hydro probably can supply information on the Nelson River and Churchill River (Rerefence 12 ).

Fonstad confirmed much of the information I already had. He reiterated that while hydro operation can be a problem in cold regions, it is being controlled in Canada by careful operation at critical times. He did mention that our situation on the Susitna, where the major impact is fisheries over a significant portion of the river, will be more difficult since the problem is not localized, as has been the Canadian experience.

H.W. Coleman

H.W Coleman

HWC/mmg

Reference 1.

analysis are J. D. Allen, L. L. Douglas, C. J. Kopec, and G. M. Pawluk. This paper is presented with the permission of ARCO Alaska, Inc. and the Prudhoe Bay Unit Co-Owners.

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Reference:
Proceedings: Cold Regions Engineering Specialty Conference, April 4-6, 1984
Canadian Society for Civil Engineering
Montreal, Quebec.

# FREEZE-UP FLOOD STAGES ASSOCIATED WITH FLUCTUATING RESERVOIR RELEASES

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ABSTRACT

Recent studies for hydropower development in northern Canada have given much attention to the potential effects of flow regulation on the winter regime of rivers, including levels and thicknesses of ice accumulations during freeze-up and breakup. Generally, increased flows during freeze-up result in higher, thicker ice covers in early winter. Fluctuating flows may detrimentally affect the stability of ice covers, particularly in the period just after freeze-up.

Abnormally high ice-pack levels occurred at Peace River town in early January 1982, associated with a particular combination of weather conditions and fluctuating releases 400 km upstream. The water levels resulting from consolidation of a fresh accumulation type of ice cover almost overtopped flood dikes that had been constructed some ten years earlier. Analysis indicates that the phenomena were associated with an unusual combination of a thin ice cover formed rapidly in late December and a succession of discharge fluctuations over the Christmas-New Year period. Using field observations of water levels and ice thicknesses, it has been possible to reconstruct an approximate history of the chain of events and to analyze the phenomena in terms of river ice mechanics.

INTRODUCTION

The Town of Peace River is located on the banks of the Peace River in northern Alberta, approximately 400 km below a hydroelectric development completed by British Columbia Hydro and Power Authority in 1972 (Figure 1). Regulation of the river by Bennett Dam has increased winter flows at Peace River town to approximately 4 times previous natural flows, and has considerably altered ice conditions in the river. During a late freeze-up period at the beginning of January 1982, coincident with notable fluctuations in power demand and plant releases over the holiday period, record high freeze-up levels occurred at the town. The purpose of this paper is to describe the sequence of events and to analyze the ice levels in terms of present understanding of river ice hydraulics.

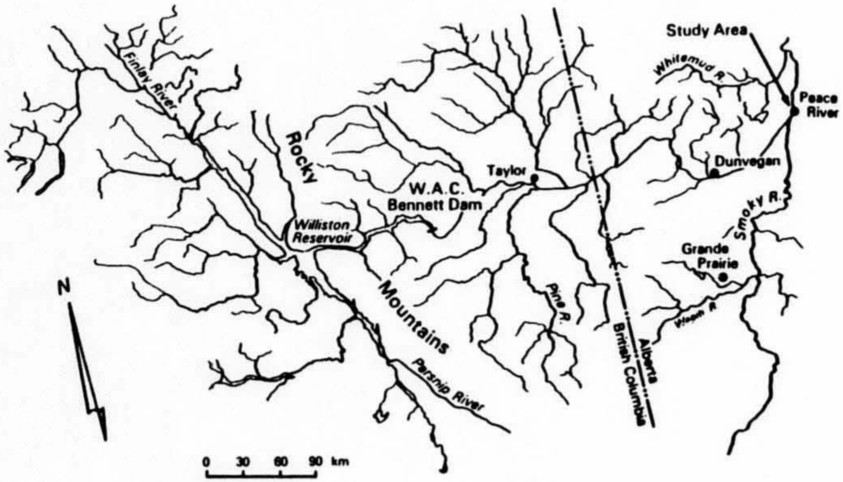


**Figure 1:** Location Map

BACKGROUND

The possibility of flooding due to ice jamming during breakup has always been present at Peace River town. Since completion of the upstream works in 1972, however, freeze-up levels and winter ice levels have been noticeably higher than before. Also, higher breakup levels than any previously recorded were experienced in 1973, 1974 and 1979. After the 1979 breakup experience, dikes built to protect the lower parts of the town against summer floods were raised by approximately 1 m to provide for ice-related floods. Freeze-up levels experienced in January 1982 were several metres higher than any previously experienced, and almost reached the record breakup level of 1979 (Figure 2).





**Figure 2:** View Upstream Towards Highway and Railway Bridges, February 1983.

Between 1972 and 1982 several studies were made of ice problems at Peace River (Nuttall, 1974; Andres, 1975, 1978; Acres, 1980; Carson and Lavender, 1980; Davies et al, 1981). Some of these studies were directed mainly to breakup conditions; others considered freeze-up and winter levels associated both with present conditions and with a contemplated future power project at Dunvegan, approximately 100 km upstream (Figure 1). In the study by Acres (1980), a computer simulation program was used to predict water and ice levels at Peace River town for various operating scenarios of the Dunvegan proposal. Field investigations were conducted in the winter of 1979-80 to assist the simulations. Another reported study (Keenhan et al, 1982) was concerned with freeze-up conditions at Taylor, approximately 300 km upstream of Peace River town.

The question of effects of hydroelectric projects on river ice conditions has received much attention elsewhere in Canada in recent years, especially in connection with northern developments like the Churchill-Nelson system in Manitoba, the James Bay project in Quebec, and a contemplated development in northern British Columbia which would impact on the Liard-Mackenzie River system all the way to the Beaufort Sea. These projects are referred to in papers by Hopper et al (1978), Michel and Drouin (1981), and Parkinson (1982). Several organizations have developed computer programs which aim to simulate ice formation, transport, freeze-up, thickening, and breakup on a more or less continuous basis, taking into account both thermal and hydromechanical processes. (Most numerical models originate in part from the St. Lawrence River studies reported by Pariset et al (1966).) These models have been applied to assess the impact of future developments by calibrating with natural data and predicting with altered hydrologic and thermal regimes. Considerable uncertainty exists, however, about the formulation of many elements of the ice regime, as discussed by Clement and Petryk (1980), Calkins (1981) and Michel (1983). It is therefore important to analyze experiences such as that described herein.

## HYDROLOGIC AND METEOROLOGIC FACTORS

The Peace River has been gauged at Peace River town since 1915, with a gap from 1932 to 1957. The mean flow is approximately 1800 $m^3/s$. Winter flows under natural conditions were mostly in the range of 200 to 500 $m^3/s$, but under regulated conditions since 1972 have ranged mostly from 1000 to 2000 $m^3/s$ (Figure 3).

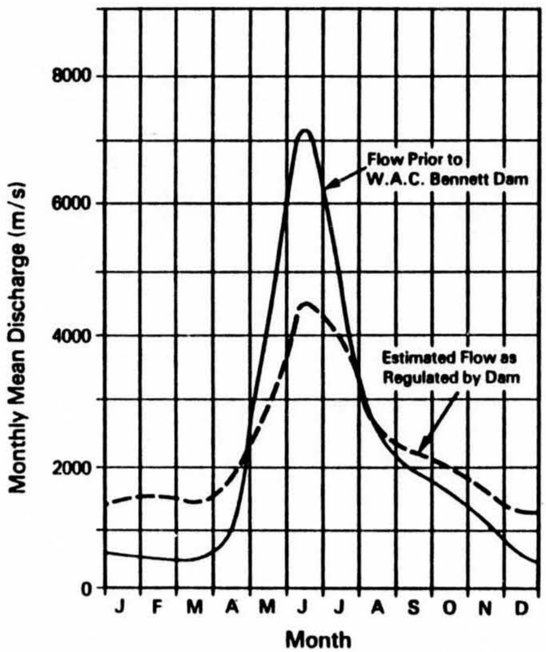


Figure 3: Monthly River Flows Downstream of Peace River





The river is located at the bottom of a deep postglacial valley with narrow fragmentary terraces. At bankfull conditions the channel width is about 550 m and the depth about 8 m. The slope is approximately 0.35 m/km. The bed is of gravel, overlying shale at approximately 5 m depth. Banks are of gravel overlain by silt, with rock outcrops where the channel abuts the valley walls.

Under natural conditions freeze-up usually occurred in early November, and breakup in late April. Under recent regulated conditions freeze-up is delayed until December, or even early January as in 1981-82. Mean January temperature is approximately -20°C. As in other regulated northern rivers, the ice cover forms by upstream progression of arrested ice floes in a process involving both juxtaposition and shoving. In the January 1982 event, a thin ice cover that had formed through the town only a few days earlier, consolidated abruptly by shoving from upstream and rose to an abnormally high level.

## SEQUENCE OF EVENTS DECEMBER 1981 - JANUARY 1982

An approximate sequence of discharges, water levels and air temperatures for the period December 15, 1981 to February 5, 1982 is illustrated in Figure 4. An ice cover began to form on the lower river early in December, but because of relatively mild weather in mid-December did not reach Peace River town until January 2nd, when the water level rose abruptly by 2.8 m at a discharge of approximately 1800 $m^3/s$ and a temperature of about -30°C. Within the next few days, the temperature dropped to nearly -40°C and the discharges dropped to below 1000 $m^3/s$ as the effect of the New Year holiday on reservoir releases communicated itself down river. A thin cover therefore progressed upstream very rapidly. By January 5th the head of the cover had reached a point 88 km upstream, where water levels rose 3.8 m at a discharge of 1200 $m^3/s$. The head of the cover had progressed upstream at a more or less constant rate of 0.30 m/s, regardless of fluctuations in discharge during this period[a].

Between Peace River and Dunvegan the average rise in stage associated with the ice cover formation was 3.3 m. With an average channel width of 500 m and a measured celerity of 0.30 m/s, nearly 500 $m^3/s$ of flow was therefore being continuously abstracted into storage, probably reducing the discharge at Peace River to a minimum of about 500 $m^3/s$ on January 4th. This caused the stage to drop about 1.1 m (Figure 4) from the peak associated with ice cover formation.

On January 7th, after the ice cover had progressed some distance upstream of Dunvegan, rapid increases in discharge resulting from

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a Personal Communication, R. Carson, Acres Consulting Services Ltd.

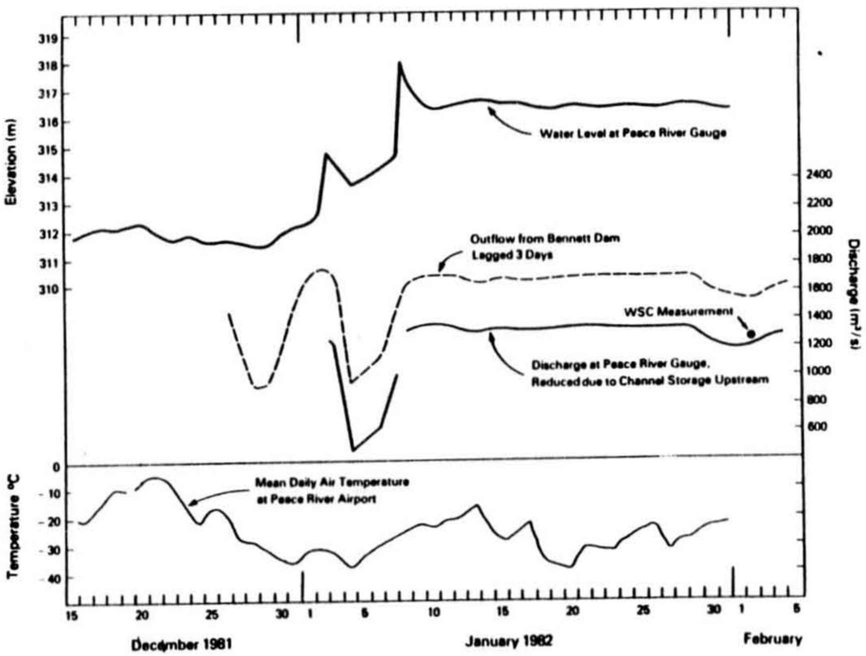


Figure 4: Sequence of Water Levels, Discharges and Temperatures, December 1981 to February 1982

resumption of normal power output at Bennett Dam a day or two earlier were followed by a massive consolidation and thickening of the new ice cover. A 9-m high jam formed 14 km below Dunvegan, but failed after about 2 hours. A surge of ice and water then moved downstream (Fonstad, 1982), reaching Peace River at 10:30 p.m. (Figure 4). The stage rose abruptly by about 3.5 m to an elevation of 318.15 m, some 3.4 m above the previous stable ice cover and only 1.5 m below the top of the flood protection dikes. Within 2 hours of the peak the stage had dropped by 0.60 m, and after about 36 hours it had dropped a further 1.15 m to an elevation of 316.4 m, where it remained more or less constant for the rest of January. Later aerial inspection indicated that noticeable consolidation of the ice surface extended to about 10 km downstream of Peace River.





On January 8th, 12 hours after the peak at Peace River, the head of the cover was observed to be only 40 km upstream of Peace River, readvancing upstream at a rate of 0.18 m/s[b]. This rate was maintained at least until January 10th. Between then and January 14th the cover advanced very slowly, probably due to warmer temperatures (Figure 4). On January 14th it resumed progression upstream at a rate of 0.18 m/s, and the head passed Dunvegan again in the night of January 15th-16th. With a discharge of about 1700 $m^3/s$ and a mean daily temperature of -25°C, the local stage rise at Dunvegan was 4.7 m.

If a stage rise of say 4.0 m was typical of the second ice front advance between Peace River and Dunvegan, the diversion of flow into storage, for a celerity of 0.18 m/s, would have been about 360 $m^3/s$. The almost constant water level at Peace River from January 10th to 31st suggests that the loss to storage was more or less constant over that period, since outflows from Bennett Dam were maintained at about 1700 $m^3/s$. The flow at Peace River would then have been about 1340 $m^3/s$. A Water Survey of Canada measurement on February 2nd (Figure 4) more or less confirms this interpretation.

MEASUREMENTS OF ICE COVER AND HYDRAULIC CHARACTERISTICS

As soon as possible after the consolidation of January 7th, high-water marks, water levels, and ice thicknesses were recorded. A high water profile and the existing water level profile were obtained on January 13th, and ice thickness measurements were obtained over the following week. Due to the very cold conditions and the rough ice, a full coverage of ice thickness measurements could not be made. However, these data were later augmented by measuring the thicknesses of shear walls as revealed during breakup in April 1982 (Figure 5).

The winter measurements indicated a relatively consistent thickness below water level of from 3.8 to 4.2 m, although in some locations the value was as low as 2.3 m. The cover appeared to be formed primarily from frazil slush in which were embedded ice floes originating from broken border ice and frozen crusts of frazil pans. The border ice ranged from 0.5 to 1.0 m in thickness and the frozen crusts were in the order of 0.3 m thick. The maximum ice height along the bank was from 0.9 to 1.5 m above the January 13th water level and more or less corresponded to the maximum water level associated with the ice cover consolidation. The perceived average ice surface on the day of survey was generally from 0.2 to 0.6 m above the water level; where shear lines were evident, ice had pushed up at least 1.6 m above the water level.

b Personal Communication, R. Carson, Acres Consulting Services Ltd.

Ice thickness measurements were also made at breakup following the passage of the ice front, when many of the exposed shear walls were still intact (Figure 5). Most of the shear walls were about 4 m thick. The reliability of these measurements is not as great as for the winter measurements, but they generally substantiate the latter.

Figure 5: Shear Walls Indicating Ice Thickness, April 1982

Open-water hydraulic characteristics were evaluated from thirteen channel cross sections and thalweg profiles surveyed in the summer of 1982. These indicate that upstream of Bewley Island (Figure 6) the channel is relatively uniform. Both the bed and water surface have a mean slope of 0.32 m/km (Figure 7). The water surface slope with ice cover also parallels the bed slope, as do highwater marks from the flood wave that accompanied ice cover consolidation. When measured ice thicknesses are plotted on the profile, the mean line for the ice/water interface also has the same slope. This suggests that more or less uniform flow prevailed for all three measured conditions. Average hydraulic characteristics as analyzed for the surveyed open-water and steady ice cover conditions are summarized in Table 1, and typical channel cross sections are illustrated in Figure 8.





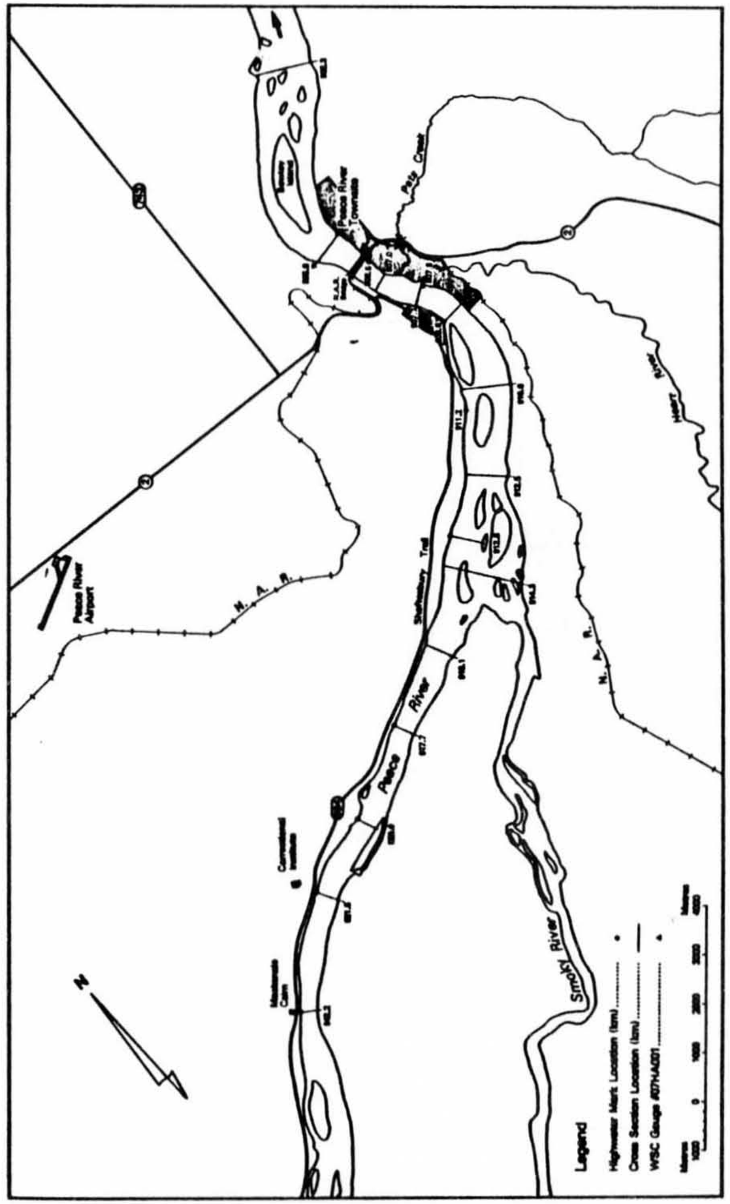


Figure 6: Study Reach Covered by Measurements

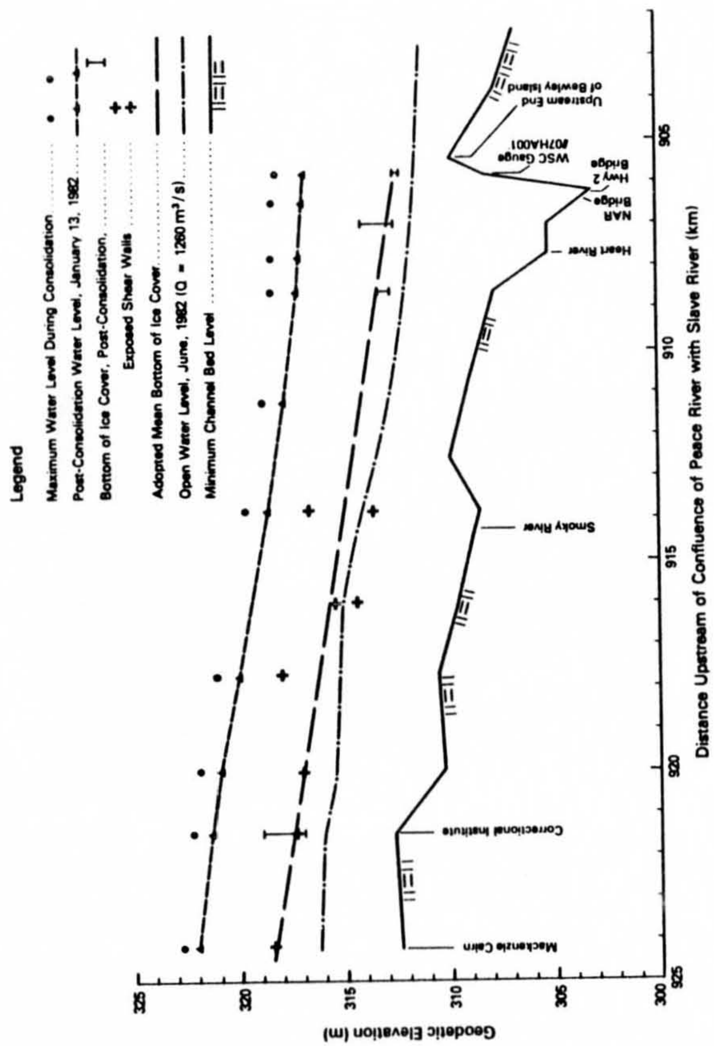


**Figure 7:** Longitudinal Profiles in Study Reach





**Table 1:** Summary of Surveyed Average Channel Characteristics

| Characteristic | Open Channel (Summer 1982) | Ice Cover (Late January 1982) |
|---|---|---|
| Discharge, Q ($m^3/s$) | 1270 [a] | 1340 [b] |
| Top width, W (m) | 520 | 555 |
| Flow Area, A ($m^2$) | 1350 | 2040 (below ice) |
| Mean Depth, h (m) | 2.9 | 3.9 |
| Hydraulic Radius, R, $R_o$ (m) | 2.9 | 1.95 |
| Mean Velocity, V (m/s) | 0.94 | 0.62 |
| Submerged Ice Thickness, $t_s$ (m) | - | 4.0 [c] |
| Manning Roughness $n_b$, $n_o$ | 0.032 [d] | 0.043 [d] (Composite) |

Notes:
- a Measured at Peace River, less Smoky River inflow.
- b Reservoir releases less abstractions to storage from ice front progression.
- c Mean submerged thickness for reach.
- d Computed with a water surface slope of 0.32 m/km.

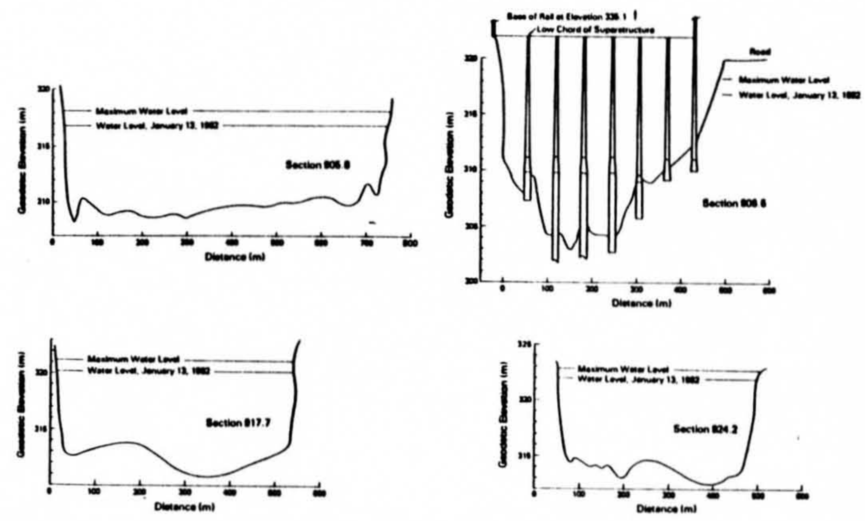


**Figure 8:** Selected Cross Sections

## ANALYSIS

### Discharge Variations

Following the failure of the jam downstream of Dunvegan on January 7th, approximately 100 km of river ice was consolidated into a length of about 50 km. Factors contributing to the subsequent high stage rise at Peace River include the initial surge of water from the failure of the jam, the increased discharge due to release from channel storage, and the increased ice thicknesses within the consolidated length. It is believed that the major flow increase during the consolidation was due to release from channel storage as the length of ice-covered river was shortened. The augmented discharge also transported the broken ice and was responsible for the increased thickness of the accumulation.

The extremely rapid stage rise suggests that both the discharge and ice thickness were increasing during this period. However, without knowing how either variable changed, the exact time of maximum ice thickness or peak discharge cannot be determined. It seems reasonable to assume that the maximum thickness was achieved at the peak gauge height and that this also defines the time of maximum discharge. Following the peak stage the ice thickness remained constant, and the reduction in stage was due to a reduction in discharge.

The discharge at the peak stage cannot be determined reliably from the gauge height records because the thickness and the roughness of the ice cover are unkown. However, if it is assumed that thickness and roughness remained constant between the peak of January 7th and the thickness measurements of late January, then the peak discharge can be estimated from the measured highwater marks as recorded and the overall roughness under ice cover as shown in Table 1. Using the same composite roughness of 0.043 and a measured mean depth of 4.9 m, the peak discharge of January 7th was estimated to be 2000 $m^3/s$ on the basis of steady uniform flow. This is somewhat larger than the routed release from Bennett Dam, estimated at approximately 1600 $m^3/s$ (Figure 4).

A crude approximation of the peak discharge can also be made by considering the conservation of volume during the consolidation. It can be estimated that approximately 1 m depth of stored water was released from the 60 km of river upstream of the consolidation, producing an inflow of 33 x $10^6$ $m^3$ into the 40 km immediately upstream of Peace River. Within this 40 km, the additional roughness of the thickened ice cover increased the depth of flow by about 0.3 m, which reduced the additional volume passing Peace River to about 27 x $10^6$ $m^3$. Gauge records suggest it is reasonable to assume that the flood wave lasted from 8 to 12 hours, corresponding to an increase in discharge of from 600 to 900 $m^3/s$. This, when added to a 1200 $m^3/s$ base flow, results in a peak discharge estimate of 1800 to





2100 $m^3/s$, which agrees reasonably well with the maximum discharge as estimated above from hydraulic considerations.

### Ice Cover Stability

Thickening of a river ice cover can occur in two ways: (i) by hydrodynamic instability at the advancing edge of the cover, whereby arriving ice floes are carried underneath the edge; and (ii) by mechanical instability within the cover, whereby hydraulic forces cause it to consolidate and thicken. From the nature of the events observed on January 7th, it is apparent that the second case applies. Various equations have been presented for analysis of this type of condition. That by Uzuner and Kennedy (1974) can be written in modified form as:

[1] $$WR_i \rho g S + Wt\rho_i g S = \mu \rho_i (1-s_i) g t^2 + 2C_i t$$

where W is the stream width; $R_i$ is the hydraulic radius associated with the ice cover; $\rho$, the density of water; g is the acceleration of gravity; S is the channel slope; t is the ice thickness; $\rho_i$ is the density of ice, $\mu$ is a dimensionless coefficient of internal friction*; $s_i$ is the specific gravity of ice, and $C_i$ is a cohesion parameter as discussed below.

The terms on the left-hand side represent the shear force per unit length on the bottom of the cover plus the downstream component of the weight of the cover. The terms on the right-hand side represent the resistance of the cover due to internal friction plus the resistance due to cohesion.

With regard to the cohesion parameter $C_i$ in Equation [1], it is important to note that the equation was developed for an uncongealed accumulation of ice floes where $C_i$ represents a "soil mechanics" type of cohesive strength as in the Coulomb-Mohr relationships, and not a shear strength of solid ice. The rationale for using Equation [1] to analyze the Peace River consolidation is that the thin surface freezing, estimated from observations to have been about 0.3 m thick, is assumed to have been effectively destroyed by flexing of the cover under the action of surges and unsteady flow. If, as suggested by Beltaos (1978), $C_i$ is taken as approximately 100 Pa, the cohesion term is then much less than the friction term and can be neglected. With $\rho$ = 1000 $kg/m^3$, $\rho_i$ = 920 $kg/m^3$, g = 9.8 $m/s^2$, and $s_i$ = 0.92, Equation [1] can be reduced to:

[2] $$\mu = 12.5\ SW(1 + R_i/0.92t)/t$$

---

* $\mu = C_o(1-p)$ where $C_o$ is Uzuner and Kennedy's "shear stress coefficient" and p is porosity.

To apply Equation [2], the hydraulic radius $R_i$ associated with the ice cover is computed from:

[3] $$R_i/R_b = (n_i/n_b)^{3/2}$$

where ice roughness $n_i = (2n_o^{3/2} - n_b^{3/2})^{2/3}$

and $$R_i + R_b = 2R_o$$

Applied to the Peace River consolidation with $n_b = 0.032$, $n_o = 0.043$, and therefore $n_i = 0.053$, $R_i$ is found to be 3.3 m. Equation [2] then gives an internal friction coefficient $\mu = 0.93$ for a total ice thickness of 4.3 m. This is within the normal range of values of $\mu$ computed for breakup jams (Beltaos, 1978), which suggests that massive consolidations occur so rapidly that the effects of downward freezing can be neglected in estimating levels and thicknesses.

## CONCLUSIONS

(1) The unusually high ice accumulation stage at Peace River on January 7-8, 1982 resulted when a rapid increase in discharge broke up and consolidated a thin new ice cover, that had formed quickly very late in the season under very low temperatures.

(2) The ice cover consolidation led to accumulation thicknesses of some 4 m over a considerable length of river, and was accompanied by a flood wave as water was released from storage in the backwater zone at the head of the previously advancing cover.

(3) Analysis of steady conditions as observed a week or two after the abrupt consolidation indicated an overall hydraulic roughness of 0.043. The roughness of the underside of the ice cover was estimated as approximately 0.053. Applied to the peak stage conditions of January 7th, this yielded an estimate for the peak discharge at Peace River of 2000 $m^3/s$, approximately 50 percent greater than immediately preceding discharges.

(4) Analysis of the hydromechanical stability of the consolidated cover, neglecting cohesion, indicates an internal friction coefficient $\mu$ of approximately 0.9, similar to values reported for ice jams under breakup conditions.

(5) It is believed that the information presented herein constitutes an interesting documentation of a severe freeze-up accumulation associated with strong discharge fluctuations, providing reasonable definition of hydromechanic parameters without the need for manipulation of both thickness and roughness.





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ACKNOWLEDGEMENTS

The first author's connection with the Peace River incident was through a brief investigative study commissioned by River Engineering Branch of Alberta Environment in February 1982, and conducted in cooperation with Messrs. M.E. Quazi and G.D. Fonstad of that branch.

The second author's involvement was through the Alberta Cooperative Program in Transportation and Surface Water Engineering, operated by Alberta Research Council in cooperation with provincial departments of Environment and Transportation and the University of Alberta. Field data were obtained by staff of the Civil Engineering Department, Alberta Research Council.



Reference:
Proceedings: Cold Regions Engineering Specialty Conference, April 4-6, 1984
Canadian Society for Civil Engineering
Montreal, Quebec

# TWO-DIMENSIONAL SIMULATION OF FREEZING AND THAWING IN SOILS

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## ABSTRACT

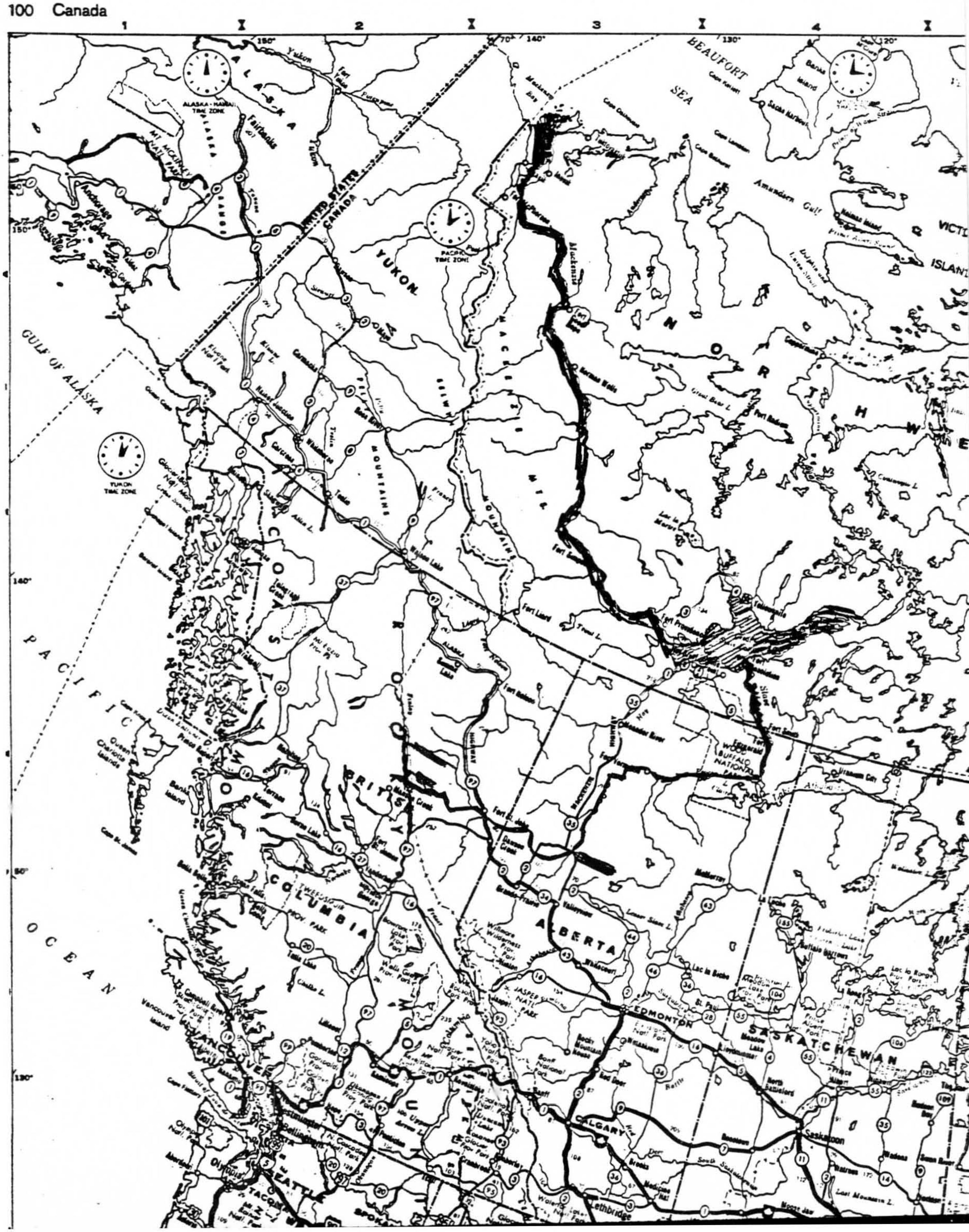
Phase change produces some of the most dramatic volume and strength change effects on soils in cold regions. Numerical solution techniques provide powerful tools for analysis of real-world heat flow problems. In our engineering practice, we have found a two-dimensional finite-element computer program called "DOT" (Determination of Temperature) to be particularly useful. Capabilities of the program include an ability to handle transient as well as steady-state problems, arbitrary geometries, inhomogeneous materials and non-uniform initial temperature distributions. Example applications of the DOT program described in the paper include calculation of thawing around a warm pipeline in permafrost, thawing around warm oil wells in permafrost (including the influence of a convection surface), and frost penetration as a result of placement of gravel fill in shallow seawater on the arctic coast. Limited data are presented comparing predicted and measured thaw for one of the examples.

## INTRODUCTION AND BACKGROUND

Phase change produces some of the most dramatic volume and strength change effects on soils in cold regions (see Andersland and Anderson 1978; Johnston 1981). Thawing of initially-frozen soils results from an increase in the soil temperature. This increase can result from (1) a surface disturbance such as stripping or compression of the tundra insulating layer, placement of a gravel pad, or concentration of surface runoff (thermal erosion), or (2) introduction of a heat source such as a warm pipeline. This thawing is accompanied by soil consolidation (expulsion of excess pore water) and a decrease in soil shear strength. The amount of soil thaw strain increases with soil ice content and soil shear strength is least before excess pore pressures have had an opportunity to dissipate.

Foundation settlement is calculated by integrating the thaw strain over the depth of thaw. Foundation bearing capacity may be greatly reduced during permafrost thaw as is available resistance to sliding on potential failure surfaces in sloping ground.

Reference 2.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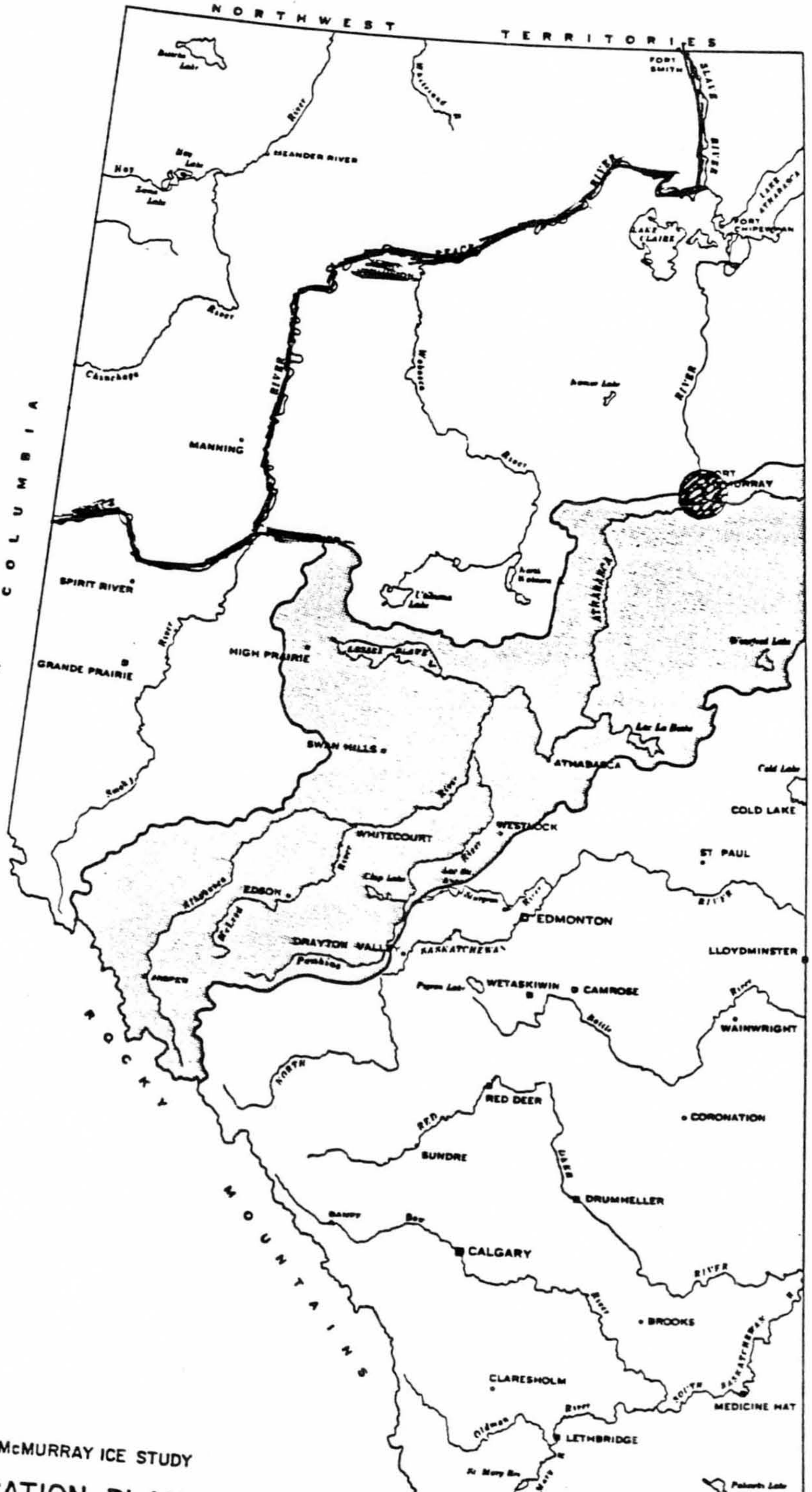
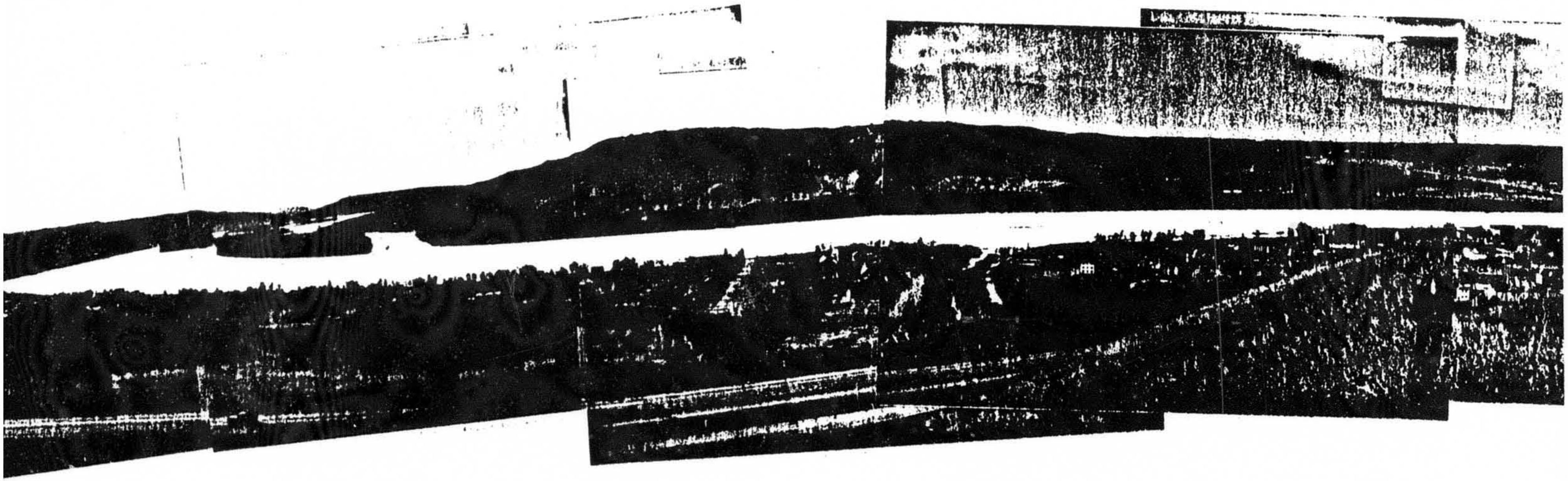
BEAUFORT
SEA
ALASKA-HAWAII TIME ZONE
PACIFIC TIME ZONE
YUKON TIME ZONE
UNITED STATES
CANADA
YUKON
GULF OF ALASKA
PACIFIC
OCEAN
Amundsen Gulf
Banks Island
BRITISH
COLUMBIA
ALBERTA
SASKATCHEWAN
EDMONTON
CALGARY
VANCOUVER
SEATTLE
Fairbanks
Anchorage
Whitehorse
Watson Lake
Fort Nelson
Fort Providence
Fort Smith
Fort Liard
Dawson Creek
Grande Prairie
Prince George
Red Deer
Banff
Lethbridge
Saskatoon
North Battleford
Lloydminster
Uranium City
WOOD BUFFALO NATIONAL PARK
Queen Charlotte Islands
Vancouver Island

