Y-H.11

Environment Canada / Environnement Canada
Environmental Conservation / Conservation de l'environnement

YUKON RIVER FREEZE-UP AND BREAK-UP STUDY

YUKON RIVER BASIN STUDY

This project was completed for the Yukon River Basin Study, an intergovernmental study funded by the governments of Canada, Yukon and British Columbia.

YUKON RIVER BASIN STUDY
HYDROLOGY
REPORT NUMBER 4

JUNE, 1984

Inland Waters Directorate
Pacific and Yukon Region
Vancouver, B.C.

Yukon River Basin Committee

YUKON RIVER FREEZE-UP AND BREAK-UP STUDY

Synthesis prepared by

R. Gerard, PhD., P.Eng.
Department of Civil Engineering
University of Alberta
Edmonton, Alberta

for

Inland Waters Directorate
Environment Canada

Yukon River Basin Study
Hydrology Report Number 4

June 1984

This project was completed for the Yukon River Basin Study, an intergovernmental study funded by the Governments of Canada, Yukon and British Columbia.

This report was funded by the Yukon River Basin Committee under the terms of "An Agreement Respecting Studies and Planning of Water Resources in the Yukon River Basin" between Canada, British Columbia and Yukon. The views, conclusions and recommendations are those of the author and not necessarily those of the Yukon River Basin Committee, or the Governments of Canada, British Columbia and Yukon.

ABSTRACT

This report describes results of "Yukon River Freeze-up and Break-up Studies" carried out jointly by Canada, Yukon and British Columbia as part of the Yukon River Basin Study. The report discusses general characteristics of the Yukon River basin as they relate to the river ice regime, describes the salient ice processes characteristic of the area, reviews historical information on the ice regime and presents the findings of surveys that were undertaken during 1982 and 1983 to monitor the break-up and freeze-up conditions between Lake Laberge and the Yukon/Alaska border. It also discusses generally the effects on the ice regime that might occur as a result of future river regulation for hydro-electric generation purposes.

RESUME

Le rapport contient les résultats des études sur la prise en glace et la débâcle du fleuve Yukon, études entreprises conjointement par le Canada, le Yukon et la Colombie-Britannique dans le cadre de l'étude sur le bassin du fleuve Yukon. On y traite des caractéristiques générales du bassin du fleuve Yukon et de leurs relations avec son régime de glace; on y décrit les caractéristiques principales des glaces de cette région, et on passe en revue les données antérieures sur le régime de glace du Yukon; de plus, on y présente les résultats des travaux effectués en 1982 et en 1983 portant sur le monitorage de la prise en glace et de la débâcle du fleuve entre le lac Laberge et la frontière du Yukon et de l'Alaska. Le rapport traite enfin de façon générale des effets que pourrait avoir sur le régime des glaces le harnachement éventuel du fleuve pour fins de production d'électricité.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

TERMS OF REFERENCE

This report was commissioned as part of the Hydrology component of the Yukon River Basin Study. Its intent is to:

1. Summarize descriptions of the ice regime of the Yukon River between Carmacks and the U.S.-Canada border near Eagle, Alaska, contained in the following reports, notes and photographs:

   a. Reports on aerial reconnaissance (and associated photographs and maps) of freeze-up in 1982 and 1983 (Janowicz, 1983, 1984) and break-up in 1982 and 1983 (Kent, 1982, 1983) on the Yukon River below Lake Laberge.

   b. Report on Yukon River Basin Flood Risk Study (UMA, 1983).

   c. Report on Yukon Flood Study (FENCO, 1974).

   d. Report on Yukon River Ice Study (FENCO, 1976).

   e. Report on Dawson Flood Study, Ice Jam of May 3, 1979 and Break-up in 1980, 81 (Orecklin, 1981).

   f. Historical review of Dawson City Flood Data 1898-1975 (DCM, 1981).

   g. Report on Yukon River breakup at Dawson, 1982 and 1983 (Bigras and Anderson, 1984).

   h. Notes by:

      (i) R.O. Lyons: Break-up at Dawson, May 12-14, 1982.

      (ii) J.C.Y. Lee: Break-up at Dawson, May 12-14, 1982.

      (iii) S.C. Bigras: Pre-breakup ice survey along Yukon River from Lake Laberge to Dawson, April, 1983.

      (iv) R.O. Lyons: Freeze-up of the Yukon River, 1983.

      (v) R.O. Lyons: Discussion with M. Alford about past ice conditions on Yukon River.

2. Provide a preliminary interpretation of ice processes in the river and preliminary appraisal of the effects on these processes of large scale water storage developments on the river.

Further analysis of associated information, such as meteorological and hydrometric data, was excluded from the present task.

PREFACE

As mentioned in the Terms of Reference, this report has been prepared to provide a preliminary description of the ice regime of the Yukon River between Carmacks and the U.S. border, and a general appraisal of the likely influences of flow regulation on that regime and its significance in the area. In keeping with the preliminary nature of the report, and the related lack of accurate data, much of the quantitative information given in the report is based on approximations. While these approximations are judged adequate for the present purpose, they may not be for others, and hence should not be taken out of context. The major limitations are indicated in the report.

The report was prepared under the direction of Mr. R.O. Lyons, Water Planning and Management Branch, Inland Waters Directorate, Pacific and Yukon Region in Vancouver, whose assistance is gratefully acknowledged. Mr. T. Kent, Environmental Consultant to the Yukon River Basin Study, provided the break-up observations and was a gracious host when the writer participated briefly in his break-up observations in 1983. Mr. R. Janowicz, Hydrologist of Indian and Northern Affairs Canada in Whitehorse collated the preliminary meteorological data used in this report, provided a copy of the historical review of floods in Dawson and, through many phone conversations, provided details of the freeze-up observations as he made then in 1983, and other background items.

INTRODUCTION

In a northern river such as the Yukon, the ice cover formed each year is an integral and important component of the river regime. Such an ice cover may provide societal benefits such as a convenient access or transportation route in an otherwise undeveloped area. On the other hand an ice cover isolates aquatic flora and fauna from the beneficial effects of sunshine and oxygen repletion, and the periods of transition between open water and ice cover disrupt access and transportation, and bring the risk of sudden and severe flooding.

The portion of the Yukon River of interest herein is that which lies in Canada, and particularly that portion between Carmacks and the Canada-U.S. border. This upper Yukon River represents a largely untapped hydropower resource - some 5 GW - a resource made more than usually attractive for such a northern locale by its vicinity to the Pacific coast, and the large natural storage in the upper catchment. Possible dam sites for development of this potential include one on the Yukon River some distance upstream of Carmacks. If built to its full capacity, such a reservoir would have a significant influence on the ice regime of the Yukon River below the site, akin to that of the Bennett Dam on the Peace River ice regime in B.C. and Alberta. A preliminary evaluation of the influence on the Yukon River ice regime of such a reservoir is a major objective of this study.

GENERAL FEATURES OF YUKON RIVER BASIN

The Yukon River catchment upstream of Eagle, Alaska, the portion of the main stem in Canadian territory, covers some 294 000 km^2, and is oriented approximately southeast-northwest. It is bounded to the southwest by the Coast and St. Elias Mountains that lie along the Pacific coast, and to the northeast by the much lower Ogilvie and Selwyn Mountains that separate the Yukon River from the western portion of the Mackenzie River basin.

Although in close proximity to the ocean, the very high mountains along the coast largely isolate the upper Yukon basin from oceanic climate influences. As a result it generally has a continental climate with little precipitation and a high temperature range. Nevertheless some Pacific influences do penetrate through the passes in the mountains near the southern end of the basin and mitigate the continental effect somewhat as far north as the Teslin River confluence. Furthermore, the lower mountains to the northeast provide some protection from the extremely cold polar air from the north, but not sufficient to avoid the sometimes intensely cold spells in winter. The monthly mean daily temperatures fall below 0°C in October, reach a minimum of about -30°C in January, and return to near zero in April, giving a mean of some 3500°C days of frost.

Annual precipitation in the lowlands of the upper basin is about 300 mm, with a minimum in April of about 10 mm, and a maximum in July of some 50 mm. About 40% of the annual precipitation falls as snow.

Above the reach of interest the Yukon River and its tributaries drain some 82 000 km^2. The zone between the mountain ranges to the southwest and northeast is the Yukon Plateau. The Yukon valley was glaciated down to about Ft. Selkirk and as a result the surficial materials of the Yukon Plateau are glacial drift. This upland area of formerly mature eroded surface was later subjected to a regional uplift that rejuvenated the streams, which have since incised into the plateau.

An important hydrological feature of the upper Yukon is the unusually large degree of natural regulation of the discharge imposed by Lake Laberge and the several large lakes further upstream. However, there are no lakes downstream of Lake Laberge, and the river is variously confined by close encroachment of the hills of the Dawson Range and Ogilvie Mountains. This confinement is particularly strong below Dawson where the Yukon moves through the Ogilvies.

A longitudinal profile of the Yukon River below Lake Laberge is given in Figure 1. Below Five Finger and Rink Rapids it seems to be a well-developed profile surprisingly free of rapids. Also shown in Figure 1 are the contributions of the various tributaries to the mean annual flow in the river. These, particularly the Teslin, Pelly, White and Stewart, contribute much more to the flow in the Yukon at Dawson than the Yukon River itself above Lake Laberge.

Although not readily apparent from the profile, the geomorphic characteristics change considerably along the reach shown, as is evident from the insets in Figure 1. From Lake Laberge to the vicinity of Yukon Crossing, just downstream of the two sets of rapids, the Yukon is a relatively narrow meandering stream. Below Yukon Crossing it widens suddenly and substantially, meandering less but displaying frequent islands. Beyond the Pelly River confluence there are occasional deep narrow sections due to confinement by the Dawson Hills. With the presumably large sediment input from the braided White River, the Yukon widens more and is noticeably anastomose down to Dawson. Past Dawson stricture by the Ogilvie Mountains returns it to a narrow irregular planform. Beyond Fortymile it begins to leave the Ogilvies and starts to return to a wide meandering channel with frequent islands.

Of the tributaries the most significant in the present context are the Pelly and Stewart Rivers, which enter the Yukon on the right bank and drain from the southeast and east respectively, and the White River, which enters on the left bank and drains from the mountains in the southwest. In contrast to the White and upper Yukon, the Pelly and Stewart Rivers are 'normal' rivers, draining the boreal forest and tundra of the hills and mountains to the east, with a minimum of natural regulation by lakes or glaciers. These streams depend substantially on snowmelt for their flow. Their discharges increase in May, reach a maximum in June and then fall off in early July except for the short contributions of occasional heavy rain. Peak flows generally come early: at the beginning of June from snowmelt, or mid-June from rainfall during the snowmelt recession when the ground is still frozen.

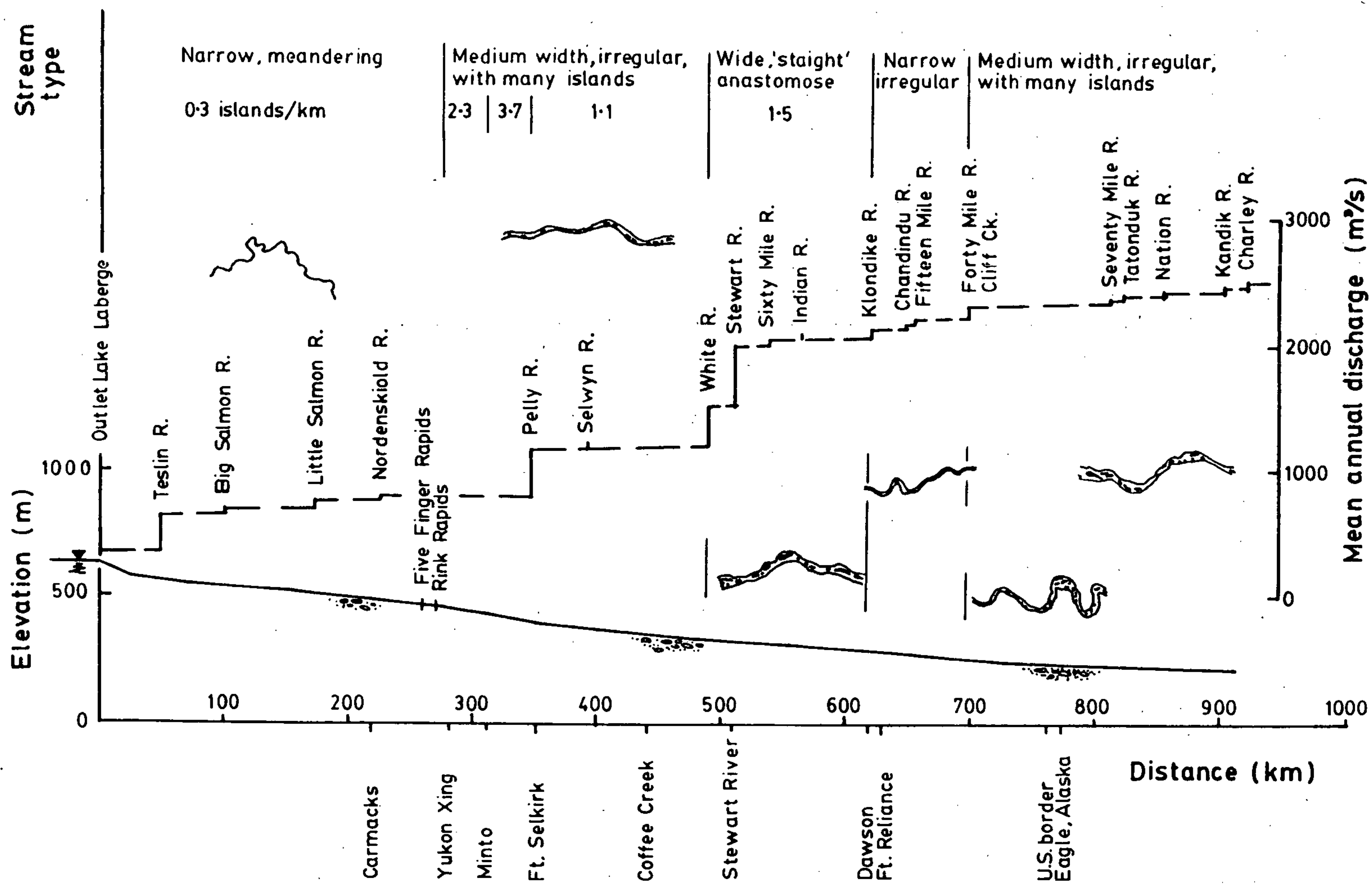

Figure 1. Longitudinal profile, mean flow and planform features of Yukon River, Lake Laberge, Yukon, to Charley River, Alaska.

The White River, on the other hand, drains from the high and glacier-covered St. Elias Mountains, and derives most of its flow from melting glaciers and ice fields. Although the somewhat irregular flow in this river is more or less evenly distributed over the warm weather period, it seems that the White River may contribute a sharp increase in flow in the spring that can be responsible for initiating break-up on the Yukon River below its confluence. The reason for this is difficult to discern at present, but may be due to the close proximity of much of its catchment to the maritime influence of the Pacific, with warmer temperatures and early spring rain.

The only significant towns along the reach of interest are Carmacks, Dawson and Eagle. Of these, by far the most important, and flood prone, is Dawson, situated at the confluence of the Klondike and Yukon Rivers. The Klondike Highway crosses the Yukon in two places: by a truss bridge, well above high water level, just upstream of Carmacks; and by ferry or ice bridge at Dawson, completing the Klondike Highway from Whitehorse to Tok, Alaska, via Dawson, known colloquially as the Top-of-the-World Highway. The portion of this highway west of Dawson is closed to general traffic in winter. It is not known to what extent the ice bridge at Dawson, and the ice cover in general in the reach of interest, is used for transportation and access in the winter. The proposed Dempster lateral of the Foothills pipeline would likely cross the Yukon at some point upstream of Carmacks.

Societal features sensitive to ice regime changes

A notable feature of the Yukon River ice regime below Carmacks is its propensity for causing severe floods at break-up and, sometimes apparently, at freeze-up (UMA, 1981). As described in more detail later, Dawson has sustained substantial damage from ice-related floods since its founding at the beginning of the century. Future floods will be even more damaging because of the strong historical significance of the town and the large sums being spent on restoration. Major ice jam floods are also frequent events at several other locations along the Yukon below Carmacks. The absence of significant settlement in these locations limits the societal significance of the jams, although a large ice jam near Coffee Creek was apparently responsible for abandonment of this settlement, and the abandoned village of Fortymile has been declared an historic site and is flood prone (FENCO, 1974).

There seems to be little information on the direct influence of an ice cover on the aquatic fauna of a water body. However, the influence of water temperature and dissolved oxygen has been well documented and found paramount. Hence, if in no other way, the formation and break-up of an ice cover has an ecological significance in that it represents the beginning and end of the 0°C and minimum dissolved oxygen regime in a reach.

As mentioned above, surface transportation across the Yukon River at Dawson is by ferry in summer and ice bridge in winter. Hence access ceases during freeze-up and break-up, as does general use of the river for transportation and access at other locations (e.g. Carmacks, Moosehide, Eagle etc.). None of the reports reviewed document the importance of such access but it is likely that, at least locally, it is politically important, if not financially.

A facility often sensitive to ice processes is a water intake. The major one in the reach of concern herein is that at Dawson. This intake is under the bed of the Klondike River near its mouth. There have been minor problems because of the propensity of the low flow channel of the Klondike to migrate in the vicinity of the confluence, and hence move away from the intake. Given the influence ice formation can have on such shallow channels this intake may be a concern, albeit a minor one,with regard to changes in the ice regime, and perhaps the morphology of the confluence, caused by flow regulation on the Yukon.

As stated earlier, the intent of this report is to describe the current ice regime of the Yukon River downstream of Carmacks, and to provide a preliminary assessment of flow regulation influence on these processes. As background for the subsequent discussion, it is worthwhile here to briefly review the general characteristics of the ice regime on a river such as the Yukon.

SALIENT RIVER ICE PROCESSES

The first requirement for ice formation is reduction of the river water temperature to 0°C. After the water temperature reaches 0°C, frazil ice -- small ice discs -- begins to form throughout the flow depth and gradually migrates to the surface to form frazil slush and, eventually, if the weather is cold enough, the familiar pan ice. Concurrent with frazil formation in the main body of the stream, border ice begins to grow on the surface in the shallow, quiet (non-turbulent) portions of the channel near the shore: as time goes on this is supplemented by trapped or attached frazil slush and pans, to form a gradually encroaching conglomerate of shorefast ice.

If the weather continues cold the concentration of pan ice gets higher and shorefast ice encroaches further into the flow. Because of the large changes in water surface width along a natural channel, there are usually several locations narrow enough that the pan ice must eventually be 'squeezed' through between the shorefast ice. Sooner or later the pans will lodge at one of these locations. The ice coming from upstream will then usually accumulate, forming the initial ice cover. Downstream of this lodgement the supply of pan ice is cut off. Freeze-up in this reach is therefore taken back a step, and frazil and pan ice production must begin again.

Time of freeze-over at a section depends on its location relative to these lodgement points, the time of lodgement, and the celerity of the accumulation front. A point a short distance upstream of a lodgement point will have freeze-over soon after lodgement occurs; a point downstream may not develop an ice cover for weeks, or even months, afterwards.

The cooling of the river, the production of frazil and pan ice, and the growth of shorefast ice, are all reasonably predictable. However, anticipation of the eventual lodgement points is difficult. Yet, without knowledge of these points, prediction of ice cover initiation and development is not possible. Hence the major task of freeze-up observations is identification of these lodgement points. Because it is likely they are sensitive to changes in flow regime, lodgement points represent the most unpredictable aspect of assessing the influence of flow regulation on freeze-up.

As the accumulation front moves back from the lodgement point, the thickness of the initial ice cover behind it will depend on the air temperature and the shear exerted on the accumulation by the flow. For air temperatures well below zero, and deep, low-velocity flow, the accumulation will be simply one layer thick, i.e. the pans will be juxtaposed. However, with air temperatures around 0°C and shallow, high-velocity flow, the accumulation may collapse and shove, forming an initial hummocked ice cover several layers thick. Because such a saturated ice accumulation will freeze faster than water, such hummocked ice formation can result in significantly thicker solid ice in late winter.

As the ice cover settles down during winter, holes left during accumulation progression may freeze over, but other holes may appear. This will be where, given time and sometimes high velocity flow underneath, even marginally-above-zero water melts through the initial accumulation and maintains open water. There is some evidence that such holes, or polynas, are favoured locations for overwintering fish.

Spring brings above-zero air temperatures, snow melt, ice cover deterioration, and the possibility of rain. Increasing discharge due to snowmelt or rain lifts the ice cover on the main channels and allows water to flood over the bottomfast ice along the shores and over the shoals and shallow backchannels, often giving a false impression of 'rotten' ice. (Ice cover deterioration is generally much slower than usually presumed, or suggested by the surface appearance of the ice.)

In rivers like the Yukon, break-up is usually caused by an ice run while much of the ice cover is still quite competent. Ice deteriorates and melts first in those areas that are shallow, were the last to freeze-over in the fall, or are subjected to above-zero water coming in from tributaries that are already open. Small accumulations of fragmented ice gradually form in these areas as warm weather progresses. The sudden readjustment of such an accumulation - perhaps due to the arrival of a large floe that has broken away from the cover upstream, for example - may cause a surge of water sufficient to move under, lift, break-up and move the downstream ice cover, which may feed or dampen the initial surge, depending on circumstances. Such relatively small actions can eventually lead to the formation and failure of an accumulation of fragmented ice -- an ice jam -- that releases a surge sufficiently large to trigger break-up and an ice run over a long reach. Observation of such releases, and the almost immediate massive disruption and fragmentation of thick, strong ice sheets, suggests that a capacity for generating large forces accompany these last, strong surges.

Like initial ice cover formation, then, break-up depends on minor idiosyncrasies of the reach. At present these can only be defined by direct observation. Furthermore, as for freeze-up, these are likely to be sensitive to flow regime changes.

HISTORICAL INFORMATION ON ICE REGIME

Because of the gold rush near the end of last century and the establishment of Dawson as a viable and lasting community, there has been much use of the river as a transportation route in winter and summer. There is therefore a large amount of information on the river ice regime contained in newspapers and other archival sources, and in the recollections of long-time residents. In connection with previous flood studies for Dawson a lot of information on break-up on the Yukon in the reach of interest has been culled from these sources.