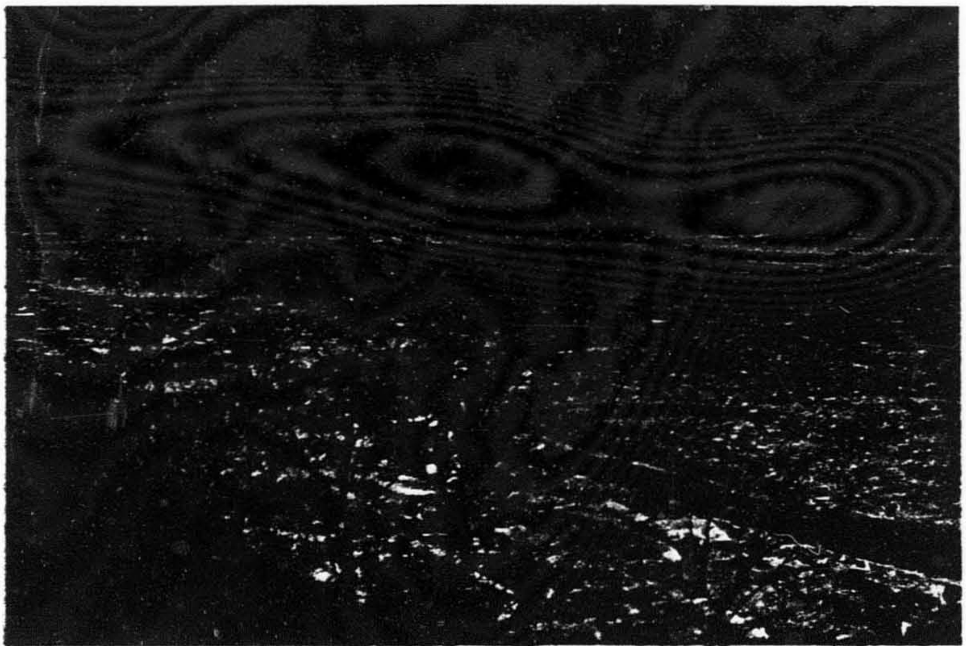


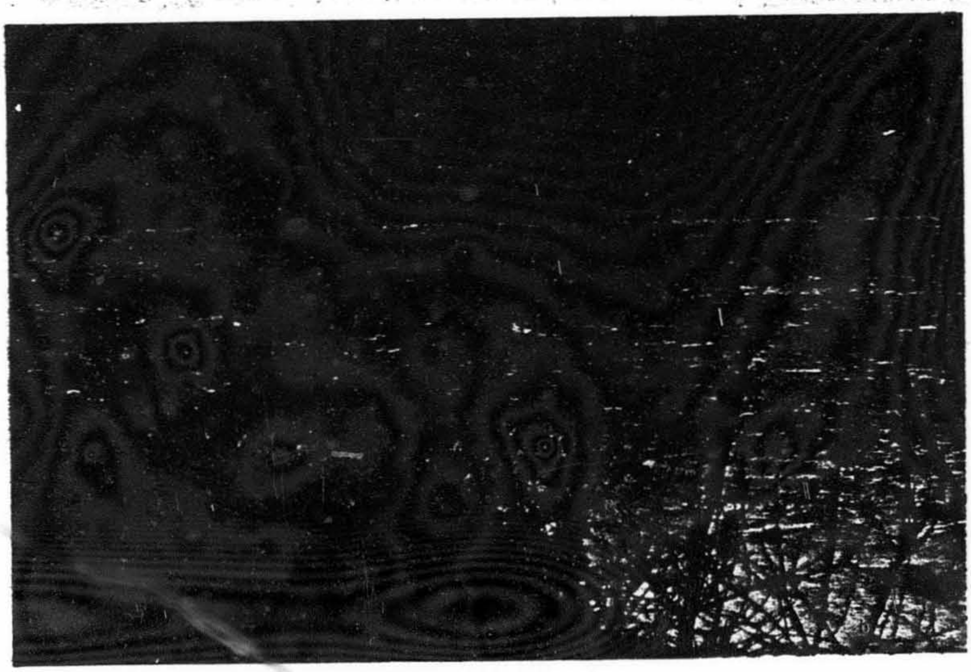

FORT McMURRAY ICE STUDY

LOCATION PLAN

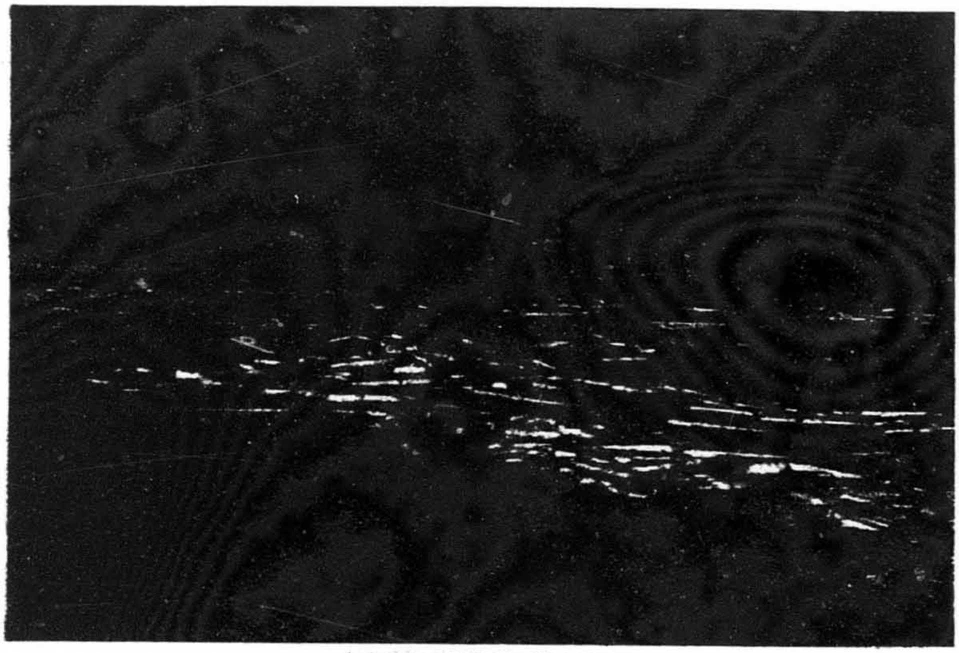
FIGURE I

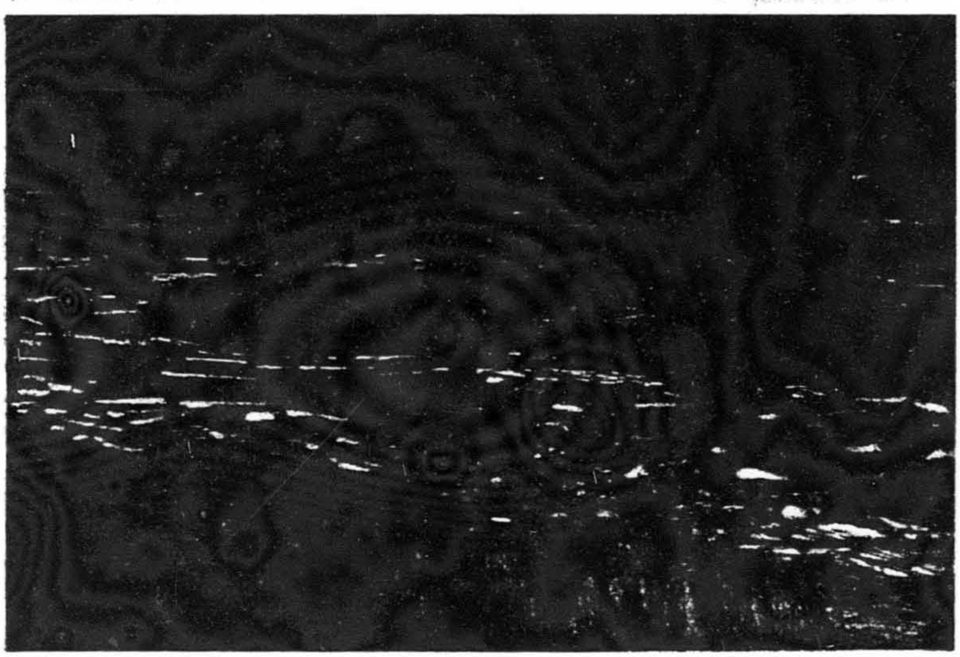






PEACE RIVER TOWN
3 APR 84





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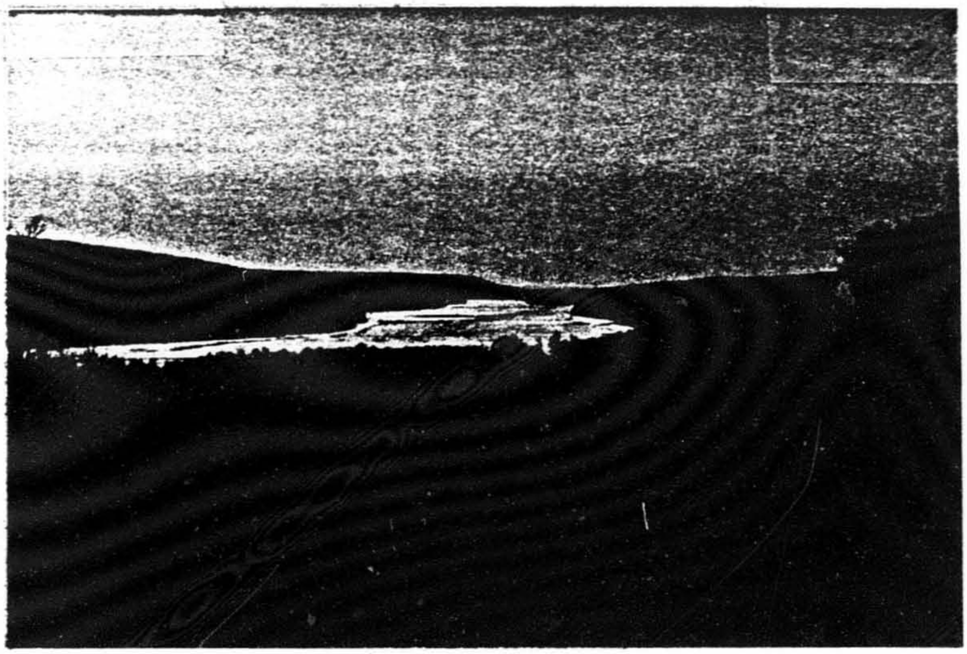

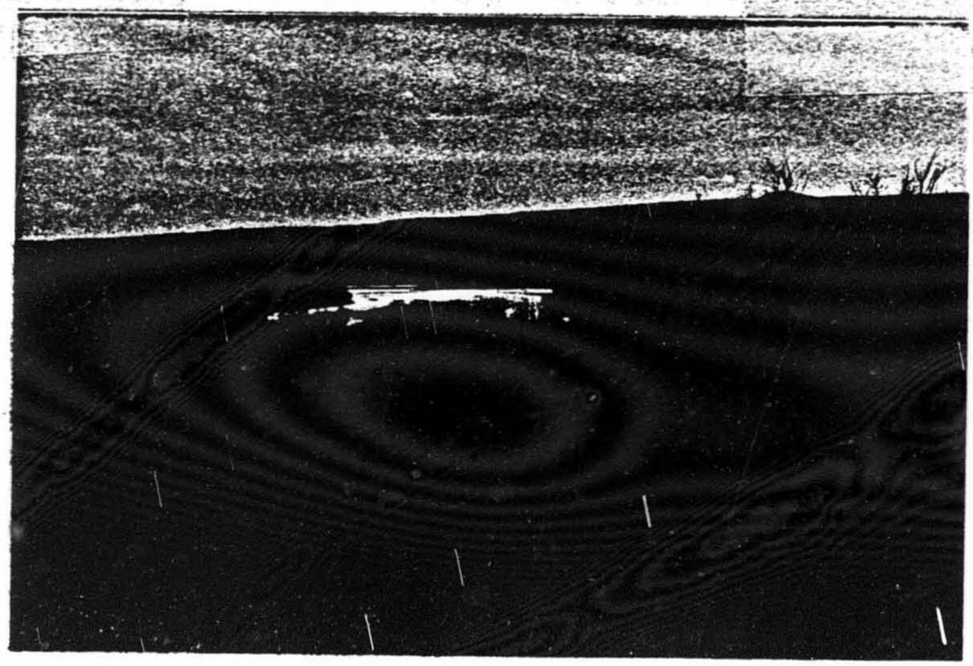

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Reference 3.

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northwest hydraulic consultants ltd.

# EVALUATION OF 1982 RIVER ICE CONDITIONS AT PEACE RIVER

Prepared for:

River Engineering Branch
Technical Services Division
Alberta Environment

Prepared by:
Northwest Hydraulic Consultants Ltd.

May 1982

# ABSTRACT

The report is based on an evaluation of river freeze-up conditions at Peace River in January 1982, when record high levels were experienced, and on an assessment of potential high stages during 1982 spring break-up, conducted before the fact.

It is concluded that high freeze-up stages were caused by a combination of late freeze-up due to a warm December and severe fluctuations in releases from Bennett Dam over the Christmas-New Year period. It is considered that there is a potential for high break-up stages comparable with those of other recent high years, but that overtopping of the town dikes is unlikely.

# CREDITS AND ACKNOWLEDGMENTS

The report was prepared by C.R. Neill, P.Eng. with assistance in analysis from W. Rozeboom, P.Eng.

Acknowledgments are expressed to Messrs. G.D. Fonstad and M.E. Quazi of Alberta Environment, Mr. D.D. Andres of Alberta Research Council, Dr. R. Gerard of the University of Alberta, and Mr. S.T. Lavender and Mr. Rob Carson of Acres Consulting Services for their cooperation in providing documents, comments and advice.

# 1. INTRODUCTION

## 1.1 Objectives

In February 1982 River Engineering Branch of Alberta Environment requested Northwest Hydraulic Consultants to investigate and report on river ice conditions at Peace River, investigations to be done in cooperation with River Engineering and Alberta Research engineers. Specifically, investigations were to be directed to causes of high freeze-up stages, potential break-up problems, and feasible remedial measures to mitigate the latter.

A brief progress report covering results of freeze-up investigations was submitted on 10 March, and a letter report covering break-up projections and recommendations followed on 22 March. The present report documents more fully and extends the material in these preliminary reports. It was submitted in draft form in April and finalized with minor revisions in May 1982.

## 1.2 Statement of Problems

The possibility of flooding due to ice-jamming at break-up has always been present at Peace River town. Since completion of Bennett Dam and Schrumm hydro-electric plant by B.C. Hydro in 1972, winter discharges in the Peace River have been greatly increased, resulting in delayed freeze-up, higher winter ice levels and greater quantities of ice, and apparently increased frequency of high levels at break-up. Higher break-up levels than any previously recorded occurred in 1973, 1974 and 1979.

Following a high summer flood in 1972, dikes were built to protect the lower parts of the town against open-water flood events. After the 1979 break-up, the dikes were raised by approximately 0.9 m.

In early January 1982, unprecedented high freeze-up levels occurred when an initial ice cover only a few days old consolidated abruptly through the town. The dikes were not overtopped, but subsurface seepage caused basement flooding. Releases from Bennett Dam were subsequently cut back by agreement in order to reduce seepage problems, and ice levels fell accordingly. Con -n arose over possible overtopping of the dikes dur.. spring break-up in April 1982.

## 1.3 Previous Studies Reviewed

River ice problems at Peace River have been the subject of several studies and reports since completion of Bennett Dam. In order to understand and analyze the causes of the 1982 conditions, previous documents provided by River Engineering Branch and others were reviewed. Brief notes on these are given below in chronological order; detailed references are given in Section 5.

Nuttall, 1974. In March 1974 Dr. J.B. Nuttall of the University of Alberta analyzed break-up flood potential and recommended local mitigative measures. The report, prepared in July 1974, covers pre-break-up investigations and actual occurrences, discusses the effectiveness of mitigative measures, and recommends future measures.

Andres, 1975. Relatively high freeze-up levels were experienced in January 1975, and local mitigative measures were again taken, but break-up proved uneventful. The report analyzes conditions in considerable detail and attempts to develop predictive relationships for maximum break-up stage.

Doyle, 1978. The Peace River ice-jam observations reported were too far downstream of Peace River town to be relevant in the present context.

Andres, 1978. The effects of a proposed hydro-electric peaking plant at Dunvegan were analyzed with respect to ice conditions downstream. The report predicts likely positions of the ice front, freeze-up levels as a function of discharge, and fluctuations in ice cover level. It is concluded that there would be no adverse effects at break-up at Peace River, and that the proposed project might be operated so as to reduce present break-up levels.

Acres, 1980. This study also analyzed effects of the projected Dunvegan development in detail, and reported the results of field investigations in the winter of 1979 - 1980. A computer simulation program was used to predict water and ice levels at Peace River for various operating scenarios.

Carson and Lavender, 1980. A short paper based on part of the above-mentioned Acres study presents a consolidated stage-discharge plot for Peace River under open water and ice conditions, including both freeze-up and break-up data.

Davies, Deeprose and Hunt, 1981. A Joint Alberta-B.C. Task Force was formed to observe, analyze and make recommendations on ice-related hazards at Peace River and their control by flow adjustments at Bennett Dam. The 1981 report, covering the 1978 - 79 season, summarizes observations, analyzes the high 1979 break-up levels, and discusses possibilities for ice-jam prediction.

In addition to these previously released documents, we reviewed a preliminary draft report by G.D. Fonstad of River Engineering Branch covering the freeze-up events of January 1982.

## 1.4 Consultations With Others

Discussions were held with Mr. G.D. Fonstad of River Engineering Branch, Mr. D.D. Andres of Alberta Research Council (formerly of River Engineering Branch), Dr. R. Gerard of the University of Alberta, and Mr. S.T. Lavender of Acres Consulting Services, to clarify previous interpretations, compare evaluations and discuss recommendations. These discussions were of great value in developing the conclusions and recommendations of this report.

## 1.5 Units and Datums

Levels at Peace River are quoted here in metres above Geodetic Datum. For heights above Water Survey of Canada gauge zero, deduct 304.8 m. Discharges are quoted in $m^3/s$.

## 2.4 Inferred Causes of High Freeze-Up Levels

In considering the hydraulic causes of the high freeze-up water levels of 7 - 8 January 1982, the following points appear most significant:

1. A relatively warm December combined with relatively high releases from Bennett Dam had delayed complete freeze-over at Peace River until 1 January or so.

2. Very cold weather in the first few days of January enabled an initial thin accumulation cover of frazil pans to advance rapidly upstream to the vicinity of Dunvegan. In the middle of this process, discharges arriving from upstream were suddenly cut in half, then raised again over a 3-day period.

   The most obvious hypothesis is that the rapid increase in discharge between 4 and 7 January caused break-up and consolidation of a cover which had formed only a few days earlier and was therefore quite weak. The resulting telescoping of the cover over a long length of river released a large quantity of water from storage as levels dropped from an ice-cover rating to an open-water rating. This storage release produced a transient flow and stage peak on the night of 7 - 8 January.

   In December 1979, as reported by Acres (1980), complete freeze-over occurred at Peace River on 24 December, and by 28 December the freeze-over front had advanced 44 km upstream. Between 30 December and 3 January, following a rapid increase in Bennett Dam releases from about 400 to 1200 $m^3/s$ a day or two earlier, the ice front retreated downstream by 12 km; the cover consolidated over a length of 26 km and thickened from about 1.0 to 2.4 m where measured at a point 18 km above Peace River. This 1979 experience appears to have been quite similar to that of 1982, the main difference being that in 1979 the consolidation did not extend over such a long length and did not noticeably affect Peace River town. By the time the 1979 discharge increases arrived, the cover in the vicinity of Peace River had been in place for a longer period than in 1982 and was presumably thick and strong enough to resist consolidation.

# 3. PROJECTION OF BREAK-UP CONDITIONS 1982

## 3.1 Past High Break-Up Events

Examination of previous studies referred to in Section 1.3 shows that high break-up water levels associated with ice jamming downstream of Peace River can result from various combinations of circumstances involving flow and ice conditions in both the Peace and Smoky Rivers upstream. According to the Joint Task Force (Davies et al, 1981): "If, for example, it appears that the combined discharge of the Smoky and Peace Rivers below their confluence will exceed 90,000 cfs (2500 $m^3/s$) or if the Smoky River itself may contribute 40,000 cfs (1133 $m^3/s$) or more, a flood situation is assumed likely . . . It should be noted that a jam downstream . . . does not have to occur to cause flooding. In 1979, a jam formed at the mouth of the Smoky and when it broke, a 15-foot high flood wave resulted in water levels of approximately 1045 feet (318.5 m) at the Town of Peace River."

Based on data tabulated in the Joint Task Force report, the three highest break-up floods of record were as shown in Table 2. Reported maximum levels were 318.6, (1979), 318.2 (1973) and 317.5 m (1974). The top of the dike near the Water Survey of Canada gauging station is at elevation 319.8 m approximately, that is, 1.2 m above the 1979 level.[a] On a purely statistical basis, the probability of attaining top-of-dike levels appears to be

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[a] The 1979 level was only about 0.3 m below the top of the dikes as they existed at that time, before they were raised.

quite low, in the order of 1%. In those three highest years, maximum rises above 5-day pre-break-up levels ranged from 4.1 to 4.5 m. (On 27 April 1982, with Peace River ice broken through the town but Smoky River not yet broken up, water level was reported as 314.2 m.)

TABLE 2. DATA FOR THREE HIGHEST BREAK-UP FLOODS AT PEACE RIVER

| Rank | Date | 5-day Pre-Breakup Elevation[a] m | Maximum Elevation m | Maximum Stage Rise Above Pre-Breakup m | Approx. Breakup Discharge at Peace River $m^3/s$ |
|---|---|---|---|---|---|
| 1 | 30/April/79 | 314.1 | 318.6 | 4.5 | 4,100 |
| 2 | 12/April/73 | 313.8 | 318.2 | 4.4 | 2,800 |
| 3 | 20/April/74 | 313.4 | 317.5 | 4.1 | 3,600 |

Extracted from Table 1 of Joint Task Force Report (Davies et al, 1981), and converted to metric units.

[a] Note

On 27 April 1982, with Peace River ice front downstream of the town but Smoky River not yet broken up, water elevation at the gauge was reported as 314.2 m. This is 1.7 lower than the elevation of the day before the break-up front passed through, reflecting the change from ice cover to open water hydraulics.

## 3.2 Feasible Mitigative Measures

Mitigative measures which have been used in past years are of two types: (i) local measures to weaken the ice through the town by plowing lanes, salting, dusting and blasting; and (ii) upstream measures to reduce Peace River discharges. Objective evidence that local measures have been successful is difficult to obtain, nevertheless these measures are not difficult to conduct and provide local reassurance that efforts are being made to reduce danger.

With regard to discharges, Figure 5 shows a break-up stage-discharge diagram based on Nuttall (1974), with added data after 1974 from the Joint Task Force report. On the basis of the scatter band shown in this diagaram, a discharge of at least 3300 $m^3/s$ is required to produce an elevation of 319.5 m. To give some margin of error, it would be desirable to be able to keep discharge to 3000 $m^3/s$ or less: at least 1 m or so of freeboard should then be available. Use of Acres' diagram (Figure 2) leads to similar conclusions.

In considering feasible restriction of Peace River discharge, the uncontrolled discharge of the Smoky River is all-important. In the three years of highest break-up levels (1979, 1973 and 1974), Smoky River discharges at Watino were about 1600, 600 and 2400 $m^3/s$ respectively. For a Smoky River discharge of say 2000 $m^3/s$, upstream Peace River discharge would therefore have to be restricted to about 1000 $m^3/s$ (35,000 cfs). If B.C. Hydro release was 1000 $m^3/s$, local inflow 500 $m^3/s$, and Smoky River flow 2000 $m^3/s$, the total of 3500 $m^3/s$ at Peace River might just reach the top of the dikes.

It appears advantageous to induce Peace River break-up before Smoky River break-up. This implies that upstream Peace River flows should be kept as high as possible up to say one week before expected Smoky River break-up.

## 3.3 Break-up Recommendations

The following summary of recommendations was contained in our letter of March 22 addressed to Mr. M.E. Quazi of River Engineering Branch.

1. Allow B.C. Hydro to resume normal operation as soon as practicable, to encourge break-up progression down the Peace River. Peaking operation is probably advantageous.
2. Develop a means of forecasting break-up date and if possible discharge for the Smoky River.
3. One week before expected Smoky break-up, have hydro releases cut as low as possible.
4. Keep monitoring break-up front, water temperature, stages and discharges.
5. Continue local ice weakening measures to provide ice passage and discourage jamming.

Reference 4.

Ref. 4

# RIVER ICE STUDY

## RIVER ENGINEERING BRANCH

Water Resources Management Services
Technical Services Division

Alberta
ENVIRONMENT

PEACE RIVER

1981/82 ICE OBSERVATION REPORT

Return to HWC

ALBERTA ENVIRONMENT
WATER RESOURCES MANAGEMENT SERVICES
TECHNICAL SERVICES DIVISION


Prepared by: G.D. Fonstad, P.Eng.
Head, River Studies Section
River Engineering Branch

Submitted by: M.E. Quazi, P.Eng.
Branch Head
River Engineering Branch


Portions of the "Alberta - B.C. Joint Task Force on Peace River Ice - Report" prepared by Alberta Environment

PEACE RIVER

1981/82 ICE OBSERVATION REPORT

Return to HWC

November 1982

## SUMMARY

This report contains the first draft of the sections of the 'Alberta - B.C. Joint Task Force on Peace River Ice' Report which were the responsibility of Alberta Environment. Other sections, written by the B.C. Ministry of the Environment and by B.C. Hydro and Power Authority, complete the report to the respective Ministers of the Environment for the two Provinces.

The report summarizes the events which occurred at freeze-up at Peace River Town in January of 1982. A presentation is made of the basement flooding problem which occurred in the West Peace River subdivision. An outline of the breakup preparation undertaken, including ice weakening efforts, is made. The observations of River Engineering Branch field staff of the breakup of the Heart, Smoky and Peace River are presented.

Finally, a proposal for a controlled mode of operation of B.C. Hydro's G.M. Shrum generating station at the WAC Bennett Dam during freeze-up at Peace River Town is included.

TABLE OF CONTENTS


| | Page |
|---|---|
| SUMMARY | i |
| TABLE OF CONTENTS | ii |
| LIST OF FIGURES | iii |
| LIST OF TABLES | iii |
| 2.0 PEACE RIVER FREEZE-UP | 1 |
| 2.1 General | 1 |
| 2.2 Sequence of Events | 1 |
| 3.0 COMMITTEE ACTIVITIES | 6 |
| 3.1 West Peace River Groundwater Flooding | 6 |
| 3.2 Breakup Preparations | 9 |
| 3.3 Ice Weakening Effort | 10 |
| 4.0 BREAKUP OBSERVATIONS | 18 |
| 4.1 Heart River | 18 |
| 4.2 Smoky River | 20 |
| 4.3 Peace River | 24 |
| 4.4 General Observations | 32 |
| 5.0 PROPOSED MODE OF OPERATION FOR 1982/83 FREEZE-UP | 39 |
| REFERENCES | |
| FIGURES | |

## LIST OF FIGURES


| Figure No. | Description |
|---|---|
| 1 | Releases From G.M. Shrum Generating Station and River Stages at Peace River Town, 24 December 82 to 30 April 82. |
| 2 | Peace River Open Water Flow Travel Times, Hudson Hope to Taylor and Taylor to Peace River Town |
| 3 | Peace River Open Water Flow Travel Times, Hudson Hope to Peace River Town |
| 4 | Lagged Releases from G.M. Shrum Generating Station and River Stages at Peace River Town, 25 December 82 to 8 January 82 |
| 5 | Accumulated Degree-Days of Freezing, Town of Peace River, to 31 December 82 |


## LIST OF TABLES


| Table No. | Description | Page |
|---|---|---|
| 1 | Breakup Front Position/Timing | 26 |
| 2 | Breakup Data, Peace River at Peace River Town | 43 |

## 2.0 PEACE RIVER FREEZE-UP

### 2.1 General

The Peace River at Peace River Town froze up, in the 1981/82 season, in an unusual manner for the river. The initial ice cover formed normally in early January. However, five days after the initial cover formation the river experienced a second staging due to consolidation of the ice pack. This second staging was in the order of 3.5 m, and brought the ice level to within 1.66 m of the top of the dikes in Peace River Town*. A complete record of hourly water levels at Peace River, and flow releases, uncorrected for travel time, from B.C. Hydro and Power Authority's (BCHPA) G.M. Shrum (GMS) generating station, for the period 24 December 1981 to 30 April 1982, is shown in Figure(s) 1.

### 2.2 Sequence of Events

The sequence of events which occurred at Peace River Town during the 1981/82 freeze-up period has been previously summarized by Northwest Hydraulic Consultants Ltd (NHCL) [(1)**], based on preliminary data and verbal reports collected by Alberta Environment, Acres Consulting Engineering Ltd. and others. Copies of this report were distributed to BCHPA, the B.C. Ministry of Environment and Alberta

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Note: * All reference to dike levels is made with respect to the dike across the river from the Water Survey of Canada gauging station.

** Numbers in parentheses refer to numbered references cited following the text of this report.

Environment. The following is a slight change to that reported sequence of events, based on an increased data base.

In its analysis NHCL presented the freeze-up events in terms of BCHPA's releases from GMS, lagged three days to allow for flow through time to Peace River Town. Figure 2 shows open water flow travel times from Hudson Hope to Taylor, and from Taylor to Peace River, based on data provided by the Alberta River Forecast Centre. Figure 3 shows these times consolidated for flow from Hudson Hope to Peace River. BCHPA's mean daily releases during the period 24 December 1981 to 7 January 1982 varied from a minimum of 800 $m^3\ s^{-1}$ to a maximum of 1777 $m^3 s^{-1}$, and had an average of 1347 $m^3 s^{-1}$. Flow through times from Figure 3 would thus be 86, 46 and 41.5 hours for the minimum, average and maximum releases respectively. For this reason the mean daily GMS releases have been plotted on Figure 4, for the period 25 December to 8 January, lagged 48 hours (instead of the 72 hours used by NHCL). Shown also are the Peace River gauge heights, based on hourly data, and Water Survey of Canada's (WSC) preliminary mean daily flows for the gauge 07HA001, Peace River at Peace River. Figure 4 should be consulted while reading the following sequence of events:

a. 25 to 28 December 1981

The river stage at Peace River generally decreased due to decreased releases from the GMS plant in response to lesser power demand over the Christmas holiday. It was originally reported that the upstream progressing ice accumulation had passed through the Town of Peace River on 28 December. The absence of a significant rise in water level on this date indicates that the river was still operating in an open water mode. The slight rise at approximately 0300 hours of 28 December could be due to a brief stationary period in the general ice flow, brought on by the reduction in surface area corresponding to the decrease in flow at Peace River from 1500 to 913 $m^3s^-$ between 26 and 28 December. The preliminary WSC records for December of 1981 show 'ice conditions' for the period 16 to 20 December, and 27 and 28 December, but show normal, or open water, conditions for the remaining time. The disappearance of ice conditions reflected in the WSC records can be explained in terms of a warm period between 19 and 22 December, as shown in the leveling-off of accumulated degree-days of freezing shown in Figure 5.

b. 28 December 1981 to 1 January 1982

The water level at Peace River rose gradually by 0.8 m until approximately 1700 hours on 1 January, in response to increased power generation releases following the Christmas break. Air temperatures, which had been at a mean daily value of -3°C on 21 December, dropped to a mean of -37°C on 1 January, with nightly lows in the order of -40 to -41°C. This caused a dramatic increase in the accumulation of degree-days of freezing, and initiated rapid ice production in the open river.

c. 1 to 2 January 1982

Water levels rose 2.63 m at Peace River while the discharge in the river was in the order of 2060 to 2170 $m^3s^{-1}$. Most of this increase corresponds to the normal experience of 'staging' at freeze-up, as the open water rating curve indicates a change of 0.06 m between the two discharges. This staging almost certainly indicates the formation of an ice cover on the river, with the corresponding increase in hydraulic resistance.

d. 3 to 4 January 1982

Water levels at Peace River dropped 1.22 m from the staging peak on 2 January. Power releases at GMS had dropped from 1777 $m^3s^{-1}$ on 30 December to 1724 $m^3s^-$ on 31 December, and further to 798 $m^3s^{-1}$ on 1 January as the load demand decreased for the New Year's holiday. W.S.C. records show the discharge at Peace River dropped from 2170 $m^3s^{-1}$ on 2 January to 1010 $m^3s^{-1}$ on 4 January, which would have caused a stage reduction of 0.81 m under open water conditions. The remaining 0.41 m of stage decrease can probably be attributed to smoothening out of the roughness of the under side of the ice cover as the roughness projections were melted off by the slightly warmer fluid flow beneath the ice.

e. 4 to 7 January 1982

Increasing GMS releases, from 798 $m^3s^{-1}$ on 1 January to 1695 $m^3s^{-1}$ on 5 January, reflecting increased load demand following New Year's Day, caused an increase in water level at Peace River of 1.03 m by 2100 hours on 7 January. This brought the stage at Peace River to within 0.2 m of the peak stage attained during ice cover formation on 2 January, though the mean daily discharge at Peace River on 7 January was 160 $m^3s^{-1}$ less than it had been on the 2nd when the ice first packed in. The mean daily discharge continued to increase into 8 January.

f. 7 to 8 January 1982

The WSC recorder chart for Peace River at Peace River shows an increase in water level of 0.60 m between 2100 and 2200 hours on 7 January. A report from a Peace River resident indicated that at approximately 2230 hours on 7 January the ice cover on the river cracked and the ice began to move downstream. The water level rose sharply a total of 3.54 m from 2100 hours on 7 January to 0100 hours on 8 January, a rate of 0.89 m $hr^{-1}$. The water level reached a stage of 13.35 m (Elevation 318.15 m Geodetic), which was 1.66 m below the top of dike across from the WSC gauge (top of dike Elevation is 319.81 m Geodetic).

A couple of hours before the ice cover ruptured at Peace River, as reported by Messers R. Carson, P. Eng. and K. Baillergeon of Acres Consulting Services Ltd., who were monitoring the Peace River freeze-up in the vicinity of Dunvegan, a resident in the Dunvegan area telephoned Mr. Carson to tell him the ice was moving at Dunvegan. Mr. Carson reported this to the local RCMP, and went out to investigate. Later evidence showed that the lengthening ice cover had progressed upstream of Dunvegan by 7 January, reportedly between 'a few' and 50 km upstream. It was not known at this time whether the whole of the ice cover at, and upstream of, Dunvegan was in motion, through this eventually proved to be the case.

According to observations by Mr. Carson, and verified later by Alberta Environment, the moving ice formed an ice jam at the downstream end of Verte Island, some 14 km downstream of Dunvegan, between 1700 and 1900 hours on 7 January. The jam attained a height of approximately 9 m, and was only in place for a few hours before it released. The available evidence indicates that the ice jam released prior to the ice movement at the Town of Peace River.

Following its rapid rise to peak at 0100 hours on 8 January, the water level at Peace River receded through the rest of the day, dropping 1.34 m by midnight. As the mean daily discharge on 8 January was 120 $m^3s^{-1}$ higher than that of 7 January, according to the WSC preliminary records, the decrease in water level must be attributed to the smoothening of the underside of the ice cover.

g. 9 to 20 January 1982

Because of the potential for serious flooding of the Town of Peace River if the new ice accumulation re-ruptured and reconsolidated, BCHPA was requested to regulate their releases from GMS to a constant value, in order to let the ice accumulation gain strength by freezing. Accordingly, as can be seen on Sheet 2 of Figure 1, BCHPA regulated their releases to an average of 1691 $m^3s^{-1}$ over the period of 9 to 20 January. In this same period the recorded discharges at Peace River had a mean of 1941 $m^3s^{-1}$, while the Smoky River had a mean discharge of 22 $m^3s^{-1}$, yielding a local inflow between GMS and Peace River of 228 $m^3s^{-1}$.

The water level at Peace River dropped a further 0.41 m on 9 January before it levelled off, with minor fluctuations, until the middle of February, when a decrease in releases caused the water level to drop a further 1.33 m (see discussion of West Peace River groundwater levels).

## 3.0 COMMITTEE ACTIVITIES

### 3.1 West Peace River Groundwater Flooding

When the water levels in the Peace River rose on the night of 7/8 January, the groundwater table in the river's floodplain responded by rising as well. Unfortunately, no data was taken during January. Groundwater levels in West Peace River were recorded at a private well by Mr. Barry Ellis, a Town employee, from 5 February, and were subsequently tied into Geodetic Bench by the Town of Peace River. The groundwater level data has been added to Figure(s) 1 in terms of corresponding gauge heights. No correction was included for river slope to transfer the levels as elevations to the WSC gauge, however, the data serves to indicate relative effects.

When the river level rose and stabilized by 9/10 January, at a gauge height between 11.5 and 12 m, the groundwater table in West Peace River came up and caused flooding in a number of basements. The groundwater response to the change in river levels was reported to be relatively moderate, as it was a matter of some twelve days before the Town started to receive flooding complaints. As BCHPA had a fairly high power demand, and the various authorities were trying to maintain the river level while the ice cover gained strength through freezing, the releases from GMS had to be held constant. Hence, little could be done at that time to alleviate the basement flooding problem in West Peace River.

The releases from GMS were held nearly constant for the period 8 to 20 January in order to let the ice accumulation at Peace River gain strength by freezing (Figure 1, sheets 2 and 3). Following this, the GMS generating station resumed its normal operations. However, the groundwater problem in West Peace River continued, as the attenuated releases from GMS did not cause a substantial river level change at Peace River Town.

In February the basement flooding problem was still acute. From the reported depths of basement flooding it was judged that if the river level could be drawn down in the order of a metre, the flooding problem would abate, hence BCHPA was requested to reduce its releases. BCHPA complied with the request and began stepping down its GMS releases on 16 February. The releases were stepped down from a mean discharge of 1615 $m^3s^{-1}$, for the first half of February, to an average of 1030 $m^3s^{-1}$ for the second half. Sheet 5 of Figure 1 shows the resulting decrease of 1.27 m in stage at Peace River over the period 19 to 25 February. In the same period the groundwater table in West Peace River dropped 0.42 m; and continued to drop a further 0.48 m by mid March. During this period the basement flooding problem in West Peace River appears to have abated, though one or two homes may still have experienced some minor flooding.

An increase in releases from GMS on 16 March caused the river level to again increase, with a corresponding increase in groundwater levels. The data shows that the increase in flows from GMS, initiated at 0600 hours on 16 March, caused the river levels at Peace River to increase 0.39 m starting at 2100 hours on 18 March. This indicates an ice-covered flow travel time, for the ice conditions which existed, of 63 hours for a discharge of approximately 1250 $m^3s^{-1}$; an increase in travel time of 15.5 hours over the open water travel time (Figure 3).

The groundwater level increase, over the period 18 to 31 March, which resulted from the 0.39 m increase in river level, was measured to be 0.34 m. This increase in groundwater level was sufficient to reinstate basement flooding in five or six homes in West Peace River. The flooding persisted until the river levels decreased following the 'break-up' of the Peace River in late April.

The data indicates that (as an initial attempt) if future occurrences of basement flooding in West Peace River are to be avoided, the ice-covered river stage at Peace River should not be allowed to increase above 11.0 m (Elevation 315.80 m, or 1036.09 ft GSC). Additional data would be required to confirm or alter this value. In this respect it is recommended that basement elevations in West Peace River be established by the Town for all of the homes in the subdivision. Additionally, in order to obtain better records of groundwater levels to determine the maximum river level that would not cause basement flooding, Alberta Environment has established three groundwater level recording wells in West Peace, and will record the levels daily throughout the ice-covered period.

3.2 Breakup Preparations

Because of the unusually high level at freeze-up and the perceived thickness of the ice accumulation in the reach through Peace River Town, it was thought that the thick ice would prove a barrier or blockage to the passage of the normal spring break-up front. As well, snowpacks in the river basins tributary to the Peace River above the Town were gauged as being above normal, which could result in above normal spring runoff. The combination of a possible blockage to the passage of the break-up front and possible high spring runoff gave every indication that an ice jam, if one occurred at Peace River, could result in serious flooding of the Town. For this reason preparations for break-up were commenced in February of 1982.

The Town of Peace River reviewed and updated its contingency plan for flooding situations in the Town. On March 3rd, a coordinating meeting was held in Peace River of most agencies, Government, Police and the like, which could be involved in providing assistance to the Town in case of spring flooding. Following this meeting, and at the recommendation of the River Engineering Branch, Alberta Environment, the Town of Peace River undertook to plow a single lane on the surface of the ice in preparation for other possible break-up mitigative measures. This aspect is discussed in more detail in the next section.

A meeting was held between the members of the Alberta - B.C. Joint Task Force on Peace River Ice, in Peace River on 25 March. At that time Alberta Environment submitted a draft report to the other members of the Committee, entitled 'Status Report and Proposed Ice Jam Mitigation

Plans, Peace River at Peace River Town'[2]. The report summarized preparations by the Town and others towards the anticipated breakup flooding, outlined a breakup observation plan, provided a summary of mitigative measures conducted in the past at Peace River, and made aseries of recommendations regarding what should be attempted to this end in 1982. After due consideration and discussion the members of the Committee agreed to the adoption of most of the recommendations, which led to the implementation of a program of pre-break-up mitigative measures.

### 3.3 Ice Weakening Effort

Ice weakening measures, in advance of breakup, were conducted as approved by the Committee. These included lane clearing and dusting, plus preblasting in specific areas identified in previous studies as being ice jam prone.

When the secondary staging occurred on 7/8 January the ice surface ended up as a jagged mass. The ice cover thickness, as measured by the Alberta Research Council in late January, was reported to be in the order of 1 m of solid ice, with up to 3 m of loose floes and accumulated slush ice beneath. The jagged surface made access and movement on the ice, for ice jam mitigation purposes, virtually impossible. It was decided to plow lanes on the ice surface, which would require the use of bulldozers, from the mouth of the Heart River to a point downstream of the Town. This would provide dual benefits in that a passable lane would exist which could be used to access the river for other mitigative measures; and the lanes themselves could be dusted with some dark

# 4.0 BREAKUP OBSERVATIONS

## 4.1 Heart River

Breakup of the Heart River was uneventful this year. Few observations, if any, were carried out prior to April 16. Alberta Environment carried out aerial inspections of the Heart River from Nampa to Peace River every second day from 16 April to 23 april, and daily thereafter until breakup occurred in the Peace River at Peace River Town on 26 April.

All observations showed the ice in the Heart River to be virtually melting in place. By 19 April the river was virtually free of ice between Nampa and the mouth of the river. There were three exceptions.

The lowest kilometre of the river, between its mouth and the NAR railway bridge which crosses the Heart River just above the '12 Foot Davis' Ballpark retained ice. This reach still contained both solid and fragmented ice. The ice, however, was deteriorating (candling and melting) rapidly due to solar radiation and thermal erosion due to the river flow. Sediments carried in the flow were, at times, being deposited on top of the ice, which would have accelerated the thermal deterioration processes.

The other two reaches where a complete ice cover existed were in areas where bank slides (one major, one minor) had constricted the Heart River. The minor slide had constricted the channel width by about 50%, and held the river ice upstream of the constriction. The ice in this in place until 28 April, when it moved down and was turned downstream to occupy the space between the ice in the shear ridge across the mouth and the right bank of the Peace River. The ice in the gap plowed and blasted in the shear ridge across the mouth of the Heart did not go out at this time, however, it was evident that most of the Heart River discharge was finding its way through the gap and into the Peace River.

The final dislodgement and run of the ice in the lower reach of the Heart River resulted in a stage decrease, possibly due more to the lowering of the Peace River levels following its breakup, of approximately 1.5 m.

4.2 Smoky River

Few known observations of the ice conditions on the Smoky River between its confluence with the Peace River and the WSC Gauge 'Smoky River at Watino' were carried out prior to 16 April 1982. From 16 to 23 April Alberta Environment carried out aerial observations every second day, and daily observations from 23 to 26 April when the ice on the Peace River went out. Additional minor observations were taken on 27 and 28 April, when the Smoky River was finally clear of ice.

More detailed observations were made for the Smoky River than for the Heart. The following is a summary of the observations made by Alberta Environment staff over the period 16 to 28 April.

a. 16 April

- Ice on the Smoky River generally darker than on the Peace River.

m, and appeared to be being forced between the chunks of the ice dam as the latter stayed virtually motionless. At first we could not tell where the fragmented ice was coming from, but after waiting for 15 - 20 minutes, it became apparent that the ice was being entrained into the river flow about 30 - 40 m upstream of the toe of the jam held by the Dam. The ice was apparently being 'simply' entrained, i.e., little to no vorticity associated with the entrainment, and passed beneath the toe of the jam and upstream half of the dam, and was re-emerging in the fragmented downstream half.

- The inspection was carried on up to Watino and back, with no ice except that grounded on the banks being present.

- Upon arrival back at the Hanging Dam the river was virtually clear of ice. Only about 0.75 km of the original jam remained, as well as grounded ice along the river banks in what were the jam's shear walls. Ice continued to be forced through the Hanging Dam.

- The ice which had flowed through the dam was small, and well dispersed, with no indication of reforming another jam.

h. 27 April

- The jam at the mouth of the river was still in place, though was 2 - 3 km longer. No flood threat was perceived.

- The river was clear of ice to Watino, except for this jam, the Hanging Dam fragments and grounded ice along the banks.

- Gauge Height was 1.911 m at 0900 hours MST at Watino.

i. 29 April

- The ice jam at the mouth of the Smoky had pushed through the most right-hand distributary channel (between the islands and the right bank of the Peace River) last night, leaving the heavily hummocked ice between the remaining islands and shoals intact.

- Smoky River clear of ice except for Hanging Dam and grounded ice along the banks.

The Smoky River breakup was therefore an uneventful occurrence, and was basically thermal (semi-static) in nature. No flooding was experienced; and the event which usually causes problems for the Town of

Peace River, that is the Smoky River ice running out before the Peace River is clear of ice, did not occur. That the ice went out in a thermal (melt) mode was attributed to the marked lack of inflow from snowmelt, as witnessed by the gauge heights recorded at Watino.

The only event of interest was the manner in which the ice, jammed on the Hanging Dam, went out.

## 4.3 Peace River

Observation of the location of the Peace River Breakup front was conducted by BCHPA from 17 March 1982, and was taken over (by agreement) by Alberta Environment when the breakup front reached the Dunvegan Bridge, or April $16^{th}$ in this case. The breakup front position and associated information is given in the following Table 1.

The breakup 'front' could be classified as a thermal (semi-static) phenomenon, as opposed to the more dynamic breakup events characterized by the fracturing and movement of a still fairly substantial ice cover under the influence of a flood wave or general rising stage due to an increase in discharge with the commencement of the spring runoff. The thermal front was characterized by the following (moving from upstream to downstream):

a. An open lead in the ice cover, varying in width from an eighth to a quarter of the width of the river. Within this open lead were small ice floes broken off of the edges of the upstream ice still attached to the banks, and a small amount of debris such as timber deadfall. The ice floes and debris covered the open lead to less than ten percent of its area.

b. At the downstream limit of the open lead was a small accumulation of jammed ice and debris, occupying a width roughly equal to the width of the open lead upstream, and varied in length from 30 to 100 m (±). This small debris jam did not appear to create a significant backwater behind it.

c. Ahead of the 'debris front' the ice cover was mostly intact, or more properly had not moved yet. A long, narrow area of very dark ice, indicating rapid deterioration, preceded the debris front, and basically followed the river's thalweg. More often than not, this 'finger' of dark ice contained a number of small areas where the ice had melted out in place, and small floes had been detached by melt.

TABLE 1
Peace River Breakup
Breakup Front Position/Timing

| Date | Time | Front[1] at Mile | Progression Rate (miles/day) | Comments |
|---|---|---|---|---|
| 17 Mar | | 88. | | 1 mile above Clayhurst Ferry |
| | | | 4.5 | |
| 23 Mar | | 115. | | |
| | | | 2.5 | |
| 25 Mar | | 120. | | |
| | | | 2.5 | |
| 29 Mar | | 130. | | |
| | | | 1.5 | |
| 31 Mar | | 133. | | 112 mi upstream of Peace River Town |
| | | | 1.5 | |
| 2 Apr | | 136. | | |
| | | | 0.0 | |
| 5 Apr | | 136. | | |
| | | | 3.3 | |
| 8 Apr | | 146. | | |
| | | | 4.8 | |
| 13 Apr | | 170. | | 75 mi upstream of Peace River Town |
| | | | 2.5 | |
| 16 Apr | 0900 | 177.5 | | |
| | | | 6.53 | |
| 19 Apr | 0840 | 197.1 | | |
| | | | 5.55 | |
| 21 Apr | 0830 | 208.2 | | |
| | | | 6.35 | |
| 23 Apr | 0845 | 220.9 | | |
| | | | 7.00 | |
| 24 Apr | 0820 | 227.9 | | |
| | | | 8.90 | |
| 25 Apr | 0800 | 236.8 | | |
| | | | 6.70 | |
| 26 Apr | 0600 | 243.5 | | |
| | | | 6.12 | |
| 26 Apr | 1600 | 246.1 | | At Bridges in Peace River |
| | | | 5.16 | |
| 27 Apr | 0830 | 249.6 | | |
| | | | 4.06 | |
| 27 Apr | 1500 | 250.7 | | |
| | | | 9.33 | |
| 28 Apr | 0830 | 257.5 | | |
| | | | 16.00 | |
| 3 May | 0940 | 337.5 | | |
| | | | 58.10[2] | |
| 7 May | 1035 | 570.0 | | |

Notes: See next Page.

i. 28 April

- Ice front at Mile 257.5 at 0830 hours, an area known as '12 - Mile Flats'.
- The front had passed through all known areas of ice jam initiation.

## 4.4 General Observations

The 1982 ice breakup on the Peace River was nowhere near as disastrous as mid-winter data indicators pointed out that it could be. That the breakup went quietly and smoothly can be attributed, by priority, to the following:

a. A cool spring which held off the snowmelt runoff until the breakup was through Peace River Town.

b. A reportedly dry late summer and fall, such there was little moisture in the ground at freeze-up. Most of the local snowmelt in spring appeared to be absorbed into the ground.

c. Controlled releases from GMS. And,

d. In some small measure, to the ice weakening efforts carried out before the arrival of the breakup front.

The first two points are natural phenomena, and hence cannot be controlled for purposes of ice jam mitigation. These two alone, however, probably contributed as much as 70 percent of the effective mitigative circumstances which led to the uneventful breakup.

The controlled releases from GMS by BCHPA likely added another 20 percent to the total effective mitigative effort. The constant, or very gradually varied flow releases within operating limits, prevented major stage changes in the river which could have precipitated a more dynamic breakup. One contingency allowance that was made, but never invoked, was to have the GMS releases cut back as snowmelt runoff increased, in order to maintain a fairly constant flow through Peace River Town. It is the constancy of discharge at Peace River Town which is desirable, both at breakup and at freeze-up.

The remaining 10 percent of the effective mitigative measures goes to the ice weakening effort. Some comments should be made concerning the efficacy of these efforts due to the costs involved.

| | |
|---|---|
| a. to Alberta Environment - | $ 21,751.14 (less wages etc.) |
| b. to Peace River Town - | $150,385.24 |
| c. to BCHPA - | |
| TOTAL | $ |

Ice thickness measurements made during the preblasting operations showed an average decrease in ice thickness along the plowed lanes of 0.62 m (2.04 ft) from the measurements made while the lanes were being plowed, with a maximum decrease of 1.05 m. Even with this reduction, some ice thickness measurements carried out for the preblasting operation, in the period of 16 to 21 April, were in excess of 2.44 m.

The plowed lanes served a second purpose, being drainage of the surface melt of the ice cover. When the winter jam (which created the ice cover) formed in January there was a certain amount of silt deposited on the ice from the flow, as well as a certain amount of debris in the form of deadfall timber. As the sun angle increased into the spring, the exposed faces of the hummocked ice surface began to melt, aided by radiation absorption due to the deposited silts and debris. The melt, however, was only of the exposed ice hummocks, above the mean ice surface, and did not contribute toward general ice weakening. Some of the meltwater found its way into the plowed lanes, and began to flow downstream. As well, in the numerous holes that were augered through the ice to test its thickness prior to plowing the lanes, river flow exchanged with the meltwater flow. Dependent upon the location of the lane surface with respect to the river's hydraulic grade line i.e., raised above or depressed below, the ice lane flow would drop down through the auger holes, or river flow would boil up through them respectively. The flow through the holes caused enlargement through thermal erosion, many holes becoming large enough for a man to drop through, and in one or two instances large enough to drop a vehicle through. With fluid flow on top of the lanes as well as beneath them, thermal erosion would occur from both sides.

The efficacy of the ice blasting downstream of Bewley Island and downstream of Six Mile Point was difficult to judge, as the breakup front passed through both of these areas at night. However, observation of the resulting craters before the arrival of the breakup front had shown that most of the blast debris which had fallen back into the craters had disappeared by the time the breakup front arrived. This can be attributed to ice floe entrainment by the river flow, and possibly to melt to a small degree. The craters allowed sediment laden river flow onto the surface, which in turn created thermal erosion around and between the craters, and possibly some increased heat absorption through the changed surface albedo.

There is a hint in the data contained in Table 1 that the ice front passed through the blasted area slightly quicker than others. See for instance the progression rates between 1500 hours on 27 April and 0830 have been located one-lane-spacing (38 m±) further towards Bewley Island. The breakup front continued to follow the second and third lanes all the way down to the end of the lanes near Six Mile Point. In this respect the thinner ice in the lanes appears to have been beneficial.

The area where the most noticeable effects, and possibly the most noticeable success in the overall ice weakening effort was achieved, was the work conducted at the mouth of the Heart River. There is little doubt but that the massive ice accumulation in the shear zone across the mouth of the Heart constituted an obstruction to both fluid and ice flow from the Heart. A good portion of the ice in the shear zone was probably grounded to the bed of the Peace River, allowing flow from the Heart through it by percolation only. Plowing a gap through the shear zone removed the surcharge load on the mean ice cover. The buoyancy of the ice remaining beneath the ice cover caused the ice to lift, most probably through the mechanism of plastic creep. This may have opened a small waterway through the ice in the shear zone. Subsequent blasting of the ice in the gap, with the charges placed at depth, appeared to cause further heave of the upper surface, and likely caused an enlargement of the waterway at the bottom of the ice.

When the little ice which remained in the Heart River (following melt) finally moved out, it was contained against the right bank of the Peace River by the shear ridge. The Heart River flow, however, was observed to be making its way through the gap. The ultimate efficacy of this work was not tested, as the Heart River neither jammed at the mouth, nor increased its discharges appreciably.

TABLE 2
Breakup Data
Peace River at Peace River Town

| Year | Breakup Date | 5-Day Pre-breakup Elevation* (m) | Discharge During Breakup: Peace River Above Smoky River*2 | Discharge During Breakup: Smoky River Above Confluence*3 | Maximum Ice Jam Elevation (m) | Maximum Stage Increase Above Pre-breakup Elevation (m) |
|---|---|---|---|---|---|---|
| 1960 | Apr 16 | 312.88 | 883.49 | 365.29 | 313.21 | 0.33 |
| 1961 | Apr 20 | 311.69 | 1112.85 | 104.77 | 311.81 | 0.12 |
| 1962 | Apr 16 | 312.30 | 866.50 | 648.46 | 313.94 | 1.64 |
| 1963 | Apr 19 | 311.75 | 3381.03 | 1093.03 | 316.14 | 4.39 |
| 1964 | Apr 19 | 312.33 | 897.64 | 206.15 | 312.15 | -0.18 |
| 1965 | Apr 14 | 311.90 | 1568.75 | 481.39 | 313.61 | 1.71 |
| 1966 | | | | | | |
| 1967 | Apr 30 | 311.90 | 291.66 | 1005.25 | 313.40 | 1.50 |
| 1968 | | | | | | |
| 1969 | Apr 15 | 311.96 | 475.72 | 948.61 | 314.89 | 2.93 |
| 1970 | | | | | | |
| 1971 | Apr 19 | 312.48 | 1260.10 | 203.88 | 313.06 | 0.58 |
| 1972 | Apr 20 | 313.21 | 1452.65 | 538.02 | 314.86 | 1.65 |
| 1973 | Apr 12 | 313.76 | 2273.84 | 515.37 | 318.18 | 4.42 |
| 1974 | apr 20 | 313.36 | 2288.00 | 1308.24 | 317.51 | 4.15 |
| 1975 | Apr 17 | 314.16 | 2174.73 | 69.94 | 314.52 | 0.36 |
| 1976 | Apr 11 | 313.94 | 1676.36 | 594.65 | 314.34 | 0.40 |
| 1977 | Mar 12 | 312.72 | 767.39 | 66.83 | 311.90 | -0.82 |
| 1978 | Apr 15 | 313.18 | 1333.72 | 215.77 | 313.49 | 0.31 |
| 1979 | Apr 30 | 314.10 | 2520.20 | 1589.99 | 318.61 | 4.51 |
| 1980 | Apr 18 | 311.81 | 651.29 | 387.94 | 313.06 | 1.25 |
| 1981 | | | | | | |
| 1982 | Apr 26 | 315.46 | 1653.00 | 247.00 | 315.94 | 0.48 |

Notes: *1 Average elevation of mean daily discharges at Peace River for 5 days prior to breakup, estimated from recorded water levels.

*2 Peace River Discharge = Discharge at Peace River - Smoky River Discharge at Watino

*3 Smoky River at Watino.

## 5.0 PROPOSED MODE OF OPERATION FOR 1982/83 FREEZE-UP

Cross sections established during the 1981/82 ice season were surveyed following breakup, However they were not available in time to conduct any analysis towards the mode of operation of GMS for the freeze-up period in 1982/83. However, the limited data and observations available from the 1981/82 season suggest a mode of operation which can be considered a first attempt at controlling the freeze-up level.

First, it was noted that for this past freeze-up the rupturing of the initial ice cover was caused by increased releases from GMS in response to an increased load demand following reduction in load over the Christmas to New Year holiday season (See Figure 1, Sheet 2 of 9 or Figure 4). Figure 1, Sheet 2 of 9, shows something like a five-fold increase in releases over the period 1 to 6 January. It is now known that the release of a moderately sized ice jam, in the vicinity of Verte Island, created a slug of flow (released from storage) which contributed to the rupture of the initial cover in Peace River, however, this release was also likely due to the stepped up releases from GMS.

The point to be made here, and in fact to the operation of any hydro generating station when the freeze-up front is passing through sensitive areas for winter flooding, is that the discharge should be held constant, or at least within reasonable limits, until the ice cover has formed and gained some internal strength through freezing. The question remains as to what would constitute the maximum desirable freeze-up level through the Town of Peace River; to allow BCHPA a reasonable amount of freedom of operation in response to load demand, and yet avoid both surface and groundwater flooding in the Town of Peace River? As groundwater flooding occurs in response to increased river levels, at a lower level than that which would cause overbank flooding, and stays for the longest time, this should be the primary consideration for attempting to control the freeze-up level. If this criteria is met, then there should be no occurrences of surface flooding due to dike overtopping from stage increases as the ice cover forms.

The limited groundwater level data available shows that a Peace River ice-covered stage, for the particular cover thickness attained in 1982, of between 11 and 12 m (Elevation 315.8 to 316.8 m; 1036.1 to 1039.4 ft) maintained the basement flooding condition in West Peace River until mid-February. BCHPA's releases during this period were in the order of 1690 $m^3s^{-1}$ (59,689 cfs) over the period 9 to 20 January to provide a constant discharge to let the cover gain strength; and varied from 1930 to 880 $m^3s^{-1}$ (68,160 to 31,080 cfs) until 16 February when the releases were cut to in the order of 1000 $m^3s^{-1}$ (35,320 cfs) in order to lessen the groundwater flooding in West Peace River.

When the GMS releases were reduced following 16 February the groundwater table dropped over a period of 12 days so that it corresponded to a gauge height at the WSC gauge of approximately 11.0 m. The corresponding groundwater level was in the order of 10.4 m (See March 1 levels, Figure 1, Sheet 5 of 9). The basement flooding problem abated with this decrease, with the exception of perhaps five homes. This suggests that the maximum allowable Peace River stage following freeze-up should be in the order of 10.0 to 10.4 m; or Elevation 314.8

to 315.2 m, say 315.0 m (1033.46 ft) is the maximum desirable river elevation. If all the basement elevations in West Peace River were known, it would be a simple matter to determine the maximum allowable river level, but they are not.

The emphasis placed earlier on the particular ice cover thickness for 1982 should be noted. Different cover thicknesses, generated by the manner of freeze-up, for a constant discharge will yield different maximum ice levels. However, as the freeze-up in January of 1982 was so unique, possibly giving an upper bound to ultimate initial cover thickness, use of the 1982 data should prove conservative. Observations from future years, hence different initial ice thicknesses, may refine this rather crude analysis and allow BCHPA a little more flexibility in operations at freeze-up.

An interesting, and rather unique analysis of the Peace River freeze-up levels by Carson and Lavender (1980)[8] of Acres Consulting Services Ltd., gives an indication of the allowable GMS releases, attenuated to Peace River, that would produce the maximum desirable ice covered level of 315.0 m. It should be noted that while their analysis was based upon leading edge stability criteria for initial ice cover formation, the figure they produced described completely (with only minor assumptions) the entire event at Peace River last year, including the secondary staging due to telescoping of the ice cover. From their figure (see Figure 2 of Ref 1) for the above allowable river stage, the maximum value of the parameter $(Q/B)^{2/3}$ should be 2, which corresponds to a discharge at Peace River Town of about 1350 $m^3s^{-1}$ (47,675 cfs). At this point in time it is not known how much the releases from GMS attenuate before reaching Peace River Town, therefore it is suggested that 1345 $m^3s^{-1}$ (47,500 cfs) be the maximum constant discharge released from GMS to arrive at Peace River with the ice front.

Figure 3 shows an open water flow travel time, for a discharge of 1345 $m^3s^{-1}$, of approximately 42 hours. Therefore the following mode of operation for GMS for the 1982/83 freeze-up period is recommended:

1. Monitor the rate of advance of the freeze-up front towards the Town of Peace River, paying attention to changes in the rate brought on by changes in atmospheric conditions, in order to be able to forecast when the freeze-up front will reach Peace River Town within 48 hours. For this purpose, it is recommended that Mile 255 (Birch Island, just downstream of Six Mile Point) be considered as the 'arrival' location, as the area is ice jam prone and could affect the Town. During this period allow BCHPA to operate GMS as load demand requires.

2. When the ice front is calculated to reach Mile 255 in 48 hours, restrict GMS releases to a maximum of 1345 $m^3s^{-1}$ to allow the discharge releases to arrive at Peace River coincident with the ice front. A smaller release, to conserve winter storage in Williston Lake and for conservatism due to the rough nature of the guidelines through which this estimate was made, would be acceptable, but not less than 1000 $m^3s^{-1}$. The discharge should preferably be held constant, or at most be allowed to fluctuate 42 $m^3s^{-1}$ (1500 cfs), providing a release of 1345 $m^3s^{-1}$ is not exceeded.

3. Closely monitor the groundwater levels in West Peace River (Alberta Environment has established three recording wells for this purpose), and if basement flooding becomes immanent, reduce the releases from GMS fully realizing that it will take 48 hours to have any effect at Peace River Town.

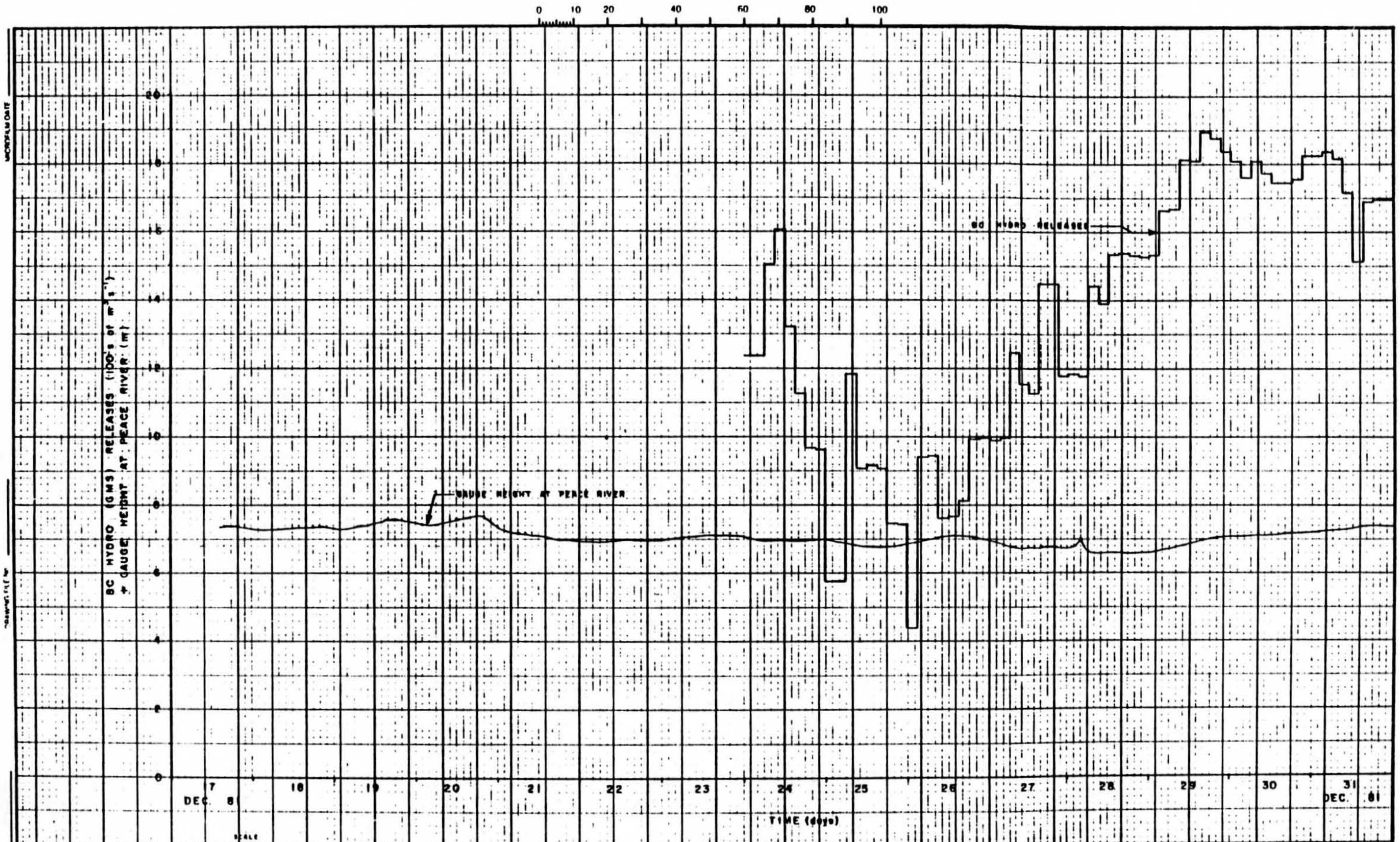
4. As was initiated in January 1982, the ice cover formation discharge should be held constant for awhile, to allow the ice cover to gain strength by freezing. Twelve days were allowed in January 1982, and it is recommended that a similar time be allowed this year.

5. Following the 12 day ice cover strengthening period, slowly step up base flows and peaking to normal operations in response to load demand. Peaking releases should not exceed base flows by too great an amount, though there is insufficient data to recommend limits at this time. If basement flooding begins to

be a problem, revert back to the operation on the day before the releases which brought on the problem, and consider that the maximum releases until breakup.

The above proposal is not as conservative as it could be, considering this will be a first attempt at setting the ice level and it aims for the maximum allowable level identified at this time. Data taken from this event should be able to refine the analysis, perhaps imposing further restrictions, or perhaps lifting some.

Emergency power generation requirements through the formation and 12 day period should be made up from other sources if possible. The Committee will have to discuss, before the need arises, the advisability of large sustained releases after the 12 day period.




Alberta ENVIRONMENT — RIVER ENGINEERING BRANCH

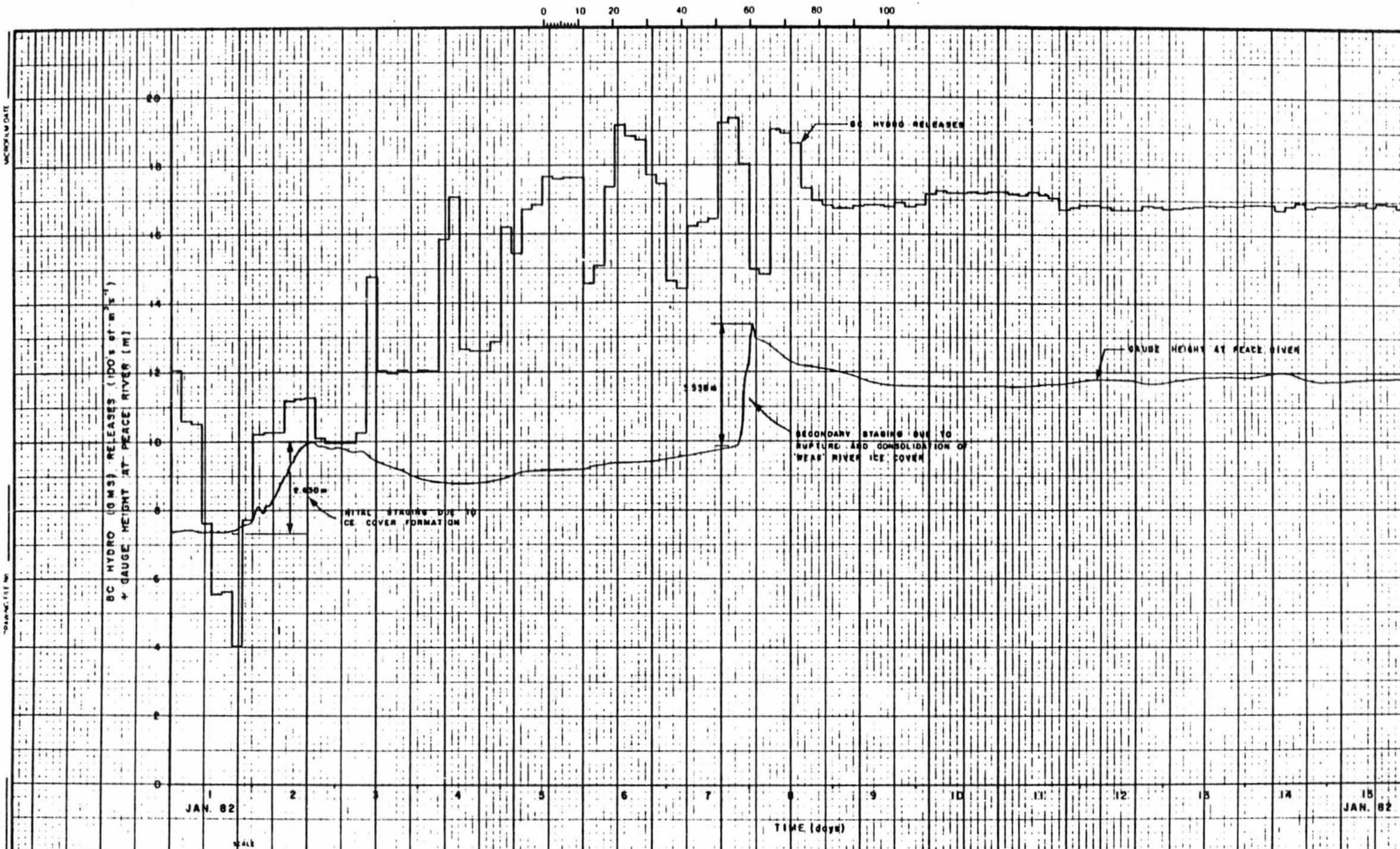
PEACE RIVER 1981-82 ICE STUDY

**B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER**

| | |
|---|---|
| SUBMITTED | DESIGNED |
| DATE | CHECKED |
| APPROVED | DRAWN |
| DATE | CHECKED |

SCALE AS SHOWN — SHEET 1 OF 9

DATE AUGUST, 1982 — FIG. No. 1




Alberta ENVIRONMENT

RIVER ENGINEERING BRANCH

SUBMITTED
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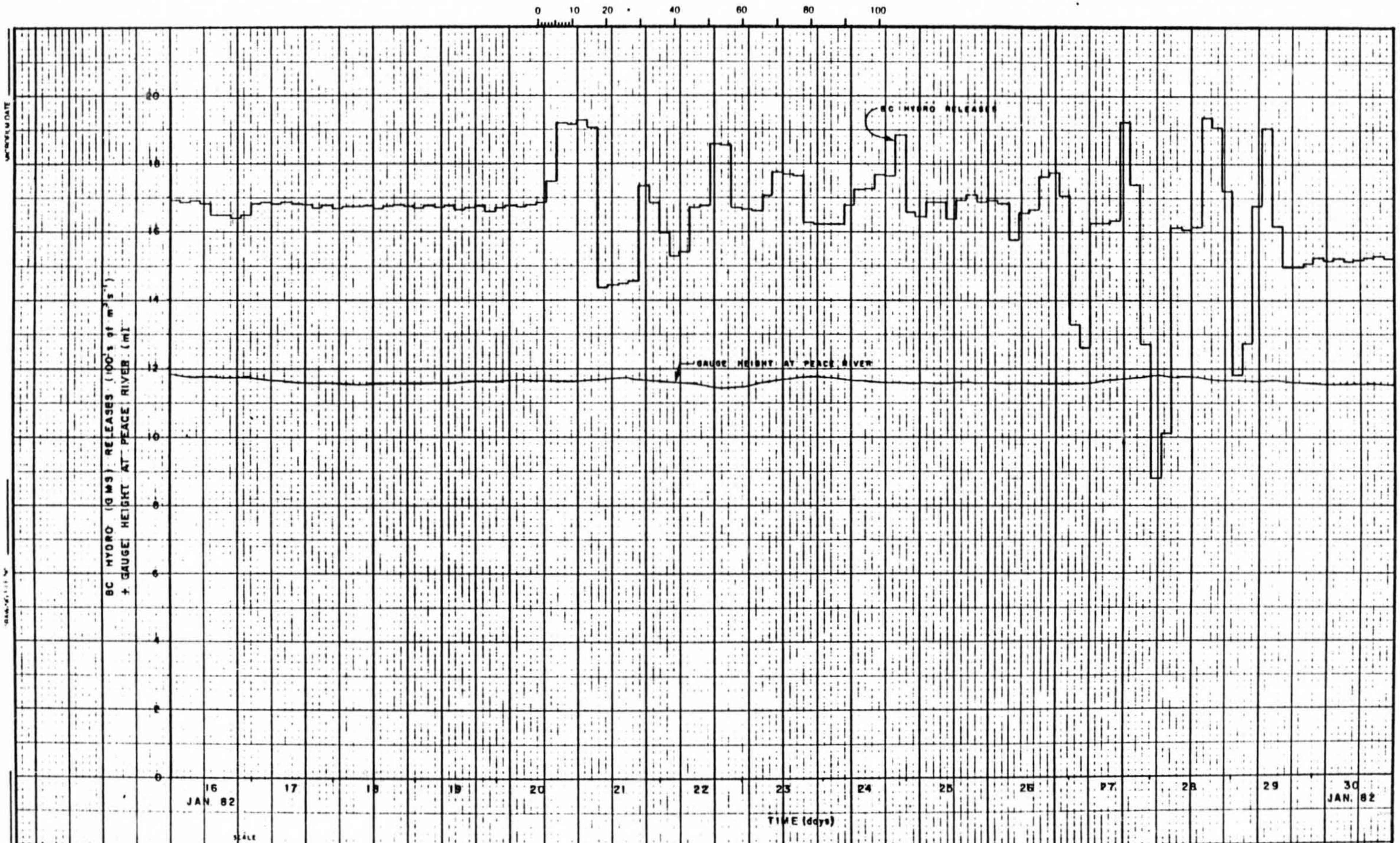
PEACE RIVER 1981-82 ICE STUDY

## B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER




PEACE RIVER 1981-82 ICE STUDY

# B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER

Alberta Environment — River Engineering Branch

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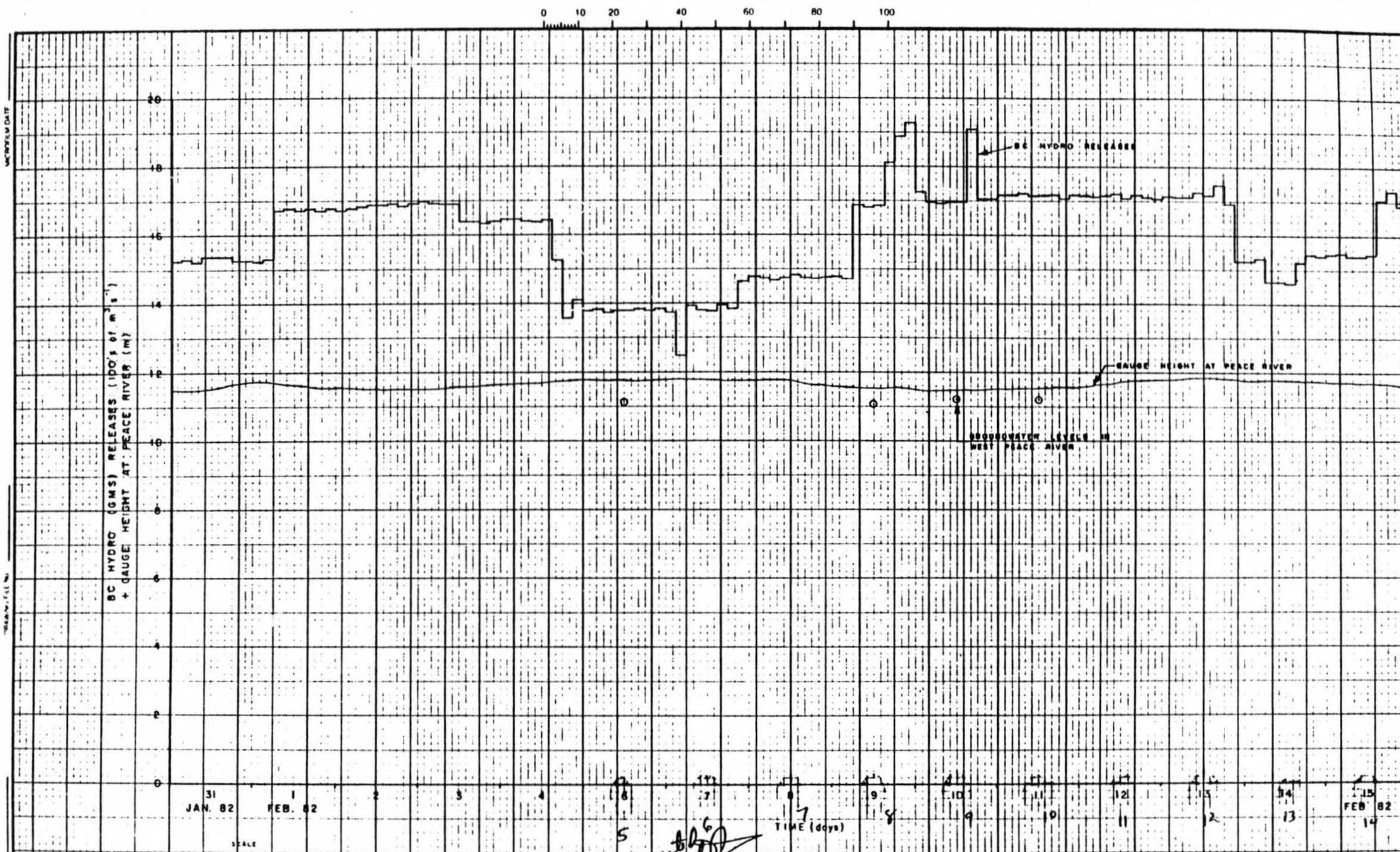
| APPROVED | DRAWN |
| DATE | CHECKED |

SCALE AS SHOWN — SHEET 3 OF 9
DATE AUGUST, 1982 — FIG. No. 1

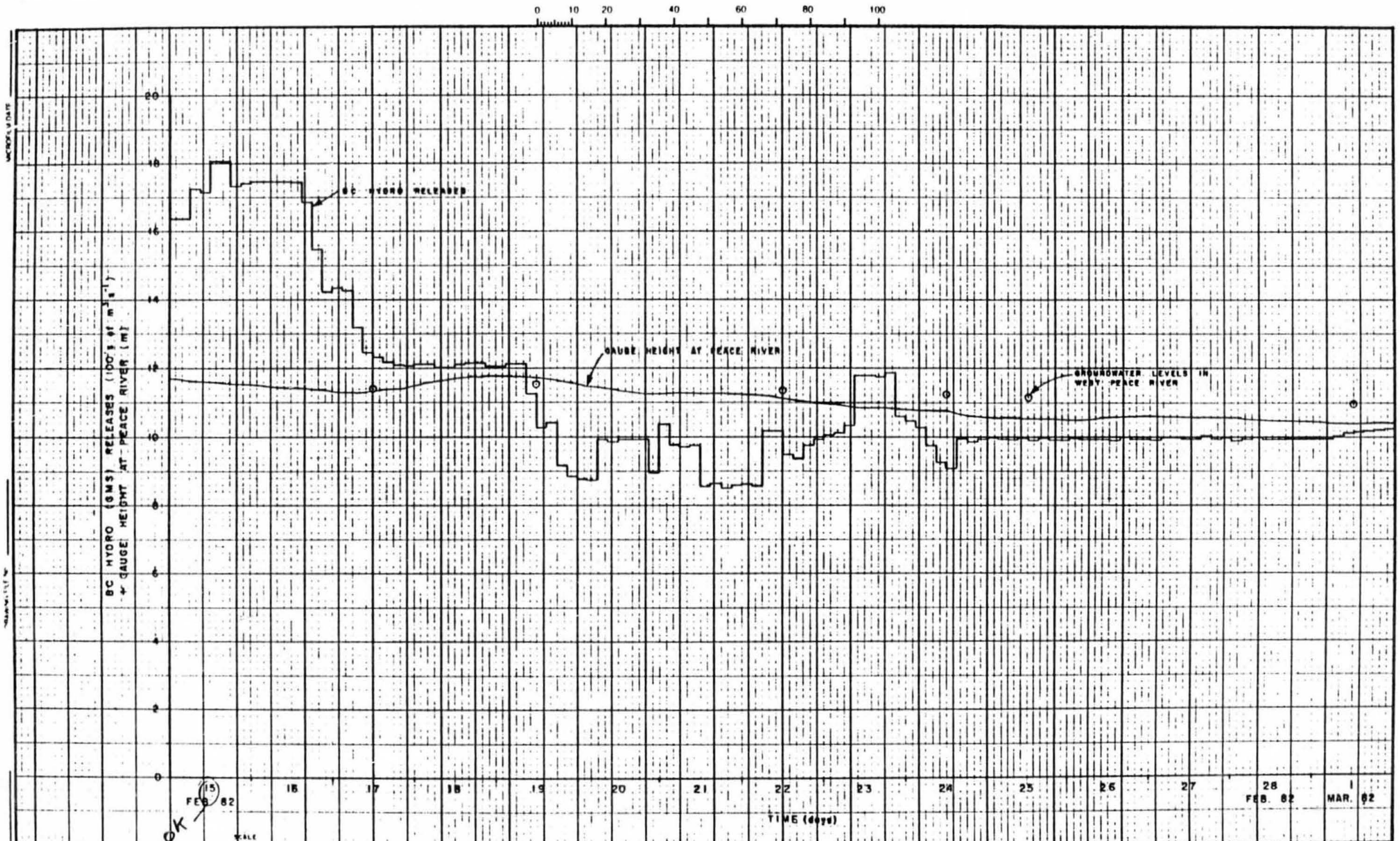



PEACE RIVER 1981-82 ICE STUDY

Alberta ENVIRONMENT — RIVER ENGINEERING BRANCH

B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER

SUBMITTED — DESIGNED




Alberta ENVIRONMENT — RIVER ENGINEERING BRANCH

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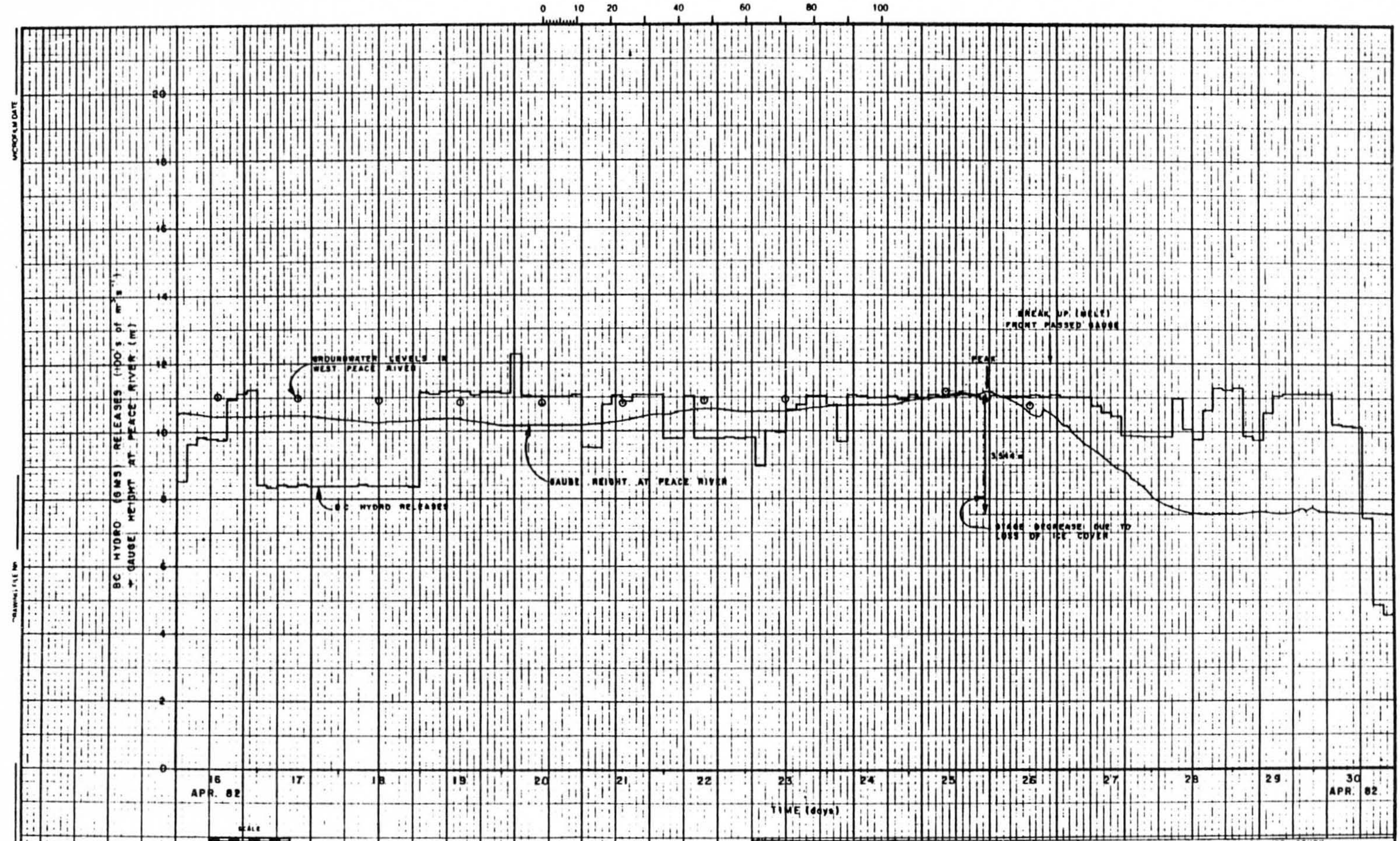
| SUBMITTED | DESIGNED |
| DATE | CHECKED |
| APPROVED | DRAWN |
| DATE | CHECKED |