BREAK-UP AT DAWSON, AND ICE JAMS UPSTREAM

Records kept in connection with the annual break-up lottery at Dawson, held by the Dawson Chapter of the IODE, give the break-up dates for each year since 1896. From this Orecklin (1981) determined the mean data of break-up to be May 10. The earliest date was April 18, and the latest May 27. Variation of break-up with the somewhat more meaningful parameter of degree days of thaw is shown in Figure 2. This is based on data given by FENCO (1974). The variation is somewhat erratic, but it seems break-up is most likely to occur after some 80-100°C days of thaw have accumulated.

The impression is given in earlier reports that break-up on the Klondike River is the 'trigger' for break-up on the Yukon River at Dawson. This seems to have been based on the fact that the Klondike River almost invariably breaks-up before and within days of the 'official' break-up time in Dawson. However, some further thought and a review of the descriptions of break-up at Dawson in past years (FENCO, 1974; DCM, 1981) suggests this is not so, particularly in years of significant flooding.

From Figure 1 it is evident the Klondike River is very small relative to the Yukon River at Dawson. Even when swollen by early spring melt, or by the very dynamic surges that seem to be released by failure of ice jams on the Klondike upstream of Dawson, flow from the Klondike is unlikely to have sufficient influence on the Yukon River to trigger break-up. This is supported by the fact that, although there is the odd year when clearing of the ice from the Klondike is closely followed by initial movement of the ice cover on the Yukon at Dawson, in most years this initial movement on the Yukon follows break-up on the Klondike by several days. The actual role of the Klondike River in break-up of the Yukon at Dawson seems to be a more indirect one: break-up on the Klondike, and the warmer water that follows, contributes to weakening the ice cover in front of Dawson, particularly bottomfast ice that likely exists on the bar at the mouth and along the right bank at Dawson.

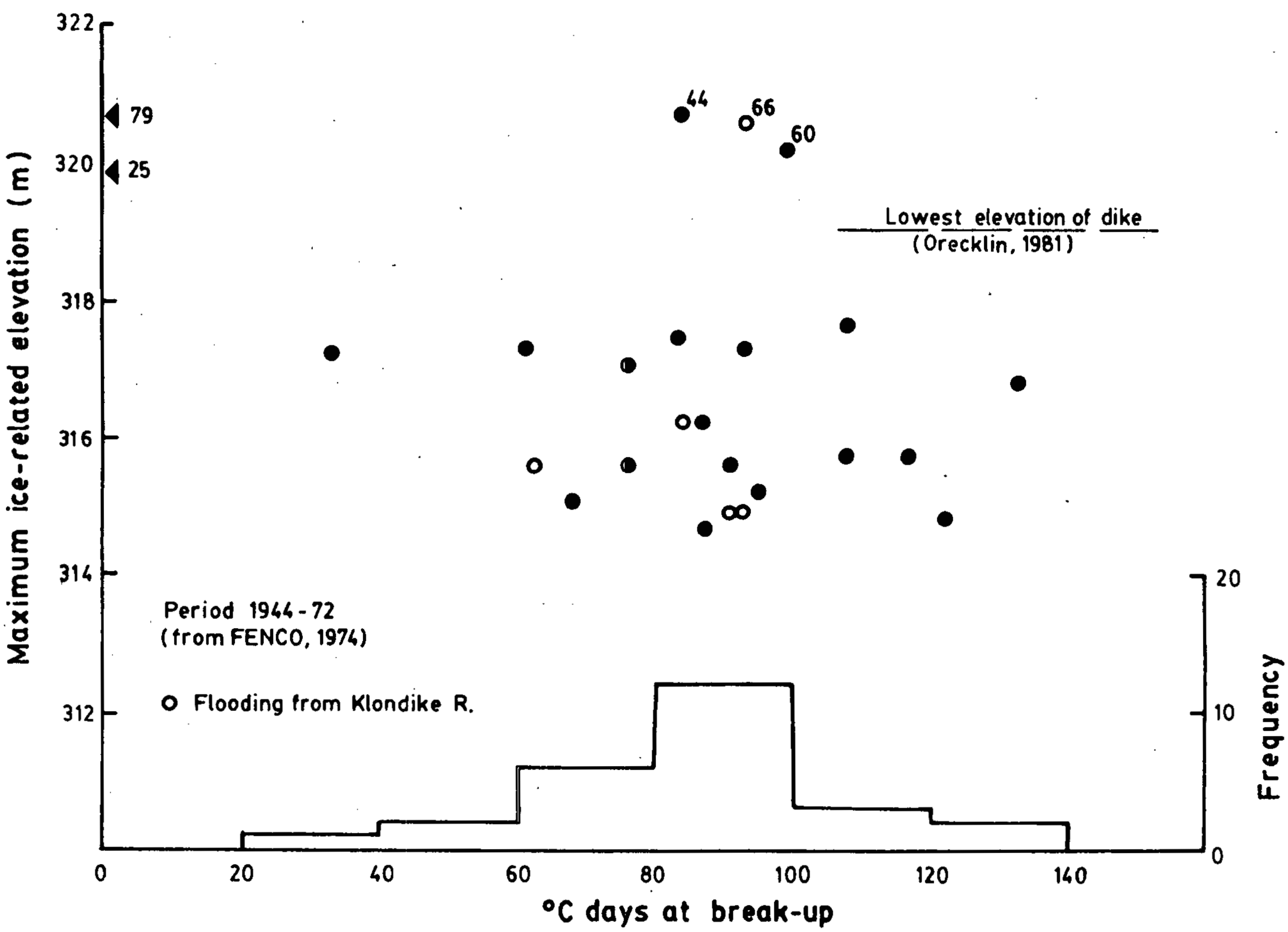

Figure 2: Time of break-up and maximum ice-related elevation, Yukon River at Dawson.

Another item raised in the past is the possible influence on break-up of the thick ice in the ice bridge constructed each year across the Yukon at Dawson. However, FENCO (1976) reports that, in at least the year they investigated it, this ice had melted in the spring to the extent that at break-up it was no thicker than the natural ice cover. Nevertheless, even if this wasn't so, a look at the ice bridge from the air indicates how small it is relative to the surrounding ice sheet, and how unlikely that it should offer any significant resistance to the massive disruptive forces that accompany the break-up and ice run, particularly the more severe ones.

It seems, therefore, that the real influences on break-up and ice jams at Dawson should be far more substantial than those of the Klondike break-up or the ice bridge. The following selection of quotations from the historical record indicate what these are:

1903, May 13 (Dawson Daily News) "The Yukon ice broke suddenly just above Klondike City. When the jam broke in the morning the water that had been held back by the ice came pouring downstream -- raising the ice opposite Dawson and breaking it into countless floes in a magnificant spectacle."

1932, (Dawson Daily News) "... at 3:25 [pm] a big ice jam came down... but stopped a few feet above the flag... Those watching saw the ice gather behind, heaving, tossing... [the flag lifted] amid the crunching, crumbling ice floes and then sailed serenely on its way -- a little white speck in the great moving ice-choked river"

and, as summarized by Orecklin (1981),
"The minute of break-up for the IODE lottery only implies that the ice at the break-up marker has moved. It is after this that the river ice from [the Yukon] above Dawson flows past the town."

From these examples and the remainder of the historical record it is clear the important cause of break-up and ice run at Dawson is the formation and failure of ice jams (break-up) in the Yukon River above the Klondike confluence. Indeed one major flood (that of 1960) seems to have been caused simply by the passage of the surge released by such a failure upstream, with little, if any, hesitation of the break-up front downstream of Dawson.

The most common locations for ice jams in the Yukon upstream of Dawson were given by UMA (1983), based on a review of archives in Whitehorse. Although not stated, the information in the archives is likely based on large ice debris accumulations observed by river pilots during travel along the river after break-up. The year and location of the jams noted are plotted in Figure 3. Of most significance with regard to break-up and flooding at Dawson are probably those near the Stewart and Sixtymile River confluences, one or other of which seems to form almost every year.

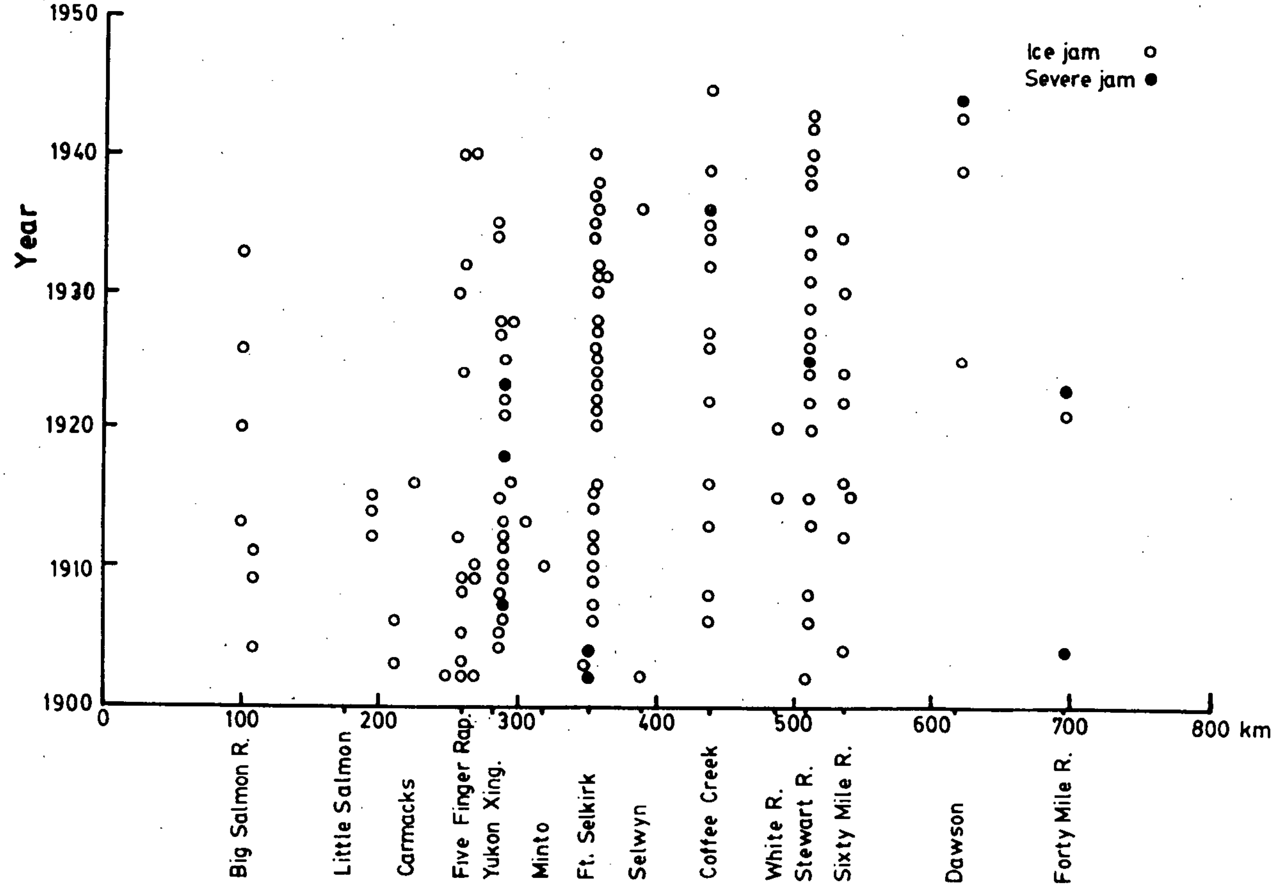

Figure 3: Past ice jam locations and frequency on Yukon River upstream of Dawson.

ICE JAMS AT DAWSON

From a variety of historical sources, FENCO (1974) prepared a quite extensive compilation of information on peak stages and the likely range of mean daily discharges during break-up at Dawson. These are shown graphically in Figures 4-6, together with stages given by Orecklin (1981) for the 1925 and 1979 ice-related floods.

FENCO (1974) provided a frequency analysis of this data. With the DCM (1981) review it is possible to extend the years of record back to 1898 and revise the ice-related frequency distribution. The ice-related flood sequence shown in Figure 4 suggests severe floods have been somewhat more frequent in the last 40 years. However, it is doubtful the apparent difference is significant and will be ignored in this reanalysis. The data also suggests that the higher stages may be from a different population from the remainder, and presumably the floods from the Klondike constitute a different population from those on the Yukon. However, in the following preliminary reanalysis these possibilities are also neglected. For the purpose of this preliminary study, the perception stage for the DCM review was selected as 317.3 m (the perception stage being that above which floods will not be forgotten by the residents, or will be noted in the archival record (see Gerard and Karpuk, 1979)). This assessment was based on the implicit definition in DCM (1981) of 'slight' flooding: a stage above the peak stage of the 1947 flood. This perception stage has also been used to include the years 1980-83 in the record as the peak ice-related stages for these years were not given in the relevant reports (Orecklin, 1981; Kent, 1982,83). Kent remarks that there was brief concern about flooding in 1982. The peak stage at break-up in 1983 was measured, but has yet to be reduced to geodetic. An effort to relate the qualitative remarks given in the DCM (1981) review to actual stage would allow a more detailed analysis of the pre-1944 stages to add to this more recent data.

The results of the revised stage-frequency analysis are given in Table 1 and plotted in Figure 5. From Figure 5 the 1:100 year ice-related stage is approximately 10.8 m, or 320.8 m geodetic. There is some indication that there is an upper limit to these ice-related stages at about this level. This may be due to relief provided by the flood plain near Dawson but, given the limited extent of this floodplain and the sometimes long duration of jams at the site, such a limit should not be assumed without further investigation.

Also shown in Figure 5 is the open-water stage frequency distribution, determined from the data given by FENCO (1974). From these two distributions the joint frequency distribution that gives the probability of a given stage being exceeded by either an open water or ice-related stage in a given year was calculated and is shown. It is apparent ice-related events dominate at the higher stages. The joint probability distribution indicates there is something more than an 80% chance the present lowest dike elevation will be exceeded in the next 10 years.

In Figure 6 the peak ice-related stages and the estimated concurrent mean daily discharges at Dawson given by FENCO (1974) are compared with

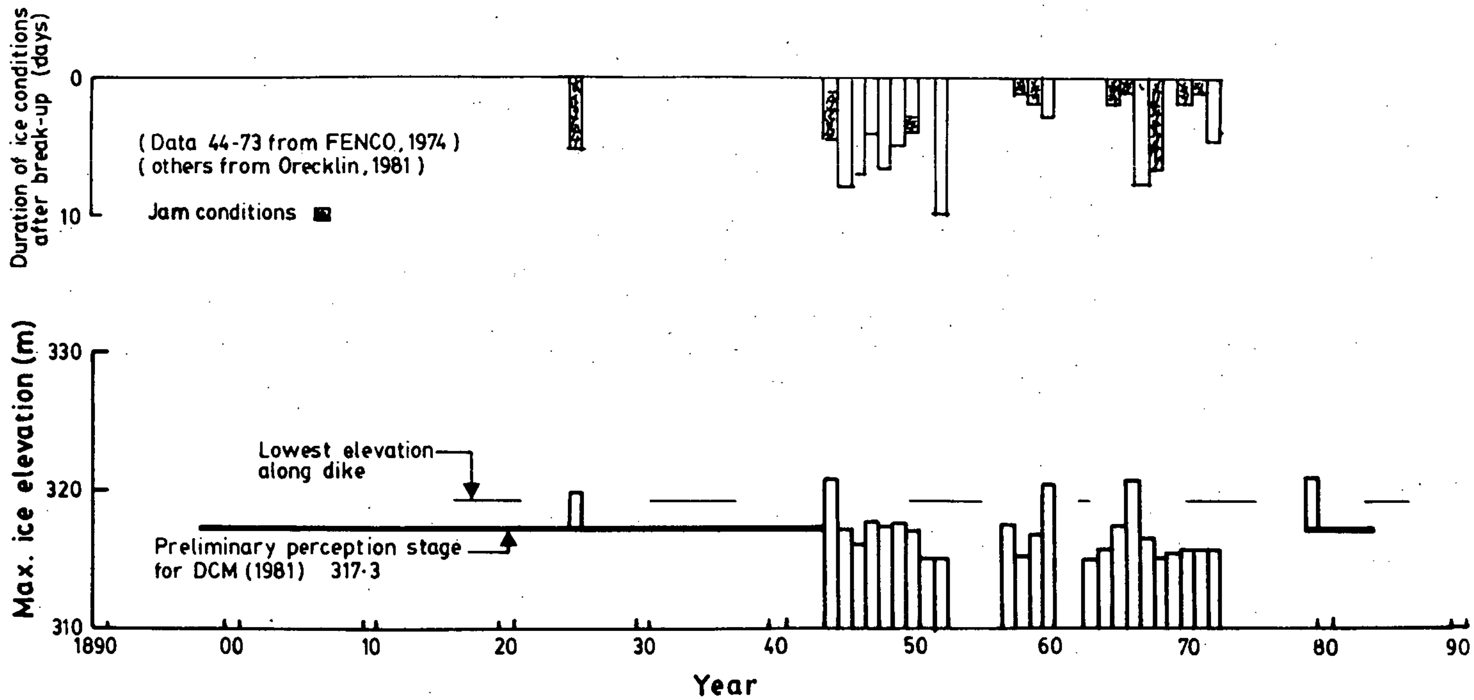

Figure 4. Chronology of maximum ice-related floods, Yukon River at Dawson.

TABLE 1: FREQUENCY ANALYSIS OF ICE-RELATED STAGES, YUKON RIVER AT DAWSON.

Year	Elevation (m)	Rank	Record length	Prob.* > (%)	Stage† (m)
1944	320.76	1	73	0.85	10.76
1966	320.61	2	73	2.21	10.61
1979	320.55	3	73	3.58	10.55
1960	320.25	4	73	4.94	10.25
1925	319.67	5	73	6.31	9.67
1947	317.64	6	73	7.67	7.64
1949	317.52	7	73	9.04	7.52
1957	317.30	8	73	10.4	7.30
1965	317.30	9	73	11.8	7.30
1948	317.29	8	23	32.8	7.29
1945	317.07	9	23	37.1	7.07
1950	316.80	10	23	41.4	6.80
1959	316.27	11	23	45.7	6.27
1967	316.22	12	23	50.0	6.22
1946	315.75	13	23	54.3	5.75
1964	315.71	14	23	58.6	5.71
1972	315.65	15	23	62.9	5.65
1971	315.62	16	23	67.2	5.62
1970	315.61	17	23	71.5	5.61
1969	315.22	18	23	75.8	5.22
1958	315.09	19	23	80.1	5.09
1963	314.94	20	23	84.4	4.94
1968	314.91	21	23	88.7	4.91
1951	314.81	22	23	93.0	4.81
1952	314.75	23	23	97.3	4.75

* Prob. $= \frac{m-0.38}{n+0.25}$

† Above open-water zero-discharge stage ≃ 310 m (extrapolated roughly from rating curve given by UMA (1983)).

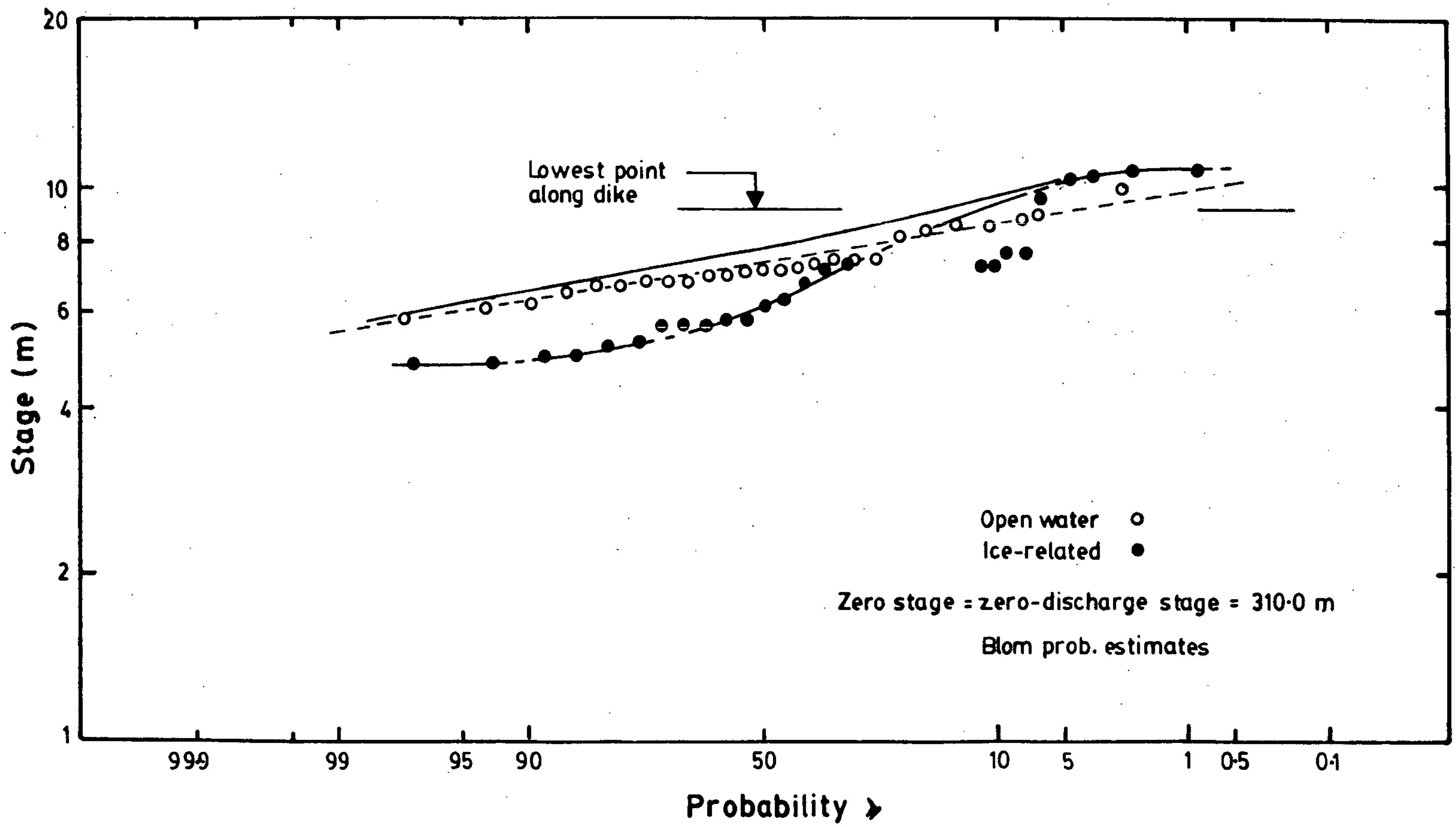

Figure 5. Stage-frequency distribution for ice-related and open water floods, Yukon River at Dawson.