PEACE RIVER 1981-82 ICE STUDY

**B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER**

SCALE AS SHOWN | SHEET 5 OF 9
DATE AUGUST, 1982 | FIG No 1




Alberta ENVIRONMENT

RIVER ENGINEERING BRANCH

PEACE RIVER 1981-82 ICE STUDY

B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER

SUBMITTED
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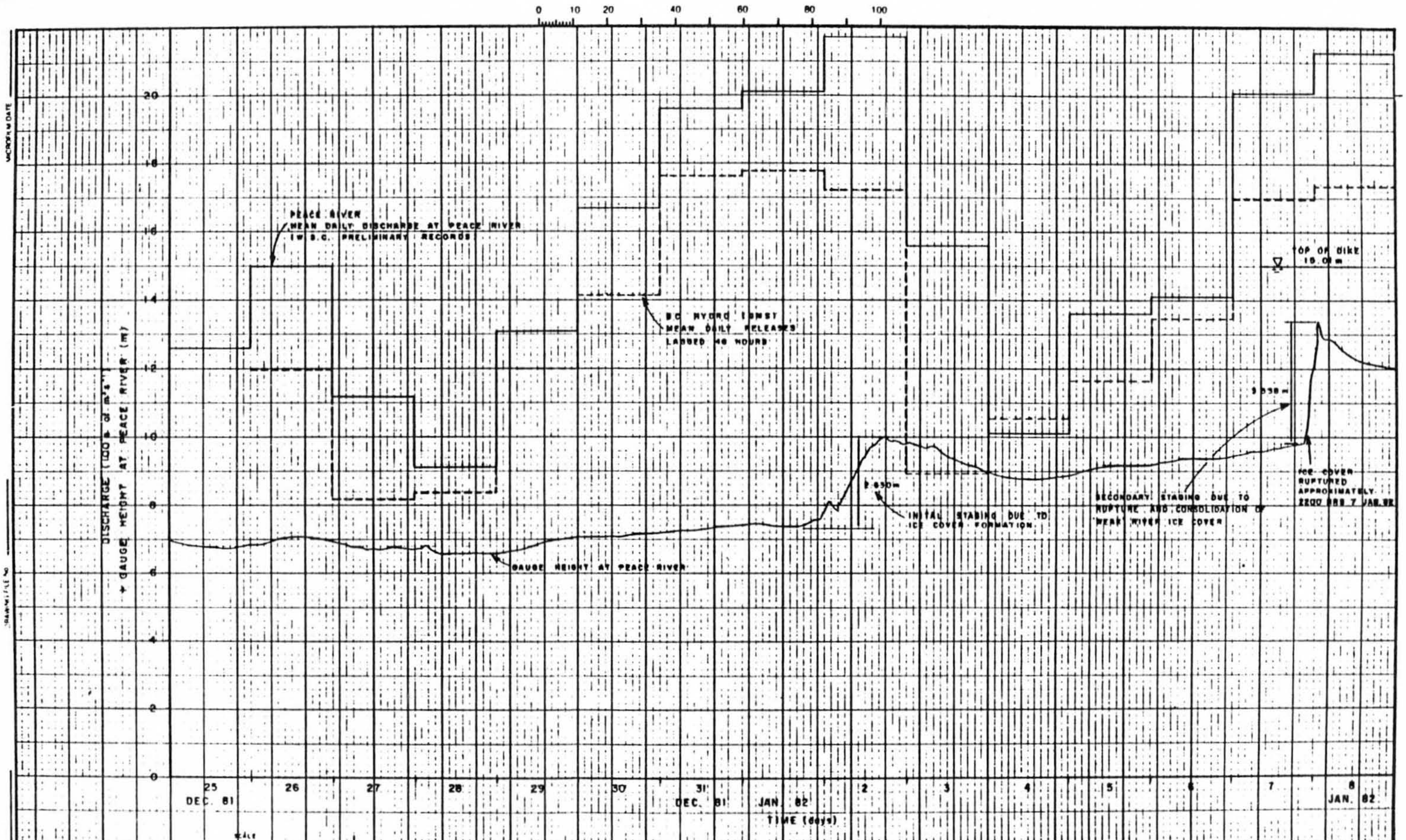
SCALE




Alberta ENVIRONMENT — RIVER ENGINEERING BRANCH

PEACE RIVER 1981-82 ICE STUDY

**B.C. HYDRO 3-HOURLY FLOW RELEASES AND GAUGE HEIGHT AT PEACE RIVER**

| | | | |
|---|---|---|---|
| SUBMITTED | DESIGNED | SCALE AS SHOWN | SHEET 1 OF 1 |
| DATE | CHECKED | DATE SEPT. 1982 | FIG. No. 4 |
| APPROVED | DRAWN | | |
| DATE | CHECKED | | |

Reference 5.

REF. 5

FOR PROJECT COSTS

F. J. PATTERSON

MANAGER HYDROELECTRIC
GENERATION PROJECTS DIVISION
B.C. HYDRO & POWER AUTHORITY
BOX 12121
555 W. HASTINGS ST.
VANCOUVER B.C.
V6B 4T6

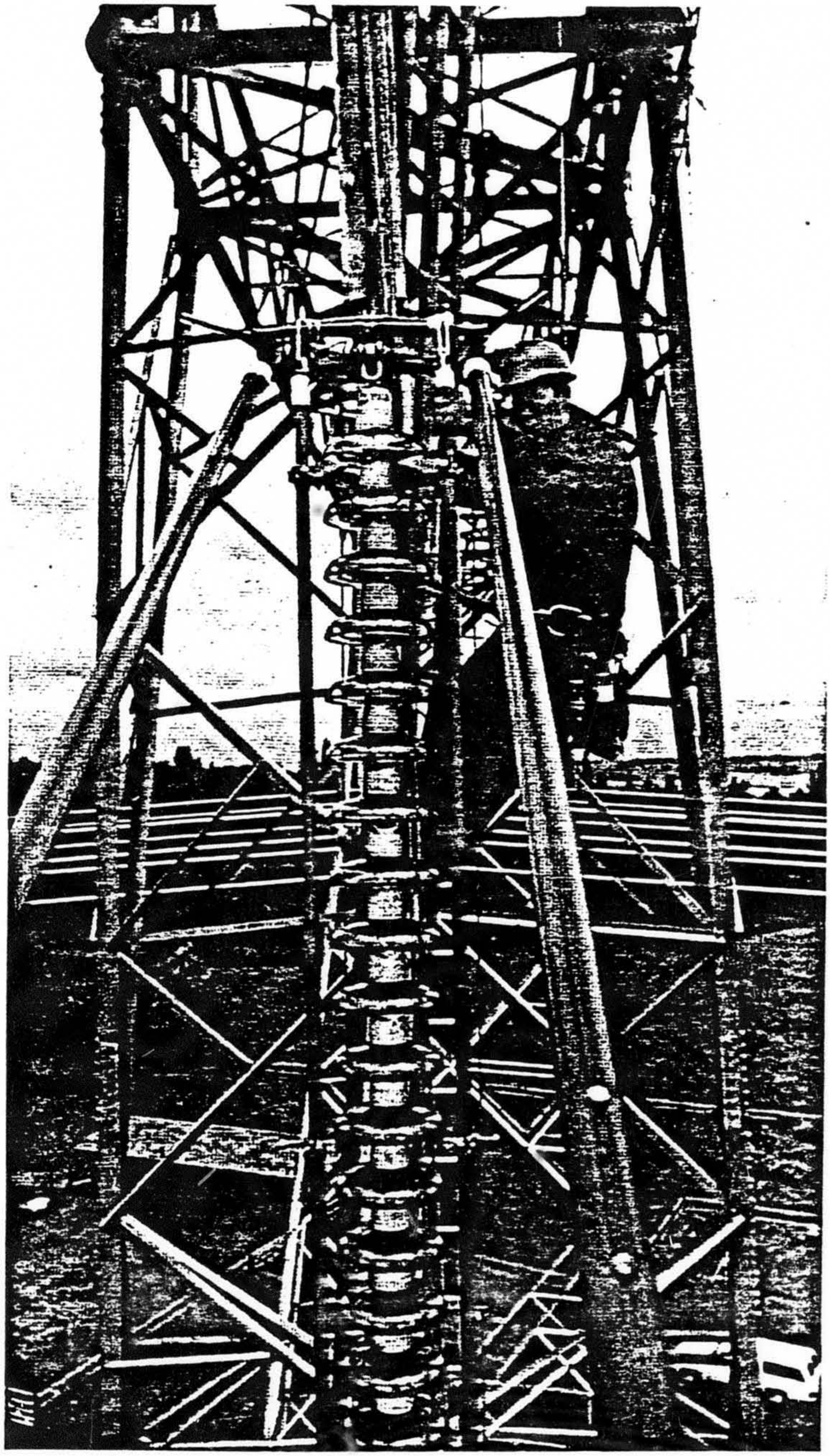
On Vancouver Island, the regional peak of 1 256 000 kW was only slightly higher than the previous winter's peak despite the addition of 4 500 new customers, most of whom installed electric space heating. This peak would have been much higher without the positive response by Vancouver Island customers to our appeal to reduce use of electricity at peak hours.

Sales of electricity in British Columbia by category of customer and percentage changes from the previous year were:

| | Year ended 31 March 1980 kW·h in millions | % increase from previous year |
|---|---|---|
| Residential | 7 612 | 2.8 |
| General | 9 136 | 3.9 |
| Bulk | 9 229 | 0.9 |
| Other systems | 226 | 4.2 |
| | 26 203 | 2.5 |

The following table shows total requirements for electricity and sources of supply for the year under review:

| | kW·h in millions | % of total |
|---|---|---|
| Requirements: | | |
| Sales in British Columbia | 26 203 | 84.4 |
| Export | 1 077 | 3.5 |
| Line loss and system usage | 3 770 | 12.1 |
| | 31 050 | 100.0 |
| Sources of supply: | | |
| Hydro generation | | |
| Gordon M. Shrum | 12 182 | 39.2 |
| Mica | 7 524 | 24.2 |
| Other | 9 140 | 29.5 |
| Thermal generation | | |
| Burrard | 624 | 2.0 |
| Other | 141 | 0.5 |
| Purchases | 1 439 | 4.6 |
| | 31 050 | 100.0 |



*South Interior live line instructor John Zucco, changing insulators on 500 kV transmission line.*

# Review of Operations

## Electric Service

Revenues from electric service exceeded $1 billion for the first time, increasing 27% from the previous year to $1,124 million. The increase resulted primarily from $233 million in sales of surplus interruptible electricity to the United States.

Sales of electricity in B.C. totalled 28 295 million kW·h, an increase of 2.6%. The highest one-hour demand ever recorded on the integrated electric system — 5 902 000 kW — occurred on January 6, 1982, up 7.8% from the previous year's high.

At March 31, 1982, Hydro was serving 1 076 926 electricity customers, an increase of 30 780 during the year. Average annual consumption per residential customer was 9413 kW·h, compared with 9001 kW·h the year before.

Approximately 7200 customers were added on Vancouver Island, about 95% of whom installed electric space heating. The Vancouver Island electric load reached a new peak of 1 341 000 kW, up 53 000 kW from the year before. Reduction in demand from transmission rate power customers, coupled with positive customer response to Hydro's appeal to curtail non-essential use of electricity during early evening hours, kept the peak load within the capacity of existing resources. Additional capacity to serve the Island will be available in fall 1983, when the mainland-Vancouver Island 500 kV transmission connection now under construction is scheduled to start operation.

A high volume of surplus electricity sales to the United States resulted from fortuitous water conditions and favourable markets. Additional revenues were realized from storage arrangements with other utilities. Surplus sales in February and March 1982 were restricted because of heavy snowpacks in the U.S. Pacific Northwest.

Runoff into major Hydro reservoirs during the year was above normal, providing adequate hydroelectric power for supplying domestic needs in B.C. as well as sales to the U.S. As a result, system generating requirements from the gas-fired Burrard thermal station near Vancouver were negligible.

The Burrard plant's role is to make up shortages of energy in low water years and to provide electricity during major emergencies or if major new projects are delayed. It is a relatively expensive source of energy which is used as little as possible. Hydro is continuing to collect emission dispersion information to support application for permits under the provincial Pollution Control Act.

Sales of electricity in B.C. by category of customer and percentage changes from the previous year were:

| | Year ended March 31, 1982 kW·h in millions | % increase (decrease) from previous year |
|---|---|---|
| Residential | 8 755 | 8.0 |
| General | 9 990 | 3.6 |
| Transmission rate | 9 305 | (3.2) |
| Other systems | 245 | 6.3 |
| | 28 295 | 2.6 |

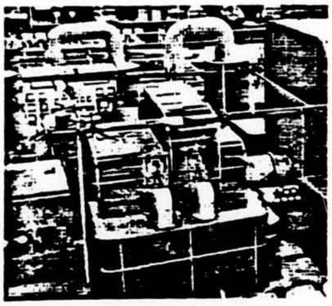
Total requirements for electricity and sources of supply were:

| | kW·h in millions | % of total |
|---|---|---|
| Requirements: | | |
| Sales in B.C. | 28 295 | 72.1 |
| Export | 6 984 | 17.8 |
| Line loss and system use | 3 971 | 10.1 |
| | 39 250 | 100.0 |
| Sources of supply: | | |
| Hydroelectric generation | | |
| Gordon M. Shrum | 13 317 | 33.9 |
| Mica | 7 149 | 18.2 |
| Kootenay Canal | 3 491 | 8.9 |
| Peace Canyon | 3 343 | 8.5 |
| Seven Mile | 2 943 | 7.5 |
| Other | 7 596 | 19.4 |
| Thermal generation | | |
| Burrard | 26 | 0.1 |
| Other | 166 | 0.4 |
| Purchases and other transactions | 1 219 | 3.1 |
| | 39 250 | 100.0 |

There were no major additions to Hydro's generating capacity during the year. The total generating capacity of Hydro's plants at March 31, 1982, was as follows:

| | Installed nameplate generating capacity (kW in thousands) |
|---|---|
| Hydroelectric plants | |
| Gordon M. Shrum | 2 416 |
| Mica | 1 736 |
| Peace Canyon | 700 |
| Seven Mile | 608 |
| Kootenay Canal | 529 |
| Bridge River | 428 |
| Other | 1 074 |
| Total hydroelectric | 7 491 |
| Thermal plants | |
| Burrard | 912 |
| Port Mann | 100 |
| Keogh | 100 |
| Georgia | 75 |
| Prince Rupert | 46 |
| Other | 114 |
| Total thermal | 1 347 |
| Total generating capacity | 8 838 |

*Burrard thermal generating plant.*



Reference 6

Note:
Taylor is located
120 km below the WAC B[illegible]
on Peace River

Ref. 6

# OBSERVATION AND ANALYSIS OF FREEZE-UP ICE JAMS ON THE PEACE RIVER NEAR TAYLOR

T. Keenhan[1], U.S. Panu[2] and V.C. Kartha[3]


## ABSTRACT

Since the construction of the W.A.C. Bennett Dam on the Peace River in British Columbia, the temperature of flow releases has been 0.5°C or higher during winter months. As a result, a long reach of ice-free river persists below the dam throughout the winter. Since 1972, when the eighth of the ten generating units was installed at G.M. Shrum (GMS) Generating Station, raising the release capacity to 1,580 $m^3$/sec, the ice cover has advanced upstream to the Village of Taylor, located 120 kilometres downstream, in only two winters, 1974 and 1979. Extensive ice measurements were carried out in 1979.

Below normal air temperatures persisted in the area for the month of February 1979 and the ice cover advanced to a winter maximum upstream location 18 kilometres above the Water Survey of Canada (WSC) gauge at Taylor. The stage increases resulting at, and upstream of Taylor due to the presence of the ice cover produced levels which approached the maximum historic summer flood levels.

The high stages resulted from the nature of the ice cover progression which was typified by the formation of freeze-up ice jams. Seven jams were observed in the 19-kilometre reach near Taylor, the average distance between jams being 2.7 kilometres.

The jams were observed to form through shoves involving collapse of the upstream extent of the ice cover. Formation of the largest jam within the reach involved the collapse of 8 kilometres of ice cover into 1.8 kilometres and produced river stage levels which overtopped the banks.

During the three-week period from 17 February to 8 March 1979 that the ice cover extended upstream of the Taylor gauge, the advance and retreat of the cover and ice/water elevations were documented by B.C. Hydro personnel. By monitoring the ice movements at Taylor and controlling the flow releases from GMS Generating Station, adequate freeboard was ensured within Taylor.

The data on ice levels and ice jams were gathered and, later, used to assess the applicability of three numerical ice jam models to Peace River. This paper presents a description of the ice jamming mechanism observed during the ice cover advance, the levels recorded at the ice jams and the results of the analysis through use of the models.



1. Sr. Hydrotechnical Engineer, Cripper Consultants;
2. Hydrology Engineer, B.C. Hydro, Vancouver,
3. Supervisor, Hydrology Section, B.C. Hydro, Vancouver.

## INTRODUCTION

B.C. Hydro has monitored ice conditions on the Peace River downstream of W.A.C. Bennett Dam since 1973 to gather data for planning and operation of hydroelectric plants. Data on river stage at freeze-up, break-up and during mid-winter have been collected annually over this period at a number of locations in British Columbia and Alberta.

During February-March 1979, a series of ice jams formed in the vicinity of Taylor, producing high water levels. Ice movements were closely monitored and extensive data were collected by B.C. Hydro. The data provided an opportunity to examine various river ice simulation models and assess their applicability to Peace River.

After the eighth of the ten generating units was installed at G.M. Shrum Generating Station, raising the release capacity to 1580 $m^3$/sec in 1972, the ice cover has advanced to Taylor only twice, in 1974 and 1979. Unlike in 1979, the observations carried out during 1974 were of a qualitative nature and, therefore, were not included in the analysis.

## DESCRIPTION OF THE 1979 ICE JAMS AND THE STUDY REACH

Below normal air temperatures persisted in the area for the month of February 1979 and the ice cover advanced to the Water Survey of Canada (WSC) gauge at Taylor on 17 February. With the continuation of cold weather, the front progressed further upstream to its maximum point of advance 18 kilometres above the WSC gauge on 1 March 1979; then with the onset of milder weather, the front retreated downstream to the gauge on 8 March 1979. During this period the discharge remained relatively constant. The flows were in the order of 1450 $m^3$/sec.

The stage increases resulting at and upstream of Taylor due to the presence of the ice cover produced levels which were exceeded only twice during the 35-year period of record. The open water floods of 1948 and 1964 produced water levels which were 1.5 and 0.8 metres higher, respectively, at Taylor. The maximum freeze-up levels observed during February-March 1979 are given in Table 1.

The high stages resulted from the nature of the ice cover progression which was typified by the formation of freeze-up ice jams.

During the three-week period from 17 February to 8 March 1979 that the ice cover was upstream of the Taylor gauge, the advance and retreat of the cover and ice/water elevations were documented by B.C. Hydro personnel. By monitoring the ice movements at Taylor and controlling the flow releases from GMS Generating Station, adequate freeboard was ensured within Taylor.

Data on ice movement was collected between the WSC gauge and the upstream terminus of the ice cover established in February 1979. The analysis of ice data was limited to this reach. The general location and the detailed layout of the study reach are shown on Figures 1 and 2, respectively.

Including the jam located just downstream of the gauge, a total of seven freeze-up jams were observed in a 19-kilometre reach at an average spacing of one every 2.7 kilometres. The locations and lengths of the jams are shown on Figure 2. The jams are numbered for reference. The lengths of the ice jams were typically 0.5 kilometres with attendant increases in stage upstream of the jam between 0.6 and 0.9 metres. Jam 5 differed in magnitude with length of 1.8 kilometres and stage increase of 2.5 metres. Formation conditions for Jam 5 differed from the others and are described later in the text. The locations of jam toes were at constricted channel sections where bed forms became prominent or the top width was suddenly narrowed. The toes were frequently located at the downstream ends of islands.

Based on the spacing of the jams observed downstream of Jam 3, aerial observations of the channel and general knowledge of the riverbed, the locations of the jam toes upstream of Jam 3 were predicted in the field with reasonable accuracy.

The regularity of the spacing of the toe locations indicated a relationship between naturally occurring changes in local bed geometry, the nature of the ice cover (i.e. strength), and backwater regime.

The freeze-up profile based on stage levels observed in the study reach, the bed profile and the open water profile are shown in Figure 3. The locations of the ice measurement points are shown on Figure 2.

The average slope of the water surface through the study reach, based on open water profiles, is 0.00040 downstream of Jam 5 and 0.00063 upstream.

Surveyed cross sections were available within the study reach from prior studies on open water profiles and the locations are shown in Figure 2. Several of the study reach cross sections are plotted in Figure 4.

## ICE JAM FORMATION ON THE PEACE RIVER

The ice regime on the Peace River has been altered by hydroelectric development. The regulated winter flows are in the order of 1420 $m^3$/sec, about five times the natural winter flow. The input of heat to the river from the reservoir has resulted in a reach of year-round open water below the dam.

Between the W.A.C. Bennett Dam and the Town of Peace River, located in Alberta 400 kilometres downstream, the flow velocities within the Peace River are too high to allow formation of bank to bank ice cover by freeze-over or growth of shore ice. Before the development, a continuous ice cover used to form by the initial establishment of intermittent ice covers which permitted localized upstream progression and eventual formation of a continuous cover. Since hydroelectric development, the ice cover is established by the upstream progression of a single ice front or leading edge which progresses from downstream of the Town of Peace River to a point of maximum advance, or upstream terminus prior to the onset of milder spring weather.

The location of the upstream terminus during a winter is dependent on the winter severity and flow conditions. In the eight-year observation period since the winter of 1972/1973, the location of the terminus has varied between 327 and 97 kilometres below the dam.

The mechanism of advance of the ice front at Taylor during 1979, as observed, is described below.

The ice cover progresses through an initial consolidation or packing of the floating ice pans until it collapses as a result of the force exerted by the flow and the gravitational effect of its own weight. The collapse of the cover or "shove" produces an ice jam which bridges the river. The jam produces additional backwater and permits the progression of the cover upstream through continued packing of the incoming ice floes. The cover advances further upstream than previously due to the additional backwater until it collapses in another shove which creates a second jam upstream. The process repeats as long as there is sufficient ice supply in the river. The average spacing between the jams in the vicinity of Taylor, as noted previously, is 2.7 kilometres. All the jams within the study reach except Jam 5 were formed in this manner.

The collapse of the loosely consolidated cover of frazil pans, required to increase internal strength, also initiates the movement of the more consolidated cover downstream. During the shoves the mass of ice moves in an accordion-like manner until sufficient resistance from the channel banks and bottom is encountered to halt the movement of the floe. The ice shoves are observed to ground on gravel bars and sides of the channel to form ice jams.

The movement of the ice cover farther downstream during the shoves, if extensive, can move an existing jam downstream. Large ice volumes are then released, or mobilized, in the shove, resulting in a massive jam further downstream. Jam 5 was formed in this manner when a jam at the location of Jam 6 collapsed during a shove. Five kilometres of ice collapsed into 1.8 kilometres producing a stage increase of 2.5 metres. Ice ridges 3 to 4 metres in height were observed in the middle of the channel. This large shove created an ice jam which appeared to have partially clogged the channel.

During February-March 1979, ice cover progressed through successive freeze-up jams on the Peace River near Taylor. Freeze-up jams were also observed on reconnaissance flights between Taylor and the Town of Peace River in 1979. Though no detailed measurements were available, the mechanism of ice cover progression is considered to be the same as described above.

## MODELLING OF ICE JAMS

Ice jams are categorized by Pariset et al (1966) into either "wide" or "narrow" channel jams. In a "wide" channel the streamwise thrust on the cover increases with distance downstream from the front edge of the cover and reaches a limiting value. The ice cover thickens through successive shoves until its internal resistance is equal to the sum of the external forces. For "narrow" jams the thrust is maximum at the front edge of the cover and shoves of the cover do not occur.

The freeze-up jams within the study reach were formed through internal collapse of the cover, and, thus, correspond to jams in a "wide" channel.

The theory describing wide river jams has been presented by Pariset et al (1961, 1966) and Uzuner and Kennedy (1974). Based on this theory, there are several computer programs for predicting the equilibrium thickness of fragmented or consolidated ice covers. In this paper, three computer programs are considered to be capable of simulating the ice jam process on the Peace River. Brief but relevant details of each of the programs (models) are given below.

For the purpose of identification, the programs are referred to as IOWAICE, HECICE, and LGLICE, each denoting the source and availability of the program.

## IOWAICE MODEL

A computer program dealing with both wide and narrow river ice jams has been developed at Iowa University. The program incorporates the theory of jams within "narrow" and "wide" channels. Calculations are carried out for the "narrow" conditions (Tatinclaux 1977) and the internal strength of the jam is tested by a force-balance. If the jam strength is insufficient to withstand the forces of the flow, then the final solution is obtained by "wide" channel jam theory (Uzuner and Kennedy 1974).

The model has been developed for a rectangular channel of constant bed slope. Since the Peace River cross sections are non-rectangular with changing geometry and bed slope along the river, the analysis requires a method of transforming the Peace River input and for interpreting program results. The following transformation which is used in sediment computations such as HEC-6 program to account for the influence of non-rectangular cross section shapes on transport capacity was used:

$$EFD = \frac{\sum_{i=1}^{N} (D_i A_i D^{2/3})}{\sum_{i=1}^{N} (A_i D_i^{2/3})} \quad (1)$$

where EFD is the effective depth, N is the total number of trapezoidal elements in a cross section determined by N + 1 points; D is the average depth of the trapezoidal elements; and A is the area of the trapezoidal element.

The variation of bed geometry along the river within the Peace River limits analysis to a single cross section. The critical cross section within the reach of interest, which is considered to produce highest jam levels, is selected by trial and error for analysis. Backwater conditions from downstream are incorporated through adjustments to bed slope at the cross section. The model does not differentiate between the bed and water surface slopes.

The results obtained from the model are transferred to the natural channel sections by locating the underside of the cover. This is done by equating the flow area, below the ice cover, of the rectangular section to the natural section. The elevation of the ice underside in the natural section is obtained from stage-area curves. The simulated thickness is retained for the natural section.

## HECICE MODEL

The Hydrologic Engineering Centre has modified the HEC-2 backwater model to incorporate the "wide" river jam stability criteria as developed by Pariset et al. The backwater capability of the program permits the evaluation of ice cover stability, while incorporating downstream conditions. An advantage of this model over the previously discussed model is that HECICE can use natural river cross sections without the need for transformation.

A "dimensionless" stability diagram is employed to analyze the stability of a jam at a given section. The stability diagram is for cohesionless cover and incorporates ice characteristics as developed on the St. Lawrence River and the Beauharnois Canal. A stability function is computed at a cross section for a given flow depth and an assumed ice cover thickness. The value thus obtained is compared to the corresponding value from the "dimensionless" stability diagram to establish whether the ice cover at the cross section is stable or not. The stability function is:

$$\lambda = \frac{Q^2}{C^2 B H^4} \qquad (2)$$

where Q is the discharge at the section; C is the Chezy coefficient; B is the stream width; and H is the upstream open water depth.

The ice profile is obtained by solving for stability at cross sections in the upstream direction.

## LGLICE MODEL

A third computer model was obtained from Lalonde, Girouard, Letendre and Associates Ltd. The program calculates hydraulic ice conditions for time intervals to simulate ice conditions during the winter from freeze-up to break-up. The program incorporates separate modules for determination of ice stability, backwater, and ice generation and deposition. The model requires meteorological and cross section data. The program which has been modified for use on the Peace River is described in detail by Petryk and Boisvert (1978) and Petryk et al (1980).

The model employs the dimensionless stability diagram described earlier. However, stability is also assessed for juxtaposition of floating ice blocks (Pariset et al) and by the use of limiting flow velocities below the cover. Additionally, ice cover is established on sections with very low velocities.

All three models used in the study reach assume that the ice jam is floating and does not ground; there is no cohesion within the jam; a semi-steady state flow condition exists; and that the uniform flow equation is adequate.

## PREPARATION OF INPUT DATA

The cross sections measured in the study reach and used in the analysis are shown on Figure 2. The Peace River in the study reach is wide and shallow with gravel bars and secondary channels around the islands. Under ice conditions, a significant portion of the cross sectional area below the water surface is filled with floating ice or carries only a small percentage of the flow. The cross sections and flow were adjusted so that only the main channel was represented in the ice analysis.

In order to simulate river stages in the study reach due to ice jamming, ice thickness and roughness of the bed and ice cover were required. Measurements of thickness of ice cover on the river could not be made during the ice-jam period. Observation of ice stranded along the banks, however, revealed ice thickness generally varying between 1.5 and 2.0 metres in the study reach except at Jam 5. Ice stranded at Jam 5 was about six metres thick. Since the ice cover remained within the study reach for only a short period of time, the observed thicknesses were not considered to have been altered by thermal growth or erosion. However, the indirect determination of ice thicknesses by observations along the banks was not considered precise and the observed thicknesses are, therefore, considered to be only an indicator of the ice thicknesses in the study reach.

The determination of the ice thickness and hydraulic roughness of the cover and bed was made by a method presented by Beltaos (1979). The method requires water surface elevation, bed geometry and the relationship of bed roughness with stage for the cross section to be analyzed. The solution relies on values of ice roughness versus thickness obtained by Nezhikhovsky (1964) for jams created by ice floes and adjusted by Beltaos for varying bed shape.

The relationship of bed roughness to stage was determined by backwater analysis without ice cover between the WSC gauge at Taylor and a B.C. Hydro gauge located 9-1/2 kilometres downstream. Open water stages at various flows were available at the two gauges from prior calibration work on open water bed roughness.

The roughness relationship developed is

$$n_b = 0.0896\ R_b^{-1.1134} \qquad (3)$$

where $n_b$ is the Manning's value for bed roughness; and $R_b$ is the hydraulic radius for open water conditions.

The above method was applied at five cross sections in the study reach. Of the five sections, cross sections 117 and 121 were located in the middle of a jam, cross section 115 was located at the head of a jam, and cross sections 119 and 124 were located between jams.

The cross sections are plotted in Figure 4. The adjustments made to their area for ice conditions, as noted earlier, are also shown.

The roughness values were calculated using two slopes; the one obtained from the open water profile; the other obtained from the ice/water profiles observed during the 1979 ice conditions. The latter was available only at cross sections located within jams. The results of the analysis are shown in Table 2. Based on the results, the roughness values obtained for the observed ice/water slope at those sections within the jams were considered more applicable to the present study.

Roughness at jam and non-jam cross sections differed consistently. The roughness of both the ice cover and the bed are higher for the sections located within a jam or at the head of a jam.

Mean roughness values for jam sections were 0.058 and 0.092 for the bed and ice cover, respectively. Similarly, mean roughness values for non-jam sections were 0.045 and 0.066 for the bed and ice cover, respectively. The jam and non-jam roughness values were weighted by their respective lengths to obtain mean roughness value for the study reach. The mean roughness values for the study reach were 0.048 and 0.072 for the bed and ice cover, respectively. These values were input to HECICE and LGLICE models. For the IOWAICE simulations, the roughness values at the respective sections were employed.

## RESULTS AND DISCUSSIONS

Simulations of ice/water levels within the study reach were made for the single discharge of 1450 $m^3$/sec, since flow variations were small.

The simulated ice/water levels and thicknesses by the IOWAICE and HECICE programs, employing the calculated roughness values, are comparable to the 1979 observed levels as shown on Figure 5. The LGLICE program reproduced the 1979 progression and retreat of the ice cover at Taylor from the observed climatic conditions. The ice levels simulated by the LGLICE program exceeded those observed in 1979. The program is being modified accordingly and the results are not available for presentation at this time.

The ice/water levels computed at the measurement locations by IOWAICE and HECICE programs are close to the observed values except at Jam 5. The simulated stages at Jam 5 given by both programs are consistently lower than the observed values. This suggests that the "floating" jam theory, employed by both programs, is not applicable to Jam 5, and that Jam 5 might have been grounded as inferred from the observations.

IOWAICE simulations were made at cross sections located at the head of, or within, the ice jams. Simulations were carried out for the roughness values previously determined and the somewhat lower values suggested by Tatinclaux (1978). The simulations were made at the cross sections using the water surface slopes from the open water profile for 1450 $m^3$/sec. Between cross sections located within the jams (117 and 121), the ice/water surface slopes obtained from observations were also used in the analysis. The results of the simulations are shown in Table 3. The ice/water levels obtained by using the calculated roughness values were close to the observed levels. The use of different slopes (Table 3) at the jam sections did not appreciably alter the results. Force balance calculations indicated collapse of narrow channels and that the jams were of the wide channel type.

During the HECICE simulations, it was found that the ice thickness at some of the downstream cross sections had to be increased above the minimum stable thickness to provide sufficient backwater to attain stability at the section of interest. The ice cover thus thickened may be considered to represent an ice jam. The HECICE freeze-up profile and location of jams are presented in Table 4.

Although the HECICE simulation produced a comparable freeze-up profile to that observed within the study reach, it did not indicate the presence of the jams below cross section 115. Ice jams were simulated upstream of cross section 115 where cross sections were available at closer intervals than in the downstream reach.

Table 5 summarizes the ice/water levels and ice thickness calculated by HECICE and IOWAICE programs. The ice/water levels simulated by the HECICE program were closer to the observed levels. Sufficient agreement on ice thicknesses is not obtained by the various programs and this aspect requires further investigation.

## CONCLUSIONS

Based on the results of the LGLICE, IOWAICE and HECICE programs, it is concluded that:

1) The cross sectional spacing employed in the HECICE and LGLICE programs is important for simulation of location and length of ice jams.

2) The roughness of the ice cover and bed for a given section should be determined by using the water surface slope as observed under ice conditions to ensure satisfactory results.

3) HECICE and IOWAICE programs are applicable to the analysis of ice/water levels on the Peace River, except in the case of large shoves as experienced at Jam E. LGLICE program requires modifications which would improve its applicability to Peace River.

## ACKNOWLEDGEMENT

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TABLE 1

MAXIMUM FREEZE-UP LEVELS OBSERVED DURING FEBRUARY - MARCH 1979

| OBSERVED IN THE VICINITY OF | MAXIMUM WATER/ICE LEVEL (GSC) (m) |
|---|---|
| WSC gauge | 406.7 |
| BM 9 * | 407.58 |
| BM 10 | not available |
| BM 11 | 409.77 |
| BM 12 | 410.38 |
| BM 14 | 412.06 |
| BM 13 | 413.46 |
| BM 15 | 413.8 |
| BM 19 | 415.68 |
| BM 21 | 415.72 |
| BM 20 | 415.72 |

* Locations of BM are shown on Figure 2.

# TABLE 2

## ROUGHNESS AND ICE THICKNESS VALUES

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CROSS SECTION NUMBER | | 115 | 117 | | 119 | 121 | | 124 |
| Discharge $Q(m^3/s)$ | | 1450 | 1450 | | 1450 | 780 * | | 1450 |
| Slope Used | | OPEN CHANNEL | OPEN CHANNEL | WITH ICE COVER | OPEN CHANNEL | OPEN CHANNEL | WITH ICE COVER | OPEN CHANNEL |
| WATER SURFACE ELEVATION | | 413.8 | 412.4 | 412.4 | 410.5 | 410.38 | 410.38 | 406.7 |
| Average hydraulic parameters for open water flow upstream of cross-section | W (m) | 551.0 | 369.6 | 396.6 | 356.9 | 299.1 | 299.1 | 490.7 |
| | H (m) | 10.64 | 12.9 | 12.9 | 9.4 | 8.4 | 8.4 | 8.3 |
| | V (m/s) | 0.338 | 0.43 | 0.43 | 0.58 | 0.41 | 0.41 | 0.48 |
| Estimated average hydraulic parameters and roughness ice covered sections | S | 0.000647 | 0.000290 | 0.001582 | 0.000449 | 0.001025 | 0.001220 | 0.000363 |
| | t (m) | 3.4 | 2.06 | 4.00 | 1.73 | 2.55 | 2.90 | 1.48 |
| | W (m) | 536. | 362.3 | 345.8 | 355.5 | 287.2 | 287.3 | 477.8 |
| | $R_i$ (m) | 3.112 | 4.203 | 3.207 | 3.571 | 2.464 | 2.485 | 3.124 |
| | $R_b$ (m) | 1.514 | 1.988 | 1.479 | 1.905 | 1.452 | 1.449 | 1.823 |
| | h (m) | 4.626 | 6.195 | 4.687 | 5.542 | 3.917 | 3.934 | 4.942 |
| | v (m/s) | 0.5840 | .64605 | .89573 | .7445 | .6946 | 0.6908 | 0.6149 |
| | $n_i$ | 0.09051 | 0.06868 | 0.09557 | 0.06650 | 0.0850 | 0.0890 | 0.06619 |
| | $n_b$ | 0.05647 | 0.04169 | 0.05800 | 0.04373 | 0.05917 | 0.05992 | 0.04605 |
| | $n_o$ | 0.07490 | 0.05601 | 0.07892 | 0.05571 | 0.07236 | 0.07432 | 0.05662 |

* Flow reduction required due to bifurcation of channel around island.

NOTE: W = channel width, H = flow depth, V = flow velocity, S = water surface slope, t = ice cover thickness, $R_i$ = hydraulic radius due to ice cover, $R_b$ = hydraulic radius due bed, h = flow depth under ice cover, v = flow velocity under ice cover, $n_i$ = Manning's roughness for underside of ice cover, $n_b$ = Manning's roughness for bed, and $n_o$ = Composite Manning's roughness for bed and ice.

TABLE 3

ICE/WATER LEVELS (m) SIMULATED BY IOWAICE PROGRAM

| Location/ Cross-Section Number | Observed Levels GSC (m) | Slope From Open Water Profile | | Slope Observed During Ice Conditions | |
|---|---|---|---|---|---|
| | | Roughness (Tatinclaux, 1978) | Roughness (Table 2) | Roughness (Tatinclaux, 1978) | Roughness (Table 2) |
| 122 | 409.5 | 408.24 | 408.83 | - | - |
| 121 | 409.8 | 409.08 | 409.16 | 409.25 | 409.11 |
| 120 | 410.4 | 409.71 | 410.19 | - | - |
| 117 | 412.1 | 411.24 | 411.77 | - | - |
| 115 | 413.8 | 412.00 | 412.30 | - | - |
| 112 | 415.2 | 414.60 | 414.71 | - | - |

TABLE 4

[illegible]

[illegible] 0.0[illegible]

[illegible] 0.0[illegible]

| Section Number | Section Spacing (m) | Discharge (m³/sec) | Energy Slope x 10⁴ [1] | Water Surface Elev. (m) | Top of Ice | Underside of Ice | Ice Cover Thickness (m) | Velocity Under Ice Cover (m/sec) | Maximum Depth, H (m) | Top Width (m) | T/H | Calculated X | Stability Curve X |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 124.000 | - | 1450.00 | 9.76 | 406.70 | 406.92 | 404.11 | 2.59 | 0.77 | 8.30 | 490.66 | 0.31 | 2.63 | 2.64 |
| 123.000 | 1295.30 | 1450.00 | 5.07 | 407.56 | 407.68 | 406.30 | 1.[illegible] | 0.58 | 9.46 | 646.56 | 0.14 | 1.19 | 1.15 |
| 122.000 | 1903.40 | 1450.00 | 5.22 | 408.57 | 408.77 | 406.33 | 2.44 | 0.71 | 8.67 | 399.82 | 0.28 | 2.48 | 2.46 |
| 121.000 | 1707.30 | 700.00 | 14.17 | 409.75 | 409.95 | 407.51 | 2.44 | 1.00 | 7.75 | 188.80 | 0.31 | 2.59 | 2.65 |
| 120.000 | 1085.40 | 1450.00 | 1.52 | 410.34 | 410.47 | 408.94 | 1.52 | 0.61 | 9.84 | 455.98 | 0.15 | 1.26 | 1.27 |
| 119.000 | 2067.10 | 1450.00 | 1.94 | 411.11 | 411.26 | 409.43 | 1.83 | 0.68 | 10.01 | 355.24 | 0.18 | 1.50 | 1.58 |
| 118.000 | 1148.20 | 1450.00 | 1.96 | 411.68 | 411.89 | 409.45 | 2.44 | 0.62 | 8.28 | 460.76 | 0.29 | 2.58 | 2.56 |
| 117.000 | 1209.50 | 1450.00 | 2.83 | 412.11 | 412.23 | 410.95 | 1.37 | 0.61 | 11.61 | 366.99 | 0.09 | 0.78 | 0.85 |
| 115.000 | 1233.80 | 1450.00 | 2.35 | 412.85 | 413.03 | 410.89 | 2.13 | 0.82 | 9.55 | 354.68 | 0.22 | 1.93 | 1.97 |
| 1141.000 | 300.00 | 1450.00 | 7.80 | 413.06 | 413.20 | 411.52 | 1.69 | 0.98 | 10.16 | 288.53 | 0.17 | 1.41 | 1.38 |
| 114.000 | 500.00 | 1450.00 | 1.85 | 413.35 | 413.41 | 412.37 | 1.07 | 0.66 | 11.05 | 453.76 | 0.10 | 0.65 | 0.63 |
| 1133.000 | 470.00 | 1450.00 | 1.57 | 413.53 | 413.69 | 411.71 | 1.98 | 0.68 | 8.43 | 415.40 | 0.21 | 2.05 | 2.07 |
| 1132.000 | 420.00 | 1450.00 | 13.22 | 413.74 | 413.89 | 412.06 | 1.83 | 1.18 | 9.94 | 274.00 | 0.18 | 1.69 | 1.59 |
| 1131.000 | 540.00 | 1450.00 | 7.96 | 414.12 | 414.51 | 412.23 | 2.29 | 0.81 | 8.02 | 480.39 | 0.29 | 2.42 | 2.49 |
| 113.000 | 450.00 | 1450.00 | 5.63 | 414.62 | 414.85 | 412.10 | 2.74 | 0.84 | 10.12 | 435.90 | 0.27 | 0.94 | 2.17 [2] |
| 1122.000 | 470.00 | 1450.00 | 3.99 | 414.84 | 415.07 | 412.33 | 2.74 | 0.82 | 11.64 | 277.70 | 0.24 | 0.79 | 2.07 [2] |
| 1121.000 | 550.00 | 1450.00 | 1.84 | 415.06 | 415.29 | 412.55 | 2.74 | 0.76 | 11.86 | 326.31 | 0.23 | 0.64 | 2.03 [2] |
| 112.000 | 330.00 | 1450.00 | 6.04 | 415.21 | 415.43 | 412.69 | 2.74 | 0.83 | 10.11 | 365.39 | 0.27 | 1.16 | 2.37 |
| 1105.000 | 320.00 | 1450.00 | 4.31 | 415.39 | 415.62 | 412.87 | 2.74 | 0.67 | 8.89 | 905.14 | 0.31 | 2.59 | 2.63 |
| 1104.000 | 360.00 | 967.00 | 1.42 | 415.49 | 415.65 | 413.82 | 1.83 | 0.39 | 8.39 | 535.00 | 0.22 | 0.75 | 1.92 [2] |
| 1103.000 | 460.00 | 967.00 | 6.78 | 415.59 | 415.76 | 413.78 | 1.98 | 0.75 | 7.19 | 336.00 | 0.28 | 2.36 | 2.40 |
| 1102.000 | 300.00 | 967.00 | 2.38 | 415.72 | 415.93 | 413.49 | 2.44 | 0.46 | 8.72 | 530.00 | 0.28 | 0.68 | 2.44 [2] |
| 1101.000 | 330.00 | 967.00 | 8.08 | 415.83 | 416.04 | 413.60 | 2.41 | 0.79 | 7.74 | 344.83 | 0.32 | 1.76 | 2.65 [2] |
| 110.000 | 310.00 | 967.00 | 6.81 | 416.06 | 416.29 | 413.55 | 2.74 | 0.81 | 9.36 | 282.71 | 0.29 | 0.94 | 2.55 [2] |
| 109.000 | 1158.50 | 1450.00 | 5.45 | 416.76 | 416.93 | 414.25 | 2.74 | 0.67 | 7.26 | 618.25 | 0.38 | 2.78 | 2.76 |

1 - Determined to Accuracy of 0.15 metres

2 - Ice thickened above minimum stable value to permit stable thickness at upstream section, i.e., jam location

TABLE 5

COMPARISON OF SIMULATED
ICE/WATER LEVELS AND THICKNESSES (m)

| LOCATION (CROSS SECTION) | OBSERVED ICE/WATER LEVEL | ICE THICKNESS (Table 2) | IOWAICE | | HECICE | |
|---|---|---|---|---|---|---|
| | | | Ice/Water Level GSC (m) | Ice Thickness (m) | Ice/Water Level GSC (m) | Ice Thickness (m) |
| 124 | 406.7 | 1.48 | - | - | 406.7 * | 2.59 |
| 122 | 409.5 | - | 408.33 | 2.25 | 408.57 | 2.44 |
| 121 | 409.8 | 2.90 | 409.16 | 2.97 | 409.75 | 2.44 |
| 120 | 410.4 | - | 410.19 | 2.02 | 410.34 | 1.52 |
| 119 | 410.5 | 1.73 | - | - | 411.11 | 1.83 |
| 117 | 412.1 | 4.00 | 411.77 | 2.08 | 412.11 | 1.37 |
| 115 | 413.8 | 3.40 | 412.30 | 3.52 | 412.85 | 2.13 |
| 112 | 415.2 | - | 414.71 | 3.54 | 415.21 | 2.74 |

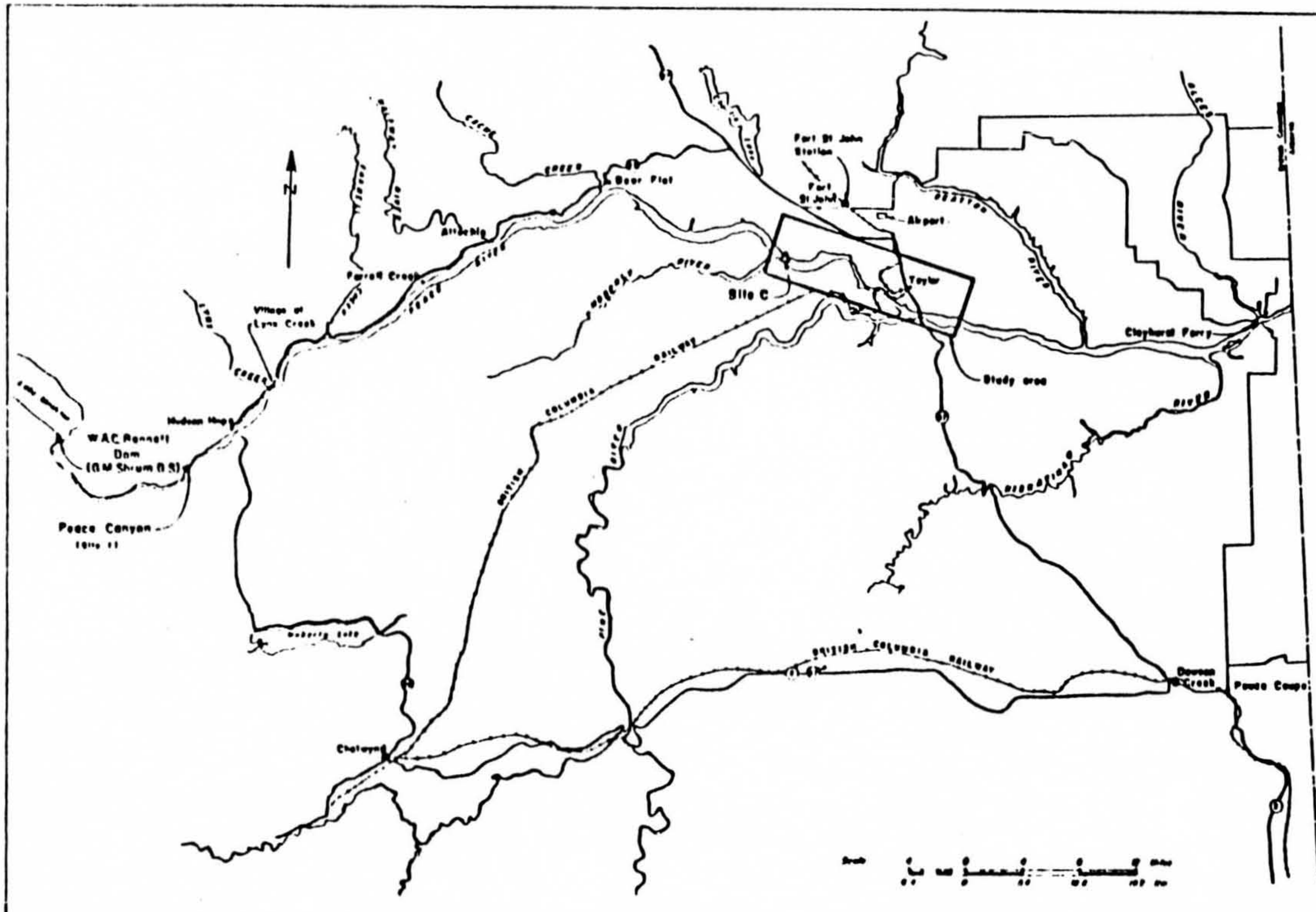



FIGURE I – LOCATION MAP

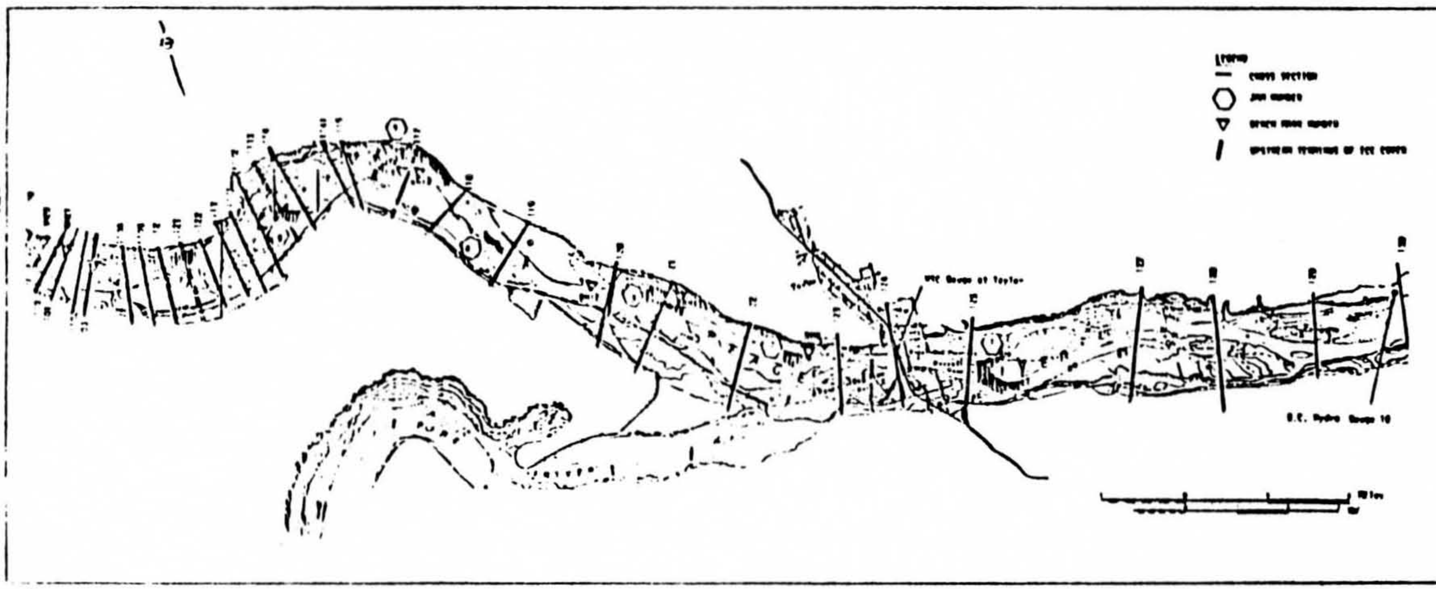


FIGURE 2 – STUDY AREA

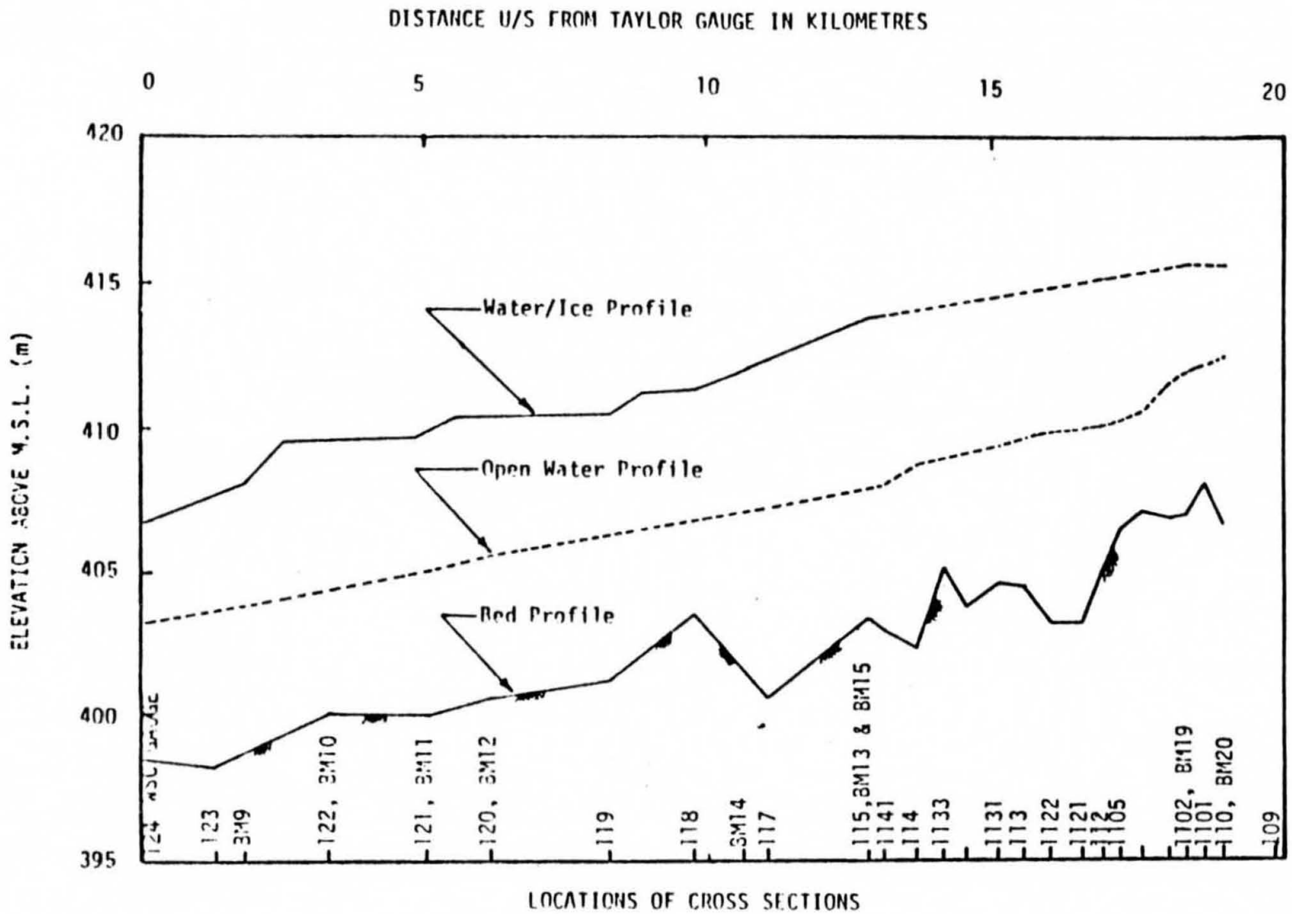
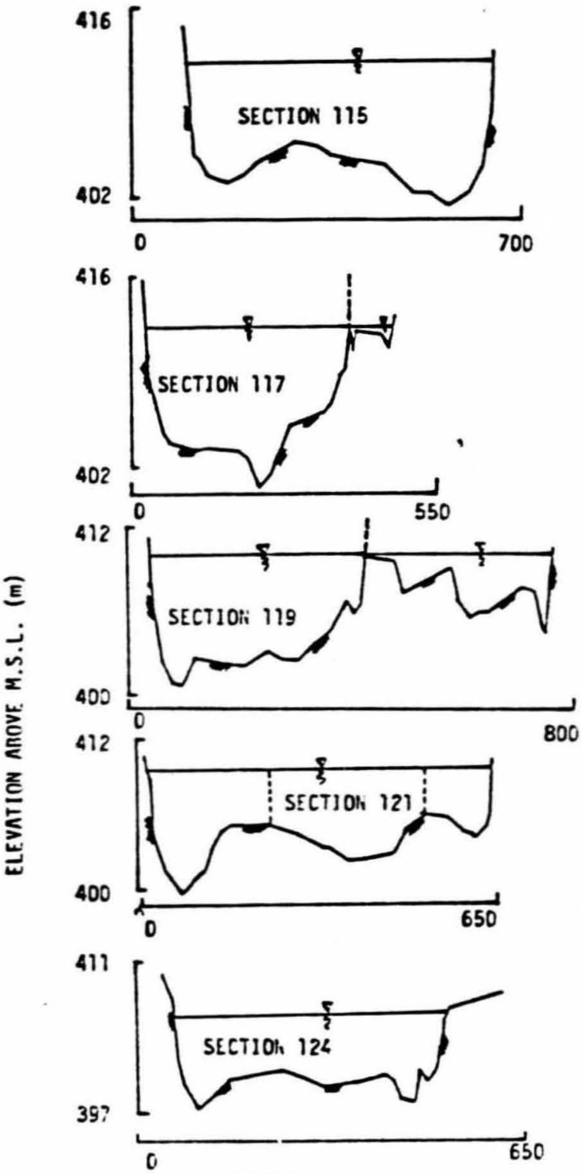



FIGURE 3: STUDY REACH PROFILES




DISTANCE U/S FROM TAYLOR GAUGE IN KILOMETRES

FIG. 4 - CROSS SECTIONS OF PEACE RIVER NEAR TAYLOR, B.C.

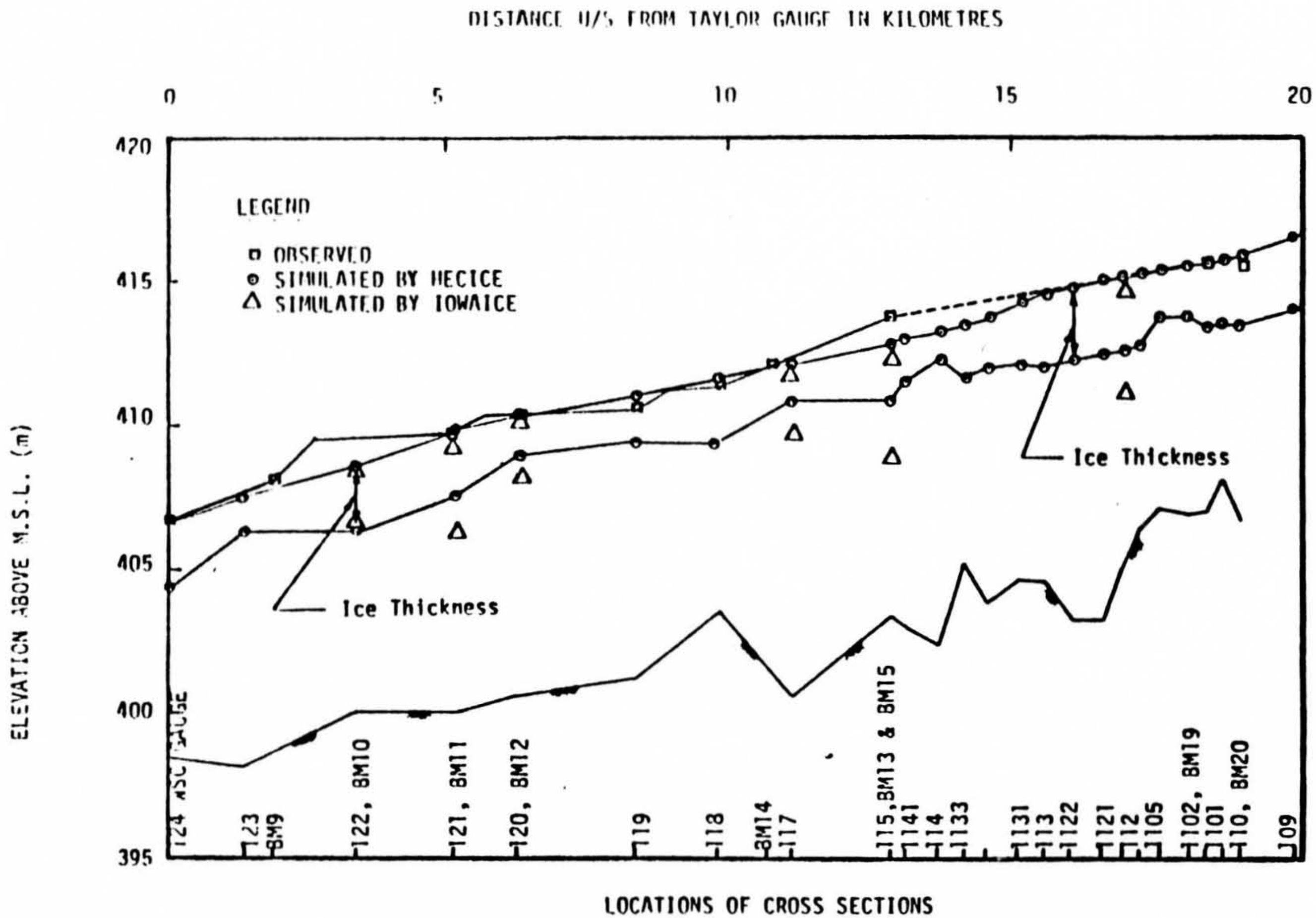
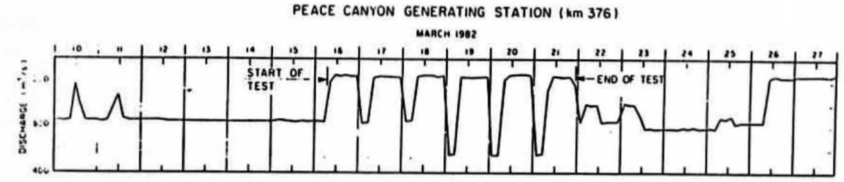
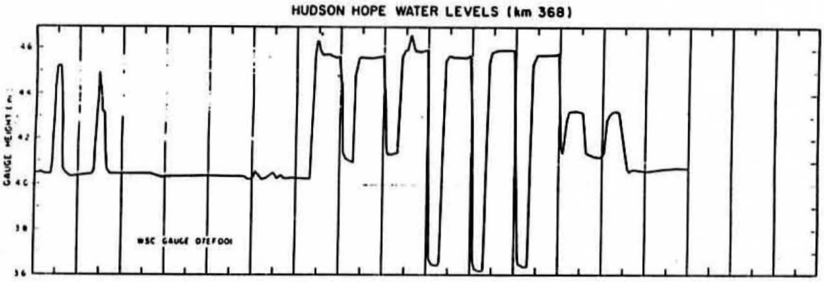
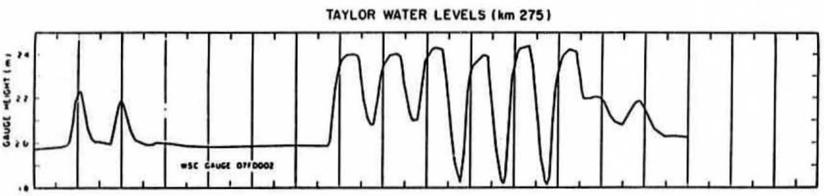


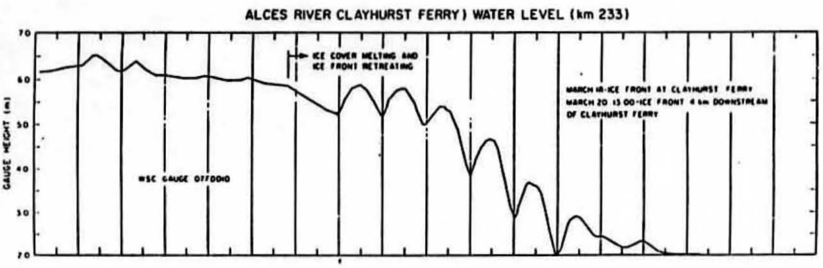

FIGURE 5: FREEZE-UP PROFILES

Reference



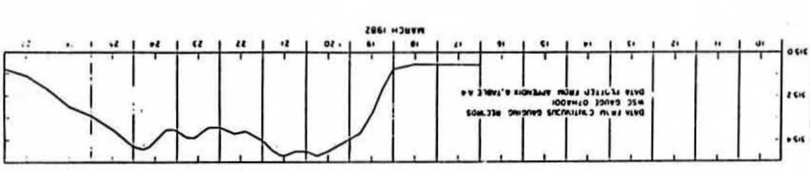



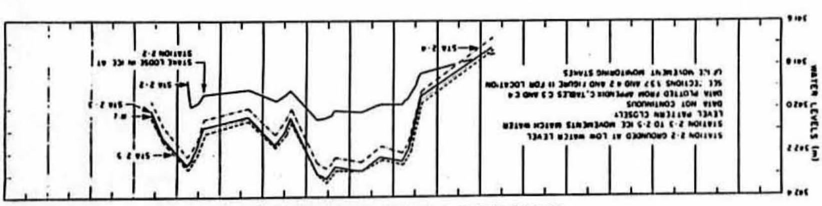

DISCHARGES AND WATER LEVELS FOR MID-WINTER TEST-MARCH 1982

CANADIAN ELECTRICAL ASSOCIATION

STUDY OF ICE COVERS SUBJECT VARYING WATER LEVEL - PHASE B FIELD STUDIES

ACRES



Reference 8.

# Peace River

## Ice Observations 1981-82

BC Hydro

Hydroelectric Generation Projects Division

Report No. H1566 October 1982

19

B.C. HYDRO

# PEACE RIVER

# ICE OBSERVATIONS 1981-82

HYDROELECTRIC GENERATIONS PROJECTS DIVISION

Report No. H1566 October, 1982

Return to HWC

Rec'd from Les Parmly, B.C. Hydro

B.C. HYDRO

HYDROELECTRIC DESIGN DIVISION

DEVELOPMENT DEPARTMENT

# PEACE RIVER

# ICE OBSERVATIONS 1981-1982

OCTOBER 1982

Prepared by P. Rocchetti / W. Karita
Hydrology Section

Approved By J. M. Salmon
Manager, Development Department

REPORT NO. H1566

PEACE RIVER ICE OBSERVATION 1981-82

CONTENTS


Section

Synopsis

1.0 Introduction

1.1 Authority
1.2 Study Program for 1981-82

2.0 1981-82 Field Observations

2.1 Field Trips
2.2 9-11 January 1982 Ice Observation
2.3 8-11 February 1982 Ice Observation
2.4 15-23 March 1982 Ice Observation
2.5 23-27 April 1982 Ice Observation

3.0 1981-82 Ice Observations by other Agencies

3.1 Ancillary Studies
3.2 Acres Consulting Services Ltd.
3.3 Northwest Hydraulic Consultants Ltd.
3.4 Alberta Environment
3.5 Peace River task Force

Appendix A - Observer's Diaries

# S Y N O P S I S

Field observations of icing conditions on the Peace River were carried out by B.C. Hydro personnel during the winter of 1981-82. This work is a continuation of the ice observation program initiated in 1972.

The field conditions of the Peace River from Fort St. John B.C. to Peace River Alberta were observed on four helicopter trips. During these trips the quality and extent of the ice formation were noted and water and/or ice levels and water temperature were measured at selected locations.

A combination of low flows and extremely cold air temperatures from January 1 to 4, 1982 resulted in a rapid upstream progression of the ice cover. Initial freeze-up at the Town of Peace River Alberta occurred on 2 January and the ice front reached Dunvegan by 6 January. An increase in flows after 4 January caused a rupture of approximately 100 miles of river ice which then consolidated into 60 miles of rough broken ice. As a result, ice/water levels at the town of Peace River rose to El.1044.3 ft. i.e. within 4 feet of overtopping the town dykes. With the continuing cold weather the ice sheet stabilized and progressed upstream to mile 86 (measured downstream from GMS), 20 miles upstream of the B.C./Alberta Border by 4 March.

The breakup as in many of the previous years was uneventful and consisted mainly of thermal erosion of the ice cover. The ice broke up at the town of Peace River on 26 April.

Various Provincial agencies and Engineering Consultants were also in the area to observe, study and make recommendations with respect to ice jam flooding hazards at the Town of Peace River. References have been made to those reports in the text.

In addition, the Peace River Ice Task Force consisting of members from B.C. Ministry of Environment, B.C. Hydro and Alberta Environment met twice before breakup and recommended measures to control ice jam flooding at Peace River.

A detailed description of freeze-up, ice cover progression and breakup on the Peace River is given in the diaries of the field observers, presented in this report.

# SECTION 1.0 - INTRODUCTION

## 1.1 AUTHORITY

Under terms of Item 1 of Assignment Number 476-121 Revision 1, dated 28 February 1977, the Hydroelectric Design Division was requested to:

"Provide engineering services related to ice studies and other hydrological studies consistent with the long-range System Plan in effect as follows:

(a) Study, observe and compile data on ice regimes of the Peace River ..............".

## 1.2 STUDY PROGRAM FOR 1981-82

A joint B.C. Alberta Task Force was formed in 1974 to co-ordinate ice observations on the Peace River System in the Provinces of B.C. and Alberta. B.C. Hydro as a member of this Task Force has continued to make observations of freeze-up and break-up in the Peace River in each winter since 1974. The overall objectives for 1981-82, as for all previous years from 1974 to 1981, were as follows:

1. Continue to identify existing and potential hazards to life and property that are the results of ice conditions on the lower Peace River.

2. Continue to investigate the ice regime of the lower Peace River.

   a) Extent and production of ice cover
   b) Timing of freeze-up and break-up
   c) Maximum river stages.

## SECTION 2.0 1981-82 FIELD OBSERVATIONS

### 2.1 FIELD TRIPS

During the winter of 1981-82, four trips were made to the Peace River. The diaries of the field observer are appended to this text. A brief discussion of the field trips and the duration of the trips are given below.

### 2.2 9-11 JANUARY 1982 ICE OBSERVATIONS

The Peace River ice broke-up unexpectedly on 8 January 1982 in the reach between mile 184 and mile 285. This resulted in rising ice/water levels at the Town of Peace River, Alberta. The objective of this trip was to observe and record this event. The observer was also to maintain liaison with Hydro's Operation's staff at the G.M. Shrum Generating Station (GMS).

### 2.3 8-11 FEBRUARY 1982 ICE OBSERVATIONS

The Peace River freeze-up front was approaching the B.C.-Alberta border. Weather conditions were similiar to those of 1979 when flooding and property damage resulted in the vicinity of Taylor, B.C. The objective of this trip was to monitor the ice/water levels at selected stations established during the 1979 Survey. Ice thickness, ice jam locations and water temperatures were measured in order to simulate the field conditions using a mathematical river ice model.

### 2.4 15-23 MARCH 1982 ICE OBSERVATIONS

Canadian Electrical Association (CEA) had commissioned Acres Consulting Services Ltd. to carry out a study on the behaviour of ice covers subject to large daily flow and level fluctuations. Some of the field observations for this study were carried out on the Peace River, and, to assist in the study, B.C. Hydro Operations were requested to make large reductions in outflows from Peace Canyon Project over a seven-day period - March 16-22. In view of the year's high ice/water level and potential hazards it was decided that B.C. Hydro staff should monitor the ice conditions during the test period.

## 2.5 23-27 APRIL 1982 ICE OBSERVATIONS

As in previous years a trip was scheduled to observe the break-up conditions. The breakup at the Town of Peace River occurred on the 27 April without any incident.

## SECTION 3.0 1981-82 ICE OBSERVATIONS BY OTHER AGENCIES

### 3.1 ANCILLARY STUDIES

Besides B.C. Hydro, during the winter of 1981-82, the following groups carried out ice studies on the Peace River in the Province of Alberta, in particular, at the Town of Peace River.

### 3.2 ACRES CONSULTING SERVICES LIMITED

Acres studied the effect of flow fluctuations on an ice sheet for the CEA.

### 3.3 NORTHWEST HYDRAULIC CONSULTANTS LIMITED

Mr. C.R. Neill assessed the pre-breakup ice conditions and made recommendations to Alberta Environment for mitigating problems expected during break-up at the Town of Peace River.

### 3.4 ALBERTA ENVIRONMENT

Mr. G. Fonstad of the River Engineering Branch prepared a status report and proposed ice jam mitigation plans for the break-up at the Town of Peace River.

### 3.5 PEACE RIVER TASK FORCE

The above agencies maintained close liason with the Task Force and exchanged data. The members of the Task Force met in Victoria on the 15 of February, in Peace River on the 25 of March and in Edmonton on the 1 of June to discuss the ways of controlling ice jams at the Town of Peace River. The members are to compile a report on River Ice Conditions in the Peace River Basin during 1981-82.

# APPENDIX A

## Observer's Diaries

Reference 9

# Peace River

# Ice Observations 1982-83



Hydroelectric Generation Projects Division

Report No. H 1641

July 1983

B.C. Hydro

# Peace River

# Ice Observations 1982-83

Hydroelectric Generations Projects Division

Report No. H1641

July, 1983

Return to HWC
Rec'd from Les Parmly
B.C. Hydro 5 Apr 84

B.C. Hydro

Hydroelectric Design Division

Development Department

**Peace River**

**Ice Observations 1982-1983**

**July 1983**

Prepared by: ______________________

Hydrology Section

Approved by: ______________________

Manager, Development Department

Peace River Ice Observations 1982-83

## Contents

Section

Synopsis

1.0 Introduction
- 1.1 Authority
- 1.2 Study Program for 1982-83

2.0 1982-1983 Field Observations
- 2.1 Field Trips
- 2.2 12 January 1983 Ice Observations
- 2.3 31 January - 4 February 1983 Ice Observations
- 2.4 17-18 February 1983 Ice Observations
- 2.5 7-8 March 1983 Ice Observations
- 2.6 11-13 April 1983 Ice Observations
- 2.7 Breakup Diary

Appendix A - Observer's Diaries

## Synopsis

Field observations of ice conditions along the Peace River from W.A.C. Bennett Dam to the Town of Peace River (TPR), Alberta, were carried out by B.C. Hydro personnel during the winter of 1982-83. This work is a continuation of the ice observation program initiated in 1972.

Ice conditions were observed during five helicopter trips. The quality and extent of ice formation were noted and water and/or ice levels and water temperatures were measured at selected locations including a test reach between Site C and the BC/Alberta border.

As the ice front approached TPR, B.C. Hydro's Operations Control Department maintained outflows at or close to 47500 cfs (1345 $m^3/s$) which resulted in a freeze-up level of 1034.25 feet (315.3m) G.S.C. Once the ice on the river reach upstream of TPR became competent, normal outflow fluctuations were resumed.

Regardless of the relatively low accumulated freeze degree-day for the winter of 1982-83, the very low GMS/PCN outflows during this period permitted the ice front to progress to mile 63 (2 miles u/s of Site C) by March 7, the furthest upstream the ice front has progressed since regulation started in 1968.

An uneventful breakup of the Peace River ice at TPR occurred when the Smoky River broke up and opened a channel past the townsite on April 21. The Peace River ice above the Smoky River broke up and passed through TPR on April 24.

A detailed description of freeze-up, ice cover progression and breakup on the Peace River is given in the diaries of the field observers, presented in this report.

# SECTION 1.0 INTRODUCTION

## 1.1 AUTHORITY

Under terms of Item 1 of Assignment Number 482-083, dated 28 July 1982 the Hydroelectric Generation Projects Division was requested to:

"Provide engineering services related to ice studies and other hydrological studies consistent with the long-range System Plan in effect as follows:

(a) Study, observe and compile data on ice regimes of the Peace River ..........".

## 1.2 STUDY PROGRAM FOR 1982-83

A joint B.C. Alberta Task Force was formed in 1974 to co-ordinate ice observations on the Peace River System in the Provinces of B.C. and Alberta. B.C. Hydro as a member of this Task Force has continued to make observations of freeze-up and break-up in the Peace River each winter since 1974. The overall objectives for 1982-83, as for all previous years from 1974 to 1982, were as follows:

1. Continue to identify existing and potential hazards to life and property that are the results of ice conditions on the lower Peace River.

2. Continue to investigate the ice regime of the lower Peace River, including:

    a) Extent and production of ice cover

    b) Timing of freeze-up and break-up

    c) Maximum river stages.

3. Establish a test reach from the B.C./Alberta border to Site C in order to collect data throughout the winter for the calibration of a river ice computer model being developed by the Hydrology Section.

## SECTION 2.0 1982-83 FIELD OBSERVATIONS

### 2.1 Field Trips

During the winter of 1982-83, five field trips were made to the Peace River. The diaries of the field observer are appended to this text. In addition a breakup diary was completed to compile the data gathered by phone from the Town of Peace River, Alberta Environment, B.C. Hydro Operations and Acres Consulting Services Ltd. and from office memorandum, because the scheduled breakup field trip was cancelled. A brief discussion of the field trips and diaries is given below.

### 2.2 12 January 1983 Ice Observations

This trip was scheduled to observe and record any adverse effects that might occur to the newly formed ice cover at TPR by flow reductions at GMS/PCN generation stations. Ice conditions of the Peace River from Fort St. John (mile 65) to TPR (mile 245) were noted. Except for lower ice/water levels, flow reductions did not appear to have any adverse effects on the ice cover.

### 2.3 31 January - 4 February 1983 Ice Observations

The Peace River ice conditions were monitored once the ice front crossed the B.C./Alberta border. Field reconnaissance indicated that ice levels would not reach 1979 maximum freeze-up levels. Data collected included the rate of progression of the ice cover and will be used to calibrate a river ice computer model being developed by the Hydrology Section.

### 2.4 17-18 February 1983 Ice Observations

The Peace River freeze-up front had advanced upstream of the Taylor bridge to the Old Fort area (mile 68). Ice/water levels were measured at selected stations established during the 1979 Survey. Ice thickness, ice jam locations and water temperatures were also measured for use in the calibration of the river ice computer model.

### 2.5 7-8 March 1983 Ice Observations

The Peace River freeze-up front had advanced just upstream of the Moberly River and Site C (mile 66). Ice/water levels at the damsite area were measured.

### 2.6 11-13 April 1983 Ice Observation

Acres Consulting Services Ltd. (ACSL) as consultants to the Canadian Electrical Association continued their study on the behaviour of ice covers subject to large daily flow and level fluctuations. At the request of ACSL, B.C. Hydro agreed to increase outflows from 11000 cfs (311 $m^3$/sec) to 35,000 cfs (1000 $m^3$/sec.) for a 2-day period. The observer undertook a field trip to the ice front location to determine whether the increase might have some effect on accelerating the rate of retreat and also to obtain open water data in the Taylor area. The increase flow was not sufficient to have any noticeable effect on the rate of erosion or break-up of the ice cover.

2.7 Breakup Diary

The events prior to and during breakup at TPR are summarized.

The Peace River at TPR broke up without incident on 21 April.

PR/rt

Attach.

P. Rocchetti

# Appendix A

# Observer's Diaries

Reference 10.

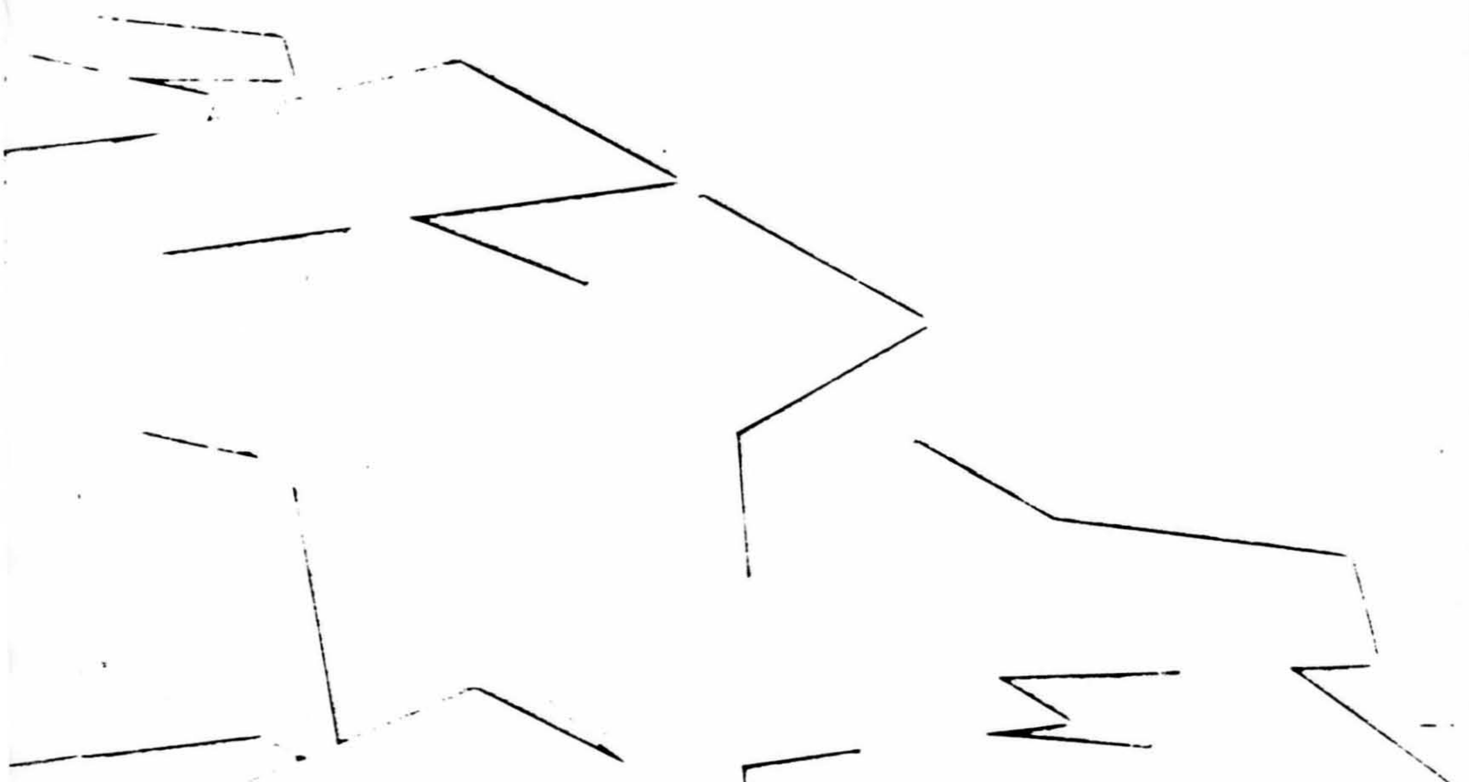
Ref. 10

# RIVER ICE STUDY

## RIVER ENGINEERING BRANCH

Water Resources Management Services
Technical Services Division

Alberta
ENVIRONMENT



SUMMARY REPORT

PEACE RIVER ICE OBSERVATIONS

1982/83 ICE SEASON

Water Resources

ALBERTA DEPARTMENT OF THE ENVIRONMENT
WATER RESOURCES MANAGEMENT SERVICES
TECHNICAL SERVICES DIVISION


Prepared by: G.D. Fonstad, P. Eng.
Head River Studies Section
River Engineering Branch

L.A. Garner, C.E.T.
Technologist
River Engineering Branch

Submitted by: M.E. Quazi, P. Eng.
Branch Head
River Engineering Branch


# SUMMARY REPORT

# PEACE RIVER ICE OBSERVATIONS

# 1982/83 ICE SEASON

March 1984

## SYNOPSIS

This report contains a summary of the 1982/83 ice formation and breakup on the Peace River at the Town of Peace River. It contains a record of the freeze-up advance rate on the Peace River; a record of the mean daily temperature at the Town; as well as a record of BC Hydro and Power Authority's flow releases from the Peace Canyon facility in British Columbia; a record of river levels at the Town, and a record of groundwater levels in the West Peace River subdivision.