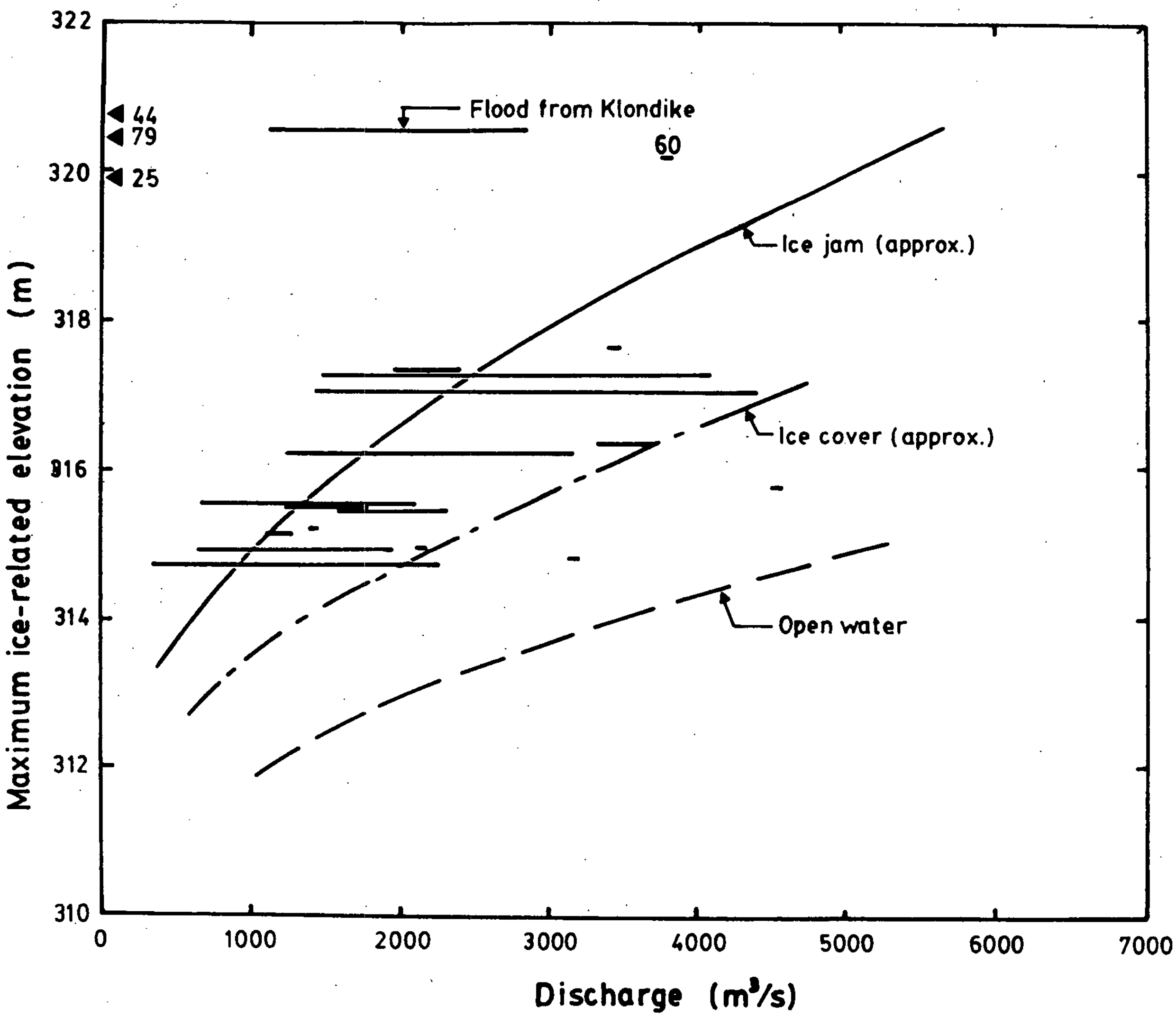

Figure 6: Comparison of observed and calculated ice-related stage-discharge relations.

estimated rating curves for solid ice cover and steady ice jam conditions. Because of the absence of hydraulic geometry data on the reach at Dawson these rating curves are very approximate, but should be adequate for the present purpose. Their derivation is described in Appendix 4. From Figure 6 it is evident the synthetic ice jam rating curve seems to provide a reasonable upper bound for the peak ice-related stage for all except the years of the worst floods (assuming the discharges at break-up in those years were not abnormally high). A review of descriptions of these floods suggests why:

1925 (DCM, 1981) "The Yukon River ice broke in front of Dawson City at 8:15 a.m. Saturday, May 9th... Fifteen minutes later it jammed near St. Mary's hospital and backed up as far as Church Street. The jam broke by 10:30 and the ice moved out." Six days later "The worst flood ever known in the Yukon began here, this Thursday [May 14] morning at about six o'clock, and the south end of the city is now under water to a depth of four or five feet."

"Thursday's flood was at its height about 4 o'clock in the afternoon. But the most damage had been done earlier, when the Yukon was running bank full of ice."

"The Yukon River was running bank full of ice and the water was rising so quickly that it soon overtopped the river bank and flooded the southend..."

1944 (DCM,1981) "The Yukon River ice... went out on May 5th at 1:27 p.m. and almost immediately Dawson had a flood." "... it was evident on Tuesday [May 9] that the crisis was far from over. All that day water kept undulating back and forth... around five o'clock Tuesday afternoon the main Yukon was fairly clear... About an hour and a half later, however, a terrific ice jam... started surging past Dawson, and the water began rising quickly..." "[Peak reached about 11 p.m.] when the high water began to drop even more quickly than it had come up...".

1960 (DCM,1981) "May 5th ... the Yukon rose and rose until at 12:00 noon it was running full of ice, bank to bank for six hours."

1966 From FENCO (1974): "Ice jam on Klondike. Flash flood without warning ... Ice and water poured over the dike along First Street." [The record, or lack of it, suggests the Yukon break-up was uneventful.]

1979 From Orecklin (1981): "At 9:40 p.m. [May 2] heavy ice began to move past Dawson, as an upstream jam

> broke. This overtopped the dike at its lowest point by 0.3 m... However, the water level soon receded and the ice flow became more heavy...
>
> At 12:15 a.m. May 3, an ice jam formed someplace below the city and the water level rapidly increased.At its maximum rate the water level rose a meter in as little as 3 or 4 minutes. By 1:20 the entire dike had water spilling over it...
>
> Apparently water overtopped the dike until 2:15 a.m. and a second jam occurred between 2:45 and 3:30.
>
> By 4:00 a.m. the water had receded..."

The 1966 flood was, therefore, not caused by ice action on the Yukon. The other four floods were all associated with a surge passing the town; that is, the situation was markedly unsteady, so that the steady-state assumption underlying the analysis that gave the ice jam rating curve in Figure 6 would be invalid. It is likely significant that most of the events that gave stages less than this rating curve were associated with ice jams downstream that stayed in place for a day or more, and hence would more closely approximate a steady state.

It therefore seems the major ice-related stages at Dawson are associated with very unsteady flow. Hence, to analytically establish an upper bound on ice jam stages at Dawson a much more elaborate unsteady flow analysis would be required, together with some plausible estimates of likely ice jam characteristics in the reach upstream of Dawson. Such an analysis is possible and may be justified for a detailed flood study for Dawson, but it is well beyond the objectives of this report.

ICE REGIME RECONNAISSANCE, CARMACKS TO U.S. BORDER

Although considerable information on break-up along this reach is available in the historical record, the information is largely site-specific. Furthermore, it is unlikely much would be found in the historical record about the manner and progression of freeze-up along the reach. Hence, to collect information on the freeze-up process, and to supplement the historical information on break-up, reconnaissance aerial observations of freeze-up and break-up along the reach were carried out over two years. For freeze-up the primary intent of the program was to determine:

(a) Lodgement points,

(b) Rate of freeze-up progression,

(c) Reach over which pan ice was produced, and the nature of these pans,

(d) The nature of the accumulation, or initial ice cover - for example, whether it was smooth or rough - if it could be perceived from the air;

and, for break-up:

(a) Progression,

(b) Manner of break-up, and

(c) Significant ice jam formation, location and behaviour.

These reconnaissance flights were made in 1982 and 1983. The freeze-up observations are described by Janowicz (1983, 1984) and those of break-up by Kent (1982, 1983), reports included herein as Appendices 2 and 3. The many related maps and photographs are available at the office of the Water Planning and Management Branch, Inland Waters Directorate, Environment Canada, Vancouver, B.C. In addition to these flights, incidental observations of the ice cover in winter were made by Bigras (1983) and Hodge (1983).

The salient features described in these reports are summarized in the following sections.

FREEZE-UP 1982

Flights were made on November 1, 12, 19 and 25. Because of the unusually cold and early fall, the lodgement and initial progression had already taken place in the reach downstream of Coffee Creek at the time of the first flight. The extent of the ice cover observed on that first flight, and the subsequent progression of the cover noted in the later flights, are shown in Figure 7. The progression is plotted relative to accumulated degree days of frost at Dawson.

First lodgement had apparently occurred in the constriction at the downstream end of the confined meander about 12 km downstream of Fortymile and 85 km from Dawson, near Cliff Creek (UTM 525 000/7 155 000). The location is shown in Figure 8. This lodgement seems to have occurred unusually early, both with respect to date and degree days of frost, and was likely aided considerably by the severe cold spell and 10 cm snowfall at the end of October. Subsequent lodgements seem to have taken place in the narrow reach just upstream of Moosehide (UTM 576 000/7 106 000), only 7 km downstream of Dawson, and in the narrow neck in the otherwise wide, island-strewn reach just downstream of the Sixty Mile River confluence (UTM 562 000/7 049 000). Presumably the lodgement near Moosehide governed the freeze-over date at Dawson. The nature of the initial ice cover at Dawson is shown in Figure 9. The only other significant lodgement point, other than Five Finger Rapids, was in or near the narrow neck immediately downstream of the Selwyn River confluence, in the bend at that location (UTM 638 000/6 967 000).

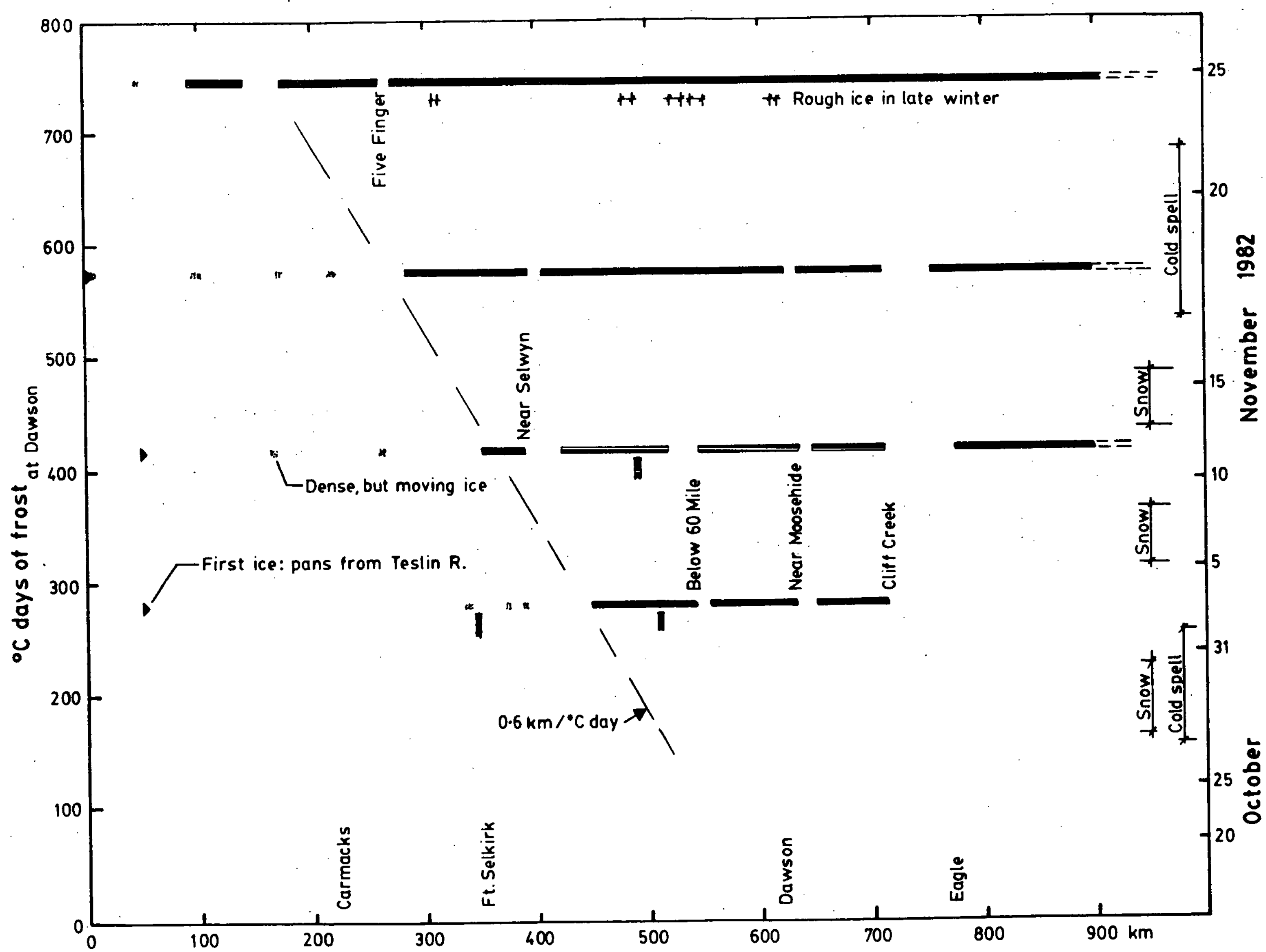

Figure 7. Freeze-up progression 1982.

Figure 8: Initial lodgement point near Cliff Creek (km 713) looking upstream (R. Janowicz, 1983).

Figure 9: Nature of initial ice cover, Dawson (R. Janowicz, 1982).

Beyond Selwyn the freeze-up front progressed at about 12 km/day or, based on Dawson temperatures, 0.6 km/°C day. If lodgement occurred at Cliff Creek near the onset of the cold spell and precipitation on October 27, the progression rate from Cliff Creek to Selwyn was considerably higher, being about 40 km/day, or 2 km/°C day.

Of the major tributaries only the Teslin, Little Salmon and White Rivers were still open at their mouths at the time of the first flight, November 1. Ice pans were first observed at the Teslin River confluence, and were coming from that tributary. This was still the situation on November 12, but by November 19 ice was being produced in the Yukon just downstream of Lake Laberge. The latter was ice-covered except at the outlet. The mouth of the White River froze over sometime between November 1-12.

FREEZE-UP 1983

Flights in this year were made on October 14, 17 and November 2, 9 and 16. The progression of the ice front is shown in Figure 10. As is evident from the degree day accumulation rate, this fall was significantly milder than that of 1982. No information was available at the time of writing on precipitation in this period.

Again initial lodgement occurred at Cliff Creek, but after about 200°C days of frost. This is substantially more than that needed to cause lodging at this site the previous year. The difference is probably due to the much colder temperatures that prevailed at lodgement in 1982, which would give the pans more strength and make it easier for them to lodge, and the snow, which would increase the amount of slush in the river. The discharge in 1983 was about 30% higher than in 1982, which would also help delay lodgement.

Lodgement again occurred in the narrow reach above Moosehide, at about the same time as lodgement took place at Cliff Creek, much as probably happened in 1982. In 1983, soon after the ice lodged at Moosehide, lodgement also occurred about 20 km upstream at a seemingly innocuous site near Swede Creek. Initial freeze-over at Dawson would again be controlled by lodgement at Moosehide. Apparently the ice cover readjusted a little after this, as the river was open at Dawson on November 16.

The next lodgement appears to have been just upstream of the White River confluence, rather than near the Sixty Mile River confluence as in 1982. The accumulation behind this lodgement extended back to the constriction near Selwyn, which was another lodgement site in 1982. At the time of the last flight ice was still passing the Selwyn site, but it was about to be closed by the accumulation advancing from the White River.

Average freeze-over progression rate from Cliff Creek to Selwyn was about 22 km/day, or 1.7 km/°C day. This latter figure is not very different from that deduced for this reach in 1982.

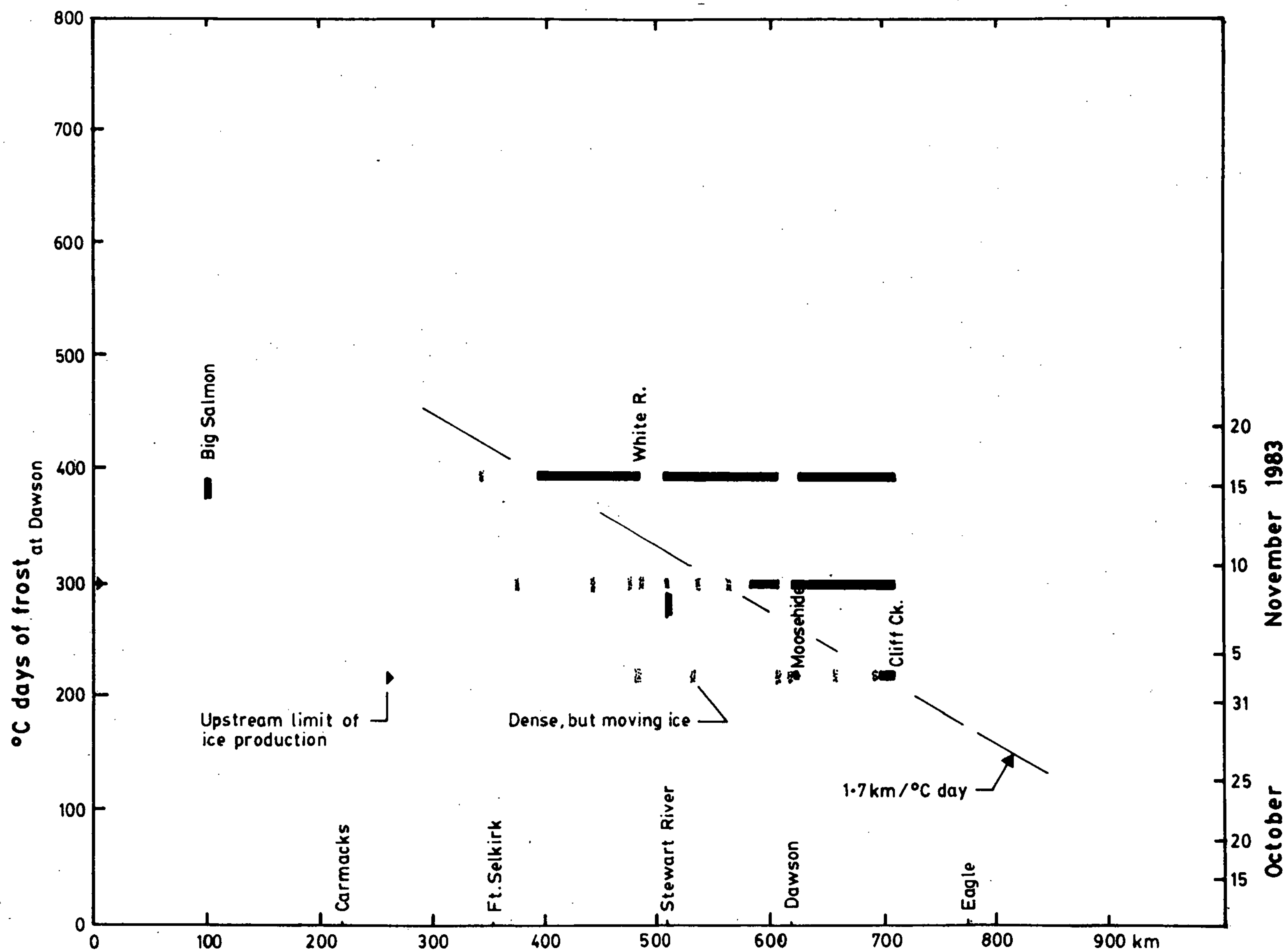

Figure 10: Freeze-up progression 1983.

During the October 27 flight, ice was noticed downstream of Five Finger Rapids, and was heavy by McGregor Creek (km 290), but disappeared upstream of McCabe Creek (km 311). It appeared again near Selwyn, but again disappeared downstream. Due to poor visibility, this was the limit of this flight. On November 2, ice production seemed to be initiated just upstream of Five Finger Rapids. On November 9 there was light ice downstream of Lake Laberge, but relatively heavy ice downstream of the Teslin River confluence, with heavy ice moving out of the Teslin. No information was given on the extent of the ice cover on Lake Laberge.

At the time of the last flight the only major tributaries frozen over at the mouth were the Stewart (sometime between November 2 and 9) and Big Salmon (between November 9 and 16).

FREEZE-UP SUMMARY

The significant lodgement locations for the Yukon River downstream of Carmacks seem to be reasonably consistent from year to year. They are near Cliff Creek, Moosehide, White River, Selwyn and Five Finger Rapids. Of these, though, only the first two and presumably the last, occurred in almost exactly the same place in the two years of observation. Lodgement at Moosehide governs freeze-over at Dawson. An analysis of lodgement time and the associated air temperature, degree days of frost (and precipitation) and discharge should lead to a useful guide as to when lodgement can be expected at each of these sites.

Progression of the accumulation front seems to have two distinct regimes. Downstream of about Selwyn it progressed at more or less the same rate in the two years, about 2 km/°C day. Above Selwyn, up to beyond Five Finger Rapids, this rate was only 0.6 km/°C day in 1982, the only year freeze-up in this reach was observed. Without more information and analysis it is difficult to discern the cause for this apparently quite sudden transition. Perhaps the coincidence of this transition point with the reach having the confluences of the Pelly, White and Stewart Rivers, and the concomitant loss of the ice input from these rivers as the accumulation moves past them, is significant.