Because of the very high freeze-up levels in the previous year, an attempt was made in 1982/83 to control the freeze-up level by controlling flow releases from Peace Canyon.

The ice pack on the Peace River at Peace River formed during the night of 4/5 January, 1983, at a steady discharge release from Peace Canyon of 1398.4 cubic metres per second. The approach and formation of the ice cover caused a stage increase at the Town of Peace River of 3.40 metres, reaching a maximum elevation of 315.35 metres GSC (1034.61 feet) at about 1000 hours on 5 January. The dike elevation across the river from the Water Survey of Canada gauging station is 319.8 metres.

The increase in the river level caused an increase in the groundwater table level in the West Peace River subdivision. This attained a maximum elevation of 314.20 metres (1030.84 feet), which was about one metre below the lowest basement elevation in the subdivision.

At breakup, an as yet undocumented breakup sequence occurred, which is described herein. Breakup at the Town effectively occurred on 24 April, 1983. No ice jamming problems were experienced, basically because breakup was a thermal process rather than a dynamic hydraulic process.

The experiment to control freeze-up levels was considered to be a success.

TABLE OF CONTENTS

Page

SYNOPSIS ........................................................ i
TABLE OF CONTENTS ............................................... iii
LIST OF TABLES .................................................. iv
LIST OF FIGURES ................................................. iv

Section

1. Introduction ................................................. 1

2. Freeze-up Observations ....................................... 1

3. Groundwater Levels in West Peace River ....................... 3

4. Winter Releases and River Levels ............................. 4

5. Breakup Observations ......................................... 4

6. Summary ...................................................... 6

FIGURES

## LIST OF TABLES


| Table No. | | Page |
|---|---|---|
| 1 | Breakup Data, Peace River at Peace River Town ........ | 7 |


## LIST OF FIGURES


| Figure No. | Description |
|---|---|
| 1 | Freeze-up Front Location and Mean Daily Temperatures |
| 2 (10 sheets) | Discharges and Water Levels |

SUMMARY REPORT

PEACE RIVER ICE OBSERVATIONS
1982/83 ICE SEASON

by:

Gordon D. Fonstad, P.Eng.*
and
Larry A. Garner, CET*

## 1. Introduction

When the Peace River at the Town of Peace River formed its ice cover in the 1981/82 ice season, extremely high river levels resulted. Therefore, recommendations were made to the Alberta-BC Joint Task Force on Peace River Ice to attempt to control the freeze-up level at Peace River during the 1982/83 ice formation period. This control would be effected through manipulation of flow releases from BC Hydro and Power Authority's Peace Canyon (PCN) facility.

Such an attempt was conducted during the 1982/83 ice formation period. This report summarizes the major observations and data collected, throughout the 1982/83 ice season, for the Peace River at the Town of Peace River.

## 2. Freeze-up Observations

The first observation of the freeze-up process was provided by the RCMP Detachment in Fort Vermilion, wherein it was reported that the Peace River was frozen over there by 23 November, 1982. Alberta Environment commenced observations of the freeze-up front on 6 December, 1982.

Observations on 6 and 9 December, 1982, showed an advance rate of 22.8 miles per day, which triggered the realization that at that rate of progression, the ice front would be at the Town of Peace River (TPR) in 3.2 days. As the procedure recommended by the Joint Task Force following the 1981/82 ice season was to have BC Hydro hold their discharges steady once the ice was forecasted to reach TPR within 48 hours, BC Hydro was contacted.

* River Engineering Branch, Technical Services Division,
Alberta Environment

BC Hydro was requested by the Joint Task Force to hold their discharge releases from PCN relatively steady in the range 1486 to 1401 cubic metres per second ($m^3$/sec; or 52,500 to 49,500 cubic feet per second (cfs)), with a target mean of 1444 $m^3$/sec (51,000 cfs). Hydro commenced this operation on 12 December, 1982, and with only occasional variation, maintained releases within the requested range. This was carried out in spite of the fact that they did not have a power load or export demand to justify these high releases.

Figure 1, attached, shows the progress of the recorded freeze-up ice front location on the Peace River, in terms of river miles below the WAC Bennett Dam, as well as mean daily temperature at the Town of Peace River. (These latter were determined by averaging the daily maximum and minimum temperatures recorded at the Peace River Airport. Subsequent analysis has shown that this mean can be considerably different from a mean calculated using hourly temperature data, which would more accurately reflect the true mean.) Figure 2 (10 sheets) records the 3-hourly releases from PCN; the recorded hourly water surface elevation as a gauge height at the Water Survey of Canada (WSC) gauge at Peace River; and, recorded mid-day groundwater elevations (in terms of equivalent gauge height) from a recording well established in West Peace River by Alberta Environment.

Unfortunately, once the steady discharge release program was established, a moderating trend in the weather slowed the ice progression rate to an average of 2.63 miles/day, as shown in Figure 1. Alternately, the slow-down might have been due to a change in the hydraulic characteristics in the river between different reaches. A few more years of record will be required to determine whether this was in fact the case. Local variations in advance rate, however, dictated that the steady PCN releases should remain in effect. Figure 1 shows that the ice front passed through TPR on 4/5 January, 1983, which is substantiated by the recorded water levels at TPR, shown in Sheet 2 of Figure 2. The mean PCN release over the period 1 to 5 January, 1983, for which the ice cover would have set in at, was 1398.4 $m^3$/sec (49,380 cfs).

As can be seen on Sheet 2 of Figure 2, the net stage increase at TPR for a relatively constant release from PCN was 3.40 m from 28 December 1982 to 5 January 1983. The duration of this increase reflects the approach of the ice-staged water levels, felt at TPR because of the backwater effect from the ice covered river downstream. The effects of the approaching ice cover were first felt when it was in the order of 17.5 miles below the bridges at TPR.

The peak stage attained was gauge height 10.55 m (to Elevation 315.35 m), which was about 0.5 m higher than that attained during the corresponding initial staging on 2 January 1982 (10.0 m); but was 2.80 m lower than the highest stage attained in January, 1982. This higher staging level in 1981/82 had been caused by secondary staging accompanying the telescoping of the ice cover on 7/8 January.

BC Hydro had been balancing power production due to the continued high releases from PCN by cutting back on releases from their Columbia River plants. As they had to maintain certain riparian flows on the Columbia, they asked the Joint Task Force if they could cut back on their PCN releases to allow higher flows in the Columbia. The Joint Task Force members agreed on 6 January, and the cutback to a mean release of about 1050 $m^3$/sec (37,000 cfs) occurred on 7 January.

Figure 2 shows the PCN releases, river levels and groundwater levels at Peace River for the balance of the ice season. Nothing untoward occurred for the balance of the winter.

It was judged that the first attempt at controlling the freeze-up level at TPR was successful.

## 3. Groundwater Levels in West Peace River

During the 1981/82 ice observation period, it was ascertained that groundwater seepage problems in basements in West Peace River occurred when the stage in the river exceeded 11.0 m ... for the ice conditions prevalent that year. By contrast, the highest recorded groundwater level for 1982/83 (of three observation wells established by Alberta Environment) was 8.0 m (Figure 2, Sheet 3, and Note to Accompany Figure 2).

The data shown in Sheets 2 and 3 of Figure 2 indicates that the groundwater table began responding to the increase in river stages within about 40 hours, and when the net increase in river stage was only in the order of 0.65 m. The groundwater level raised approximately 1.73 m in the 19 day period from 29 December 1982 to 16 January 1983. The data indicates that the groundwater level appeared to remain in the order of 1.0 to 1.5 m below the adjacent river level for the balance of the winter*.

During the initial river staging, the rate of rise of the groundwater level increased on about 2 January, 1983, when the river level was about 2.4 m higher than the groundwater level. The groundwater level continued to rise after the river staging was complete (and even as the river stage dropped following the lowering of PCN releases on 7 January), driven by the differential head between the river level and the groundwater table. The groundwater level reached an initial peak on 16 January as a result of the staging, and a second slightly higher peak on 22 January in response to a short duration increase in the river level.

The recorded groundwater elevation on 22 January, 1983, was Elevation 314.20 m (1030.84 ft). According to the TPR Town Engineer, the lowest basement elevation in West Peace River is Elevation 315.25 m (1034.30 ft). Thus it should be possible to set the Peace River ice

*Note: These levels are subject to correction as outlined on the 'Note to Accompany Figure 2' levels at TPR approximately a metre higher than in 1982/83, though this would leave little margin for groundwater level fluctuation throughout the balance of the winter. This metre increase should be taken from the gauge height following the levelling off and slight reduction in river stage caused by the roughness of the underside of the ice cover smoothening out.

Because the discharge releases from PCN were reduced on 7 January, the above maximum groundwater levels are likely less than they would have been had the release of 1398.4 $m^3$/se (49.380 cfs) continued for another week or more. As the discharges were reduced, causing a reduction in river stage commencing in the mid-afternoon of 9 January, there was insufficient data to ascertain whether or not groundwater seepage problems would have occurred for the particular PCN releases.

## 4. Winter Releases and River Levels

From 21 January to 24 February, BC Hydro's power releases from PCN were low, being in the order of 500 to 600 $m^3$/sec (17,660 to 21,190 cfs). These were further reduced to about 450 $m^3$/sec (15,890 cfs) over the period 25 February to 25 March, with only a few instances of peak releases in the order of 700 $m^3$/sec or lower. PCN releases were again reduced on 25/26 February to in the order of 320 to 250 $m^3$/sec (11,300 to 12,360 cfs) until 11 April 1983, again with isolated peak releases.

Throughout this period, the water water levels at the WSC gauge tended to drop with the reduced releases. Beginning with a gauge height of about 8.5 m, the river level dropped with successive reductions in discharge to in the order of 8.0 m, then to about 7.5 m. On 6 April the river level began to rise, with no corresponding increase in PCN releases, hence likely reflects stepped up local inflows from snowmelt. BC Hydro stepped up their releases for 12, 18 and 6 hours on 7, 8 and 9 April, respectively, however these were after the river level at TPR began to rise. The total increase was about 0.75 m over the period 6 to 12 April.

## 5. Breakup Observations

On 11 April, BC Hydro increased the PCN releases to about 1000 $m^3$/sec (35,315 cfs) for a 51 hour period. This increase followed the philosophy set out by the Joint Task Force during the 1981/82 breakup period, to try and initiate breakup in the Peace River before the Smoky River broke up, as experience had shown that if the Smoky broke first it would tend to cause ice jamming problems for TPR.

During the 1983 breakup, a breakup sequence occurred which, to the best of our knowledge, had not happened in the years since ice studies first commenced at TPR. In previous years, either of two breakup sequences had been noted at Peace River. One sequence was that the Smoky River has broken up first, e.g., 1979, forcing its ice into the Peace River. When this occurs, high water levels have been experienced at TPR, caused by jamming of the excessive ice in the river. In most years, however, the Peace River has broken up first, e.g., 1982. In this sequence a main breakup front travelled down the Peace River in an orderly fashion, causing breakup in either a thermal or dynamic manner. The Peace River ice at TPR has been cleared out through this sequence before the Smoky River broke up.

In 1983, however, the Peace River opened up a narrow lead in the ice through the TPR reach, by thermal processes, before the Smoky River broke up and before the main breakup front was anywhere near TPR. The lead opened up on 14 april, some ten days before the main breakup front passed through TPR. In the intervening time it grew in both length and width, such that by 24 April upwards of 80% of the width of the river was clear of ice.

The following summarizes the major observations made during 1983.

Rising stages at TPR on 14 April, in response to the increased releases from PCN on 11 April, caused the ice cover to flex, and areas along the lower bank-ice-hinge-lines filled with water. Concurrently, an open lead developed just below Lee Island in the right hand channel around Bewely Island. The main breakup front was still well upstream, being in the order of 120 miles away. By 22 April this lead had extended upstream, covering a reach from just above the mouth of the Heart River to just below Lee Island, and occupying the right hand channel around Bewely Island.

The main breakup front was reported to be at Mile 124 on 12 April, retreating about 3 miles per day. By 20 April breakup had occurred at Dunvegan (Mile 182.8), with all ice floes in the river clearing Dunvegan that evening.

On 21 April the lower 2.5 km of the Smoky River ice was gone, but had not shoved into the Peace River ice. Presumably the floes were entrained into the Peace River flow and carried away. Flow was breaking out onto the Peace River ice. The remainder of the Smoky River ice melted in place.

A later report on 22 April had the open lead at TPR developed about 80% of the way up to the mouth of the Smoky River, and extending downstream to about Mile 250.5. At 2000 hours that day, the main breakup front was located at Mile 229.2, about one mile upstream of the Shaftsbury Ferry. The ice cover between Mile 229.2 and the mouth of the Smoky River was, however, still in place.

At 1100 hours on 23 April, the ice front was located at Mile 232.5 (2.5 miles downstream of the Shaftsbury Ferry), and had about 1.9 miles of broken ice jammed in the river upstream of it. By 2100 hours the front had moved down to Mile 233.4, and had 1.1 miles of jammed ice floes behind it.

On 24 April at 1000 hours the ice front was at the MacKenzie Cairn observation point (Mile 235.30), and commenced moving at 1015 hours. Progression of the front was in a similar manner as had occurred in

1982, with leads melting out ahead of the front, then the jammed ice moving down into these leads and coming to rest. The breakup front passed Mile 236.89 (Correctional Institute pumphouse) at 1340 hours, and passed Mile 240.18 at 1535 hours, with jammed ice extending upstream to Mile 237.79. The ice thickness was estimated to be in the order of 0.6 to 0.7 m.

Upon reaching the open lead below the mouth of the Smoky River, the front progressed quickly. A local peak in the Peace River stage occurred at 1720 hours on 24 April, reaching a local maximum gauge height of 8.940 m at the WSC gauge. By 25 April at 1500 hours, the breakup front had progressed downstream to Mile 270, some 24 miles below the Highway 2 bridge at TPR.

A breakup summary table, including the data for 1983, is included as Table 1. As can be seen in the table, the peak river stage at 'breakup' on the Peace River at TPR on 24 April was only 0.35 m higher than the five-day average pre-breakup stage. The reason for this can be readily seen in Sheet 9 of 10 of Figure 2. The local lowering of water levels on 22 April was likely due to the enlargement of the open lead through TPR. From 23 to 24 April a rise in stage of about 1.07 m accompanied the passage of the breakup front, however, to be consistent with reporting criteria from previous years, the peak on 24 April was 0.35 m higher than the previous five-day average level.

## 6. Summary

The 1982/83 ice season on the Peace River at TPR was uneventful. The ice pack built in at a level that did not cause seepage problems in basements in West Peace River. The manner in which the ice cover built in indicates a successful attempt at controlling freeze-up at TPR (for the meteorological conditions experienced that year).

While the ice cover was built in at a fairly high discharge, in order to allow BC Hydro some leeway in their release operations for the balance of the winter, this leeway was not fully tested. Due to a low power demand throughout the balance of the winter, BC Hydro cut their releases to well below average.

The data indicates that it may be possible to increase the level at which the ice was set in, by approximately a metre.

Breakup was uneventful in 1983, the dominant process being thermal deterioration of the ice accompanied by a 'melt front' rather than a dynamic breakup front. A new breakup sequence was observed at TPR in 1983, being the melting of a substantial open lead at TPR well in advance of the approaching 'melt front'.

A comprehensive set of data were collected through the 1982/83 ice season, which should greatly assist future analyses.

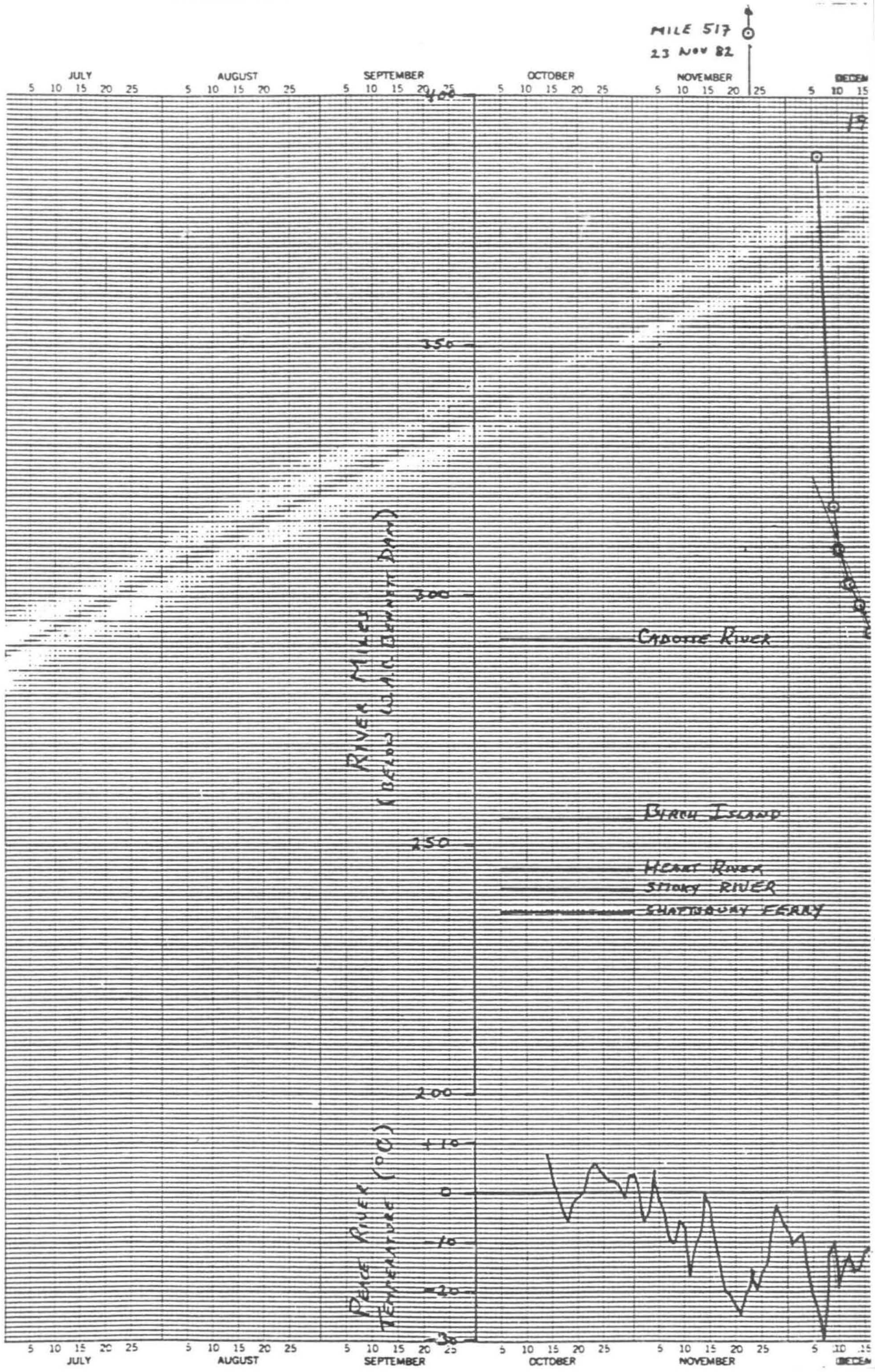
TABLE 1
Breakup Data
Peace River at Peace River Town

| Year | Breakup Date | 5-Day Pre-breakup Elevation*1 (m) | Discharge During Breakup: Peace River Above Smoky River*2 | Discharge During Breakup: Smoky River Above Confluence*3 | Maximum Ice Jam Elevation (m) | Maximum Stage Increase Above Pre-breakup Elevation (m) |
|---|---|---|---|---|---|---|
| 1960 | Apr 16 | 312.88 | 883.49 | 365.29 | 313.21 | 0.33 |
| 1961 | Apr 20 | 311.69 | 1112.85 | 104.77 | 311.81 | 0.12 |
| 1962 | Apr 16 | 312.30 | 866.50 | 648.46 | 313.94 | 1.64 |
| 1963 | Apr 19 | 311.75 | 3381.03 | 1093.03 | 316.14 | 4.39 |
| 1964 | Apr 19 | 312.33 | 897.64 | 206.15 | 312.15 | -0.18 |
| 1965 | Apr 14 | 311.90 | 1568.75 | 481.39 | 313.61 | 1.71 |
| 1966 | | | | | | |
| 1967 | Apr 30 | 311.90 | 291.66 | 1005.25 | 313.40 | 1.50 |
| 1968 | | | | | | |
| 1969 | Apr 15 | 311.96 | 475.72 | 948.61 | 314.89 | 2.93 |
| 1970 | | | | | | |
| 1971 | Apr 19 | 312.48 | 1260.10 | 203.88 | 313.06 | 0.58 |
| 1972 | Apr 20 | 313.21 | 1452.65 | 538.02 | 314.86 | 1.65 |
| 1973 | Apr 12 | 313.76 | 2273.84 | 515.37 | 318.18 | 4.42 |
| 1974 | Apr 20 | 313.36 | 2288.00 | 1308.24 | 317.51 | 4.15 |
| 1975 | Apr 17 | 314.16 | 2174.73 | 69.94 | 314.52 | 0.36 |
| 1976 | Apr 11 | 313.94 | 1676.36 | 594.65 | 314.34 | 0.40 |
| 1977 | Mar 12 | 312.72 | 767.39 | 66.83 | 311.90 | -0.82 |
| 1978 | Apr 15 | 313.18 | 1333.72 | 215.77 | 313.49 | 0.31 |
| 1979 | Apr 30 | 314.10 | 2520.20 | 1589.99 | 318.61 | 4.51 |
| 1980 | Apr 18 | 311.81 | 651.29 | 387.94 | 313.06 | 1.25 |
| 1981 | | | | | | |
| 1982 | Apr 26 | 315.46 | 1653.00 | 247.00 | 315.94 | 0.48 |
| 1983 | Apr 24 | 313.38 | 1340.00 | 400.40 | 313.73 | 0.35 |

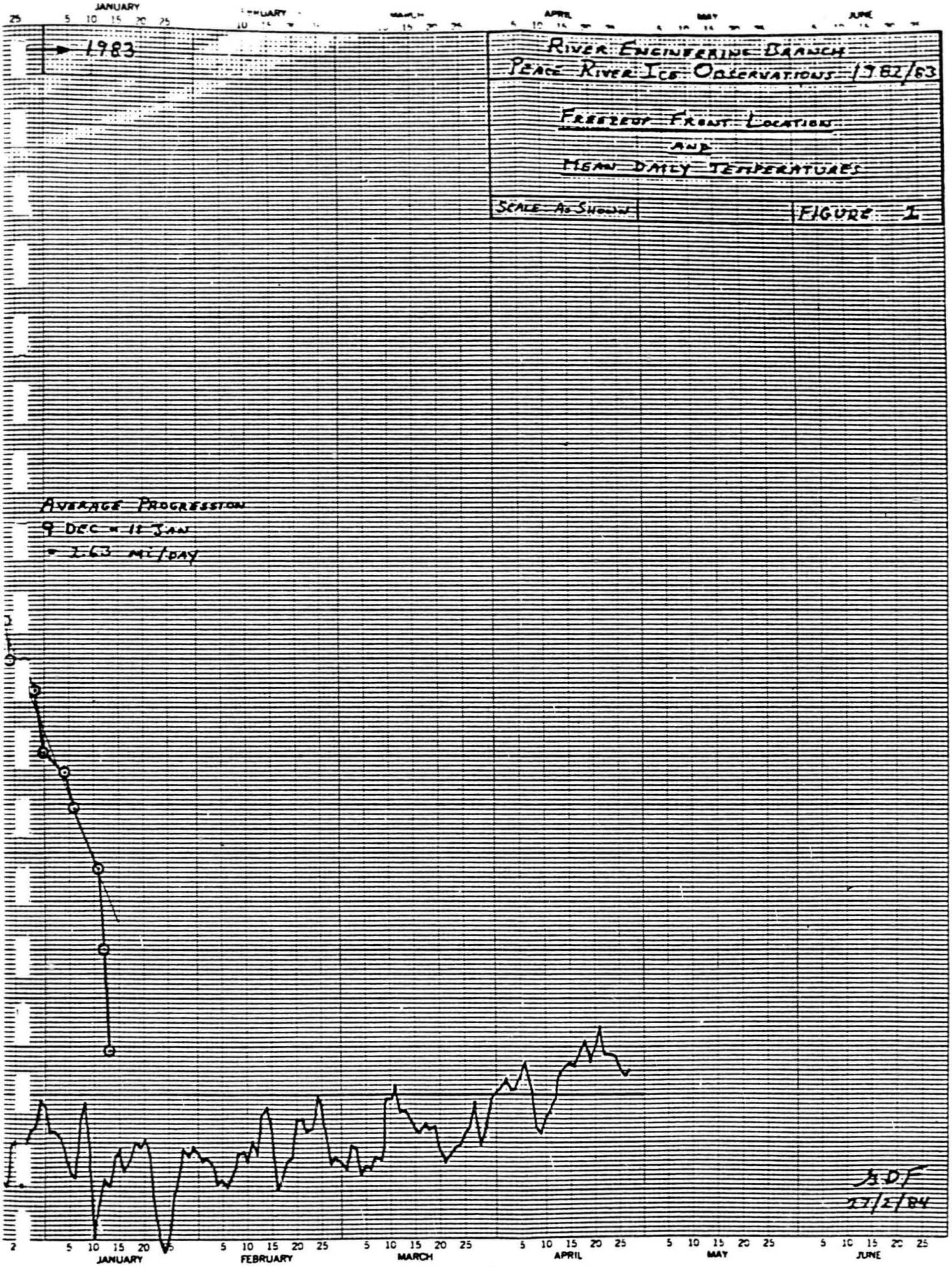
Notes: *1 Average elevation of mean daily discharges at Peace River for 5 days prior to breakup, estimated from recorded water levels.

*2 Peace River Discharge = Discharge at Peace River - Smoky River Discharge at Watino

*3 Smoky River at Watino



MILE 517
23 NOV 82
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
RIVER MILES (BELOW W.A.C. BENNETT DAM)
400
350
300
250
200
CADOTTE RIVER
BIRCH ISLAND
HEART RIVER
SMOKY RIVER
SHAFTSBURY FERRY
PEACE RIVER TEMPERATURE (°C)
+10
0
-10
-20
-30



1983
River Engineering Branch
Peace River Ice Observations 1982/83
Freezeup Front Location
and
Mean Daily Temperatures
Scale As Shown
Figure 1
Average Progression
9 Dec – 11 Jan
= 1.63 mi/day
B.D.F
27/2/84
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE

## Note to Accompany Figure 2

A note should be made before any reader attempts to compare groundwater levels recorded in 1982/83 with those recorded in 1981/82. The data for 1981/82 was plotted by subtracting the WSC gauge zero elevation from the groundwater elevations to obtain an equivalent gauge height. However, this then did not include an allowance for the fact that the water levels in the river adjacent to the groundwater wells was in the order of 0.97 m higher than the river level at the WSC gauge, due to the distance between the wells and the gauge and the final longitudinal slope of the ice covered river. This resulted in a plot which showed the groundwater level higher than the river level, which was found not to be the case. The 1982/83 data has been corrected to incorporate this difference, hence make the river level/groundwater level data more compatible.

The River Engineering Branch considers that it might have made an error of up to 0.4 m in adjusting the groundwater elevations to equivalent gauge height. Thus the plotted points in Figure 2 may be 0.4 m lower than they should be. This error will have to be verified through a more detailed calculation procedure involving the river levels recorded by Water Survey of Canada at their gauge at Peace River, plus those recorded by Alberta Environment at the Peace River Correctional Institute.

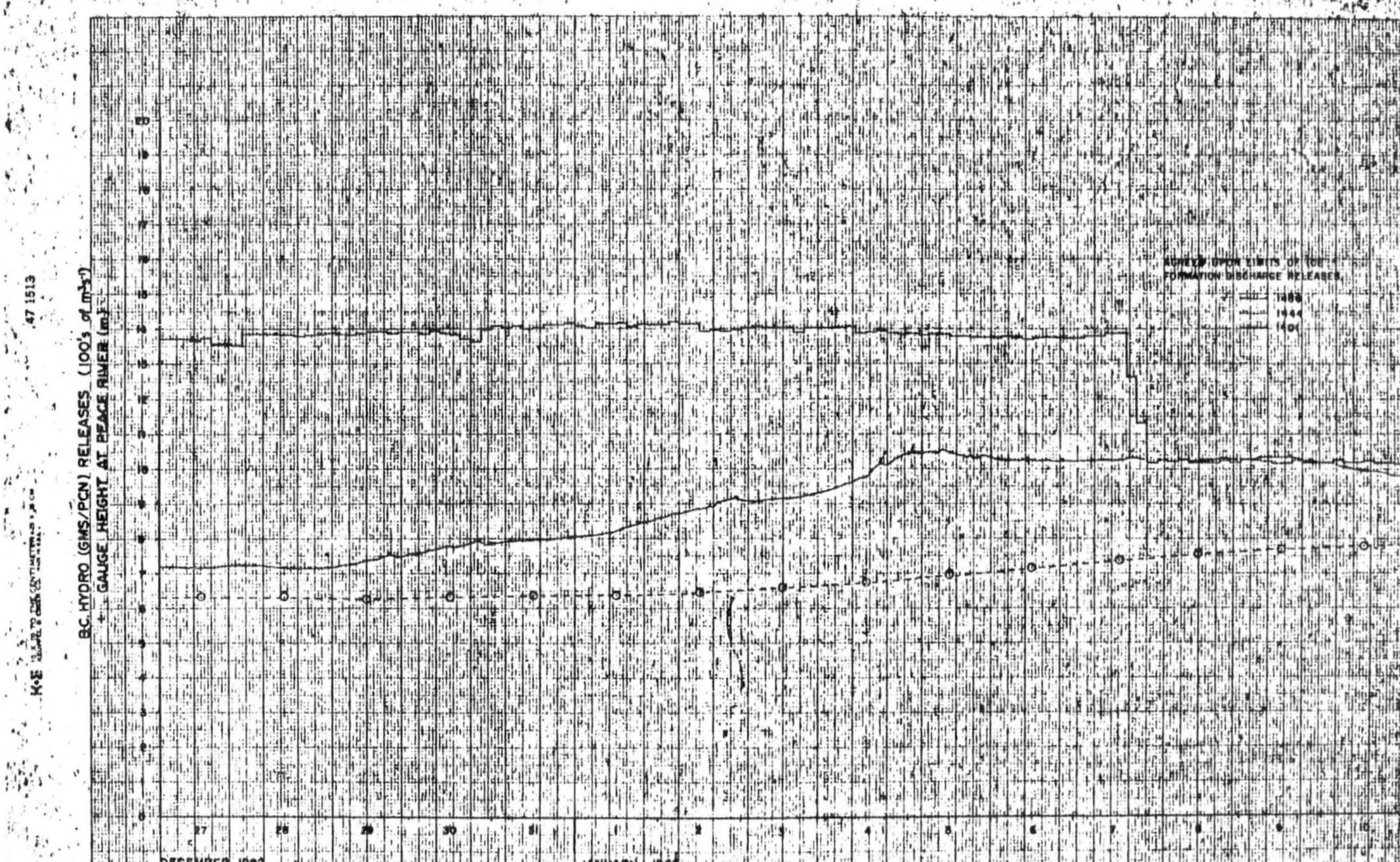

B.C. HYDRO (GMS/PCN) RELEASES (100's of m³s⁻¹)
GAUGE HEIGHT AT PEACE RIVER (m)
FORMATION DISCHARGE RELEASES
27
28
29
30
31
1
2
3
4
5
6
7
8
9
10
DECEMBER 1982
JANUARY 1983
TIME

FIGURE 2

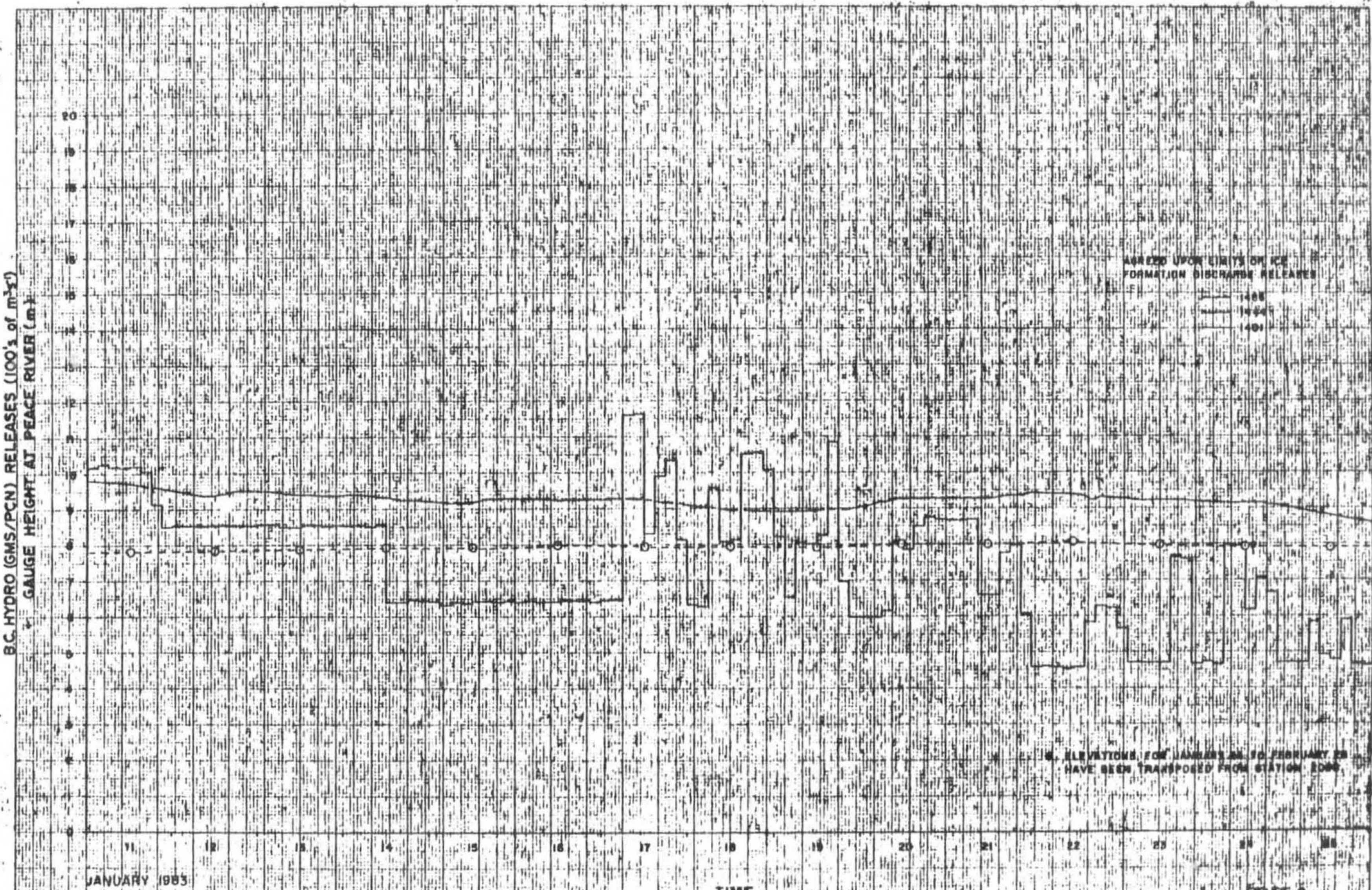



FIGURE 2

K·E 47 1513

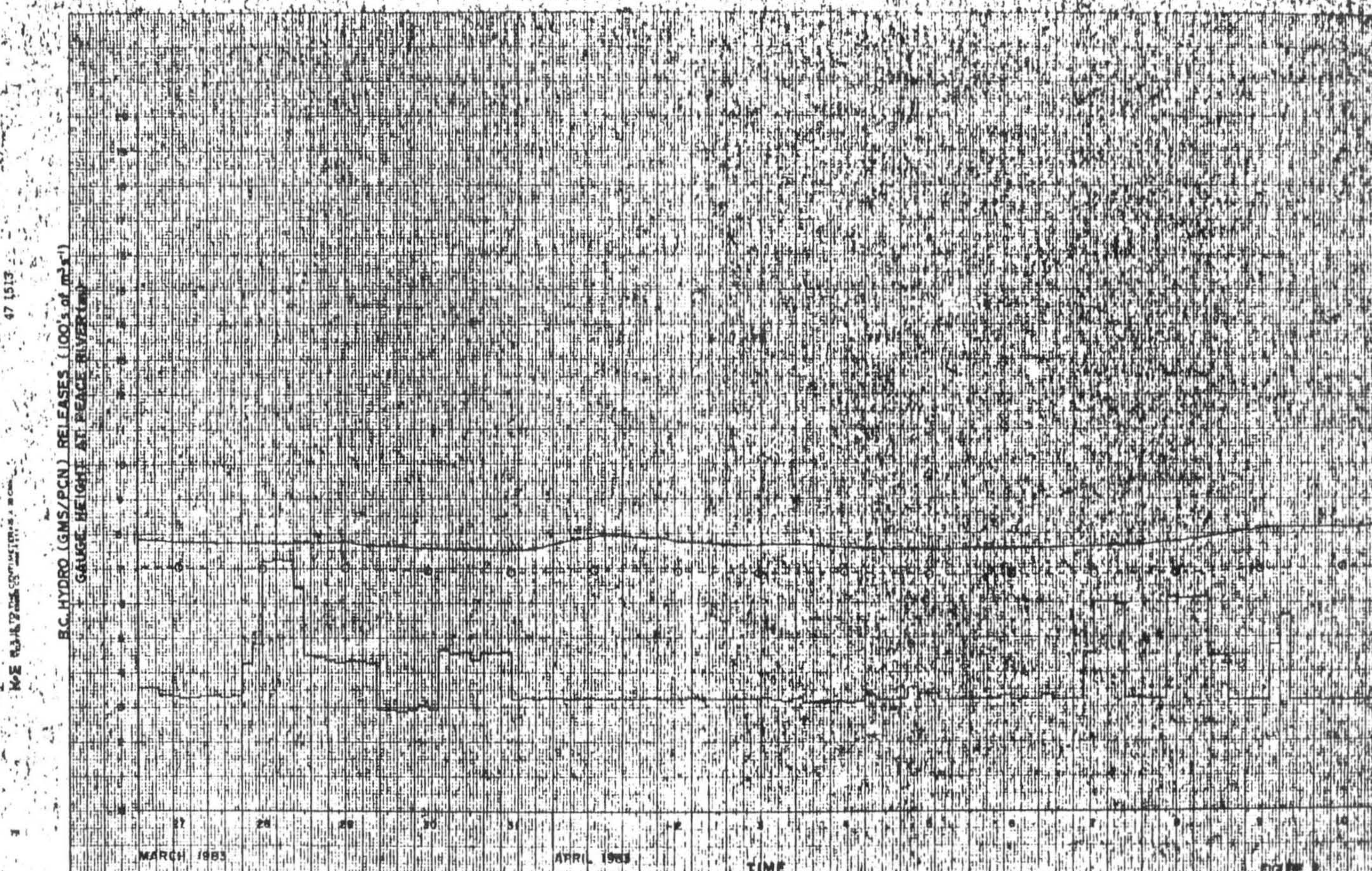
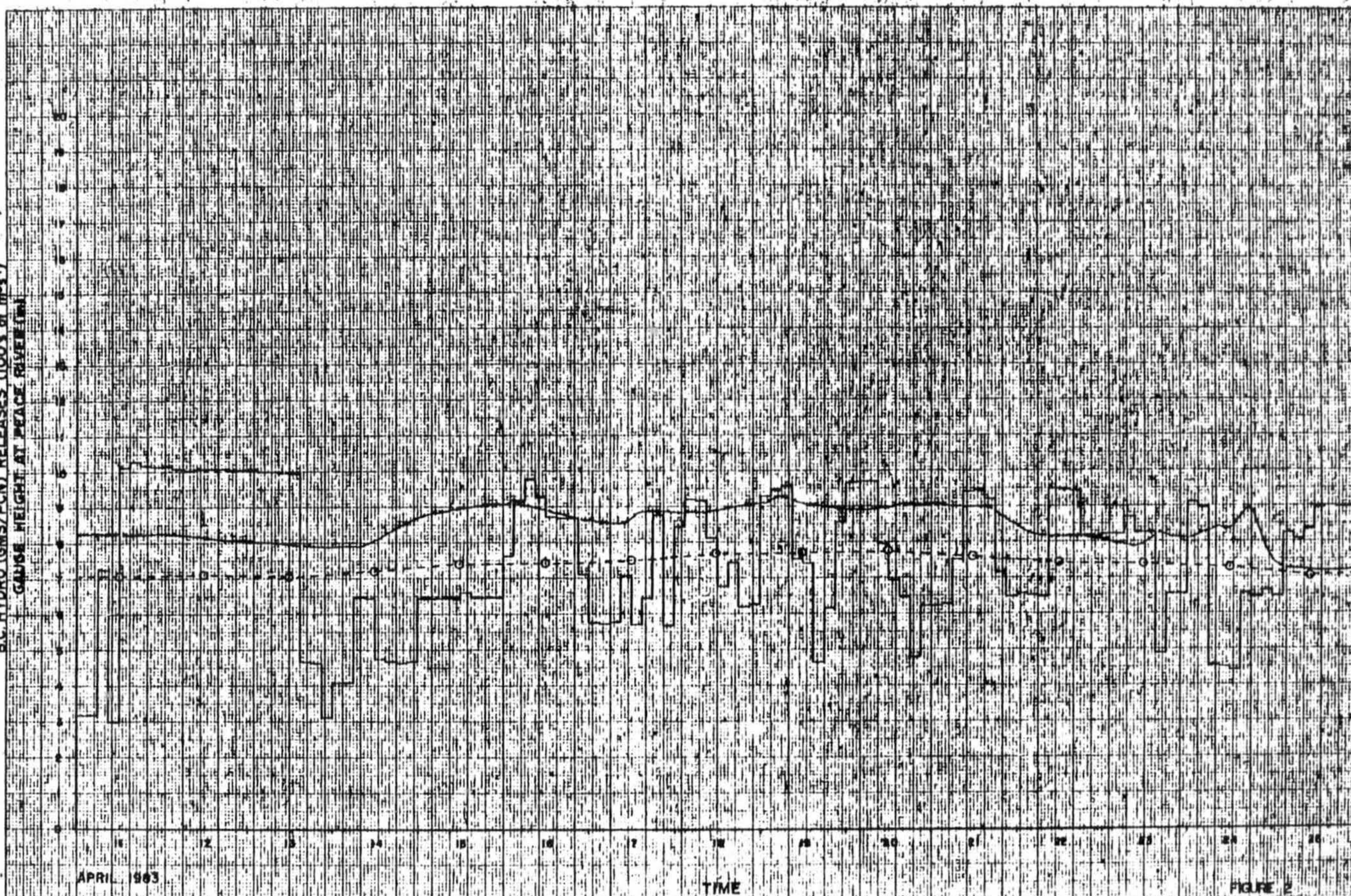

B.C. HYDRO (GMS/PCN) RELEASES (1000's of m³s⁻¹)
GAUGE HEIGHT AT PEACE RIVER (m)
27
28
29
30
31
1
2
3
4
5
6
7
8
9
10
MARCH 1983
APRIL 1983
TIME

FIGURE 2


B.C. HYDRO (GMS/PCN) RELEASES (100's of $m^3s^{-1}$)
GAUGE HEIGHT AT PEACE RIVER (m)
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
APRIL 1983
TIME
FIGURE 2

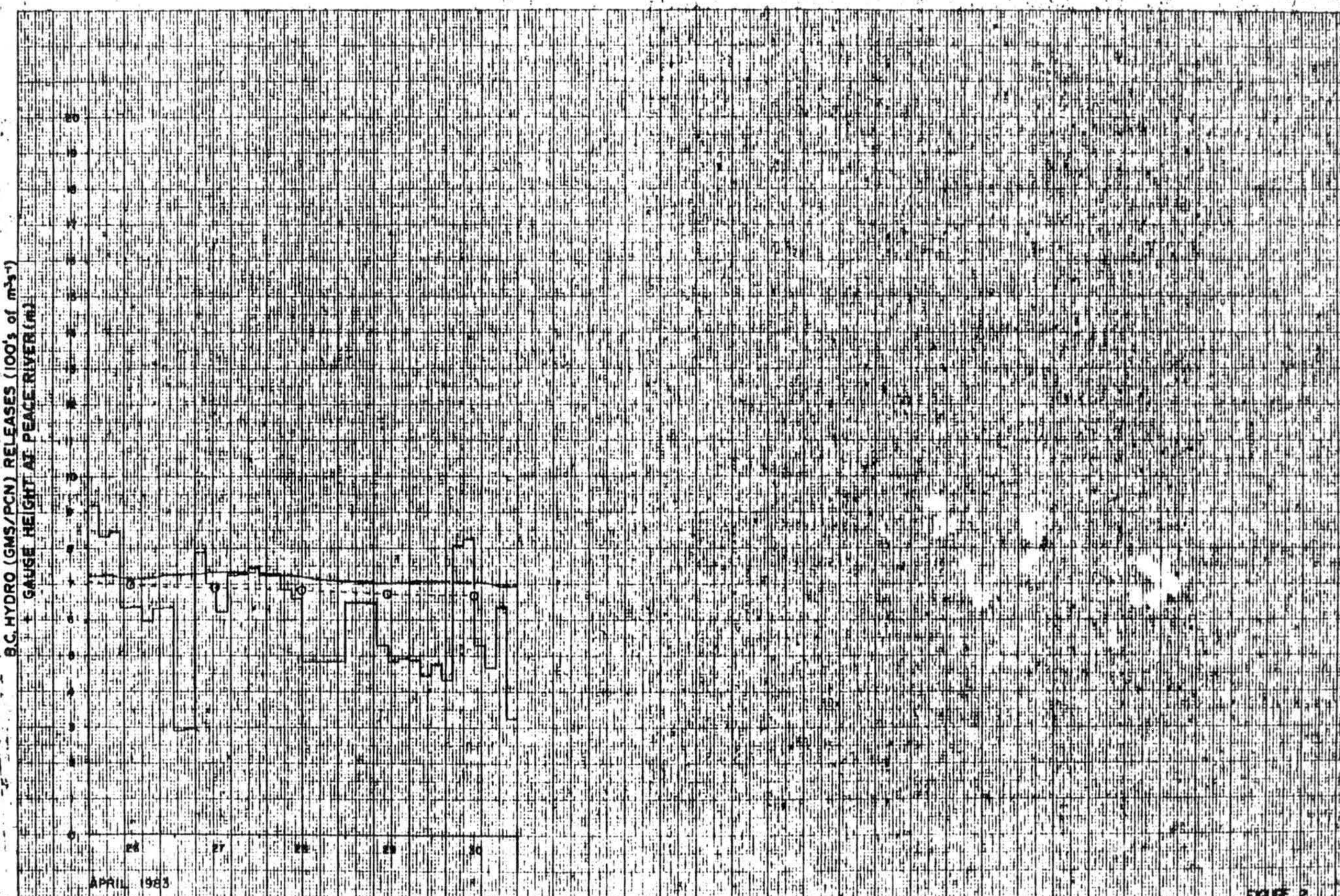

B.C. HYDRO (GMS/PCN) RELEASES (100's of $m^3s^{-1}$)
GAUGE HEIGHT AT PEACE RIVER (m)
20
10
0
26
27
28
29
30
APRIL 1983

FIGURE 2

Reference 11

Ref. 11

# RIVER ICE STUDY

## RIVER ENGINEERING BRANCH


Water Resources Management Services
Technical Services Division

Alberta
ENVIRONMENT


1982 SPRING BREAKUP AND MONITORING REPO

ATHABASCA AND CLEARWATER RIVERS

AT

FORT McMURRAY

ALBERTA DEPARTMENT OF THE ENVIRONMENT
WATER RESOURCES MANAGEMENT SERVICES
TECHNICAL SERVICES DIVISION

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# 1982 SPRING BREAKUP AND MONITORING REPORT

# ATHABASCA AND CLEARWATER RIVERS

# AT

# FORT McMURRAY

December 1982

## FOREWARD

The following report, which describes the 1982 spring breakup event at Fort McMurray, is part of a continuing research program to study breakup and other ice-related phenomena on Alberta rivers. This program is carried out by the Civil Engineering Department of Alberta Research Council in co-operation with Alberta Environment and Alberta Transportation, under the auspices of the Alberta Co-operative Research Program in Transportation & Surface Water Engineering. The prime intent of this report is to document the 1982 breakup in order to facilitate future comparisons.