The major tributaries seem to have freeze-up regimes that do not depend on freeze-over of the Yukon at the confluences, except for the White River, which remains open for some distance upstream of the confluence until freeze-over on the Yukon closes off the mouth.

The ice production front (other than direct input from the tributaries) had moved back to near Lake Laberge by the time 300-500°C days of frost had accumulated.

WINTER 1982-1983

Open-water leads in the ice cover are thought to be significant to fish. Those on the Yukon between Lake Laberge and White River in mid-March, 1983, were documented by Hodge (1983).

At the time of this survey, Lake Laberge was ice-covered, but the Yukon River was open for 22 km downstream of the outlet. Below that point there were many open leads of various lengths, usually less than 1 km. Inspection of the distribution of the leads suggests that the number per unit length of river is directly, and almost linearly, related to the number of islands per unit length. For example, between Lake Laberge and Yukon Crossing, a reach with few islands, open leads averaged about 0.1/km, whereas in the island-strewn reach between Minto and the Pelly River confluence, the frequency was 0.7/km. In fact, along the 500 km reach surveyed the open lead frequency was simply 0.2 times the island frequency (on 1:250 000 map). It is not clear what implication such a relation has on the common assumption that open water leads are associated with groundwater inflow.

Bigras (1983) conducted a winter reconnaissance of the ice cover between Carmacks and Dawson between April 13-15, 1983, noting the surficial appearance of the ice cover. There were several reaches of rough ice, indicated in Figure 7, that were presumably associated with shoving of the initial ice cover at freeze-up. These locations seem only broadly related to the observed lodgement locations.

Bigras and Anderson (1984) report measurements of the ice thickness on the Yukon River at Carmacks and Dawson, and on the Klondike and White Rivers just upstream of their mouths. FENCO (1974) give the average ice thicknesses on the Yukon River at Dawson measured over 20 years by Water Survey of Canada. It appears from this that ice thickness at a given location varies little from year to year. Over the 20-year period at Dawson the mean ice thickness in April was 1.0 m, with a standard deviation of only 16%. In 1983 Bigras found an average of 0.84 m, with a maximum of 1.1 m, with little snow ice. At Carmacks the average thickness was 0.78 m in 1983, with a maximum of 1.1 m, and about 50% was snow ice; the thicknesses on the tributary streams were significantly less, being 0.61 m, 0.89 m and 20% snow ice on the White River, and 0.57 m, 0.77 m and no snow ice on the Klondike River.

BREAK-UP 1982

As described by Kent (Appendix 2 herein) some eleven reconnaissance flights were made along the Carmacks-Eagle reach of the Yukon River, or part thereof, over the period May 9 to 18. These flights were begun on receiving word (May 4) that the ice had deteriorated substantially at Carmacks. At the time of the first flight the White River was open for at least 100 km upstream of the confluence, the Klondike River had broken-up (May 7) and 66°C days of thaw had accumulated.

A summary of the observations made during these flights is given in Figure 11, plotted against accumulated degree days of thaw. (As discussed earlier, break-up at Dawson is only roughly related to degree days of thaw, but this is a simple parameter that is more physically meaningful than just the date, and so should help to relate the events of one year to that of another.) Also shown in Figure 11 are the date and the precipitation recorded in the Stewart-Pelly catchments. The more detailed observations of break-up in the vicinity of Dawson are summarized in Table 2.

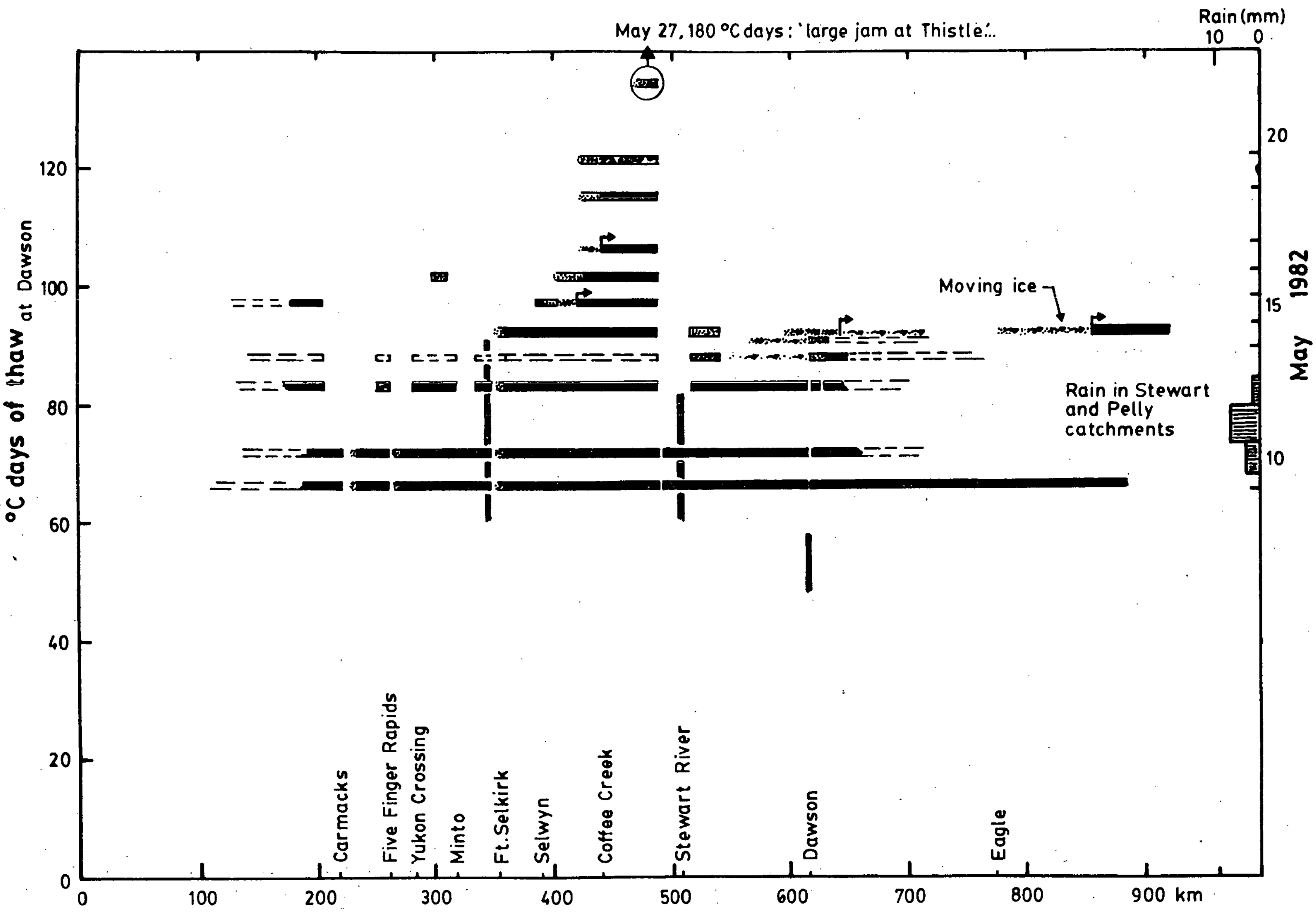

Figure 11. Break-up progression, 1982.

TABLE 2: SEQUENCE OF EVENTS DURING BREAK-UP AT DAWSON, 1982.

(Note: To give a direct indication of the passage of time 1 line ≈ 1 hour)

May 12	1700	River open at Klondike confluence
May 13	0000	
	0715	Water level up 1.5 m from 0300
	1030	Water level going up at 0.6 m/h; ice jammed just upstream of Klondike
	1145	Major ice movement; rapid rise in water levels; pans ≈ 1 m thick, competent
	1330	Pack ice backed up to ferry crossing from Fort Reliance jam; significant rise in water level
	1900	River clear at Dawson; water levels down 'significantly' from 1300; ice jam gone from upstream of the Klondike
	2000	River running full of ice
	2030	River clear
	2100	Channel full of moving ice
	2125	Ice stopped running (river clear?)
	2225	Jam upstream of Klondike
	2230	River at Dawson running ice, but channel not covered
	2345	River running full of ice
May 14	0200	River free of ice
	0830	Ice run begins
	0940	Ice moving past Dawson
	1030	River running full of ice at ≈ 5 km/h
	1200	River running full of ice; water level rise of 2 m
	1300	Water levels still rising; concern about flooding
	1330	Water levels falling
	1430	Water levels falling
May 14	1600	River clear at Dawson

The Klondike River broke up and ran on May 7. Initial movement of the ice at Dawson took place at about noon, May 13, 6 days later. Sometime before that the ice cover on the Yukon had melted near the Klondike River confluence and in the vicinity of Moosehide. The water levels in the Yukon had increased by 2 m or more and, shortly before the initial movement, ice from upstream of the Klondike River had moved and jammed just upstream of Dawson. It was presumably failure of this jam that caused break-up and the first ice run at Dawson. The ice in this first run moved down to join a small jam of local ice from near Moosehide that had formed at Ft. Reliance. After this initial run, there were intermittent runs of ice that moved past Dawson from the reach upstream of the Klondike River which were presumably also stored in the Ft. Reliance jam. In the early morning of the next day, May 14, the Yukon at Dawson was clear of ice.

Then, at around 0830 h, a major ice run from upstream began to pass Dawson and ran for some 4 hours, at about 1.5 m/s. This ice was again presumably being stored in the Ft. Reliance jam because the water levels in Dawson rose dangerously, to the extent that there was concern about flooding. At 1330 h the water levels began to fall. Subsequent observations showed the jam at Ft. Reliance had released.

At 1500 h the break-up front generated by this jam failure was at the Chandindu River. This represents an average front celerity of about 2.7 m/s. Ahead of this ice run the river was open, with only a small amount of ice debris moving on the surface, so break-up on this reach had already taken place. On the same flight, at about 1530 h, an apparently independent break-up front was seen far downstream, about 80 km downstream of Eagle, with an ice run behind it extending back some 80 km. Evidently there had been another jam well downstream of the Ft. Reliance jam that had also failed on May 14.

Before the initial ice run through Dawson on May 13, some 85°C days of thaw had accumulated and the ice on the Yukon in the many-island reach between the Stewart and Klondike Rivers "consisted of rotting channel ice with well developed leads around the islands." Both the Klondike and White Rivers had been open for several days previously. The Stewart River, near the mouth, broke up the day before the initial movement at Dawson (May 12), because on that date "ice was flowing on the Stewart just upstream of the confluence and the Stewart itself was clear of ice for approximately 40 km upstream. Several minor ice jams were noted on the Yukon river, downstream of the Stewart."

It appears, therefore, that break-up at Dawson was triggered by the break-up and ice run of the "rotting" ice between the Stewart and Klondike Rivers. This ice was 'prepared' for break-up by the 85°C days of thaw, and the associated solar radiation, and probably to some extent by the relatively warm water from the White River and the Yukon further upstream. (On May 14, Kent (1982) measured the water temperature on the White River near the mouth to be 2.0°C, and on the Yukon below Sixty Mile River to be 1.5°C. Previously, on May 12, the Yukon River at Ft. Selkirk and Dawson had been 1.0°C, and the Klondike River above the mouth 0.5°C.). It is likely, but far from certain, that the ice run in the portion of this reach which caused the initial movement in Dawson was triggered by the break-up surge from the Stewart River, assisted perhaps by the 12 mm or so of rain reported in the area over the three days previous.

Upstream of the White and Stewart Rivers, break-up was following a remarkably similar, but somewhat later, timetable. As for the White River-Dawson reach, the many-island reach of the Yukon upstream of the Pelly River was first prepared for break-up by the warm weather and the warm water moving down from the upper Yukon. By May 16, or after about 100°C days and the rain mentioned above, the Pelly River ice moved out and accumulated against the more competent ice about halfway between Selwyn and Coffee Creek. Upstream of this accumulation the river was open back to Lake Laberge. In the absence of any ice cover upstream, and hence ice jams and break-up surges moving downriver, this jam remained until the ice cover downstream had rotted. It was still in place when the observation program terminated on May 19, after the same 120°C days. During a routine flight along the river on May 27, after about 180°C days, Alford reported the river open except for "a large jam and flood at Thistle [just upstream of the White River] -- ice piled high on banks. Settlement at Thistle (Jerry Coture's) was badly flooded -- Monte's [WSC] cabin at former gauging station (at mouth of White) was flooded about 1 ft" (Lyons, 1983).

BREAK-UP 1983

Again break-up below Carmacks was observed by means of daily reconnaissance flights from Dawson, this time over the period April 28 to May 5. Another flight was made on May 8. At the time these flights were started break-up had progressed to Carmacks, the White and Klondike Rivers were open, and 50°C days of thaw had accumulated. A graphical summary of the observations is given in Figure 12, again plotted against degree days of thaw. Dates are also shown. Details of events at Dawson are given in Table 3. Although complete meteorological records were not available at time of writing, no substantial rain in the area was noted in these flights. However, an increase in the flow in the White River was noted on April 30. Hence, there may have been some rain in the upper White River catchment. This, or much milder weather over the glaciers, would be needed to explain the flow increase.

As indicated in Table 3, the Klondike River had broken up on April 27 and, as mentioned, by April 30 there was significantly more water coming from the White River (which, on May 3, had a temperature of 1°C). By the morning of the next day (May 1) water levels were rising in Dawson, there was significantly more open water in the White-Stewart River reach, a large area of open water had developed at the confluence of Swede Creek (km 605), and the open area at the Klondike confluence had enlarged, as had that near Moosehide.

At about 1400 h the ice between Swede Creek and the Klondike River ran, causing break-up in Dawson. Water levels rose rapidly. The tripod for the break-up pool was destroyed at 1528 h. Ice movement continued until 1600 h, when the large 'ice bridge' floe jammed briefly just downstream of Dawson. The stage had risen 1-1.5 m. Ice floes in this run were 0.6 to 0.8 m thick, and quite competent.

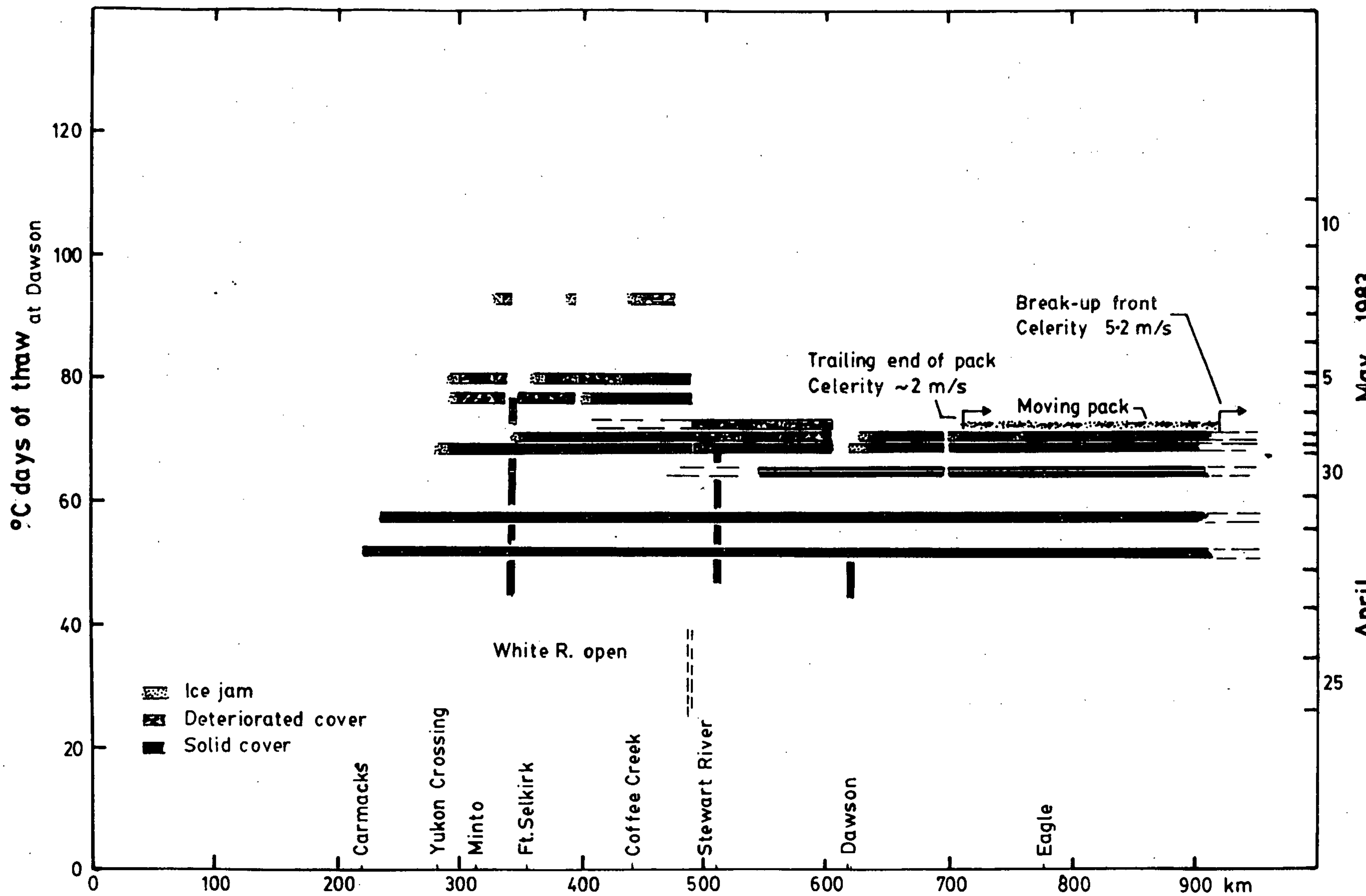

Figure 12. Break-up progression, 1983.

TABLE 3: SEQUENCE OF EVENTS DURING BREAK-UP AT DAWSON, 1983.

(Note: To give a direct indication of the passage of time 1 line ≈ 1 hour after April 30)

April 27		Klondike River open
April 30		"Significantly more water flowing down the White River; and an increase in water levels was noted on the Yukon downstream of the White River confluence" (Kent, 1983)
May 1	0000	
	1030	Open areas at Klondike confluence and at Moosehide have expanded; small jam just below Ft. Reliance; solid competent ice below that
	1400	Ice pans moving along west bank; stage rising
	1500	Stage rising rapidly: water overflowing ice upstream of Klondike
	1528	Tripod destroyed; floes against ice at ice bridge
	1600	Stage up 1-1.5 m since 1400; floes of competent ice 0.6-0.8 m thick; ice from between Klondike and Swede Creek
	2000	Water levels dropping
	2050	Ice moving at Dawson; water levels rising
	2140	Dawson clear; jam just downstream of Moosehide, another near Twelve Mile Creek against good ice
May 2	0945	River clear from Dawson to head of jam about 3 km downstream of Ft. Reliance (km 630); jam toe 10 km above Chandindu (km 640) against competent ice cover.
	1545	Stewart River out at confluence; ice moving between Sixty Mile and Indian River (km 540-560); jam at Indian River
	1645	Heavy ice run in Dawson; jam at Moosehide
	1800	Ice run stopped at Dawson
	2000	Ice running again
	2130	Moosehide jam finished building; river clear at Dawson
	2320	Ice cleared through Moosehide and beyond
May 3	0000	
	1030	River clear from Swede Creek to trailing end of run just downstream of Cliff Creek (km 715)
	1130	Break-up front at Charley River (km 925)
May 3	1215	Trailing end of run at Eagle (km 775)

Water levels were falling at 2000 h but were rising again at 2050 h, when the ice began to move again at Dawson. An hour later (2140 h) the river was clear at Dawson, there was a jam just downstream of Moosehide, and another, against the solid ice cover, at 'Twelve Mile Creek'. Overnight the Moosehide jam moved, collected the Twelve Mile Creek jam and lodged against solid ice near km 640, about 10 km upstream of the Chandindu River. The jam extended back to just downstream of Ft. Reliance, a length of some 40 km.

At 1545 h on this day (May 2) it was noted the Stewart River had broken up, at least near the confluence; there was a jam at Indian River (km 562); and there was ice moving over the 20 km reach between there and Sixty Mile River. The nature of the ice cover upstream and downstream of the White River confluence is shown in Figure 13. The difference a tributary can make is evident.

At 1630 h another jam had formed at Moosehide, and there was a heavy run of ice from near Swede Creek moving past Dawson. This run stopped at 1800 h, but began to run again at 2000 h. By 2130 h the Moosehide jam had finished building: by 2320 it had failed and moved out of sight (from the Dome). Next morning (May 3) at 1130 h the break-up front had moved as far as Charley River in Alaska, a distance of some 300 km in about 16 h.

If failure of the Moosehide jam and/or the jam at the Chandindu River triggered break-up over this whole reach, it represents a break-up front celerity of at least 5.2 m/s (19 km/h). The continuous running pack extended back from the front about 140 km, and the trailing end of this was moving at about 2 m/s (from observations about an hour apart). This latter velocity suggests that 16 h earlier the front should have been in the vicinity of the Fifteen Mile River, a location not too inconsistent with break-up in the reach being triggered by failure of either the Chandindu or second Moosehide jam. The more or less solid ice cover over a 300 km reach had, therefore, been reduced to about 140 km of fragmented, packed, but moving, ice by passage of the break-up front.

As in 1982, break-up at Dawson seems to have been triggered by the run, after about 70°C days, of the more deteriorated ice cover between Dawson and Swede Creek. This seemed to be triggered in turn by contributions from one or both of the White and Stewart Rivers: the high discharge on the White River may have been the prime instigator.

Also as in 1982, break-up upstream of the White River was similar to that downstream, but somewhat delayed. By May 1, or 70°C days, the break-up front from Lake Laberge had reached Yukon Crossing. Seven days, but only 25°C days, later (May 8) the ice cover downstream from there had degraded and moved, leaving a final ice jam upstream of a quite deteriorated ice cover between Coffee and Thistle Creeks. In 1982 this had been approximately the situation after 120°C days, and it took another 60°C days, or 8 days, to move down to the White River confluence.

(a) Looking upstream towards Thistle Creek.

(b) Looking downstream towards Stewart River.

Figure 13. Yukon River ice cover near White River confluence, 83.05.02.16:00.

BREAK-UP SUMMARY

Break-up progression in the two years of observation were remarkably similar. Break-up at Dawson was triggered by relatively small ice runs from between the Klondike River and Swede Creek. Failure of the jam (or jams) formed in the reach downstream of Moosehide was, shortly afterwards, responsible for causing break-up well into Alaska. The initial movement near Swede Creek was apparently caused by increased flows, or break-up, on either or both of the Stewart and White river.

Break-up upstream of the White River occurred significantly later and seemed to wait for the break-up front to move down from Lake Laberge. Significant ice jams were formed as this front progressed slowly through the Pelly-White River reach. In both years the final action seems to have been the failure of a large accumulation, or jam, in the vicinity of Coffee Creek. In this regard the two years were consistent with descriptions in the historical record. The surge of ice and water released by failure of this "Coffee Creek jam" apparently posed no threat to Dawson.

EFFECT ON ICE REGIME OF REGULATION FOR HYDRO-POWER PRODUCTION

As mentioned earlier, there are several possible ways to utilize the hydro-power potential of the upper Yukon basin. Of most concern for the Yukon River below Lake Laberge would be medium to large scale hydro-electric developments that have been proposed for the Yukon River in the Carmacks area and for the Pelly and Stewart Rivers. In this discussion the effects of a large reservoir and hydro-electric plant on the Yukon River upstream of Carmacks, much as proposed as the Phase III mid-Yukon development, has been used as an example to illustrate the possible consequences of such flow regulation on the ice regime of the river. Furthermore, it is assumed that the plant operation would increase the freeze-up, winter and break-up discharges, and the plant would, at least occasionally, be called on to accept sudden increases in load. This is similar to the operation of the Bennett Dam and Williston Reservoir on the Peace River in British Columbia mentioned earlier, a large river in a similar climate to the Yukon River, and with a flood prone town, Peace River, a considerable distance downstream of the dam. Therefore, the oft-reported influence of this reservoir on the ice regime of the Peace River in British Columbia and Alberta gives, in a general sense, an indication of the likely influence of a similar reservoir on the Yukon River.

EFFECTS ON FREEZE-UP

Operation of a hydro-power plant and reservoir upstream of Carmacks would result in discharges and water temperatures higher than natural moving down the river from this point during the freeze-up period. Water temperature in the river a given distance downstream is directly related to the initial temperature and, approximately, to the discharge: if the discharge is doubled during a period of below-freezing temperatures, the distance to where the water reaches freezing will approximately double, for the same initial water temperature and meteorological conditions. The influence of tributaries modifies this. In its natural regime the rate of cooling of the Yukon River below the Stewart River confluence is significantly increased by input from the major tributaries below Lake Laberge, as these contribute a large portion of the discharge at Stewart and cool faster. A reservoir near Carmacks would remove the immediate cooling effect of the tributaries between Lake Laberge and Carmacks, which contribute about half the flow at Carmacks. Considering all these effects it is evident a large reservoir and hydro-electric plant near Carmacks would cause a substantial delay in ice production each year compared to the natural regime. This would, in turn, cause a delay in freeze-over of the river in the reach down to at least the U.S. border.

There would be other contributions to a delay in freeze-over. A substantial increase in discharge during freeze-up will delay lodgement, even for the same amount of ice in the river. Indeed the effect of the increased discharge and water temperature might be such that initial lodgement in the reach above Eagle is suppressed and freeze-over in this reach depend on accumulation progression from a site downstream of Eagle,where the influence of the changed discharge and temperature had been sufficiently mitigated by tributary inflow for lodgement to occur. Such a displacement and delay in lodgement would add further significant delay to freeze-over in the reach of interest.

An additional factor delaying freeze-over, and one which would contribute to higher freeze-up water levels and perhaps flooding at freeze-up, is that the additional drag on the accumulation caused by the increased discharge may result in thicker initial freeze-up accumulations. This would slow the accumulation progression. A related point is that fluctuations in discharge caused by sudden, and possibly inadvertant, load fluctuations at the plant could result in a substantially higher discharge over a short period. This can cause an accumulation formed under the preceding lower discharge to suddenly collapse and 'shove' over a large reach of river. The water released from channel storage by this action could compound the high discharge and cause substantially thicker accumulations and higher stages. A good example of such an event on the Peace River, and the subsequent threat of flooding of the Town of Peace River, is described by Neill and Andres (1984).

From the above discussion it is evident that, for a variety of reasons, substantial delays in freeze-over in the reach of interest and higher freeze-up stages could be expected if a large dam were to be constructed upstream of Carmacks. Of the various contributions to this, the delay in ice production and the change in accumulation thickness can be simulated quite well, given the general geometry of the river and the planned releases from the reservoir. The delay in lodgement, at known lodgement locations, could likely be defined through empirical analyses of lodgement under natural conditions. However, the displacement of lodgement locations by the changed flow regime will be difficult to define with the current state-of-the-art.

EFFECTS ON BREAK-UP

If, by spring, an ice cover has been able to progress to near the reservoir, the postulated increase in discharge at break-up, and the closer proximity of the reservoir, would significantly delay the warming of the water that seems to play an important role in break-up on the Yukon River upstream of the White River confluence. Furthermore, the discharge increase would cause higher stages prior to break-up for some distance downstream, which would reduce freeboard and protection from flooding along this reach.

Beyond these obvious effects, though, may be much more significant changes wrought in the somewhat subtle, but apparently very significant, role played in the break-up process by tributaries along the reach of interest. The field observations of break-up in the past two years suggest that discharges from the White and Stewart Rivers, together with the warmer temperature of these discharges, play an important role in initiating break-up in the reach downstream of the Stewart River, and hence at Dawson, and indeed well into Alaska. With a larger discharge at break-up the influence of these tributaries would be less, although probably not negligible.

If the tributary influence were rendered negligible and the discharge from the reservoir held steady over the break-up period, it is probable that break-up in the reach below White River would progress much like it does under natural conditions upstream of White River. It is evident from the two years of observation, and the historical record, that under natural conditions large ice jams can form upstream of the White River, such as those noted near Coffee Creek and Ft. Selkirk, even though a considerable number of degree days of thaw have accumulated. If the influence of the White and Stewart Rivers are reduced enough that the ice downstream of the Stewart remains, albeit in a deteriorated condition, the jams would have to progress downstream through this ice, with the result that they may build in magnitude. If the break-up front, or jam, failed suddenly before it reaches Dawson, the surge released may well be higher as it passed Dawson than the surges that cause flooding in Dawson under the natural regime. If, on the other hand, the break-up front moved past Dawson in a more 'regular' fashion, but stalled somewhere downstream of Dawson, as is prone to happen under the natural regime, again higher stages might result. In both cases, though, an important modifying influence may be the degree of ice melting that would have taken place over the period the break-up front would have taken to move down as far as Dawson, and the situation at Dawson might be no worse than it is under the natural regime when the Coffee Creek jam fails. Changes caused by the aggradation that could probably occur at the White River confluence is difficult to appraise.

If the tributary influence remained largely unchanged, break-up processes near Dawson would likely be independent of break-up upstream of the White River, much as it is under the natural regime, and hence ice-related flooding would not be reduced and indeed might be worse, particularly if plant operations create inopportune surges.

In short, the influence of a hydro-power operation near Carmacks on the break-up regime downstream is difficult to discern on the basis of only qualitative information. A final decision must await quantitative simulations of freeze-up progression, ice decay and surge formation and progression for a variety of scenarios. Nevertheless it does seem that the possibility of a more detrimental break-up regime cannot be ruled out. As well as delaying the final clearing of the river, the reservoir influence might be such as to cause significantly higher stages at break-up.

The tributaries pose another problem. From the historical record break-up and jamming on the Klondike River can cause severe flooding in Dawson. Under the natural regime, flooding from the Klondike seems to be associated with surges caused by the formation and failure of jams well upstream of the mouth. This, of course, would not be influenced by an increase in discharge on the Yukon River. However, a higher stage on the Yukon at freeze-up and break-up might make it easier for these surges to move into the Yukon and thereby might reduce the flooding caused at Dawson, despite the higher base stage at the confluence. Degradation at the mouth of the Klondike, due to lower mean summer stages on the Yukon, might further facilitate the passage of surges from the Klondike. However, flooding might then be caused by a jam formed at the mouth, something which does not seem to occur under the natural regime.

At present break-up surges from the Stewart and Pelly Rivers seem sufficient, at least in some cases, to cause break-up on the Yukon River near the confluences and hence allow the ice run in these tributaries to clear the mouth. An increase in the relative size of the Yukon at break-up, due to higher break-up discharges, might allow it to resist the impetus of a break-up surge from the tributary and cause the ice run on the tributary to stall at the confluence. If this occurred the frequency of ice jams at the mouths of the tributaries would increase. This may be of little consequence, however, because of the absence of settlements at these locations.

EFFECTS OF ICE REGIME CHANGES

It is evident from the above discussion that regulation of the Yukon River near Carmacks for hydro-power production would have a significant effect on the ice regime. Freeze-over would be delayed and the duration of the freeze-up process, from initial ice production to freeze-over, would be increased. At break-up the period between the beginning of ice deterioration and final clearing of the ice might also increase. As discussed earlier these effects would significantly impede river utilization for access and transportation, and may also have a substantial effect on the ecological processes in the river. Furthermore, an increase in ice-related flooding caused by the change in ice regime, both at freeze-up and break-up, cannot be ruled out at this stage.

Hydro-power reservoirs on the major tributaries would effect the tributary much as described above. The effect on the Yukon River below the confluence at freeze-up would be similar to that described above for a reservoir on the Yukon, with the magnitude, or significance, of the effect depending on the magnitude of the change in discharge relative to Yukon River flow at the confluence.

The effect of tributary regulation on break-up on the Yukon River below the confluence may not be so straightforward. As discussed above break-up on the Yukon River below about the Stewart River confluence seems to be quite dynamic, and to be triggered by seemingly innocuous events. If this proves to be the case even small changes in the flow regime of a tributary, particularly flow surges, might have an important influence on break-up on the mainstem.

Many of the ice regime processes are now quite well understood and amenable to analysis. Others can be approached by investigating bounds of behaviour under a range of likely scenarios. Firmer conclusions could therefore be drawn after the necessary hydraulic and hydrologic data has been collected, and numerical simulations of the ice regime carried out. Such an effort would only be justified in connection with the engineering investigation of a firm development proposal. The information collected during this preliminary investigation has been sufficient to indicate that the influence of regulation on the ice cover will likely be significant and detrimental to activities in the region and to the river ecology, and should, therefore, be given serious consideration in a final engineering investigation.

SUMMARY AND CONCLUSIONS

The results of reconnaissance of the ice regime of the Yukon River downstream of Carmacks over two seasons, and substantial historical information collated in earlier reports, have been reviewed to provide a basis for preliminary assessment of the effect of flow regulation on the ice regime. Based on this review, the major features of the natural ice regime in the reach of interest have been summarized herein, and the probable, qualitative, effects of regulation discussed. It is concluded that changes in ice regime would likely be substantial and would be detrimental to utilization of the ice cover for transportation and access by residents and industry in the area; could exacerbate ice-related flooding along the reach, an item of particular concern at Dawson; and could have a significant effect on the river ecology. It is therefore a subject worthy of more detailed study in the event a firm proposal for development of the hydropower potential of the upper Yukon is forthcoming.

REFERENCES

Bigras, S.C., 1983. Letter dated September 6, 1983, to R.O. Lyons and attachments giving ice survey data taken April 13-15, 1983.

Bigras, S.C. and Anderson, J.C., 1984. "Yukon River break-up at Dawson, YT, 1982 and 1983", Report prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C. by National Hydrology Research Institute, 60 p.

DCM, 1981. "Historical review of Dawson City flood data, 1898-1975", Report prepared for Department of Indian and Northern Affairs, Whitehorse, Yukon by Dawson City Museum and Historical Society (DCM), March, 1981, 180 p.

FENCO, 1974. "Yukon flood study", Report prepared for Northern Natural Resources and Environment Branch, Indian and Northern Affairs, Whitehorse, Yukon Territory by FENCO Consultants Ltd., May, 1974, 78 p.

FENCO, 1976. "Yukon River Ice Study, Dawson, Yukon Territory", Report prepared for Northern Natural Resources and Environment Branch, Indian and Northern Affairs, Whitehorse, Yukon Territory by FENCO Consultants Ltd., October, 1976, 50 p.

Gerard, R. and Karpuk, E., 1979. "Probability analysis of historical data", American Society of Civil Engineers, Journal of Hydraulics Division, v. 105, no. HY9, Sept., pp 1153-1165.

Hodge, A., 1983. Annotated 1:250 000 map sequence showing open water leads, Yukon River between Lake Laberge and White River, March, 1983.

Janowicz, R. 1983. "Winter ice cover 1982-83", Report prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C. by Indian and Northern Affairs Canada, 5 p (attached to this report as Appendix 1).

Janowicz, R. 1984. "Summary of freeze-up observations 1983", Informal notes prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C. by Indian and Northern Affairs Canada, 5 p. (attached to this report as Appendix 1).

Kent, T.D. 1982. "A survey of the timing and progression of the ice breakup on the Yukon River, 1982", Report prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C. by T.D. Kent, Environmental Consultant, 25 p (attached to this report as Appendix 2).

Kent, T.D. 1983. "A survey of the timing and progression of the ice breakup on the Yukon River, 1983", Report prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C. by T.D. Kent, Environmental Consultant, 25 p (attached to this report as Appendix 2).

Lee, J.C.Y. 1982. Informal notes on ice break-up at Dawson, May 12-14, 1982.

Lyons, R.O. 1982. Informal notes on ice break-up at Dawson, May 12-14, 1982.

Lyons, R.O. 1983a. Informal notes on ice freeze-up survey, October 27, 1983.

Lyons, R.O. 1983b. Memorandum to file on comments about ice conditions in Yukon River by Monte Alford, November 7, 1983.

Neill, C.R. and Andres, D.D. 1984. "Freeze-up flood stages associated with fluctuating reservoir releases," Proceedings of CSCE/ASCE Cold Regions Specialty Conference, Edmonton, Alberta, April.

Orecklin, M. 1981. "Dawson flood study: Ice jam of May 3, 1979; 1980 and 1981 break-up", Report prepared by Northern Affairs Program, Department of Indian and Northern Affairs, Whitehorse, Yukon Territory, 37 p.

UMA, 1983 "Yukon River Basin flood risk study", Report prepared for Yukon River Basin Study, Inland Waters Directorate, Pacific Region, Environment Canada, Vancouver, B.C., by Underwood McLellan Ltd., October, 1983, 83 p.

APPENDIX 1.

FREEZE-UP OBSERVATIONS, 1982 and 1983

YUKON RIVER BASIN STUDY

Project No. 41

PHASE II

FREEZE-UP 1982

Ric Janowicz
Hydrologist
Northern Affairs Program
200 Range Road
Whitehorse, Y.T. Y1A 3V1

22 August 1983

FREEZE-UP 1982

by Ric Janowicz

INTRODUCTION

This report summarizes winter freeze-up observations taken during our overview flights along the Yukon River between Whitehorse and Eagle, Alaska. The purpose of the survey was to record freeze-up conditions with these possibly acting as indicators of spring break-up. It is hoped that existing relationships between freeze-up and break-up features will become evident upon comparing the respective surveys. This will provide a greater understanding of the spring break-up process on the Yukon River by identifying critical reaches. Selected reaches may be further studied possibly leading to measures for preventing or lessening detrimental effects associated with the break-up process.

SURVEY METHODS

A chartered single engine fixed wing aircraft was used to carry out the surveys which took place on November 1-2, November 12, 19 and 25. Photographs were obtained using a hand-held 35 mm camera. Selected photographs with captions accompany this report. These are arranged in a downstream order. Photograph and freeze-up feature locations are noted on 1:250,000 topographic map sheets. The following map sheets arranged in a downstream order provide coverage for the Yukon River between Whitehorse and the international boundary downstream of Dawson:

105D	Whitehorse
105E	Laberge
105L	Glenlyon
115I	Carmacks
115J & K	Snag
115O & N	Stewart River
116B & C	Dawson

Specifically ice jams and bridging, and open water areas were identified with respect to location and areal extent. The variation in these features between flights were also noted. No attempt was made to interpret the observed freeze-up features beyond noting evident patterns.

A more extensive survey of the Marwell subdivision in Whitehorse was carried out. This consisted of daily ground observations during the freeze-up period supplemented by occasional overview flights. This study will be summarized in a separate report under preparation by the author.

SUMMARY OF OBSERVATIONS

November 1 - 2, 1982

The upper river (upstream of Lake Laberge) was generally ice free with the exception of side channels and some reaches of low velocity adjacent channel banks. A notable exception was observed at a sharp corner immediately upstream of Lake Laberge (photo 4-16*) where some bridging was evident. The southern end of Lake Laberge was solid (1-0A) as were lake margins.

Floating ice pans were first observed entering the Yukon River from the Teslin River (1-1). The density of the pans generally increased progressing downstream and varied directly with velocity which is evident from accumulation patterns. This is illustrated by many of the photos which show ice pans accumulating along channel edges and gravel bars closely following sediment deposition patterns.

Dense ice across the entire cross-section was first observed at Five-Finger Rapid (4-10). Low elevation photos illustrating the progression of pans to floes were taken at Minto (4-6, 4-4). The first occurrence of jamming by large floes occurred immediately upstream of the Pelly River (1-27). Jamming next occurred downstream of Black Creek resulting in a limited advance of the ice front (2-0). Very heavy accumulations of ice approaching the bridging stage were observed downstream of Cripple Creek (2.5). Bridging was next observed at Selwyn with sections of relatively open water downstream of this point. The ice cover was solid at Coffee Creek and generally remained solid downstream to the Sixty Mile River with the exception of isolated open leads.

A large open-water section approximately 10 kilometres in length was observed downstream of the Sixty Mile. Similarly, a 20 kilometre openwater section was observed between Moosehide, downstream of Dawson, and the Chandindu River. The Yukon was then solid for approximately 60 kilometres downstream at which point it reopened at Cliff Creek (downstream of the Fortymile River) and remained open at least 100 kilometres downstream of Eagle (3-5, 2-35).

The overview flight proceeded southeast following the Tintina Trench until the Stewart River was intercepted near McQuesten. The flight

---

* Photographs are referenced throughout this report by roll and frame number. These photographs are available for viewing at Water Planning and Management Branch, Inland Waters Directorate, Vancouver, B.C. and from the author in Whitehorse, Y.T.

continued following the Stewart to Stewart Crossing where a southern heading was taken to intercept the Pelly River at Pelly Crossing. A western heading was then taken to follow the Pelly to the Yukon River.

The Stewart River was generally solid though several large open leads were observed (3-26, 3-28, 3-29). In comparison to the Stewart River a greater proportion of the Pelly River was observed to be open between the Pelly River and the mouth. All other tributaries of the Yukon were solid at the observed reaches (generally near the mouth) with the exception of the Little Salmon River which has an upstream lake influence. Open leads were observed on most of the major tributaries.

November 12, 1982

Much of the Yukon River between Whitehorse and Lake Laberge was observed to be solid on this flight. Specifically the river was frozen downstream of the Marwell subdivision for approximately 5 kilometres to Croucher Creek. It was then open for approximately 6 kilometres below which point it was solid for the most part to Lake Laberge. The southern end of Lake Laberge had experienced some ice growth since the last flight. No ice was observed above the Teslin River though pans were sighted entering the river at this point. A possible jamming location was sighted downstream of Klondike Bend (5-6). Floe formation was first observed downstream of the Little Salmon River (5-11) and the first occurrence of jamming was observed at Five Finger Rapid (5-19). Floating ice below this point was generally very dense. Bridging was observed at Wolverine Creek (upstream of Fort Selkirk) at which point the river was generally solid downstream. This is approximately 1 kilometre upstream of the first ice jam sighted November 1. A large open water reach, approximately 30 kilometres in length, was noted between Cripple Creek and Penler Creek (upstream of Coffee Creek). Several open reaches were sighted downstream of the Stewart River. These consisted of a 3 kilometre section immediately downstream of Stewart River and a 15 kilometre section upstream of the Sixty Mile River. This reach was observed to be solid during the November 1 flight. A 10 kilometre reach was open upstream of Moosehide. Coinciding in southern limit, this was approximately half the length of the open water observed during the November 1 overview flight. The river was again open downstream of Cliff Creek. The southern limit coincides with the November 1 location, however the ice front had advanced considerably to a point immediately downstream of Eagle. The length of the open water reach was approximately 50 kilometres.

November 19, 1982

The Yukon River above Lake Laberge was generally solid. A potential jamming site with heavy ice accumulation was observed approximately 1 kilometre downstream of Lower Laberge. Relatively large floes were sighted entering the Yukon from the Teslin River. Heavy ice, large floes and several potential jamming locations were sighted at several locations to a point downstream of Carmacks where the first jam was observed. The river was generally solid below Yukon Crossing.

A 10 kilometre open lead existed immediately downstream of Selwyn. This was coincident in location but smaller than the November 12 open water reach. A 3 kilometre long reach of open water was observed upstream of the Sixty Mile River. Again this is coincident in location but smaller than that of November 12. Several open leads downstream of the Sixty Mile appeared to have opened up since the previous flight.

The open reach downstream of Moosehide corresponded in both downstream and upstream location to the November 12 location. The ice front had advanced considerably upstream of Eagle to a point approximately 8 kilometres upstream of the international boundary. The open water reach was approximately 25 kilometres in extent but corresponded in southern limit to the previous flights at Cliff Creek.

An overview flight of the White, Donjek and Nisling Rivers disclosed many open leads. The frequency of these appeared to increase travelling upstream in the system.

November 25, 1982

The last overview flight took place on November 25, 1982, at which time the upper river was solid below the Marwell subdivision. Similarly Lake Laberge was solid throughout with the exception of the outlet (11-2). Floating ice was observed in the Yukon River above the Teslin for the first time. The ice had advanced upstream to a point immediately upstream of Cassiar Bar (11-3). An open water reach, approximately 35 kilometres in extent, was observed between Byers Camp below Big Salmon to a point immediately downstream of the Little Salmon River which was still open. An open water reach approximately 10 kilometres in extent existed downstream from a point immediately upstream of Five-Finger Rapid.