The Athabasca River in the vicinity of Fort McMurray normally produces ice jamming during breakup. In some years severe ice jams have caused high water levels which resulted in extensive flooding of the lowlying areas within the City of Fort McMurray.

In 1982, breakup at Fort McMurray occurred on April 26. At the MacEwan Bridge gauge a 5.25 m increase in stage was recorded above a pre-breakup ice surface elevation of 241.5 m G.S.C. The progression of the breakup was observed from Grand Rapids to Fort McMurray. Water levels were taken between Little Fishery River and Poplar Island, and miscellaneous velocity measurements were taken at the MacEwan Bridge. Temporary jamming was observed at five separate locations upstream of the MacEwan Bridge, and a jam lasting for approximately 3.5 hrs occurred between the MacEwan Bridge and the confluence of the Clearwater River. In addition to the data presented herein, there are numerous 35 mm color slides, additional color prints, 8 mm film and newspaper accounts of the breakup available from the various co-operating agencies.

## ACKNOWLEDGEMENTS

T. Ridgeway and M. Anderson of Alberta Research Council assisted in the collection and recording of the field data. E. Emery (summer student) Alberta Environment assisted in the assembly and preparation of the data. The Public Works Department for the City of Fort McMurray collected and supplied the gauge information for the Clearwater River; D. Andres, P. Eng. of Alberta Research Council made helpful comments in the preparation for breakup and in a review of this report. G. Fonstad, P. Eng. of River Engineering Branch, Alberta Environment also reviewed this report.

TABLE OF CONTENTS


| | Page |
|---|---|
| FOREWARD | i |
| ACKNOWLEDGEMENTS | ii |
| TABLE OF CONTENTS | iii |
| LIST OF FIGURES | iv |
| LIST OF PHOTOGRAPHS | v |
| LIST OF ABBREVIATIONS | vi |
| INTRODUCTION | 1 |
| PRE-BREAKUP CONDITIONS AND SUMMARY | 3 |
| BREAKUP | 6 |
| JAMMING AND RELEASE DOWNSTREAM OF MacEWAN BRIDGE | 8 |
| CLEARWATER BREAKUP AND MONITORING | 10 |
| CONCLUSIONS AND DISCUSSIONS OF THE 1982 BREAKUP | 11 |
| REFERENCES | |
| FIGURES | |
| PHOTOGRAPHS | |

## LIST OF FIGURES


| Figure No. | Description |
| --- | --- |
| 1 | Location Plan - Drainage Basin Athabasca River at Fort McMurray |
| 2 | Maximum and Minimum Temperatures (March - April 1982) |
| 3 | Cumulative Degree Days of Thaw (Spring 1982) |
| 4-5 | Pre-breakup Reconnaissance and Jamming Locations |
| 6 | April 26 - Breakup at Fort McMurray |
| 7 | Jamming and Release Downstream of MacEwan Bridge (April 26) |
| 8 | Gauge Height and Velocity Profile MacEwan Bridge (April 26) |
| 9 | Christina River - Clearwater River Breakup (April 27-29) |
| 10 | Gauge Locations - Clearwater River |
| 11 | Gauge Height Readings - Clearwater River (April 26-29) |
| 12 | Highwater Mark Survey - Athabasca River |

# INTRODUCTION

Based on 24 years of recorded data (1958-81) the average breakup date of the Athabasca River in the vicinity of Fort McMurray is April 28. Ice jamming during the breakup event is not uncommon.

Between Fort McMurray and the mouth of the La Biche River (Figure 1) the time of breakup deviates from the usual pattern that follows the warming trend which is typical of the area upstream of the Town of Athabasca and the more southern portions of the Athabasca River drainage basin. Often, the fourteen rapid sections between Athabasca and Fort McMurray break up when there is only a slight increase in discharge. In this reach, the high channel slope gives rise to larger velocities and shear stresses, which can initiate breakup well in advance of other sections of the river. When the ice in the rapid sections deteriorates, ~~and~~ it moves downstream, accumulating in areas of low velocity. As the discharge increases and the ice deteriorates further, small jams move downstream, compound and alternately move, jam, and buildup again. In most years these small jams have compounded into a severe jam which can cause stage increases of 2-10 m above normal summer water levels

In 1982, breakup on the Athabasca River at Fort McMurray occurred on April 26 and a maximum increase in stage of 5.25 m from a pre-breakup ice surface elevation of 241.5 m G.S.C. was recorded at the MacEwan Bridge. Temporary jamming was observed at five separate locations between Cascade Rapids and the MacEwan Bridge. A jam lasting for approximately 3.5 hrs occurred just downstream of MacEwan Bridge.

Doyle (1977), Doyle and Andres (1978) and Doyle and Andres (1979) provide the most recent references which document the more significant ice jamming that has occurred in the past decade. References are also provided in earlier reports which document major ice jams which occurred in the Fort McMurray vicinity prior to 1970.

## PRE- BREAKUP CONDITIONS AND SUMMARY

The following section of this report is a summary of the information collected from various agencies prior to the 1982 breakup. This information can be compared to that from previous years, and may have application towards the prediction of future breakup or other ice related phenomena associated with the Athabasca River.

A summary of the relationships among discharge, air temperature, and degree days of thaw during breakup for the Athabasca River at Fort McMurray are provided in Figures 2 - 3. Additional data collected prior to breakup was recorded as outlined below:

March 9-10 (photos 1 & 2) - A ground and aerial reconnaissance flight of the of the Athabasca River from Crooked Rapids downstream to Suncor was made with D. Andres, Alberta Research Council. The primary purpose of the flight was to establish a series of geodetic bench marks to aid in monitoring future breakup and ice jam flooding in the area of Fort McMurray. The following conditions were noted at that time:

- solid ice cover from Crooked Rapids downstream to Suncor,
- accumulated precipitation since November was 78% of the normal,
- average temperatures were 1.4°C above normal, and
- a monitoring and an observation program was set-up with WSC and ARFC.

March 25 - Air temperature and precipitation were monitored for Slave Lake, Athabasca and Fort McMurray.

As of March 26 - solid ice cover remained on both Athabasca and Clearwater channels.

- minimum daily temperatures remained below 0°C during the night - mean daily temperature between March 19-23 = 5.5 ° C.

- 4 mm of additional precipitation since March 10, and snow on ground (SOG) = 32 cm.

April 1 - Based on available snow pack data, 1700-2266 $m^3$/sec was predicted as the maximum flow for breakup (1:2 year flood Q = 2200 $m^3$/sec).

As of April 5 - solid ice cover remained
- between March 26 - April 5 there was 16 hrs of thaw (0°c)

- heavy snowfall between March 28 and March 31 resulted in an additional 26.2 mm of precipitation

- snow on ground = 52 cm

- mitigative measures to induce thermal weakening of the ice cover were discussed with the City of Fort McMurray

April 8: - Daily monitoring commenced on W.S.C. gauging station for the Pembina River at Jarvie, Athabasca River at Windfall and Athabasca River at Athabasca. There is no telemark reporting daily for the Athabasca River at Fort McMurray, therefore, lead times of 7 days on the average between breakup of the Pembina River at Jarvie and the Athabasca River at Hondo and 2 days between the Athabasca River at Hondo and the Athabasca River at Athabasca (Andres -1981) were monitored closely to assist in predicting the breakup event at Fort McMurray (Photo #'s 3 & 4).

April 14: - There were open leads developing in the rapid sections.

- An additional 84 hrs of thaw (0°C) occurred since April 5 total = 124 hrs.

- There was 24 hrs of continuous thaw (0°c) between April 12-14

April 16 (Photos 3-17) - Aerial reconnaissance was made from the Athabasca - Pembina Confluence to Fort McMurray.

- open leads in the rapid sections were enlarging and there was only a slight breakup of the ice cover surrounding the leads.

April 19 - An additional 82 hrs of thaw (0°c) occurred since April total = 224 hrs.

- continuous thaw was recorded between 0700 hrs, April 17 to 0200 hrs, April 19.

- additional precipitation since April 15 = 7.5 mm. Total precipitation since November = 93% of the normal.

- snow on ground was reduced to 15 cm.

- aerial reconnaissance was planned for April 26 or sooner if the warming trend continued.

April 25: - Blasting materials were transported and available in Fort McMurray as of April 25, 1982. Blaster waiting in Peace River to be placed on stand-by in the event of a serious jam that could cause flooding to Fort McMurray.

- there was continuous melt since April 19.

- last report of snow on ground April 21, 6 cm, additional precipitation = nil.

- Athabasca River at Athabasca stage increased 1.2 m from April 19, 1982

- April 25, 1982.

- breakup for the Athabasca River at Athabasca occurred between 1530 - 1800 hrs on April 24, 1982.

## BREAKUP

(April 26 - Photos 19-34, 37, 38, 40)

On the morning of April 26, an aerial reconnaissance was made from Fort McMurray upstream to Grand Rapids. The toe of the main ice run had proceeded to Long Rapids by 0857 hrs (Photo 22). There was running ice from Long Rapids upstream past Grand Rapids and then as far upstream from Grand Rapids as could be observed from the air (Photo 19). At that time, from the area of the toe of the main ice run to a location described as the cabin site (Photos 26 & 27), which is downstream of Cascade Rapids, the channel was free of running ice (Photos 23 & 24). From the cabin site, (Photo 25), a consolidating weak ice cover extended to a point just upstream of Mountain Rapids. From upstream of Mountain Rapids, there was competent ice which extended downstream through Fort McMurray and past Tar Island.

The toe of the main ice run met the head of the consolidating ice at approximately 1200 hrs. At the cabin site there were signs that previous temporary jamming had occurred prior to April 26, (Temporary Jamming Location #1, Photos 25-27). Between 1200 and 1330 hrs temporary jamming was observed at Locations 2 & 3 before the impact of the main ice run pushed into the head of the competent ice immediately upstream of Mountain Rapids (refer to Figure 4-5 and Photos 28-35). Between 1330 and 1504 hrs another temporary jam developed through Mountain Rapids as a large solid ice sheet, which covered the entire width of the channel, moved and pushed its way through the rapids (Photos 28-29). Additional jamming was not observed but from measurements of the shear walls at Locations 4 & 5, it is estimated there was temporary jamming between 1504 and 1640 hrs (refer to Figure 6 and Photos 35-36).

At 1640 hrs (Photo 37) the running ice had reached the MacEwan Bridge piers. Additional jamming took place through the bridge and immediately upstream of the Clearwater Confluence for 3.5 hrs until it released and moved past the confluence at approximately 2030 hrs (Photo 41).

## JAMMING AND RELEASE DOWNSTREAM OF MacEWAN BRIDGE

(between 16:40 hrs and 20:30 hrs - April 26, 1982)

The maximum gauge height recorded at the MacEwan Bridge during breakup was 246.75 m G.S.C. (refer to Figure 8).

As previously mentioned, the moving ice reached the MacEwan Bridge at 1640 hrs and spent approximately 3.5 hrs consolidating and building head behind it. At 1700 hrs reverse flow was observed along the left bank of the Clearwater channel at Roche Islands. The Athabasca flow was entering the upstream side of the Clearwater channel while the Clearwater flow was still passing the downstream side.

Slight movement occurred in the main Athabasca channel and at 2000 hrs a spillover or release channel developed downstream of the MacEwan Bridge, directly opposite the Clearwater Confluence (refer to Figure 7 and Photo 40). At 2030 hrs movement commenced immediately downstream of the MacEwan Bridge. The first spill over channel became blocked with competent ice in the far left channel immediately downstream of the MacEwan Bridge.

Between 2030 and 2055 hrs the entire left side of the channel released with a flow velocity of approximately 3.5-4.5 m/sec. There were solid ice sheets tossed against one another, with water spouting and the flow turned a dark chocolate brown indicating the bed was eroding. The running ice proceeded downstream, and from the observed shear walls, evident in Photos 61-62, there could have been temporary jamming just upstream of Poplar Island sometime after 2055 hrs.

At 0800 hrs the next morning the stage had dropped approximately 1.5 m at the MacEwan Bridge. The Athabasca channel was open, but running ice was still present downstream to Tar Island and past the McKay Bridge. Competent ice remained in the Athabasca Channel at the Clearwater confluence. The flow from the Clearwater River continued to pass with only a slight increase in stage and no overbank flooding along the Clearwater channel was observed.

## CLEARWATER BREAKUP AND SUMMARY

(between April 27 & 29)

Monitoring of the Clearwater River was continued after the Athabasca breakup, because of the remaining competent Athabasca ice at the confluence. This ice did not move during the breakup and the ice cover on the Clearwater remained intact (Photos 51-53 & 55-56). Gauge readings for three established gauging sites on the Clearwater channel were collected by the City of Fort McMurray (Figures 10 - 11).

Based on historical data for the W.S.C. gauging station, Clearwater River at Draper (Sta. 07CD001), the Clearwater at that particular location normally breaks up on the same day as the Athabasca River.

On April 27, between 1500 and 1800 hrs, the stage on the Clearwater at the Waterways gauging station increased approximately 1.0 m. At that time, there was an additional accumulation of ice downstream from Waterways to the confluence, indicating that breakup had occurred somewhere in the Clearwater drainage basin upstream of Fort McMurray.

On April 28, an aerial reconnaissance was made of the Clearwater and it was observed that the Christina River had peaked. The Christina and the Clearwater channel downstream of the Christina confluence was free of a solid ice cover. Breakup of High Hill Creek, which is a tributary to the Clearwater River located upstream of the Clearwater - Christina confluence, assisted in consolidating the accumulated Clearwater ice against the competent Athabasca ice at the confluence. During the night of April 29, the consolidated Clearwater ice which had blocked the confluence, was released along the far right side of Roche Island resulting in an open channel and thereby reducing the danger of possible flooding.

## CONCLUSIONS AND DISCUSSIONS OF THE 1982 BREAKUP

The below normal temperatures and additional snowfall just prior to the normal time of breakup, combined with an above average snow pack in the upper Athabasca basin, created a concern for a potentially high and rapid runoff. As well, the slowly deteriorating strength and thickness of the ice cover, with the possibility of a sudden return to below normal temperatures, placed an additional concern towards having abnormal ice conditions. With these concerns, spring breakup on the Athabasca River near Fort McMurray was closely monitored.

In comparison to previous years, Fort McMurray experienced an uneventful breakup in 1982. A 5.25 m increase in stage resulted in a maximum gauge height of 246.75 m G.S.C. at the MacEwan Bridge. The maximum velocity, upon release of a temporary jam just downstream of the MacEwan Bridge, was estimated between 3.5 - 4.5 m/sec.

The fact that a stable jam did not occur upstream prior to the ice run reaching Fort McMurray, could have been the main reason for an uneventful breakup. Another reason could have been the temporary jamming that did occur between the MacEwan Bridge and the Clearwater confluence may have assisted in preventing a jam from occurring downstream of the Clearwater confluence.

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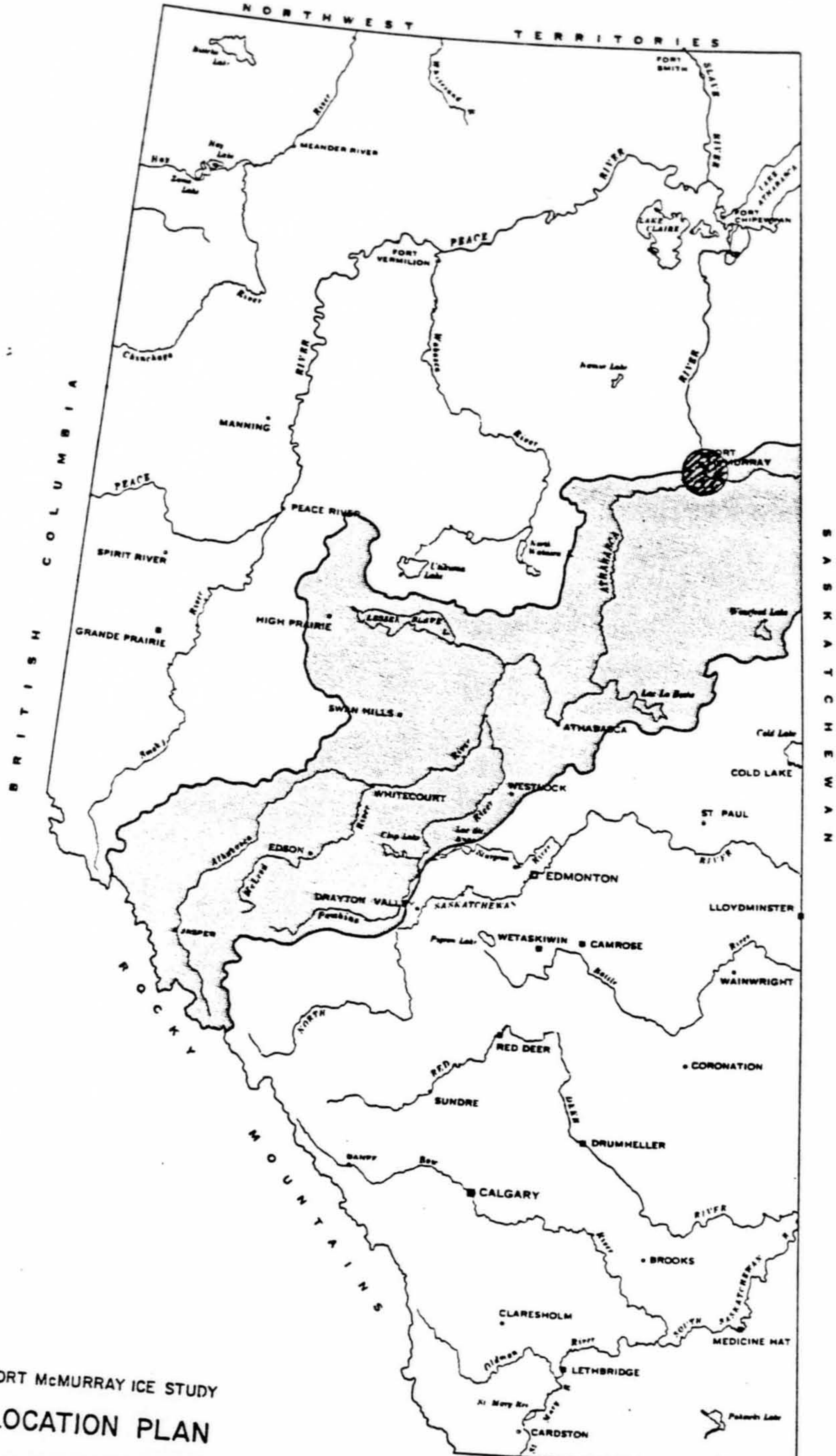
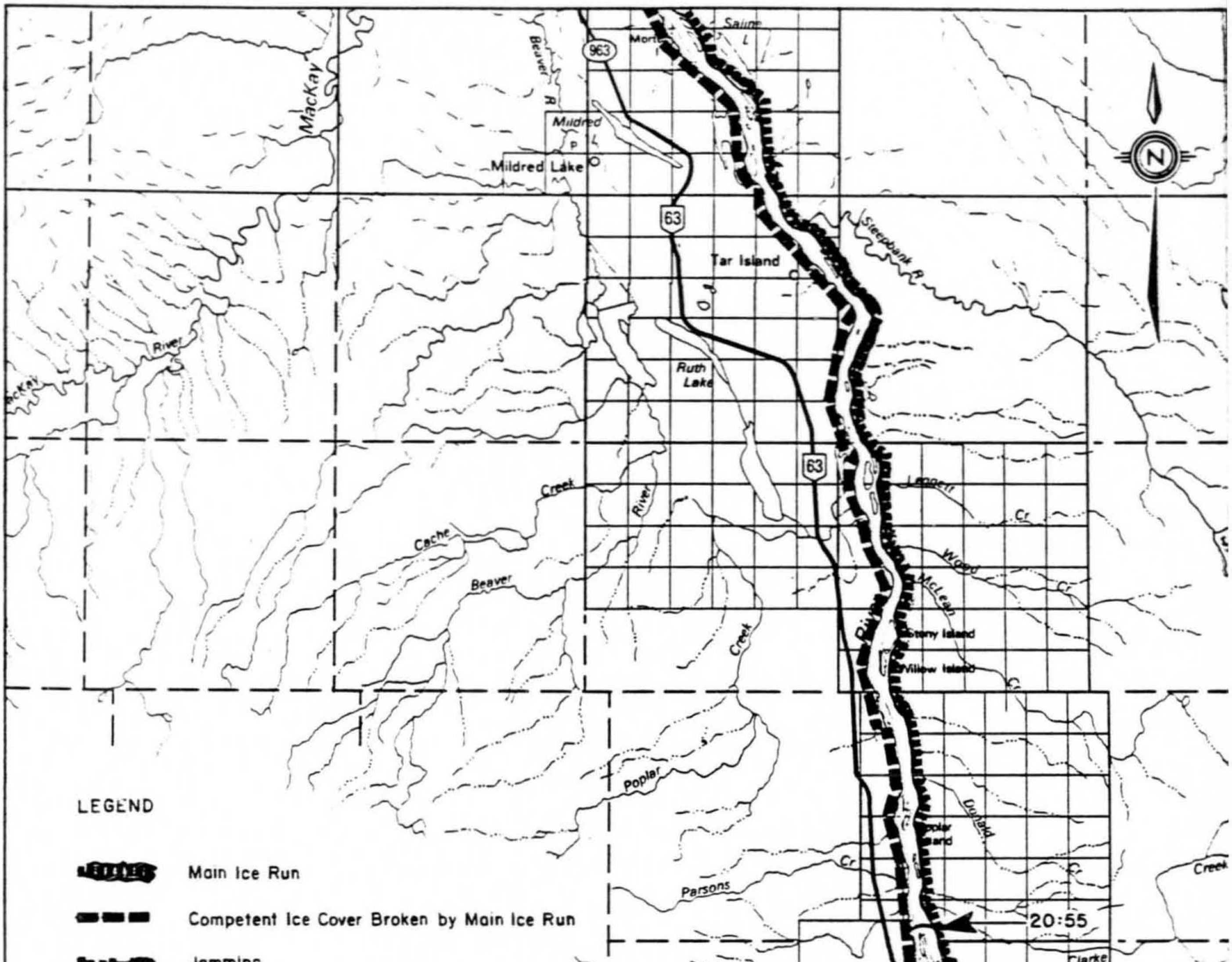



FORT McMURRAY ICE STUDY

# LOCATION PLAN

FIGURE 1




Alberta ENVIRONMENT

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FORT McMURRAY ICE STUDY

## ATHABASCA BREAK UP

APRIL 26, 1982

SCALE
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SHEET 6 OF 12
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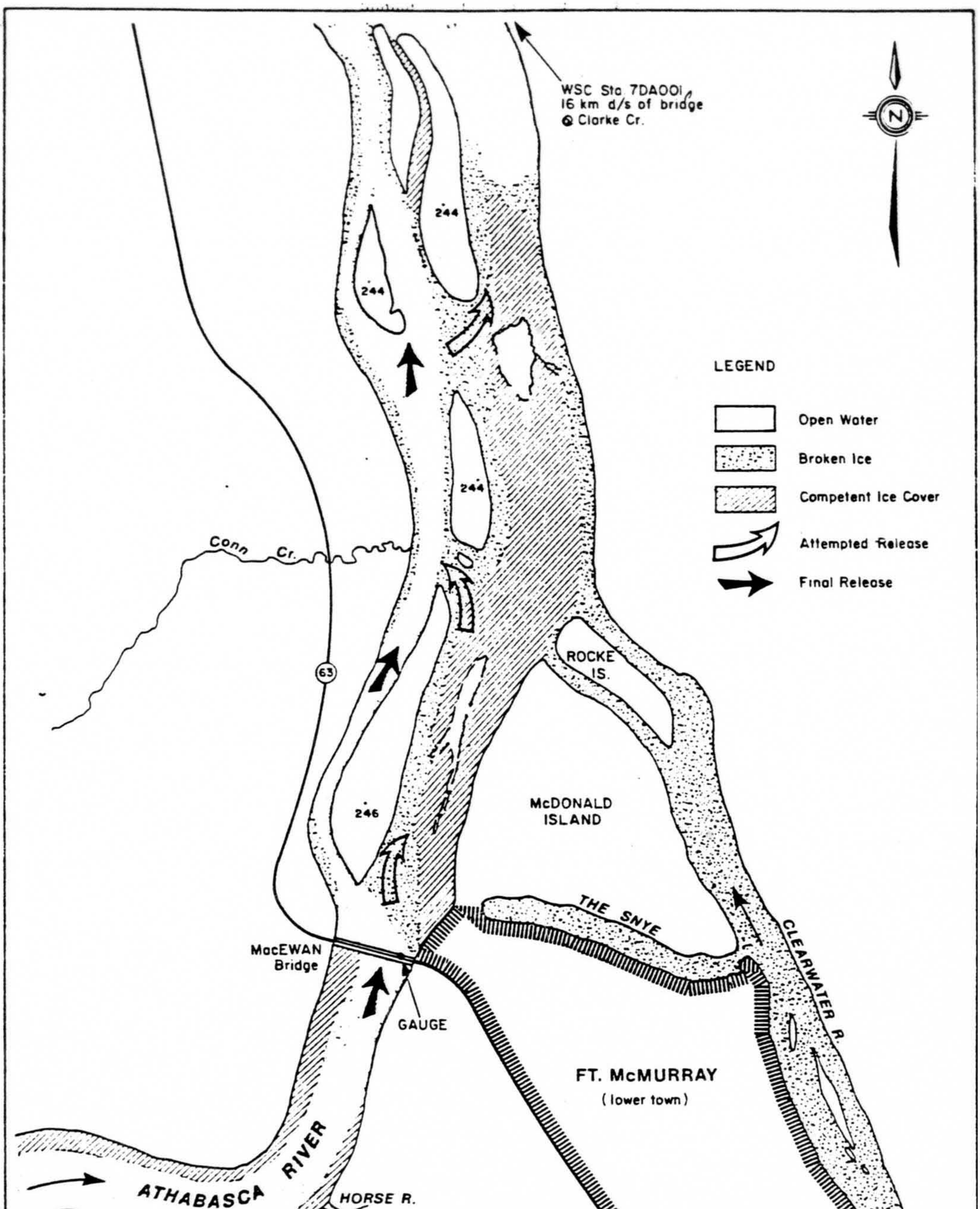


Alberta ENVIRONMENT

RIVER ENGINEERING BRANCH

FORT McMURRAY ICE STUDY

JAMMING & RELEASE DOWNSTREAM OF MacEWAN BRIDGE

APRIL 26, 1982

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**FIGURE No. 7**

Reference 12.

Manitoba Hydro
Lower Nelson River

Ref. 12

# EXPERIENCE WITH RIVER ICE AT THE LIMESTONE SITE

BY R. W. CARSON*

## 1. INTRODUCTION

Limestone Generating Station will be the fifth hydroelectric site to be developed by Manitoba Hydro on the Nelson River in Northern Manitoba. Its location is shown on Figure 1. It will have a head of approximately 29 m and ten units of 126 MW capacity each. First power is currently planned for the fall of 1988. The general arrangement of the completed structures is shown on Figure 2.

The sequence of construction activities and heights of cofferdams are governed by river ice conditions which are more severe than at any of the previously developed Nelson River sites.

This paper is intended to form an update of two previous papers[1,2] on the project, with concentration on the description of the ice conditions experienced since the construction of the first stage cofferdam.

## 2. NATURAL ICE CONDITIONS ON THE LOWER NELSON RIVER

As described in some detail in the previous papers[1,2], ice accumulation on the lower Nelson River is a process of ice jam progression upriver from the Nelson Estuary, fed by ice generated in the swift open river. Increases in water levels due to the ice accumulation are typically about 10 m, with some areas as much as 14 m above normal summer levels.

Before the construction of Kettle Generating Station, ice generating potential existed from Gull Lake to Hudson Bay, a distance of some 230 km. The production of enormous volumes of frazil ice from this open water area caused the ice jam to progress as much as 25 km upstream of the Kettle site by winter's end, or a total of some 175 km from Hudson Bay.

After the impoundment of Kettle Generating Station's forebay in 1970, a thermal ice cover was formed on the reservoir early every winter and thus eliminated this open water area from contributing ice to the lower reaches of the river. As a result, the ice jam progression slowed considerably and typically ended just downstream of the Long Spruce site (some 20 km downstream of Kettle Generating Station) in the years 1970 to 1977.

## 3. PLANNING OF RIVER ICE MANAGEMENT DURING CONSTRUCTION OF LIMESTONE

During the early planning stages of the Limestone development (1974 to 1976), construction of Long Spruce Generating Station was proceeding, but its reservoir had not yet been impounded. The future effect of the loss of ice generating area upstream of Long Spruce therefore had to be estimated. The most important question was whether or not the ice jam progression would be slowed so much as to prevent it from reaching the Limestone site. This would mean that the cofferdams for that project would only have to be

* Hydraulic Department Head, Crippen Acres Engineering, Winnipeg.

designed for open water levels (some 12 m lower than for ice conditions), and river diversion through a partly completed spillway or powerhouse would not have to cope with passage of large volumes of solid ice.

Early in the studies, engineering judgement based on approximate calculations of open water areas, ice generation rates, etc, indicated that year round open water conditions could not be expected at the Limestone site after the impoundment at Long Spruce. This was confirmed by the results of a detailed computer model which simulated

- the generation of ice as a function of open water areas and daily mean air temperatures during the winter

- the reduction of open water areas by border ice growth as a function of river velocity and degree-days of freezing

- the accumulation and stability of slush ice at the leading edge of the ice jam

- the submergence of ice at the leading edge if the approaching velocities are excessive, and the deposition of this ice downstream on the underside of the cover

- the shoving and thickening of the ice cover under the computed hydraulic forces exerted on it

- the backwater profile in the ice covered and the open reaches under study.

The decision was made that river diversion during construction must be devised to cope with very severe ice conditions. Detailed hydraulic model studies of the river ice conditions during the plant's construction were then undertaken at Lasalle Hydraulic Laboratory in Montreal.

Construction of the Stage 1 cofferdam which encloses the area of the concrete structures (see Figure 3) began in 1976, in preparation for completion of the first units in 1983. The construction proceeded over three summer seasons - the upstream leg in 1976, the river leg in 1977, and the downstream leg in 1978. The construction of the rest of the project has been shelved temporarily, due to the slower growth of demand for electricity than was experienced in the early to mid-1970's.

## 4. EXPERIENCE WITH THE RIVER ICE

### 1976 - 1977

In the first winter after the construction of the upstream leg, Long Spruce's reservoir had not been impounded. The ice front reached the Limestone site early in the winter and progressed upstream. Because the river flows varied widely on a daily basis, the ice front repeatedly progressed rapidly during times of low flows (early weekday mornings and weekends) and was shoved back when the river flow was later increased. On one occasion, the ice front was forced downstream to the Limestone site from 10 km upstream in a period of about three hours.

During this time, an estimated volume of 70 000 000 $m^3$ of ice passed through the 360 m wide diversion channel between the end of the cofferdam and the south river bank. Only minor damage due to ice gouging at the corner of the cofferdam was incurred. The resistance of the cofferdam to damage was attributed mainly to the surface freezing which had occurred prior to the arrival of the ice jam.

Later, the ice front resumed its upstream progression and eventually reached within 2 km of the Long Spruce cofferdam before the arrival of spring. The maximum water level recorded that winter at the Limestone cofferdam was el 70.5 m, which correlated well with the hydraulic model simulation of el 70.0 m, for comparable flow conditions.

In the spring, the ice behind the cofferdam became grounded as predicted by the hydraulic model studies, and there were large areas of stranded ice 5 to 10 m thick. Fortunately, the strong flow of water past the end of the upstream leg cleared the area where construction of the river leg was to resume, and work was able to start late in June.

1977 - 1978

In the fall of 1977, the Long Spruce reservoir was impounded, and as expected, the ice front progression in the ensuing winter was markedly slower than in previous years. The winter was very mild, and the ice front only reached the foot of the rapids below the Limestone cofferdam and did not progress through the diversion channel. The maximum water level was approximately el 65 m, or only about 5 m of staging above open water conditions.

In the spring of 1978, even though the ice did not reach its maximum potential thickness, considerable volumes were left stranded in the area where work was to resume on the downstream leg of the cofferdam. The ice delayed the resumption of work until early July. Fortunately, the construction schedule was reasonably flexible in that final year and the downstream leg was still completed before the onset of winter.

1978 - 1979

By 1978, the decision to postpone construction of the Limestone plant had been made by Manitoba Hydro, and the ensuing winter was the first of many through which the cofferdam was to remain.

During the construction of the cofferdam, the crest level was purposely chosen to be approximately 2 m lower than the maximum level indicated by the hydraulic model tests. The logic behind this was as follow:

- while the computer model indicated clearly that the ice could reach the Limestone site in mid- to late winter, there was still some uncertainty as to whether the ice front could progress upstream past the site the 10 km necessary to generate the maximum levels predicted by the model

- overtopping by a metre or so before construction of the plant began would not likely cause any significant damage

- topping up by 1 to 2 m could be done later prior to the start of construction if it was proven necessary. Thus, if it was not necessary, there would be some saving in cost of the cofferdam construction.

The winter of 1978-1979 was colder than normal, and the ice front progression more rapid than in the previous year. River flows were also quite high, averaging some 4,000 $m^3/s$ in late February. By early March, the leading edge of the ice cover had progressed some 8 to 10 km upstream of the site, and the resulting jamming of ice caused water levels to exceed the upstream crest of the cofferdam by about 1.6 m. The area inside the cofferdam rapidly filled with water, and eventually overtopped the downstream leg. Flow over the cofferdam continued for several days until the river level gradually subsided.

There was no significant damage done to the cofferdam during the overtopping. This good performance was attributed to

- the frozen surface of the cofferdam was resistant to erosion .

- the water initially flowed over the crest in a thin sheet and created a resistant coating of ice, over which the subsequent flow passed

The following spring, the area within the cofferdam was left to drain by natural seepage, and took until the following winter to recede to open water levels of the river.

1979 - 1980 and 1980 - 1981

Both these winters had above normal temperatures, and the ice front progression stopped downstream of the cofferdam, causing only minor increases in water level.

1981 - 1982

The winter of 1981 - 1982 was colder than the two previous years and the ice front progression followed that of 1979 very closely. River flows were somewhat less than 1979, and the peak water level was reached on March 9, about 0.1 m above the upstream crest. A thin sheet of water flowed over the upstream crest for several hours. The volume of the overflow was quite small and only caused the inside water level to increase by a fraction of a metre.

A graphical summary of the maximum water levels experienced at the cofferdam is shown on Figure 4.

## 5. SUMMARY

Mathematical and physical models were used to plan the concept of river ice management for the construction period of the Limestone plant. The predictions of both models relative to the first stage of river diversion have been verified by the observations of the river behaviour since the completion of the cofferdam. Topping up of the cofferdam by 2 m will be required before resumption of the plant construction, which may be as early as the summer of 1982.