SUMMARY

A summary of observations noted during the 1982 freeze-up on the Yukon River are summarized in this report. Four overview flights on the Yukon River between Whitehorse and Eagle, Alaska, were made on November 1-2, November 12, 19 and 25. No attempt was made to interpret the observations other than note evident patterns of the freeze-up features.

An abnormally cold fall resulted in the freeze-up process commencing much earlier than usual. Because of this the November 1-2 overview flight saw the Yukon River generally solid below Coffee Creek, where usually water is still flowing at Dawson during this time. This did not permit the observation of the early stages of freeze-up downstream of this point though the later stages were observed. The location of the freeze-up features are noted on the accompanying topographic map sheets* as are photograph locations.

The ice front advanced progressively usptream during the successive flights until the majority of the river was ice covered. The location of the ice front was noted to be at Wolverine Creek, upstream of Fort Selkirk; at Yukon Crossing, downstream of Five-Finger Rapid; and at Cassiar Bar, downstream of the Teslin River on the November 12, 19 and 25 flights respectively. Ice jams were first observed at a location upstream of Fort Selkirk, at Five-Finger Rapid, at a point downstream of Carmacks, and at Cassiar Bar during the November 1-2, November 12, 19 and 25 flights respectively. Major open water reaches were consistently noted between Cripple Creek and Britannia Creek downstream of the Pelly River; between Henderson Creek and Reindeer Creek, downstream of the Pelly River; between Moosehide and Ballarat Creek, downstream of Dawson; and downstream of Cliff Creek which is downstream of the Fortymile River.

The results of this portion of the Winter Ice Cover and Break-up Study will complement future studies in providing a better understanding of the spring break-up process on the Yukon River. Doing so will hopefully lead to a solution for preventing or lessening detrimental effects associated with the break-up process.

---

* Topographic map sheets showing field notes are available for viewing at Water Planning and Management Branch, Inland Waters Directorate, Vancouver, B.C. and from the author in Whitehorse, Y.T.

YUKON RIVER BASIN STUDY

Project No. 41

PHASE V

FREEZE-UP 1983

Ric Janowicz
Hydrologist
Northern Affairs Program
200 Range Road
Whitehorse, Y.T. Y1A 3V1

February 1984

FREEZE-UP 1983

by Ric Janowicz

October 14, 1983

No ice was observed in the Yukon River upstream of the Pelly River, though some side channels were solid. Floating ice was first seen entering the Yukon from the Pelly River (10-14-1-10*). This ice melted progressing downstream and the river was again ice free approximately 25 kilometres downstream. The next floating ice was observed entering the Yukon from the Stewart (10-14-1-12) where ice was observed in both main and side channels (10-14-1-14). This ice was again melting downstream. Slush ice was observed entering the Yukon River from the Sixty Mile River which was seen to have a potential jamming location near the mouth (10-14-1-15). No floating ice was observed in the Klondike River, or in the Yukon River downstream to the Fortymile River. A series of aerial photograph reference points were selected with the hope that these may facilitate the estimation of stage variation in the reach between Dawson and Cliff Creek, a point downstream of the Fortymile River. The locations of these are listed separately.

October 27, 1983

The upper Yukon River was free of floating ice though shore ice in the main channel and side channels was observed. No pan ice was observed in the Teslin. The first such occurrence was noted at the Big Salmon River where ice was seen entering the Yukon River (10-27-1-3). Due to the still warmer Yukon River water this ice melted approximately 1 kilometre downstream. Slush ice was observed on the Little Salmon River (10-27-1-5) but this too melted approximately 1 kilometre downstream.

The river appeared to begin generating its own ice downstream of Five Finger Rapid. The first heavy ice was observed at McGregor Creek where the Yukon had approximately 30 percent coverage. This disappeared downstream however as the river was generally free of ice at McCabe Creek.

The Pelly River near the mouth was observed to contain considerable quantities of ice pans and floes (10-27-1-12). Floes on the Yukon itself were first seen forming at a point upstream of Cripple Creek near Selwyn (10-27-1-13), however, they slowly disappeared downstream

----

* Photographs are referenced throughout this report by month, day, roll and frame number. These photographs are available for viewing at Water Planning and Management Branch, Inland Waters Directorate, Vancouver, B.C. and from the author in Whitehorse, Y.T.

indicating the river was still warm in this reach. It is known that relatively warm groundwater flows enter the river at several locations in this reach. The ice was again essentially melted at Isaac Creek downstream of Selwyn (The Selwyn River was open).

Due to poor visability it was not possible to proceed farther downstream and the aircraft turned around at Ballarat Creek a short distance upstream of Coffee Creek.

The Stewart River was intercepted on the return trip and followed downstream for a short distance. Heavy ice was observed along the travelled reach as indicated by the photograph taken near Rosebud Creek (10-27-1-19).

The Pelly River was also intercepted at a point upstream of the mouth and followed almost to Pelly Crossing. Heavy ice was observed along the entire reach with several jams and potential jamming locations (10-27-2-4) including the one at Bradens Canyon (10-27-2-7). Ice was also observed on the Takhini River near Whitehorse (10-27-2-13).

November 2, 1983

Lake Laberge had only some shore ice along the edge. The Teslin River was clear of ice and the first ice observed in the Yukon River was at the Big Salmon River (10-27-2-20). Slush ice was observed in the Little Salmon River though it disappeared a short distance downstream as did ice from the Big Salmon. Ice was also observed entering the Yukon River from the Nordenskiold River near Carmacks and again disappearing downstream.

The Yukon River appeared to be generating small amounts of ice a short distance upstream of Five Finger Rapid increasing in quantity progressing downstream. Little ice was evident at the mouth of the Pelly River indicating the presence of jams upstream on the Pelly River (10-27-2-24A).

A potential jamming location was noted a short distance downstream of Fort Selkirk where the pans appeared to become better defined (11-2-2-0). The density of the pans increased moving downstream as is evident for the photograph of the Selwyn River mouth (11-2-2-2). The first occurrence of floe formation was noted at Isaac Creek (11-2-2-3) with very heavy ice at Coffee Creek (11-2-2-6).

The first occurrence of jamming was observed at Thistle Creek (11-2-2-8) followed by several key jamming locations immediately upstream of the White River (11-2-2-9, 10, 12).

Heavy ice was observed at the Stewart River (11-2-2-13) with a potential jam immediately downstream. A more serious jam was noted at Rosebute Creek downstream (11-2-2-15). Several potential jamming locations and jams of various sizes were noted between this point and Dawson (11-2-2-15, 16, 16, 18, 19, 20, 21). Since the river was not yet solid these key jamming locations were particularly obvious.

A large jam at Dawson extended the length of the river adjacent the community (11-2-2-22; 11-2-3-14). This was the most dramatic example to this point. After a small break the jam was continuous to a point upstream of Moosehide (11-2-3-15). The jam appeared to be quite dense at this point.

Progressing downstream the next jamming location was at the Chandindu River approximately 25 kilometres downstream of Moosehide (11-2-3-16). The river was generally open until a point immediately downstream of the Fifteenmile River where dense ice indicated a potential jamming location (11-2-3-18). The next jam, a relatively small one, was located at a point approximately 5 kilometres upstream of the Fortymile River (11-2-3-19).

Though the Fortymile River itself was open, ice on the Yukon River was backed up to this point from Cliff Creek approximately 10 kilometres downstream (11-2-3-20, 21).

What is thought to be a key jam was observed at Cliff Creek which is located at the first of a series of tight bends downstream of the Fortymile River. A considerable amount of pan ice was swept beneath the jam and downstream (11-2-3-24, 25; 2-2-4-0A, 0). Though considerable amounts of pan ice was observed below this point to Eagle there was no bridging.

On the return trip to Whitehorse the Stewart River was intercepted near McQuesten where ice was jamming and squeezing through a constriction (11-2-4-20). Due to poor visibility it was not possible to proceed upstream, therefore the river was followed downstream towards the mouth. A long reach of open water was observed near Rosebud Creek (11-2-4-21).

The Pelly River was intercepted at Pelly Farm where the river was solid to a point downstream near the mouth where a lead opened (11-2-4-22). The river above this point was open for approximately 10 kilometres where a jam was located at a sharp bend (11-2-4-23). Further upstream a jam was observed at Bradens Canyon (11-2-4-24). Generally the Pelly River appeared to have more jams than the Yukon River with sequences of long jams and open water.

On the return to Whitehorse pan ice was observed in the Takhini River (11-2-4-24-A).

November 9, 1983

This flight was carried out by Jim McFarlane, Water Survey of Canada, Whitehorse.

The Yukon River below Lake Laberge was observed to have light ice. Heavy ice was observed on the Teslin River with numerous bridges. Relatively heavy ice was observed in the Yukon below the Teslin River (11-9-1-1). The Big Salmon River near the mouth was solid with the exception of small open leads (11-9-1-2). Very little ice was observed on the Little Salmon River. Due to fog cover in the valley the river was not visible from this point to Minto. Visibility was poor below this point; however, considerable ice pans were observed to Fort Selkirk where the ice on the Pelly was very heavy. The first bridging of the Yukon was observed above Black Creek downstream of Fort Selkirk (11-9-1-7). Another jam was observed immediately downstream of Black Creek where the ice was seen squeezing through the canyon (11-9-1-10, 11). Very heavy ice with some bridging was observed downstream to the Indian River. These are illustrated by the accompanying photographs of points near Isaac, and at Coffee and Thistle Creeks (11-9-1-12, 14, 16).

As observed previously a key bridging location appears to be a point immediately upstream of the White River The White River is open near the mouth while the Yukon is solid (11-9-1-17, 19, 20).

The Stewart River was observed to be completely solid as were the Sixty Mile and Indian Rivers. The presence of heavy ice in the Yukon River is again illustrated by the photographs of the Yukon at Stewart Island, immediately upstream of the Sixty Mile River, and immediately downstream of the Indian River (11-9-1-21, 22, 11-9-2-1). The river was generally solid from this point to Swede Creek immediately upstream of Dawson. This is illustrated by the photographs of the Yukon River downstream of the Indian River and near Swede Creek (11-9-2-4, 5). Heavy moving ice was observed on the Klondike River and the Yukon at Dawson was open (11-9-2-6). The Yukon River was solid between Moosehide and Cliff Creek. Accompanying photographs show the ice cover at the Chandindu River and Fifteenmile River (11-9-2-11, 12).

A major jam was located at Cliff Creek (11-9-2-13). Ice pans and floes were observed in the Yukon downstream of this point to Eagle. No jams were sighted in this reach. Photographs of Eagle and the international boundary illustrate the degree of ice cover (11-9-2-15, 16).

November 16, 1983

Freeze-up progressed quite rapidly since the previous week. Approximately 50% of the Teslin River had ice pans (11-16-1-2) as observed near the mouth. The Big Salmon River was noted to be solid near the mouth. A potential jamming cross-section was noted at a sharp bend downstream of Walsh Creek (11-16-1-3). The Little Salmon River was open and the Yukon main channel was quite dense with pan ice in that reach (11-16-1-5). The density appeared to be increasing in the Carmacks area while the Nordenskiold River was open a short distance downstream (11-16-1-7, 8). Pan ice was starting to back up as well as squeeze through at Five Finger Rapid (11-16-1-9).

Floe formation was first observed in the Minto area (11-16-1-12). This process was further developed and potential jamming locations were noted both upstream and downstream of the Ingersoll Islands (11-16-1-14, 15).

The Pelly River was open at the mouth though very dense ice was observed downstream (11-16-1-16, 17). This appeared to thin out a little downstream but became dense again with increasing floe development downstream (11-16-1-20).

A major jam was observed at the Selwyn River and downstream of this point (11-16-1-21, 22, 23). The river was generally solid below this point as illustrated by the photographs of Britannia Creek with a small open lead, Ballarat Creek, Coffee Creek, Kirkman Creek and Thistle Creek (100 metres open lead) (11-16-2-0A, 0, 1, 2, 3).

The Yukon River below the White was open as during previous surveys (11-16-2-5).

The Stewart River appeared to be solid upstream of the mouth while the Yukon River itself remained open (11-16-2-6). The open water reach on the Yukon ended at Stewart Island (11-16-2-7) and the river was generally solid downstream from this point.

The river opened up near Swede Creek (11-16-2-12 looking upstream) and remained open to Fourth Creek between Moosehide and Fort Reliance downstream of Dawson (11-16-2-14). The Klondike River at Dawson was open (11-16-2-13).

The river remained solid from this point to Cliff Creek (11-16-3-1, 2, 3, 3A). Below this point the river remained open. Fewer pans were observed than in previous surveys indicating the jam may be more complete. It appeared as if slush ice was passing through the jam.

On the return to Whitehorse it was noted that Lake Laberge at the upper end was partially open (11-16-4-0) while the Yukon upstream was solid to a point downstream of the Takhini River (11-16-4-3, 5). The River was open above this point (11-16-4-7).

APPENDIX 2.

BREAK-UP OBSERVATIONS, 1982 and 1983

A SURVEY OF THE TIMING AND PROGRESSION OF THE ICE BREAK-UP ON THE YUKON RIVER, 1982

Prepared by T.D. Kent

Under contract to
Inland Waters Directorate
Environment Canada
Vancouver British Columbia

T. D. Kent Environmental Consultant, Ottawa, Ontario

TABLE OF CONTENTS

INTRODUCTION

The Yukon River rises in Bennett Lake and flows approximately 3,200 km through the Yukon Territory and Alaska to the Bèring Sea. A continuous ice cover is present from November (when freeze-up normally occurs) through late April, with break-up generally taking place in mid-May.

Recent ice research, such as that undertaken by the National Hydrology Research Institute, has shown that both the duration and the thickness of ice cover can have a considerable environmental and economic impact. Much of the current work examining ice regimes of northern rivers has taken place along the Mackenzie River in the Northwest Territories, where ice cover plays an important economic role in providing transportation links between remote communities during the winter. The length and nature of both the freeze-up and break-up periods, when the waterway cannot be used by either boats or motor vehicles is of major concern.

While the impact of ice conditions along the Yukon River in terms of difficulty of transportation access between river communities has diminished with the construction of the Klondike Highway between Whitehorse and Dawson City, spring flooding, as a result of ice jamming, does occur in communities along the river. Substantial damage results both at Dawson City (the most recent being the flood of 1979) and at Carmacks.

Terroux et al, (1981), have indicated that thick ice increases the potential for ice jamming and subsequent back water flooding. In addition, thick ice may indirectly augment such processes as ice shove and thrust against channel banks, island shores and channel beds, thereby increasing levels of sediment production and deposition. The same authors have also indicated that the jamming of ice pans during the freeze-up period can promote locally thick ice. Ice covers form as water levels are falling during the fall and winter. If the ice cover forms at higher than normal water levels the resulting cover has a much greater areal extent. This has implications during the spring break-up in that water levels may have to rise above freeze-up levels before there can be significant movement of the ice.

Very little work has been undertaken, to date, which specifically examines the ice regime of the Yukon River. Much of the work has been concentrated on observing the ice jam floods which have occurred in the vicinity of Dawson City. With the possibility of rapid future development and corresponding increases in discharge regulation, the need to obtain base line data is necessary.

Objectives of this study were as follows:

1) to conduct an ice survey along the Yukon River from Lake Laberge to Dawson City, including the lower reaches of the Stewart, Pelly and White Rivers in order to determine the following:
   a) the progression and timing of the ice break-up
   b) the location, magnitude and duration of ice jams along the watercourse, in addition to the extent of ice thrust and ice scour on the river banks
   c) the areal extent of backwater flooding associated with ice jamming.

Secondary objectives were to:

a) determine the thickness of the ice cover by examining pans of ice stranded on shore at points which were accessible by road
b) obtain water temperatures where access to the river was feasible.

LITERATURE REVIEW

As indicated in the previous section, very little research has been carried out which specifically examines the nature of ice break-up along the Yukon River. This is due, in large part to the location of communities along the reach of the river between Whitehorse and Dawson City. The only "major" settlement between those communities is Carmacks.

The little work that has been undertaken has been very site specific, dealing primarily with the break-up conditions 32 km upstream and downstream of Dawson City and was instigated by the recurrence of severe ice jam floods.

Fenco Consultants Ltd observed the break-up on the Yukon and Klondike Rivers at Dawson City in 1976, reporting on the location, nature and extent of ice jamming and related water levels. Their report showed that ice jams occurred under certain conditions:

1) in narrow reaches of the river
2) in shallow portions where ice becomes grounded or stranded in downstream portions of the ice jam
3) in wide reaches where islands obstruct the free flow of ice.

Acting on Fenco's recommendation to institute a program of regular ice observation, Orecklin (1981), observed the major ice jam flood which occurred at Dawson City on May 3, 1979, and has reported subsequent break-up events at that location in 1980 and 1981. While the majority of his report is devoted to a detailed description of the 1979 flood, Orecklin briefly describes ice conditions along the Yukon River between Dawson City and Whitehorse. Orecklin found that on May 2, 1979, the Yukon River between Whitehorse and Lake Laberge was open and free flowing, and that the reach of the river downstream of the Pelly River was generally ice bound with a few short, open leads. The White River was free of ice, the Yukon River was open between the White and Stewart Rivers; downstream of the Stewart River, ice jams were common and in some cases, several kilometres in length. The Yukon River at Dawson was open downstream as far as Moosehide; from that point Orecklin reports that the Yukon ice was competent. The Klondike River broke at Dawson on May 1, 1979. Orecklin reports unspectacular break-ups during 1980 and 1981.

While the two previously mentioned reports are useful in that they record specific break-up events at a specific location, little can be learned about the progression and timing of break-up along the Yukon upstream of Dawson City.

Terroux et al, 1981, have indicated that the timing and progression of river ice break-up is typically a function of several interrelated variables including: freeze-up characteristics, ice thickness and condition prior to break-up, climatological conditions prior to and during break-up and the discharge, and temperature regimes of the river. Since these variables are conditions which will vary from year to year it is necessary to institute a long term data collection program which would permit the identification of trends and interactions between the variables, thereby facilitating prediction of break-up events if one or more of the variables were to be manipulated.

METHODOLOGY

Although break-up is a function of the interrelated variables discussed in the foregoing, time did not permit detailed investigations relating to pre-break-up ice conditions on the Yukon River. The study was, therefore, limited to observation of the actual break-up process on the river.

Break-up was monitored primarily by means of oblique 35 mm aerial photography in order to determine the progression and timing of break-up. The photography was acquired over an 11 day period from May 9 to May 19 using a hand held 35 mm camera in a chartered Cessna 206. Due to the advanced state of the break-up (Carmacks was almost clear of ice on May 9) the aerial surveys were concentrated on the reach of the Yukon River between its confluence with the Pelly River and Dawson City. Supplemental ground based photography was obtained at Dawson City, Fort Selkirk and several other locations where fixed wing and helicopter landings were feasible.

The thicknesses of stranded pans of ice were obtained on the Klondike and Yukon Rivers at Dawson City and at Fort Selkirk. Water temperature data were also gathered at those locations as well as at the confluence of the White and Yukon Rivers and below the confluence of the Yukon and Sixty Mile Rivers.

Yukon River Ice Break-up

Break-up along the Yukon River must be assumed to be initiated in a fashion typical to northern rivers; that is to say rising water levels caused by snowmelt runoff in the southern portions of the drainage basin. The determination of break-up progression in the upper reaches of the river is hampered by the presence of large open areas of water which do not freeze over in the winter. Such areas of open water are common occurrences and are generally found as far downstream as Five Fingers Rapids.

While, as with other large northern rivers, the 1982 break-up along the Yukon River was not a sequential event, there was a general south to north progression of ice clearance. Downstream of Lake Laberge, break-up (ice clearance) progressed in the following generalized order.

a) the reach of the river downstream of Lake Laberge to Carmacks
b) the area downstream of the confluence of the Yukon and Klondike Rivers at Dawson City
c) the reach between the White River and Dawson City
d) the reach between Carmacks and the Pelly River
e) the reach between Fort Selkirk and the White River.

Field Observations

Prior to the commencement of field work on May 9, 1982, contacts were established with the Royal Canadian Mounted Police detachments located in the river communites of Carmacks, Pelly Crossing and Dawson City. Telephone contact was maintained with these sources on a regular basis from April 19, 1982 to May 6, 1982.

Ice conditions at Carmacks started to deteriorate between April 23, when solid ice existed (and people were still crossing the river) and April 28 when the ice was becoming slushy, overflow was occurring and shore leads were developing. By May 4, ice crossings were prohibited by the police and the channel at the upstream end of the community was 60% clear of ice.

Reports from Dawson City indicated a more rapid deterioration of ice, particularly on the Klondike River, where ice had gone out on April 28 approximately 16 km upstream of Dawson, creating a potential flood hazard for the community of Rock Creek. Klondike River water was overflowing Yukon River ice. On May 3, water was running freely in places on the Klondike River, overflow on the Yukon had increased to a depth of approximately one metre, however, light vehicles had only just stopped using the ice bridge. Shore leads were beginning to develop.

On May 4, the R.C.M.P. in Dawson reported that flood damage had occurred at Rock Creek. On May 7, the Klondike River broke-up completely and ice began to run. From May 9 to May 19 aerial reconnaissance was carried out along the length of the river.

May 9

On May 9, 1982 an aerial survey of the Yukon River was conducted between Whitehorse and Dawson City in order to obtain base line information. The Yukon River from Whitehorse to approximately 16 km above Carmacks was completely clear of ice, confirming earlier telephone reports, (it should be noted that Lake Laberge was completely ice bound with the exception of the lake outlet). Carmacks itself was clear of ice. Downstream of Carmacks there was progressively more ice in the river, however, although break-up was well underway there was no evidence of movement. Well developed shore leads and rotting, probably thoroughly candled ice characterized the whole of the Yukon River from downstream of Carmacks to Dawson City. The Pelly and Stewart Rivers were still ice bound, however, the White River was completely clear of ice for at least 100 km upstream from its confluence with the Yukon River.

Yukon River ice downstream of Dawson City to the Alaska border appeared to be more competent; significantly fewer shore leads were observed. The Klondike River was broken-up and flowing freely from its confluence with the Yukon River as far upstream as Rock Creek. Three ice jams were present in that reach of the river, however none of the jams was of a significant size. Klondike River water was overflowing onto Yukon River ice at Dawson, but there was no indication of ice movement on the Yukon River. In the Dawson City area, downstream of the Klondike confluence, the Yukon River was ice bound from shore to shore, however small shore leads had developed on the east bank. While the water level had risen approximately one metre during the day (Dawson City municipal employees), there was no significant cracking in the ice cover or breaking of the shore lead hinges.

May 10

On May 10, no significant changes where evident in the condition of either the Yukon or Klondike Rivers at Dawson City. Upstream of Dawson no movement of ice was noted until just downstream of the White River where minor movement of ice had occurred. Some movement was also noted in the vicinity of Britannia Creek, upstream of the White River, as well as below Carmacks.

May 12

The next complete survey of the Yukon River from Whitehorse to Dawson City took place on May 12. Most small creeks in the upper reaches were running clear and flooding (as a result of the previous two days of rain). The first evident change from the May 10 survey occurred at a point 16 km above Carmacks. The solid ice cover on the Yukon River had cleared out from that point, downstream through Carmacks to just above Five Fingers Rapids, where an ice jam had formed. Five Fingers Rapids was clear of ice, however, the downstream reach of the river was ice bound, characterized by deteriorated ice with well developed shore leads. Several small ice jams occurred in this reach of the river, and in the area of the Hoochekoo Bluff/where open areas, particularly in the downstream sections, were encountered. Generally in the whole portion of the river from Yukon Crossing to McCabe Creek the ice had moved. Further ice jamming was noted near Minto.

In the vicinity of the Ingersoll Islands the river ice was rotten and open areas occurred, usually around the islands. A channel had opened along the east bank. Ice was moving near the downstream end of the islands. A series of small jams were present from that point through to Fort Selkirk, where a significantly more extensive jam occurred.

The jam located at Fort Selkirk was composed of relatively small blocks of weak, saturated, candled ice pans. There was no evidence of backwater flooding.

Downstream of Fort Selkirk, there was very little evidence of ice movement. Generally, shore leads were well developed and the ice was deteriorating, but the main channel was ice bound. Upstream of Cripple Creek, open patches of water were evident, while in the vicinity of Britannia Creek the channel ice appeared to be more competent. Generally there was very little change noted in this area since May 10.

Below its confluence with the White River, the Yukon River was open to the Stewart River. Ice was flowing on the Stewart just upstream of the confluence and the Stewart itself was clear of ice for approximately 40 km upstream. Several minor ice jams were noted on the Yukon River, downstream of the Stewart.

General conditions downstream of the Stewart consisted of rotting channel ice with well developed leads around the islands. Backwater flooding was noted at the confluence with the Sixty Mile River, indicating rising water levels on the Yukon.

The Yukon River was open upstream of the Klondike (just above the last islands) as well as downstream of the community. An ice jam had formed at Moosehide, on the west side of the third island above Fort Reliance and on the east side of the river below Fort Reliance.

There was, however, no sign of ice movement at Dawson City. By 22:00 hr a significant shore lead opened on the west side of the Yukon River; cracks in the ice appeared at the same time.

May 13

By 03:00 hr on May 13 at Dawson City, the shore lead developing on the west side of the river had opened considerably to a point opposite and just downstream of the Bank of Commerce. Water levels were rising rapidly. At 07:15 hr the western shore lead had opened into a channel extending about 100 metres downstream of the bank. Pans of ice flowing downstream were piling up. Water levels had risen approximately 1.5 metres since 03:00 hr.

The Yukon River upstream of the Klondike showed no significant change when it was surveyed by helicopter at 09:00 hr. Downstream of Dawson, in the vicinity of Moosehide and Fort Reliance there was evidence of backwater conditions. No significant change in the ice conditions on the reach of the river in Dawson was noted, however ice in the vicinity of the western shore lead was becoming water logged.

Upstream of the ice front, water was flowing under the ice for a distance of 20 or 30 metres, coming to the surface under pressure through holes in the ice cover.

By 10:30 hr water levels at Dawson were rising quickly, at an estimated rate of 0.6 m/hour (Lee, personal communication). At approximately 11:45 hr the western 30% of the ice cover started to move. Immediately prior to this movement the shore leads had broken a channel to within 30 metres of the Dawson ice bridge. At 12:00 hr a large movement of ice occurred accompanied by a rapid rise in water levels; the whole of the channel ice cover began to move, breaking into ice pans of varying size, some of which were piled onto the shore. These stranded pans were characteristically 1-2 metres thick and were composed of thick candled ice.

Observations made by Lee at Moosehide (downstream of Dawson), showed that the ice was moving at approximately 0.3 metres/second. At 13:00 hr the ice was moving past Fort Reliance, however it was jamming at the first river bend below that location (approximately 27 km downstream of Dawson).

By 13:30 hr the ice jam located at Fort Reliance had extended as far back as the ferry crossing in Dawson City, causing a significant rise in upstream water levels but there was no danger of flooding at that time.

The main channel of the river in the vicinity of Dawson was clear of ice at 19:00 hr, however, ice pans combined with large amounts of debris were still trapped near the east bank. Water levels had dropped significantly since 13:30 hr (Lee, personal communication). Ice had stopped running.

At 21:00 hr the channel at Dawson was again full of moving ice. By 21:25 hr the ice had stopped running. An aerial survey indicated that running ice originated from the reach between the Stewart and Klondike Rivers. At 22:25 hr a jam formed on the Yukon River above the Klondike River, the ice jam at Fort Reliance was still in place and water levels appeared to be rising at that location. The Yukon River at Dawson was running at 22:30 hr but the channel was not full of ice. At 23:45 hr the river was full of ice from bank to bank, however, by 02:00 hr on May 14, the river was relatively free of ice.

May 14

At 09:40 hr Yukon River ice from above the Klondike River was again observed to be moving through Dawson City and by 10:30 hr the channel in Dawson City was full of ice which was travelling at approximately 5 km/hour (Lee, personal communication). The Yukon River upstream of Dawson was relatively clear of ice to just below the Stewart River, however, the main channel in the immediate vicinity of the Stewart River confluence was ice covered.

At 12:00 hr broken ice was running bank to bank in the channel at Dawson City; water levels had risen approximately 2 metres. By 13:00 hr water levels were still rising and there was the potential for flooding, however, by 13:30 hr, the ice jam at Fort Reliance was moving and water levels had dropped. At 14:30 hr water levels at Dawson had also dropped and the channel from Dawson through to Fort Reliance was clear of solid ice, however, loosely packed ice pans were moving in that reach. Bank to bank broken, but more solidly packed moving ice was encountered at Chandindu Creek. Downstream of Cassiar Creek solid ice was noted occupying approximately half the channel. Tightly packed moving ice was observed from the Forty Mile River downstream as far as Cliff Creek. From that point to Eagle, Alaska, the river was clear of ice, with the exception of some island channels. Tightly packed moving ice was again encountered from Eagle as far downstream as the Nation River in Alaska where a solid bank to bank ice cover was encountered. By 16:00 hr, moving ice had cleared through Dawson City to a point approximately 10 km downstream of Chandindu Creek.

At 17:20 hr ice was running on the Yukon River from just below the Stewart confluence to approximately 4 km below the Sixty Mile River. Downstream of that point to the Canadian border, very little ice remained in the river.

May 15

On May 15, ice was moving on the Yukon River in the section from its confluence with the Pelly River downstream to Cripple Creek, where an ice jam was located. The ice jam which had been located at Fort Selkirk on May 12 had broken up on the evening of May 14 for the Pelly River cleared of ice during a 12 hour period beginning at 19:30 hr on May 14. (Danny Joe, personal communication).

The Cripple Creek jam extended to Isaac Creek and from that point for a distance of approximately 8 km downstream to Britannia Creek, ice in the Yukon River was moving. From Britannia Creek to the confluence of the Yukon and White Rivers, the channel was ice bound, open water occurred around the islands and water levels appeared to be rising.

Conditions upstream of Fort Selkirk were generally open. Ice pans occurred around islands in quiet water areas away from the main channel flow. A small jam occurred just below Hoochekoo Creek at Yukon Crossing, however, from that point the river was free of ice to well upstream of Carmacks (16 km).

May 16

The ice located 16 km upstream of Carmacks had cleared out by the afternoon of May 16. Ice was running in the river just above Five Fingers Rapids. Apart from ice pans packed around islands, the channel was clear to Hoochekoo Bluff where a jam extending downstream to McCabe Creek occurred. The river downstream of McCabe Creek was clear of ice to Isaac Creek. The river was jammed again approximately 2 km downstream of Pedlar Creek. There was no indication of movement within the ice jams. On the north shore in the vicinity of Kirkman Creek, a channel had opened around islands located in that reach of the river. Very little change had occurred in the location or in the condition of the ice at the confluence of the Yukon and White Rivers, however, the downstream edge of the ice appeared to have "moved" upstream approximately 0.5 km.

May 17

By 12:30 hr on May 17 the ice front, which was located at Britannia Creek on the previous day, had moved downstream to a point just above Pedlar Creek. There was evidence of ice movement from that point to Cripple Creek. Downstream of Cripple Creek, through Kirkman Creek to the White River there was no significant change in the condition or the location of the Yukon River ice.

Downstream of the Stewart River, the Yukon was completely clear of ice except for some pans stranded along the shore.

May 18

Twenty-fours hours later, on May 18 the Yukon River was basically clear of ice to just above Pedlar Creek where a jam occurred which extended to downstream of Ballarat Creek. From downstream of that point solid ice was encountered which showed no signs of movement. The channel on the northeast side of the river from Kirkman Creek to the White River was open.

Closer examination of this reach of the river, at low altitude, revealed that water levels were extremely low. It was observed that the ice in the river for approximately 2 km upstream of the White River was solidly grounded and appeared to be melting insitu. Further upstream, in the vicinity of Ballarat Creek water seemed to flow freely under the ice, but there was no sign of ice movement.

General conditions below Britannia Creek had not changed by 20:30 hr, however, ice had started to run (for short distances) just downstream of Kirkman Creek. Pressure ridges were observed. Water was coming through the ice under pressure and overflow was occurring. The same pre-break-up processes which were observed immediately prior to the break-up at Dawson were occurring on this stretch of the river. However, by 14:35 hr on May 19, there was no significant change in the river's condition. Although there was still ice in this stretch of the river, it was felt that it represented an anomalous condition and that within the context of this preliminary study, the value of the information obtained by continuing the survey did not warrant the additional costs.

Water Temperature

Terroux et al, 1981, have shown that in conditions of low discharge which occurred on the Mackenzie River during the 1980 and 1981 break-up periods, high water temperatures (between 8°C and 9°C) contributed significantly to the rate at which the ice cleared out of the river. In order to determine whether a similar condition existed on the Yukon River in 1982, water temperatures were obtained at several locations. The samples were collected in open areas of water appearing behind minor ice jams or ice fronts. However, because of logistical limitations and access difficulties, most temperature data were collected downstream of ice covers, a fact which most certainly lowered temperature readings. Additional water temperatures collected at a later date by R.O. Lyons, in ice free water in the vicinity of Whitehorse show only slightly higher values.

TABLE I

WATER TEMPERATURES

LOCATION	TEMPERATURE	DATE
Yukon River at Fort Selkirk	1.0°C	May 12
White River at Yukon River	2.0°C	May 14
Yukon River below Sixty Mile River	1.5°C	May 14
Yukon River at Dawson City	1.0°C	May 12
Klondike River at Dawson City	0.5°C	May 12
Yukon River at Whitehorse*	3.0°C	May 15
Yukon River at Miles Canyon*	3.5°C	May 16
Yukon River at Whitehorse*	4.9°C	May 16

*Temperature collected by R.O. Lyons

Although the temperature readings listed above show that some heat (stored in the water) was available to melt ice, the importance of heat transfer as a mechanism in the 1982 break-up was not unusual.

SUMMARY

The 1982 break-up of Yukon River ice followed a generalized sequence characteristic of break-up on many rivers. The sequence is described below.

1. **Development of Shore Leads.** Shore lead development is a function of conditions which occur during the autumn freeze-up period. Ice covers form when the discharge is at "normal" levels. After formation of ice at a particular water level, discharge usually decreases; the ice cover lowers creating what can be best described as a hinge between the channel and the shore. With the advent of spring melt conditions, snowmelt and precipitation run off generally overflows the hinges creating shore leads. Increasing discharges resulting from the melt lift the channel ice cover creating a major weakness in the ice cover.

2. **Deterioration of Channel Ice.** The rate of deterioration in the competence of the channel ice is a function of such climatological variables as air temperature, insolation, wind and water temperature, during freeze-up periods, over the winter and during break-up. Air temperature, wind and channel aspect, during the winter determine ice thickness while air temperature, insolation, and the amount of heat stored in the water during break-up determines the rate of deterioration of channel ice (Terroux et al, 1981). Increase in discharge resulting from snowmelt and precipitation contribute a mechanical aspect to ice break-up.

3. **Ice Jams and Backwater Flooding.** Terroux et al, 1981, and Egginton (personal communication) have indicated that a thick ice cover which is mechanically broken-up (as in the case of a rapid rise in discharge) increases the potential for large ice jams and subsequently higher levels

of backwater flooding. The thicker ice will break into larger pans of ice than would occur under a thin ice cover condition. Larger pans are more susceptible to wedging in narrow channels or grounding in shallow reaches of a river. Generally ice jams composed of large pans of competent ice are tightly packed, stronger and of greater duration than those created by small pans of thin candled ice.

Break-up along the Yukon River in 1982 was unspectacular in nature. There were no major ice jams, no significant flooding occurred, and the ice pans were for the most part small and composed of relatively thin, candled ice. The ice jams which did occur were loosely packed, of little strength and of short duration. There were no hanging dams or ice jams composed of large thick ice pans and subsequently no significant flooding occurred. None of the Yukon River communities were flooded, although the community of Rock Creek on the Klondike River was extensively flooded by backwater caused by an ice jam.

As previously indicated, the 1982 break-up was not a sequential event. Although there was a general south to north trend in the progression of ice clearance, this progression was not consistent. The progression of break-up from Lake Laberge downstream to the Canada-U.S. border is described in the following:

a) Ice first cleared on the reach of the river downstream of Lake Laberge through to Carmacks. Alford (personal communication) reports that invariably portions of this section of the Yukon River remain open throughout the winter. Earlier break-up in this section may be attributed to higher volumes of water being released from Marsh Lake throughout the winter and possibly due to warmer climatic conditions in the upper reaches of the Yukon River.

b) The area downstream of the confluence of the Yukon and Klondike Rivers broke up and cleared of ice on May 13, 1982, 5 days after the mean break-up date of May 8 calculated by Orecklin, (1981). Ice ran in this stretch of the river for a period of almost 36 hours. The Klondike

River broke up on May 7, 1982, and during the six day interval between the two events, Klondike River water overflowed Yukon River ice. According to local sources in Dawson City, the Yukon River generally breaks up between 4 and 7 days after the Klondike River. The process of break-up on the Yukon below Dawson City may be assumed to have been accelerated by the break-up of Klondike River six days prior to the Yukon River event.

c) The reach of the river between the White River and Dawson City began to run on May 14 (Slides May 10). There seemed to be a corresponding increase in discharge from the White River, although the Stewart River confluence with the Yukon River did not clear of ice until 4 days later. It would appear that increasing discharge on the White River triggered the mechanical break-up of the candled ice below its confluence with the Yukon River (Slides May 14).

d) The sector of the river between Carmacks and the Pelly River cleared of ice, that is to say that ice pans were running freely by May 15. No major tributaries (of the importance of the Pelly or Stewart Rivers) are present in this section of the river and therefore, there can be no sudden increases in discharge contributing to mechanical break-up. It would appear that the break-up in this portion is the continuation of a sequential process beginning in the upper reaches of the river.

e) Although by May 18 the reach between Fort Selkirk and the White River was generally clear of ice to Britannia Creek, this section of the river was the last to clear of ice. Several hypotheses may be put forward to explain this anomalous condition:

1. that high discharges from the White River impeded the flow of Yukon River water retarding break-up,
2. this reach is generally very narrow, contained between steep mountains and is known to have a very severe climate during the winter (Williams, personal communication). Depending on

microclimatological conditions ice may be much thicker.

3. that thick ice was grounded in the channel just above the White River confluence in conditions of very low water and was simply melting insitu.

CONCLUSIONS

a) Break-up of the Yukon River ice cover between Lake Laberge and the Canada-U.S. border took place over a period of approximately 27 days from April 23, when solid ice conditions still existed at Carmacks to May 19, when the whole river, with the exception of the reach between Britannia Creek and the White River, was clear of ice.

b) Break-up on the Yukon River in 1982 was not a sequential event. The upper reaches are the first to clear of ice followed by the lower sections and finally the middle portion. Three tributaries, the Klondike, White and Pelly Rivers seem to accelerate Yukon River break-up in their respective reaches.

c) Release of ice at and below Dawson City seems to facilitate break-up upstream, between Dawson City and the Sixty Mile River.

d) No major flooding occurred along the Yukon River, no communities suffered flooding, no major ice jams occurred. Flooding caused by an ice jam did however occur at the community of Rock Creek on the Klondike River.

e) Ice on the Yukon River immediately prior to break-up appeared to be thoroughly candled, and relatively thin.

f) The reach of the river between Fort Selkirk and the White River is an anomalous condition, which may be the result of local climatological conditions.

RECOMMENDATIONS

While the observations contained in this report are useful in establishing the sequence of break-up events, the actual timing and progression is dependent on a number of interrelated variables. In order, therefore, to develop a complete understanding of the break-up process, the consultant makes the following recommendations for future studies:

1. that freeze-up characteristics be examined in detail;

2. that ice thickness be obtained along selected portions of the river, specifically at river communities; in the reach above the White River and at the confluences of major tributaries, prior to ice deterioration;

3. that the microclimate of the river between Fort Selkirk and the White River be examined in detail;

4. that the discharge regime of the Yukon River and its tributaries be monitored throughout the break-up period. At the very least, increases in water levels should be surveyed regularly at the major confluences and at communities. This would require extensive helicopter support as fixed wing landing areas along the river are very limited;

5. that the temperature regime of the river during break-up be examined in detail;

6. future monitoring of break-up should be done utilizing vertical aerial photography of the river, which would facilitate and improve the accuracy of the mapping of the progression and timing of ice movements. Vertical stereophotography would also permit determination of ice conditions;

7. observers should be in the field prior to, or shortly after the first

deterioration of ice is reported;

8. liaison should be established with the Water Survey of Canada for the reporting of ice conditions prior to the commencement of field work.

REFERENCES

Fenco Engineering, 1976, Yukon Flood Study, Department of Indian and Northern Affairs, Whitehorse, Yukon.

Orecklin, M., 1981, Dawson Flood Study, ice jam of May 3, 1979; 1980 and 1981, break-up, Department of Indian and Northern Affairs, Whitehorse, Yukon.

Terroux, A.C.D., D.A. Sherstone, T.D. Kent, J.C. Anderson, S.C. Bigras, and L.A. Kriwoken, 1981, Ice Regime of the Lower Mackenzie River and Mackenzie Delta, Inland Waters Directorate, Environment Canada, Hull, Quebec.

APPENDIX 1

SLIDES

Several hundred 35mm slides were taken in the course of the survey and are available for viewing at Water Planning and Management Branch, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C.

APPENDIX 2

MAPS

The ice cover as occurred on each day of the survey was mapped on 1:250,000 scale NTS maps. These maps are available for study at Water Planning and Management Branch, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C.

A SURVEY OF THE TIMING AND PROGRESSION OF

THE ICE BREAK-UP ON THE YUKON RIVER, 1983

Prepared by T.D. Kent

Under contract to
Inland Waters Directorate
Environment Canada
Vancouver British Columbia

T. D. Kent Environmental Consultant, Ottawa, Ontario

Table of Contents

1. INTRODUCTION

The Yukon River rises in Bennett Lake and flows approximately 3,200 km through the Yukon Territory and Alaska to the Bering Sea. A continuous ice cover is present from November (when freeze-up normally occurs) through late April, with break-up generally taking place in mid-May.

Recent ice research, such as that undertaken by the National Hydrology Research Institute, has shown that both the duration and the thickness of ice cover can have a considerable environmental and economic impact. Much of the current work examining ice regimes of northern rivers has taken place along the Mackenzie River in the Northwest Territories, where ice cover plays an important economic role in providing transportation links between remote communities during the winter. The length and nature of both the freeze-up and break-up periods, when the waterway cannot be used by either boats or motor vehicles is of major concern.

While the impact of ice conditions along the Yukon River in terms of difficulty of transportation access between river communities has diminished with the construction of the Klondike Highway between Whitehorse and Dawson City, spring flooding, as a result of ice jamming, does occur in communities along the river. Substantial damage results both at Dawson City (the most recent being the flood of 1979) and at Carmacks.

2. Problem

A requirement exists for the acquisition of reliable and representative baseline ice data for the Yukon River against which future changes in the river's regime may be evaluated. Acquisition of this baseline date with a sufficiently long period of record to allow a rigorous statistical analysis is often difficult to obtain. The potential effects of major changes in the regime of the river are therefore, hard to predict.

Terroux et al, 1981, has indicated that the timing and progression of ice break-up is typically a function of several interrelated variables including the following: freeze-up characteristics, ice thickness and condition prior to break-up, climatological conditions prior to and during break-up, and the discharge and temperature regimes of the river. The interrelationship between these variables will affect the timing and progression of the break-up event. For example, thick, competent ice broken-up by high discharge will be more likely to form large, strong ice jams than would weak, candled ice.

Since these variables will change on an annual basis, it is necessary to institute a long term data collection program which would permit the identification of trends and interactions between these variables. The data base would facilitate the prediction of break-up events if one of the variables were to be manipulated. For example, if large scale discharge regulation was instituted on the Yukon River, the effects of that regulation on the break-up characteristics of the river could be predicted using the long term data base.

3. Previous Work

Very little research has been carried out which specifically examines the nature of ice break-up along the Yukon River. That which has been undertaken is, with the exception of Kent (1982), site-specific, and deals primarily with break-up conditions 32 km upstream and downstream of Dawson City.

Fenco Consultant Ltd observed the break-up on the Yukon and Klondike Rivers at Dawson City in 1976, reporting on the location, nature and extent of ice jamming and related water levels. Their report showed that ice jams occurred under certain conditions:

1) in narrow reaches of the river
2) in shallow portions where ice becomes grounded or stranded in downstream portions of the ice jam
3) in wide reaches where islands obstruct the free flow of ice.