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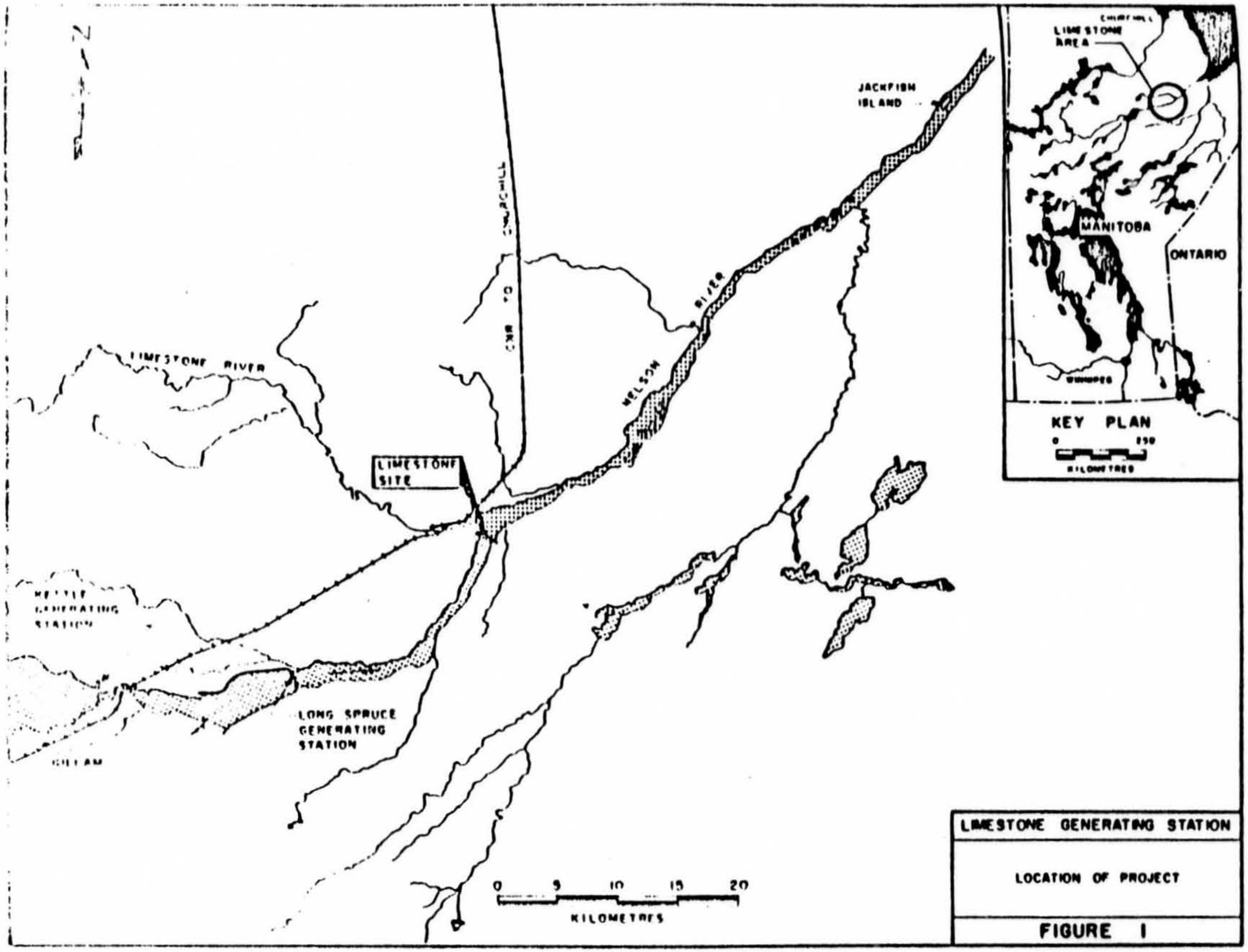
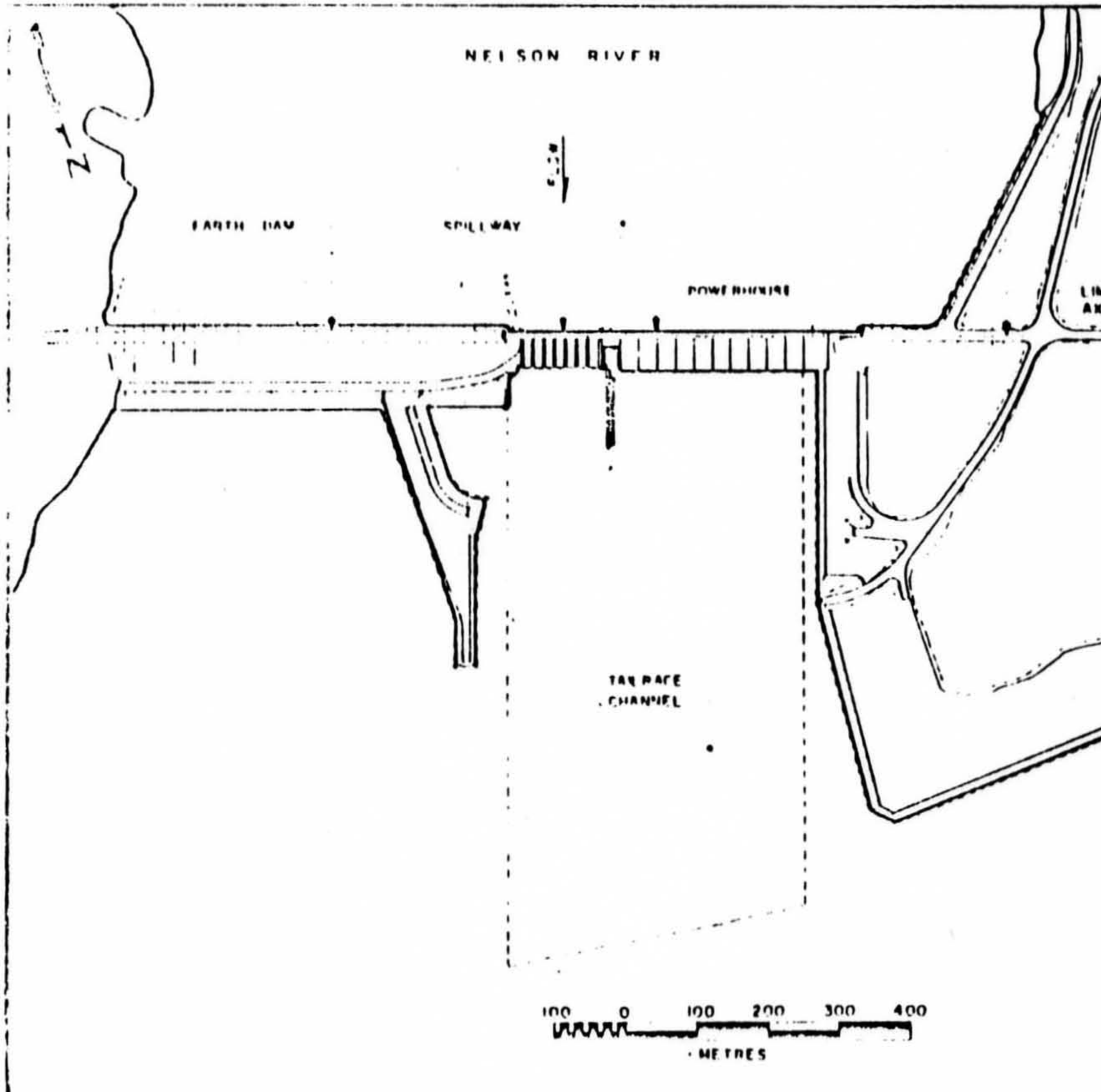



LIMESTONE GENERATING STATION

LOCATION OF PROJECT

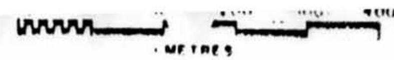
FIGURE 1




LIMESTONE GENERATING STATION

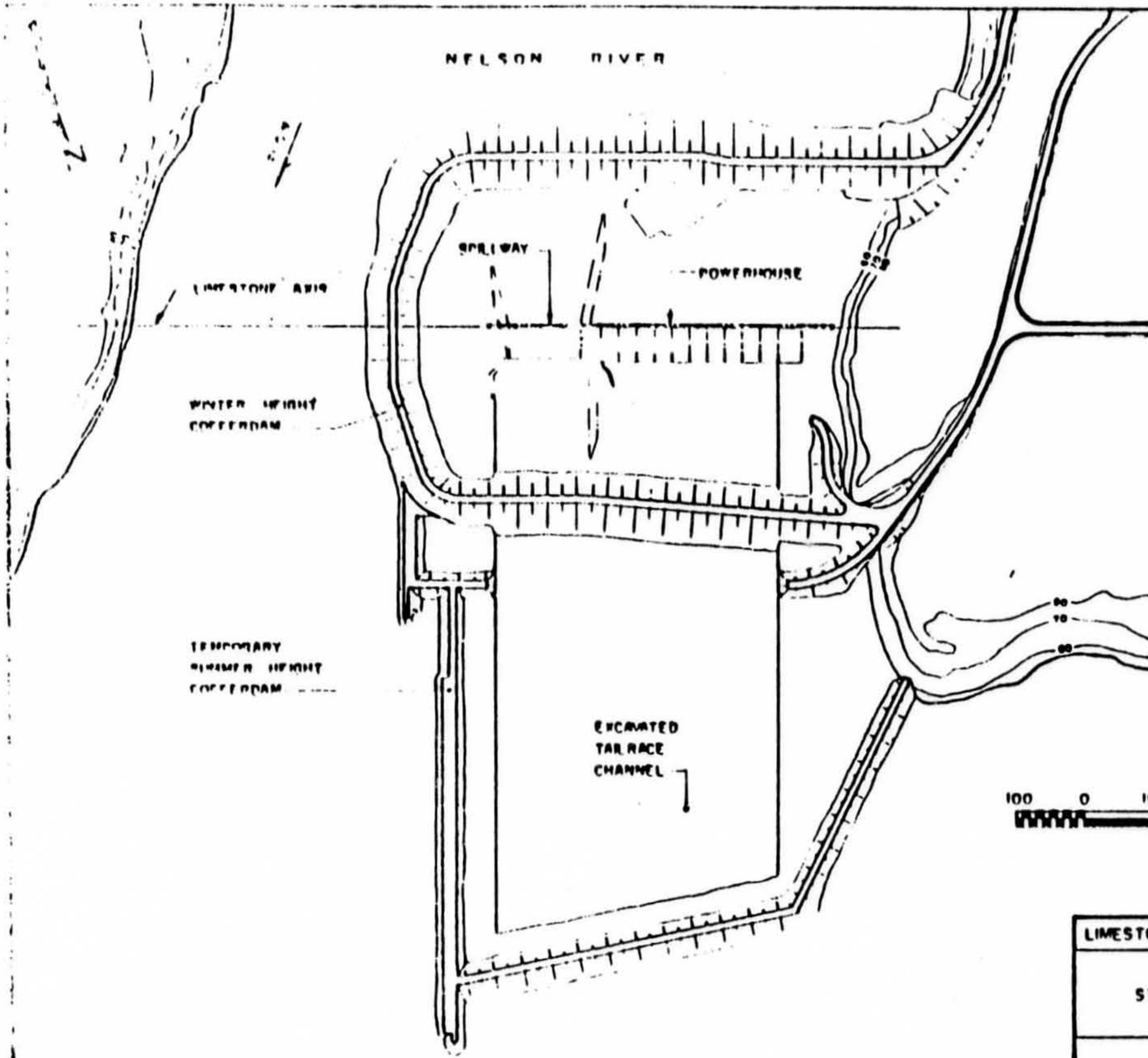
GENERAL ARRANGEMENT OF COMPLETED STRUCTURES

FIGURE 2




GENERAL ARRANGEMENT OF COMPLETED STRUCTURES

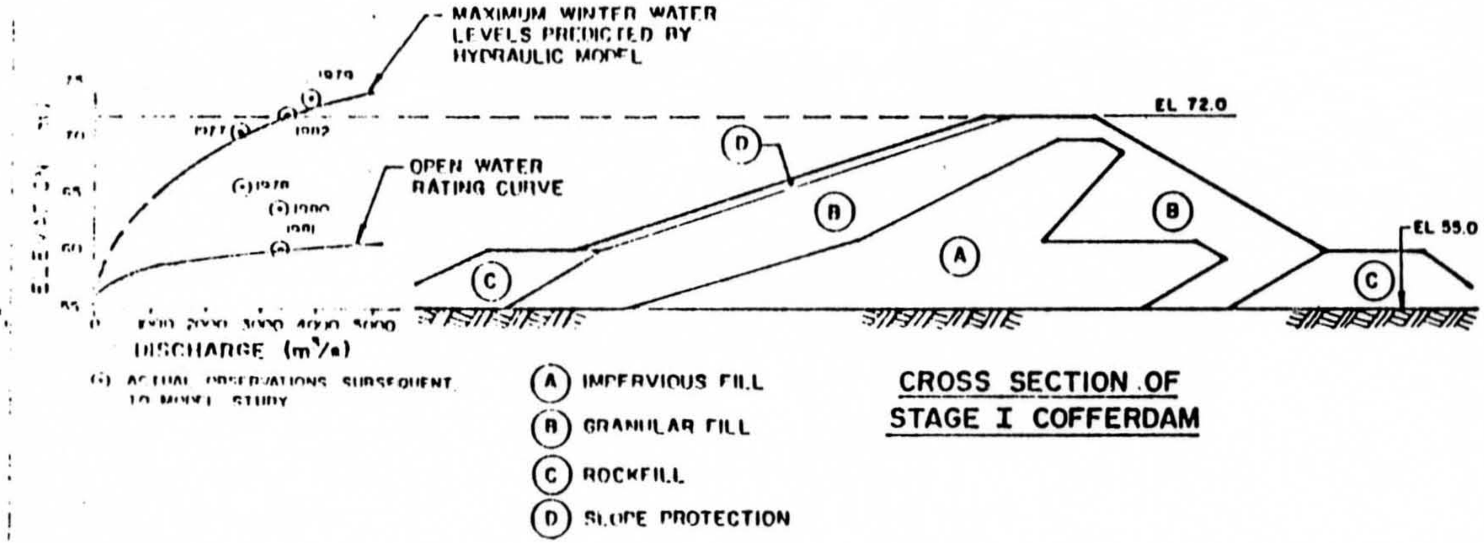
FIGURE 2




LIMESTONE GENERATING STATION

STAGE I DIVERSION

FIGURE 3




**CROSS SECTION OF STAGE I COFFERDAM**

LIMESTONE GENERATING STATION

RECORDED MAXIMUM WATER LEVELS 1976 TO 1982

FIGURE 4

## DISCUSSION

### S. Petryk, Rousseau, Sauve and Warren Inc.

The author has presented a very interesting and useful paper comparing computed and hydraulic model results with field data.

During the workshop presentation, it was mentioned that stable ice cover conditions were observed in the cofferdam opening even though the corresponding mean velocities were relatively high. Also the headlosses between the upstream and downstream sides of the cofferdam were generally higher than observed in the hydraulic model - probably due to the cohesiveness in the packed ice. It would be appreciated if the author would give a quantitative description of flow conditions in the opening when the headloss was a maximum between upstream and downstream of the cofferdam. Specifically what was the discharge, mean depth including ice cover in the opening, and the headloss between the upstream and downstream sides of the cofferdam?

### Reply by R. Carson

The maximum headloss between the upstream and downstream cofferdam legs (see Figure 3) occurred during the overtopping of the cofferdam in March 1979. The upstream water level was el 73.6 m, the downstream water level el 68.5 m, with a river flow estimated at 4,000 to 4,300 $m^3/s$. The riverbed elevation in the diversion channel around the cofferdam is approximately el 55.0 m, with very little variation either laterally or longitudinally. The mean depth including ice cover at the upstream corner of the cofferdam would therefore have been approximately 18.6 m, and at the downstream corner approximately 13.5 m.

### R. Gerard, University of Alberta

Is the ice accumulation thickness caused primarily by shoving or simple frazil accumulation from underneath?

### Reply by R. Carson

The mathematical model of the ice processes shows that with the strength parameters and n-values used, the final ice thickness is dominated in most of the river by shoves. Nevertheless, the simulations do show deposition of frazil ice which occurs at distinct constrictions in the river, and which triggers shoves further downstream because of the increasing hydraulic forces caused by the growing frazil deposits.

The observations of the physical model of the Limestone reach showed that there was significant shoving occurring, but that there was also movement of ice particles in the flow beneath the cover. It would be safe to say that while the shoving appears dominant, the two processes are inextricably linked in the formation of the ice cover on the Nelson River.

S. Beltaos, Canada Centre for Inland Waters

You mentioned that the ice Manning coefficient had to be increased with ice cover thickness in order to "match" the observations. Did you have observations on ice cover thickness as well as stage or simply stage?

Reply by R. Carson

The majority of the observations were stages at some 18 locations along a 120 km length of the lower Nelson River. However, in the winters when exploratory drilling of the foundations at potential dam sites were done, ice thicknesses were obtained at those sites. Unfortunately, measurement of an overall average ice thickness which could permit a rigorous comparison to the mathematical simulation could not be obtained because the location of the ice/water interface could not be distinctly discerned. Nevertheless, the rough estimates of ice thickness, based on these measurements did support the calculated values. For example, the calculated thickness at the Limestone site was about 9 m. The best interpretation of the drilling done by Manitoba Hydro in 1974 suggested a thickness of 7.5 m. This drilling was done in mid-winter at least six weeks after the ice cover formed. Considering the cover had consolidated to some extent and may have been eroded or smoothed somewhat from the flow beneath it, the comparison appears reasonable. In this area, the best estimate of n-value of the ice to match the observed stage was 0.09.

In the lower reaches of the river, where the slope is much less (0.0003 versus 0.0025 at Limestone) and velocities are lower, the observed stages were best simulated with an n-value of the ice at 0.015 to 0.025. Here, the simulated ice thickness was near 2 m, but no ice thickness measurements were made (no potential dam site). However, it was obvious from the appearance of the ice cover (relatively smooth surface, no large pressure ridges) that it was much thinner than in the steeper reaches upstream.

J. Cowley, Acres Consulting Services Ltd.

For comparison with the investigation described in the last paper (Gerard and Andres) can you mention what range of roughness values were successful in your mathematical modelling.

D. Andres, Alberta Research Council

Most models which attempt to predict the thickness of an accumulation, hence stage, require some knowledge of the roughness of the cover and the internal strength of the cover. Would you comment on the values of each of those parameters used in calibrating the model to match observed water levels.

Reply by R. Carson

The best calibration of the mathematical model was with n-values of ice as follows.

| | | | | |
|---|---|---|---|---|
| Reach 1 | km 0 to 12.5 | | 0.05 | local steep reach near estuary |
| Reach 2 | km 12.5 to 52.7 | | 0.015 | thinnest ice cover, mildest slope of the river |
| Reach 3 | km 52.7 to 60 | | 0.025 | |
| Reach 4 | km 60 to 71.7 | | 0.06 | |
| Reach 5 | km 71.7 to 120 | | 0.09 | thickest ice cover, steepest slope of the river, includes Limestone site |

With regards to ice strength, a Pariset and Hausser "$\mu$"-value of 1.5 was used, where

$\mu$ = $K_1 \cdot K_2 \tan \emptyset = 1.5$

$K_1$ = ratio of lateral stress in the ice cover to the streamwise stress

$\tan \emptyset$ = coefficient of friction of the ice

$K_1 \cdot \tan \emptyset$ = 0.18

$K_2$ = coefficient of internal strength of the ice cover (related to development of passive resistance of the fragmented ice mass)

In calculating the internal strength of the-ice cover the mathematical model uses

$$F_{ice} = K_2 \cdot \rho' \cdot \left(1 - \frac{\rho'}{\rho}\right) \frac{g t^2}{2} \cdot W$$

where $F_{ice}$ = maximum ice strength

$K_2$ = defined above

$\rho'$ = ice density

$\rho$ = water density ($\rho'/\rho$ = 0.92)

$g$ = acceleration of gravity

$t$ = ice thickness

$W$ = width of river at that location

Forces transferred to the banks are calculated from

$$F_{bank} = 2 \cdot f_L \cdot K_1 \cdot \tan \emptyset \cdot t \cdot D$$

where $F_{bank}$ = force transferred to the river banks over a distance D

$f_L$ = streamwise stress in ice cover

$K_1 \cdot \tan \emptyset$ = 0.18 (as defined above)

$t$ = ice thickness

$D$ = length of increment of river (in the model it is distance between cross sections)

The value for cohesion suggested by Pariset and Hausser in their [illegible] paper ([illegible] of river length) was used in the simulation, but because of the very thick ice cover, it has very little influence on the stability of the ice cover. The simulation is essentially 'cohesionless'.

D. Calkins, CRREL

Would you feel confident to apply the mathematical model to the next down-stream power plant without doing a physical model also?

Reply by R. Carson

No. While mathematical modelling of ice processes is steadily improving, I do not believe it is quite as good as physical modelling, which, when properly constructed, operated and interpreted, can address three dimensional flow characteristics. The enormous costs of construction of the large cofferdams and structures on the Nelson River gives an economic incentive to use all of the best techniques available.

# HANGING DAMS IN THE MANITOBA HYDRO SYSTEM

H.R. Hopper[1] and R.R. Raban[2]

## Abstract

The Manitoba Hydro system is primarily hydro-electric with its peak demand in the coldest part of the winter season. Unfortunately this time of the year is characterized by several hydraulically restrictive types of ice formation including static ice, juxtaposition ice covers, ice jams, and hanging dams.

This paper discusses hanging ice dams in the Manitoba System and the collection of data relevant to the analysis of their resistance to river flow.

A brief description is presented on ice cover development on the Lower Nelson River which is attained by the formation of ice jams and hanging dams.

An example is presented of successful measures taken to virtually eliminate hanging dam formation on a sensitive reach of the Burntwood River near Thompson, Manitoba, where the potential staging could not be tolerated.

A specific hanging dam in the Upper Nelson River and its effect on the river system is discussed.

A field program undertaken to define and monitor hanging dam formation is itemized. The methods of obtaining data, the equipment used, and the problems encountered are presented for discussion at the workshop.

[1] Manager, [illegible] Department, [illegible] Planning Division, Manitoba Hydro.

[2] Hydraulic Engineer, Special Studies Section, System Planning Division, Manitoba Hydro

## Introduction

The intent of this paper is to promote discussion on hanging ice dams and the collection of data which are relevant to the analysis of resistance to river flow.

Manitoba Hydro is monitoring and/or observing the process of freeze-up and break-up over a large river system which could serve as a prototype for the study of the resistance of ice to river flow.

The collection of field data is expensive, so it is essential that we obtain and/or develop efficient ways of collecting relevant data for the analysis and understanding of the various phenomena of ice formation and break-up.

We, at Manitoba Hydro, are not research scientists nor is the corporation structured for research. However, in our day-to-day operation we encounter ice problems and the better our understanding is, the more successful our operation becomes. Thus we invite suggestions on data collection and its interpretation, and are prepared to freely share for mutual benefit the results of our work.

In 1966 when the decision was made to proceed with the hydro-electric development of the Churchill Nelson river systems (Figure 1), we had some

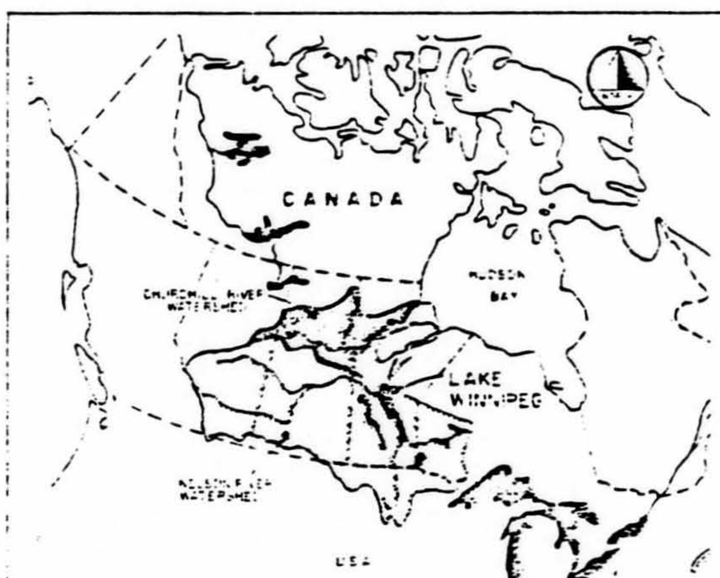



FIGURE 1 - NELSON AND CHURCHILL RIVER WATERSHEDS

appreciation of the potential problems that might result from ice formation and break-up but had not undertaken a comprehensive analysis of potential ice problems.

The concept of development visualized ten sites on the Nelson River and four sites along the Burntwood River plus the regulation of Lake Winnipeg and the diversion of a substantial flow from the Churchill River to the Nelson via the Rat-Burntwood river system. This development complex included many different ice regimes, each with unique problems.

Lower Nelson River

The Lower Nelson river contains a 140km reach that is an example of a wide (1 000m) relatively shallow river where frazil ice is generated along its entire length (Figure 2). Ice cover is attained by the formation of ice jams and hanging dams, their subsequent failure and reforming, with the river channel eventually becoming filled with ice accumulations 6m to 12m thick. There are four major power sites in this reach, two of which have been built and the cofferdam constructed for the third. River handling during construction of the Kettle Generating Station is described in a paper by Macdonald and Hopper[1]. Ice processes at the Limestone site are described in a paper by Simonsen and Carson[2].

Burntwood River

The Burntwood River is an example of a narrow river which experienced winter flows in the order of 20 - 34 $m^3/s$ prior to diversion and 950 $m^3/s$ after diversion. It was imperative that before diversion we gain some appreciation of the behavior of the waterway so that adequate mitigation measures could be taken.

Studies undertaken by Manitoba Hydro and consultants[1*] identified problem areas which are documented in unpublished reports. The most detailed study was that carried out by Crippen Acres Engineering for Manitoba Hydro and is described in a paper by Hopper, Simonsen and Poulier[3].

One of the areas of concern was the reach of the river flowing past the city of Thompson (Figure 3). It was predicted that a major hanging dam would form causing river stages that were entirely unacceptable. The measures taken to forego this potential danger include the construction of a control structure and the installation of an ice boom at Manasan Falls [illegible] upstream of Thompson. The structure consists of two rock and earthfill groins. Its purpose is to increase the upstream water level sufficiently to promote formation of a stable ice cover behind the upstream ice boom and thus eliminate the ice generating reach of open water (See Figure 4). A description of the design and construction of the control structure is contained in a paper prepared by Janzen and Kuluk[4].

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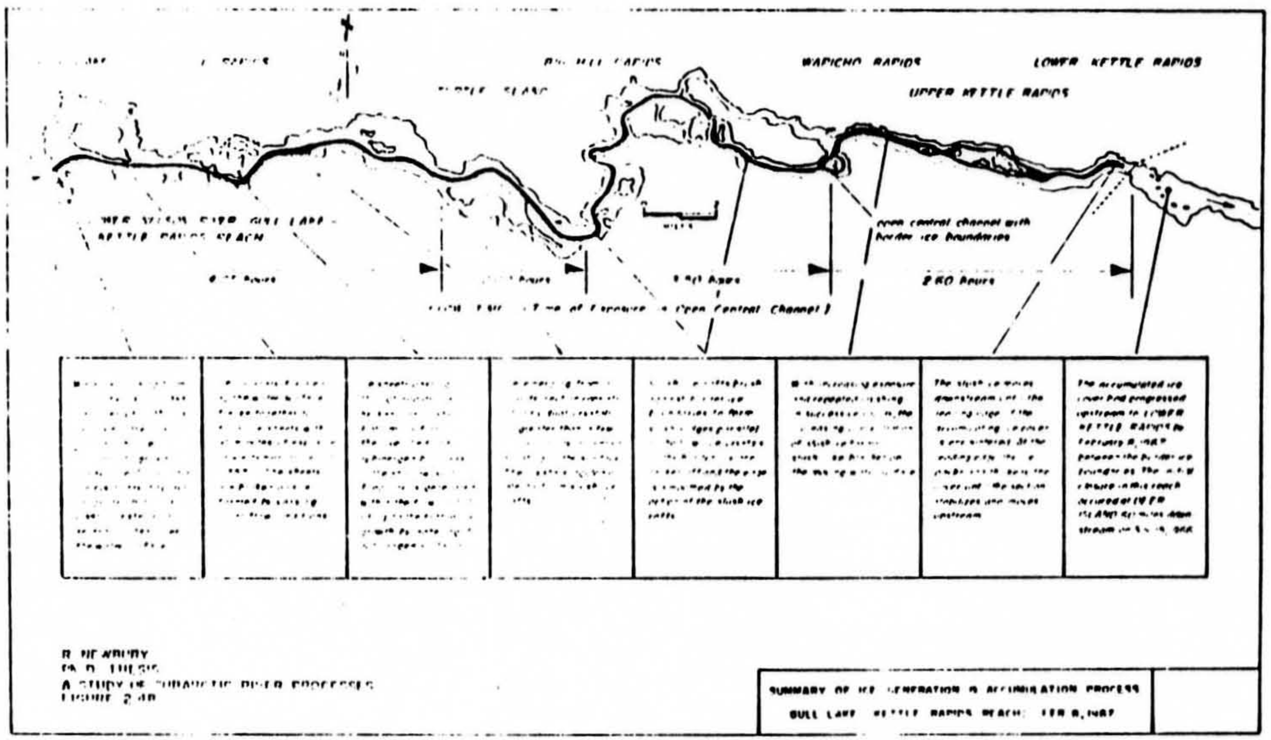
1* - [illegible] Underwood McLellan & Associates
- Crippen Acres Engineering
- LaSalle Hydraulic Laboratories
- [illegible]


WAPICHO RAPIDS
LOWER KETTLE RAPIDS
UPPER KETTLE RAPIDS
open central channel with
border ice boundaries
2.60 hours
SUMMARY OF ICE GENERATION & ACCUMULATION PROCESS

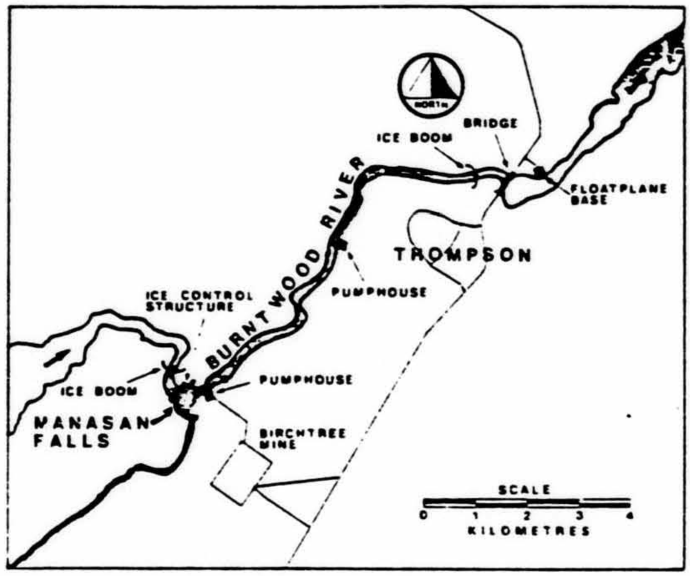



FIGURE 3 - MANASAN - THOMPSON REACH

Figures 5 and 6 compare the resulting water surface and ice profiles for the 1979-1980 winter season to those predicted, had preventative measures not been taken. The results to date have been totally successful with staging reduced by as much as eight metres from the most severe prediction.

Lake Winnipeg Regulation

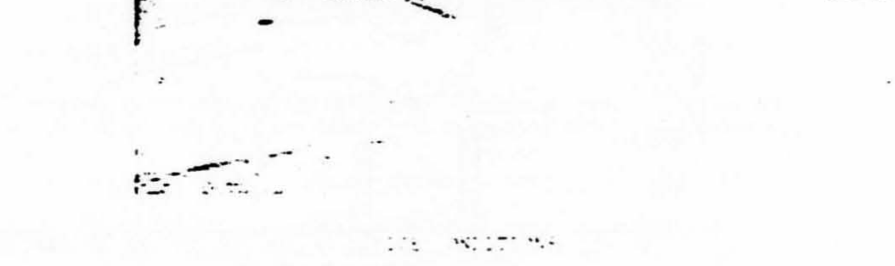
The Lake Winnipeg Regulation project provides a live storage reservoir of [illegible] m³ to serve a potential 8 000 MW of downstream development. Regulation is attained by a control structure at Jenpeg approximately 120km downstream of a natural lake outlet control at Warren Landing.

This reach of the river is characterized by a series of wide expanses and shallow lakes connected by narrows having rapids or swift flowing water (Figure [illegible]).

The concept of development added three diversion or bypass channels to the natural river system resulting in a complex hydraulic network. The analysis of its operating characteristics under ice conditions and the subsequent performance of this waterway is of prime importance to the operation of [illegible] hydro-electric system.

One of the areas of [illegible] concern is downstream of Whiskey Jack Narrows in the [illegible] channel and bypass channel.


OPEN WATER CONDITIONS




ICE CONDITIONS

FIGURE 4[illegible] MANSAN FALLS ICE CONTROL STRUCTURES

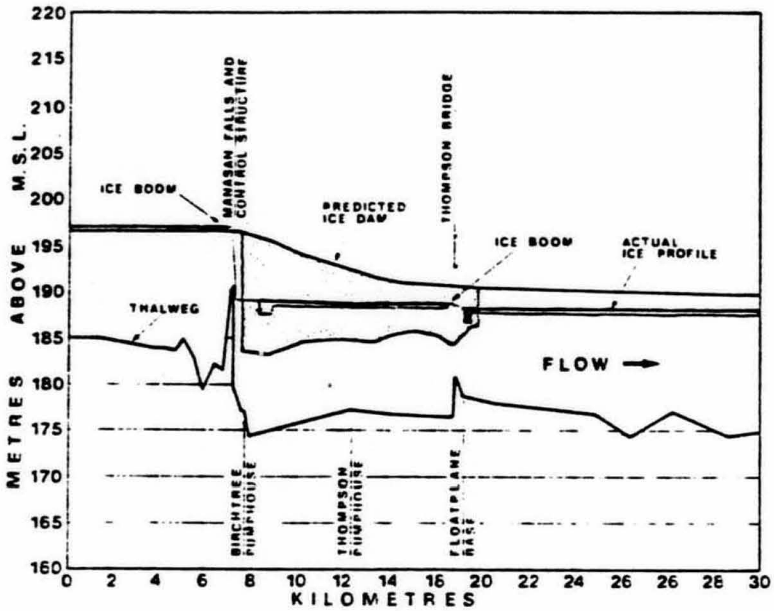



FIGURE 5 - ICE PROFILE 850 $m^3/s$ MANASAN - THOMPSON REACH

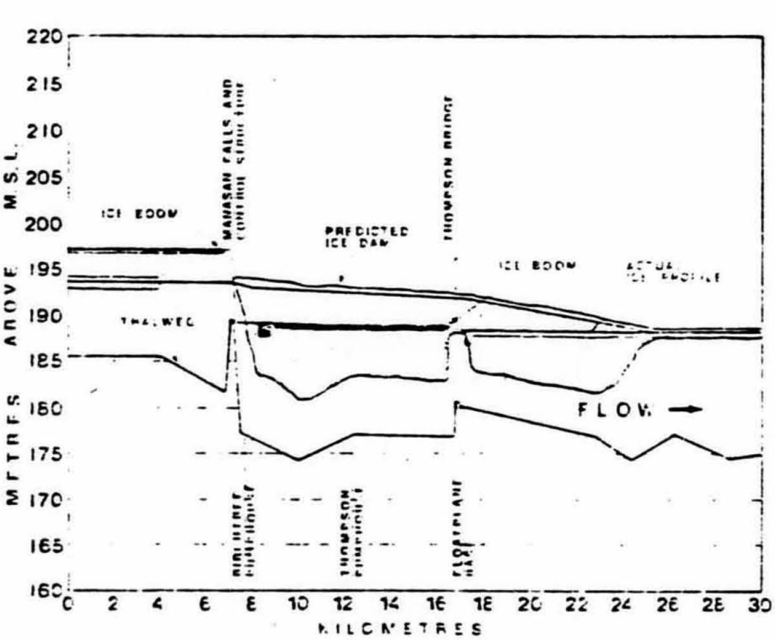



FIGURE [illegible] - ICE PROFILE 96[illegible] $m^3/s$ MANASAN - THOMPSON REACH

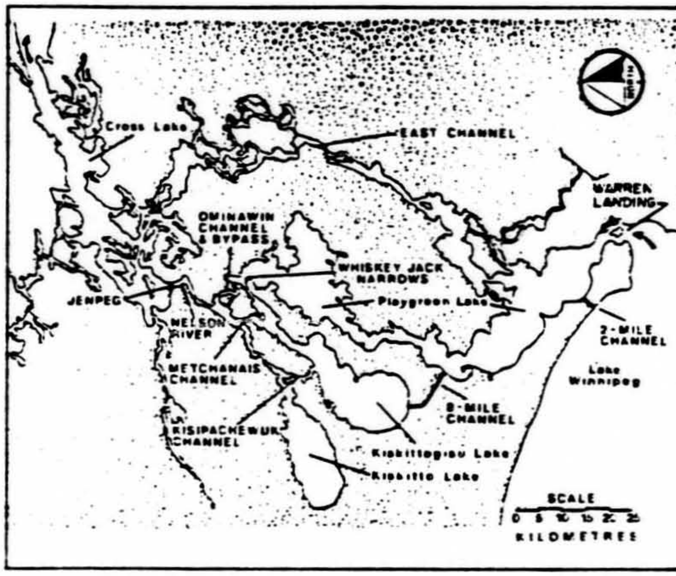



FIGURE 7 - LAKE WINNIPEG OUTLET LAKES

The Ominawin bypass channel was constructed to supplement the capacity of the Nelson River through the Kisipachewuk, Metchanais and natural Ominawin channels (Figures 7 & 8). Its incorporation into the system has resulted in a significant increase in flow and subsequent hanging dam formation in the upper Ominawin channel. Fortunately the resulting loss in Upper Ominawin capacity is partly compensated by the associated increase in flow through the Metchanais and Kisipachewuk channels.

Ice formation in the Ominawin reach has been extremely variable over the five year period of Lake Winnipeg regulation. A hanging dam forms each year; but its location and size changes each winter. A typical example, experienced during the 1979/1980 winter season is shown on Figure 9. It may become advantageous to incorporate ice control facilities or operating techniques to reduce hanging dam formation in this reach.

Monitoring Program

Manitoba Hydro has implemented the following field program for the purpose of defining hanging dams along the Churchill River Diversion route:

Data should be obtained at all apparent hanging dam locations.

Photographs should be taken of all interesting or unusual phenomena. Ice buildup and channel cross sections should be defined by obtaining the following measurements at three to six test holes along selected cross sections. Cross sections should be located based on judgement of field supervisor and office staff with an average spacing of 200m at any apparent constriction, and a minimum of two sections at any location being investigated.

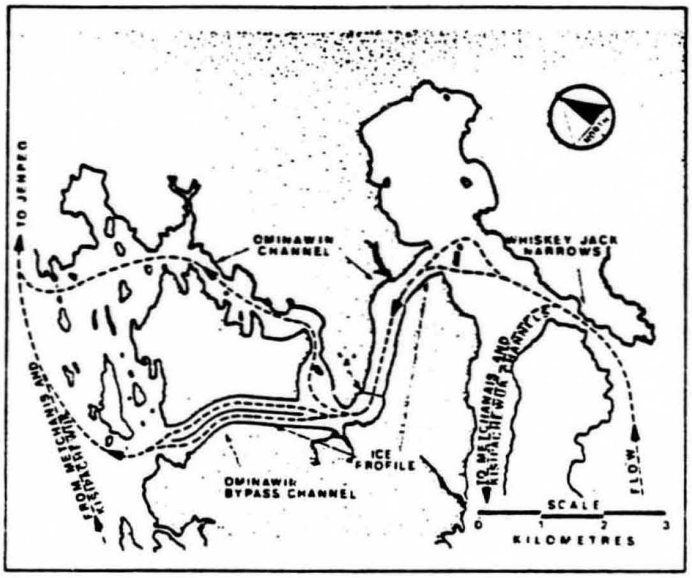



FIGURE 8 - OMINAWIN CHANNEL AND BYPASS CHANNEL

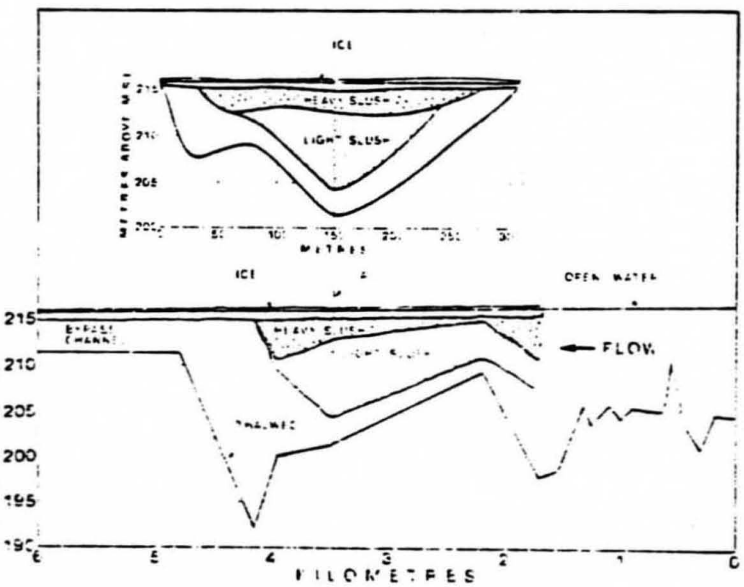



FIGURE 9 - HANGING ICE DAM UPPER OMINAWIN CHANNEL

The measurements required at each test hole are:

- Consolidated ice thickness,
- Heavy slush ice thickness,
- Light slush ice thickness,
- Snow cover thickness,
- Depth of water,
- Static water level and ice level,
- Water velocity profiles under the ice accumulation.

Water surface profiles are required from a point upstream to a point downstream of each apparent constriction. Measurements should be spaced at 150m to 500m intervals. Elevations should be taken at each of the selected ice survey sections.

Test sections should be accurately referenced to existing cross sections and gauges. Benchmarks should be established where profiles cannot be related to known gauges.

Monitoring Problems

We have not been able to obtain meaningful measurements of slush ice density and porosity. Success is limited mainly because of the difficulty in obtaining undisturbed samples. When a sample is extracted its properties change almost immediately in the characteristic sub-zero weather. Transferring to insulated containers further disturbs the samples and makes a realistic analysis difficult. Success in obtaining density and porosity measurements is further limited by the fact that only the top layer of the slush deposit can be sampled.

For practical reasons definition of ice density has been divided into the following three categories.

"Consolidated Ice" is identified as the solid surface layer, up to two metres thick, which must be penetrated with an ice auger. There is no free water in this layer. Usually this surface layer is rough and irregular with silt-like impurities that tend to dull auger blades.

"Heavy Slush" is usually found in a layer immediately under the consolidated surface ice. The thickness of this layer is measured by pounding through it with a special steel probe that has pointed ends with a loose bar of steel inside for impact (Figure 10). It is difficult to identify the lower boundary of the heavy slush but it is defined as the point at which the probe no longer has to be pounded through the accumulation.

"Light Slush" is defined as the layer through which the probe can pass without pounding. At times there can be a layer of light slush sandwiched between two layers of heavy slush but usually the light slush is deposited under the heavy slush layer. At times the light slush can be moving and it is suspected that there is considerable discharge through this layer.

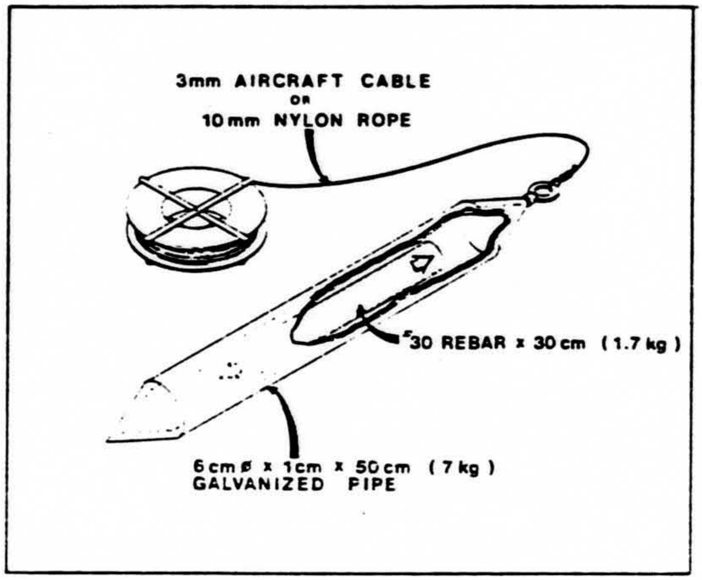



FIGURE 10 - PROBE FOR PENETRATING SLUSH ICE

There is often a problem retrieving the probe through the thicker deposits of ice because it tends to freeze in. In many cases the 3mm aircraft cable used to suspend the probe has failed in tension during retrieval attempts.

Snow cover thickness measurements are straight forward with only minor complications introduced by drifting and irregularity of the ice surface.

Water depths are obtained by lowering the probe to the channel bottom and sounding in the conventional manner. Fluid drag in fast water sections will tend to pull the weight downstream and will sometimes result in exaggerated depth measurements. Usually this is only a problem in narrow deep sections with large ice deposits, and high velocities. The free water depth under the ice deposit is sometimes difficult to define because the lower boundary of the light slush deposit is not easily identified.

Static water level and ice level measurements are straight forward to obtain except when there is built up pressure under the ice and a "blow out" condition exists. "Blow out" is the name given by field staff to the geyser that is sometimes encountered when the consolidated ice layer is penetrated. The water spout has been measured up to two metres in height and may take half an hour or more to subside. The associated problems are obvious especially in -30°C weather.

Velocity profiles under a hanging dam are obtained using a standard winter flow meter and a 'Slush-N-All' weight assembly (Figure 11). The weight is