Orecklin (1981), observed the major ice jam flood which occurred at Dawson City on May 3, 1979 and has also reported on the subsequent break-up events at that location in 1980 and 1981. Although a substantial portion of Orecklin's report is devoted to the description of the 1979 Dawson flood, it does contain a brief account of the ice conditions which occurred along the Yukon River between Whitehorse and Dawson City in 1979.

Orecklin found that on May 2, 1979, the Yukon River between Whitehorse and Lake Laberge was open and free flowing, and that the reach of the river downstream of the Pelly River was generally ice bound with a few, short open leads. The White River was free of ice, the Yukon River was open between the White and Stewart Rivers; downstream of the Stewart River, ice jams were common and in some cases, several kilometres in length. The Yukon River at Dawson was open downstream as far as Moosehide; from that point Orecklin reports that the Yukon ice was competent. The Klondike River broke at Dawson on May 1, 1979. Orecklin reports unspectacular break-ups during 1980 and 1981.

The first document (Kent, 1982) which specifically examined break-up processes along the length of the Yukon River from Lake Laberge to the Alaska-Yukon border was produced for the Inland Waters Directorate of Environment Canada in 1982. The timing and progression of the break-up was reported and some water temperature data was collected. However, logistical difficulties precluded the gathering of data relating to freeze-up characteristics, ice conditions prior to break-up, discharge regimes and climatological factors, all of which affect the prediction of break-up events. A summary of the report's findings follows:

a) Break-up of the Yukon River ice cover between Lake Laberge and the Canada-U.S. border took place over a period of approximately 27 days from April 23 when solid ice conditions still existed at Carmacks to May 19, when the whole river, with the exception of the reach between Britannia Creek and the White River, was clear of ice.

b) Break-up on the Yukon River in 1982 was not a sequential event. The upper reaches are the first to clear of ice followed by the lower sections and finally the middle portion. Three tributaries, the Klondike, White and Pelly Rivers seem to accelerate Yukon River break-up in their respective reaches.

c) Release of ice at and below Dawson City seems to facilitate break-up upstream, between Dawson City and the Sixty Mile River.

d) No major flooding occurred along the Yukon River, no communities suffered flooding, no major ice jams occurred. Flooding caused by an ice jam did however occur at the community of Rock Creek on the Klondike River.

e) Ice on the Yukon River immediately prior to break-up appeared to be thoroughly candled, and relatively thin.

f) The reach of the river between Fort Selkirk and the White River is an anomalous condition, which may be the result of local climatological conditions.

4. Project Objectives

The primary objective of the present study is to continue the collection of the baseline data relating to the timing and progression of ice break-up along the Yukon River from Lake Laberge to Dawson City, including the lower reaches of the Stewart, Pelly and White Rivers. Particular emphasis will be placed on the reach of the river between Carmacks and Dawson City.

Primary project objectives are:

a) to determine the timing and progression of ice break-up;

b) to determine the location, magnitude and duration of ice jams and associated backwater flooding;

c) to determine the thickness and character of the ice cover immediately prior to break-up by examining pans of ice stranded on shore at accessible points;

d) to obtain water temperatures wherever possible;

e) to compare information gathered with previous observations, particularily those obtained in 1982.

5. Methodology

Data Acquisition (Timing and Progression)

In order to adequately assess the downstream progression of ice, it is necessary to observe break-up immediately downstream of Lake Laberge. As it was not feasible to be in the field to observe that event, contacts were establised and maintained with Royal Canadian Mounted Police Subdivisons located at Carmacks and Dawson City in order to obtain information relating to ice conditions. When it appeared, from these observations, that break-up at Carmacks was imminent, field work began.

The 1983 break-up along the Yukon River was monitored from the air using a chartered Cessna 206. Oblique aerial colour video tape imagery and oblique aerial 35mm slide photography was obtained over an 11 day period from April 28 to May 8 1983. Actual observations took place on consecutive days from April 28 to May 5. The last flight took place on May 8.

It was also proposed to obtain stereo aerial photography at the confluences of major tributaries and at Dawson. However, due to logistical problems involving local air charter firms, the aircraft necessary for the completion of this portion of the work was not available and the stereo photography was not acquired.

In addition to the aerial photography, supplemental ground based photography was obtained at Dawson City, Fort Selkirk, Ballarat Creek and several other locations where fixed wing and helicopter landings were feasible.

The thickness of stranded pans of ice were obtained at Dawson City. Water temperature data was collected at Minto and at the confluence of the White and Yukon Rivers.

6. Yukon River Ice Break-up

Break-up along the Yukon River must be assumed to be initiated in a fashion typical to northern rivers; that is to say rising water levels caused by snowmelt runoff in the southern portions of the drainage basin. The determination of break-up progression in the upper reaches of the river is hampered by the presence of large open areas of water which do not freeze over in the winter. Such areas of open water are common occurrences and are generally found as far downstream as Five Fingers Rapids.

While, as with other large northern rivers, the 1983 break-up along the Yukon River was not a sequential event, there was a general south to north progression of ice clearance, similar to that which occurred in 1982. Downstream of Lake Laberge, break-up (ice clearance) progressed in the following generalized order.

a) the reach of the river downstream of Lake Laberge to Carmacks
b) the area downstream of the confluence of the Yukon and Klondike Rivers at Dawson City
c) the reach between the White River and Dawson City
d) the reach between Carmacks and the Pelly River
e) the reach between Fort Selkirk and the White River.

6.1 Observations

Prior to the commencement of field work on April 28, 1983, contacts were established with the Royal Canadian Mounted Police detachment at Dawson City, the Department of Renewable Resources, Yukon Territorial Government in Carmacks and the Water Survey of Canada in Whitehorse. Telephone contact was maintained with these sources on a regular basis from April 11, 1983 to April 26. A National Hydrology Research Institute team reported ice thicknesses at Dawson City and Carmacks.

6.2 Pre-Field Observations

April 11

On April 11, Monty Alford (Water Survey of Canada) reported that the Yukon River in the vicinity of the Stewart River confluence was covered by thick and stable ice. There had been no substantial thaw and temperatures ranged between -20°C and 0°C. Overflow was observed by Alford at the confluence of the Donjek and White Rivers on April 9.

April 13

On April 13, the Dawson City R.C.M.P. reported that the mouth of the Klondike River was open and that there was less than 1 metre of ice in the Yukon River. The ice bridge at Dawson City was becoming "slushy" and one lane had been closed. Temperatureswere still ranging between -20°C and 0°C. The Department of Renewable Resources at Carmacks indicated there was some overflow evident at that location. S. Bigras (N.H.R.I.) reported that the ice at Carmacks was deteriorating quickly, that it was weak and wet and approximately66cm - 110cm in thickness. Very little snow was left in the hills around Carmacks.

April 14

On April 14, Bigras reported that the White River was still frozen and that ice thicknesses ranged between 66cm and 89cm. The reach of the Yukon River between the White and Stewart Rivers was frozen; freeze-up ice jams were evident. There was open water in the vicinity of Stewart Island and a shore lead extended downstream from Stewart Island for a distance of approximately 8km. Shore leads were observed at Rosebutte Creek; the Klondike River was open and flowing at the Yukon River confluence, however there was no overflow. Open areas were evident in the Moosehide and Fort Reliance areas downstream of Dawson City.

April 15

Bigras reported that ice on the Yukon River at Dawson City ranged between 63cm and 109cm in thickness. These measurements were obtained in a cross-section just upstream of the ice bridge. The ice was generally covered by snow varying in depth from 13cm to 36cm, however some areas of the reach were clear of snow.

April 16

No change was reported in the condition of the ice at Carmacks.

April 19

The Department of Renewable Resources indicated that the ice at Carmacks was rotting in situ. Temperatures ranged between 4°C and 8°C.

April 20

Dawson City R.C.M.P. indicated that the ice bridge was still being used and that ice on Kondike River was intact upstream of the Yukon River confluence.

Open areas were observed at Carmacks. The Department of Renewable Resources also reported that cracks were developing in the ice cover and that the ice was becoming saturated. Air temperatures remained in the 5°C to 10°C range.

April 25

Ice at Carmacks started to move at the highway bridge on April 25. Ice pans were moving upstream of the bridge and there appeared to be clear water upstream of Carmacks. Small streams were flowing and air temperatures were above 20°C (Department of Renewable Resources).

April 26

Dawson City R.C.M.P. reported that the Klondike River was starting to break-up although the Yukon River ice cover was still intact. An open area on the Yukon River was reported just upstream of the Klondike confluence. Air temperatures varied between 15°C and 20°C for the previous three days.

6.3 Field Observations

April 28

On April 28, 1983 an aerial survey of the Yukon River was conducted between Whitehorse and Dawson City (Slides 1/1 -4/2) in order to obtain base line information. The Yukon River from Whitehorse through Carmacks was clear of ice. Ice at Carmacks broke up on April 27. It should be noted that Lake Laberge was completely ice bound with the exception of the lake's outlet. Downstream of Carmacks there was progressively more ice in the river, with open areas located around islands. Well developed shore leads and open water occurred downstream as far as Five Fingers Rapids. Downstream of Rink Rapid, the ice appeared to be more competent, however break-up along the whole length of the river from Carmacks to Dawson City was well underway. There was no evidence of ice movement, however at Fort Selkirk, just downstream of the Pelly River confluence the river was open (Slide 2/11). The Pelly River was ice bound at the confluence.

Downstream of Fort Selkirk there was no open water, with the exception of shore leads. There was no evidence of ice movement and the ice was relatively clear of snow. Shore leads occurred primarily around islands. In the vicinity of Isaac Creek there was significantly more open water and ice pans were evident. Just upstream of Ballarat Creek there was evidence of ice movement, however downstream of that location the ice was generally much more competent.

The White River was open and flowing; the Yukon River downstream of the White was ice bound with the exception of shore leads around islands. The Stewart River was ice covered at the confluence. Downstream of the Stewart River the Yukon River was ice covered. The ice was generally competent, shore leads and open areas were noted around islands. All tributaries in this reach were open and flowing. Below the Sixty Mile River confluence with Yukon River, there were fewer shore leads and ice appeared to be much more competent.

The confluence of the Klondike and Yukon Rivers was open; the Klondike River was completely clear of ice having broken up on April 27 (Slide 3/22). Downstream of the confluence, shore leads were developing in Dawson, although the ice cover was still competent. There was no indication of rising water levels, indeed very little water was evident (Slide 3/31). Open water was evident at Moosehide, however competent shore to shore ice was observed downstream of that point.

April 29

On April 29, no significant changes were evident in the ice conditions on the Yukon River at Dawson City. The ice was competent and had shown no evidence of movement. A small ice jam was located just downstream of the open area located at Moosehide. From that point, ice conditions were characteristically competent although shore leads were developing. Small open water areas were observed just downstream of the Forty Mile River which was still ice bound. There was, however, evidence that this tributary was breaking-up. Upstream of Dawson no significant changes were observed.

April 30

On April 30, Carmacks was completely clear of ice, with the exception of stranded pans of ice located on bars and on the shore. Pans of ice were observed moving in the Yukon River downstream of Carmacks as far as Mt. Monson, where a small ice jam occurred. A small jam was observed upstream of Five Fingers Rapids, however there was no major change in the ice conditions along this reach of the river. Generally, open areas occurred around islands, particularily in the vicinity of Hoochekoo Bluff and in the Ingersoll Islands (Slides 6/6, 6/8).

At the confluence of the Pelly and Yukon Rivers, the leads observed during previous flights appeared to have lengthened, however there was no major change evident in the vicinity of Fort Selkirk. A small ice jam was observed just downstream of Fort Selkirk. In the vicinity of Victoria Rock, the Yukon River was generally ice bound, with shore leads developing rapidly around islands. No major changes, with the exception of expanding shore leads, were noted as far downstream as Coffee Creek. No changes in ice conditions were evident at Coffee Creek; shore to shore competent ice was observed from that point to the confluence of the Yukon and White Rivers.

The first evident change from the survey of April 29 occurred at the White River. Significantly more water was flowing down the White River; and an increase in water levels was noted on the Yukon, downstream of the White River confluence (Slides 7/5, 7/6). The Stewart River confluence was still ice bound, and the Yukon River downstream of the Stewart River remained ice covered; no major changes were observed to the Sixty Mile River. Downstream of that point more open water was observed as far as the Indian River. From the Indian River through to and downstream of Dawson City no changes in ice conditions were noted.

May 1

During the night of April 30 - May 1, water levels along the Yukon River at Dawson were rising, although the increases did not appear to be rapid. Water levels on the Klondike River also appeared to be rising. By 10:30hr, the open area at the confluence of the Klondike and Yukon Rivers had expanded, and the shore lead adjacent to the Bank of Commerce had widened (Slide 8/6). There was, however, no evidence of ice movement downstream of Dawson as far as Moosehide. The open water area located at Moosehide had enlarged since April 30 and a small ice jam was located just below Fort Reliance. Downstream of Fort Reliance solid, competent ice was encountered.

Upstream of Dawson there was no sign of movement, although a large area of open water had developed at the confluence of Swede Creek. A relatively small ice jam was observed in the vicinity of the Indian River, however ice in the reach from the Indian River to well above the Sixty Mile River showed no significant change. However, in the vicinity of the Stewart River much more open water was observed. Water levels were rising and a jam was observed at Stewart Island. Significantly more open water was observed in the reach of the Yukon River between the Stewart and White Rivers (Slide 8/22). Water levels appeared to be dropping as indicated by stranded ice floes (Slide 8/22).

Upstream of the White River no changes were observed in ice conditions. There was no evidence of ice movement, rising stage or of significant changes in the development of open areas or of shore leads. Some minor movement was observed at Cripple Creek, downstream of Fort Selkirk. Large open leads had developed in the vicinity of Victoria Rock; these leads were continuous from Fort Selkirk. The ice jam located just downstream of Fort Selkirk had not changed; the Pelly River at the confluence of the Yukon River was still ice covered. No major change was observed upstream of the Pelly River although an open channel extending through the downstream end of the Ingersoll

Islands had developed. However between the upstream end of the islands and Big Creek no major changes were observed. A small ice jam was developing downstream of Minto where an large open lead had formed.

A rather large ice jam occurred in the vicinity of McCabe Creek and extended as far upstream as Yukon Crossing (Slide 9/10). The Yukon River was clear of ice from this point upstream.

Break-up at Dawson City occurred between 14:00hr and 16:00hr on May 1. At 14:00hr, ice pans were observed to be moving along the west bank of the Yukon River just downstream of the Klondike confluence. There did not appear to be a significant change in water levels at that time, although the stage was rising. By 15:00hr however water levels were rising rapidly and overflow was developing downstream of the Klondike River. A channel of moving ice was developing in the middle of the ice cover, the tripod at the Bank of Commerce was destroyed by the ice at 15:28hr. Ice pans began to pile against the ice bridge which remained intact. The large ice pan on which the ice bridge was located moved a few metres downstream and grounded, effectively jamming further movement of ice pans through Dawson at 16:00hr. During this time water levels in Dawson rose between 1 and 1.5 metres. Ice pans which were pushed on to the river banks revealed that the ice was indeed very competent. Very little candling was observed and ice thicknesses were measured at between 60 and 80cm (Slide 10/21). Ice upstream of the Klondike River as far as Swede Creek broke up and ran in conjunction with break-up at Dawson City. Water levels were dropping at 20:00hrs.

By 20:50hr, the ice began to run again at Dawson; water levels were rising. By 21:40hr, ice had cleared through Dawson City and had jammed just downstream of Moosehide. Downstream of Moosehide another ice jam was located in the vicinity of Twelve Mile Creek and below that point there was no evidence of ice movement.

May 2

At 09:45hr the Yukon River at Dawson City was completely clear of ice with the exception of stranded pans of ice to a point approximately 3km below Fort Reliance. Water levels had dropped back to pre-break-up levels. Downstream of Fort Reliance an extensive ice jam composed largely of small, loosely packed pans of ice was observed. The downstream end of the jam was located approximately 10km above the Chandindu River. In the vicinity of the Chandindu River the ice cover was still relatively competent. Although large areas of open water had developed during the previous 24 hours. Below the Chandindu River few open areas were evident and the ice cover appeared to be more competent. Open areas were concentrated around islands.

The confluence of the Forty Mile and the Yukon Rivers was open; a small ice jam was located just downstream of that location. There was no evidence of ice movement downstream of Forty Mile River although an ice jam was located at the Alaska-Yukon border and an open channel was observed in the Yukon River at Eagle, Alaska.

Upstream of Dawson city, the Yukon River was clear of ice to a point approximately 1km below Swede Creek. Upstream of Swede Creek, the channel was still ice bound although there was a great deal more open water. From Garner Creek, upstream to almost the Sixty Mile River the channel was generally open, and ice was flowing. The Yukon River was open and flowing relatively freely from the Sixty Mile River as far upstream as the White River. Water levels in this reach of the river had dropped significantly.

The reach of the river upstream of the White River, however, showed no major change as far upstream as Kirkman Creek where a small ice jam occurred. The channel was open at Coffee Creek; there was some evidence of ice pan movement. No major change was observed at Ballarat Creek although open areas and pan movement was evident upstream of that location. A small ice jam was located at Isaac Creek and an open channel extended upstream to Selwyn Creek. Substantially less ice and more movement was observed upstream of Pedlar Creek. A few minor jams occurred in this area. Between Pedlar Creek and Cripple Creek there was no evidence of movement, although downstream of Victoria Rock in the reach to Cripple Creek ice was moving.

A large ice jam was located at Fort Selkirk (Slide 13/4). The jam extended from the downstream end of the settlement to just above the confluence of the Yukon and Pelly Rivers. The Pelly River was ice covered at the confluence although water was flowing in upstream reaches.

An open channel extended through the Ingersoll Islands to a point just downstream of Big Creek where an ice jam occurred. No change was observed in ice conditions upstream of Minto.

By 15:45hr, ice in the Stewart River at the confluence with the Yukon had gone out and jammed approximately 2km downstream of the confluence. Large ice pans were located at the Sixty Mile River and between the Sixty Mile and Indian Rivers ice pans were moving. An ice jam composed of relatively small ice pans was located at the Indian River. Downstream of that point to Swede Creek there was no sign of ice movement and the channel was open from Swede Creek through Dawson to just below Moosehide where an ice jam occurred. At 16:45hr ice was running heavily at Dawson and continued to run until 18:00hr. The Moosehide jam was building significantly and continued to build until approximately 21:30hr. Ice began to run again at 20:00hr and by 23:20hr the ice had cleared out of Dawson through Moosehide as far as could be observed from the Dome above Dawson.

May 3

On May 3, the Yukon River was clear of ice from Swede Creek downstream through Dawson, past the Forty Mile River to Coal Creek where running ice was encountered. Tightly packed, moving ice was prevalent from this point downstream as far as the Kandik River in Alaska. The upstream end of the moving ice travelled downstream from the Coal Creek to Eagle Alaska a distance of approximately 50km in under 2 hours. Upstream of Dawson City the Yukon River was clear of ice to above Swede Creek. Minor ice jams were located, primarily behind islands in quiet water areas, however an open channel extended almost to the Indian River. In the vicinity of the Indian River, although there was evidence of substantially more open water, there was little indication of ice movement. However above that point the channel was generally clear of ice to the confluence of the Sixty Mile and Yukon rivers. Running ice was encountered at the Sixty Mile River (Slide 14/15). Upstream of the Sixty Mile River the Yukon River was generally clear of ice with the exception of small ice floes. Above the White River confluence no significant changes in ice conditions were observed.

May 4

By 10:40hr on May 4, the reach of the river above the White River began to show some significant change. Approximately 2km of ice between the White River and Thistle Creek had cleared out. However upstream of Thistle Creek there was no evidence of ice movement although water levels appeared to be rising. Even though there was no movement, leads appeared to be widening significantly. There was evidence of large scale movement upstream of Coffee Creek. At 12:15hr, ice was moving at Ballarat Creek. Downstream of Isaac Creek significant movement was observed and several ice jams were noted. Downstream of Fort Selkirk, large areas of ice had moved. Ice movement occurred to approximately Selwyn Creek and from that point to Cripple Creek the river ice was still relatively competent. No change was noted in ice conditions above Fort Selkirk.

Downstream of the White River, the Yukon was completely clear of ice to the Indian River. At that location an ice jam approximately 6km in length was observed. Stranded ice jams were noted in areas around islands.

May 5

Ice was running in the Yukon River at Dawson at 09:35hr and the light run continued until 11:30hr. Water levels were continuing to drop.

Upstream of Dawson, the river was clear of ice with the exception of stranded pans of ice. Although the Indian River jam was still in place the dropping water levels had stranded the jam. A channel of flowing water was observed through this area and continued upstream through to the Stewart River. Water levels were dropping along the whole length of the Yukon River.

Very little change was observed upstream of the White River. The ice was generally competent from the White River to Coffee Creek where a jam occurred. Although the ice was competent, water levels appeared to be rising and open areas are more extensive. A great deal of ice movement and jammingwas evident upstream of Ballarat Creek through to downstream of Victoria Rock where competent ice was encountered. A large ice jam was located adjacent to Fort Selkirk. Fort Selkirk was completely clear of ice.

There was still a substantial amount of ice in the Ingersoll Islands, however there was evidence of ice movement. A small ice jam occurred just downstream of Big Creek. Open water was noted from that point to the Minto airfield. Above Minto relatively competent ice was encountered and again at Hoochekoo Creek. The ice jam downstream of Yukon Crossing was still intact.

May 8

The Yukon River was clear to a point approximately 8km downstream of Big Creek. Only stranded ice pans remained in the river. A small ice jam was located at the upstream end of the Ingersoll Islands and there was little evidence of ice movement in the islands although there was an open channel and a great deal more open water. The open channel extended from the ice jam noted, past Fort Selkirk to downstream of Victoria Rock where an ice jam was encountered. The jam extended to just upstream of Black Creek where ice occurred which showed no evidence of movement. Open water extended from 6km downstream of Black Creek to 5km upstream of Cripple Creek. There was evidence of some jamming and competent ice located 10km upstream of Isaac Creek. Downstream of that location a clear channel was evident which extended to Coffee Creek. A jam was located at Coffee Creek and downstream of that point to the Thistle Creek alternate patches of clear areas and competent ice occurred. Running ice was encountered at Thistle Creek. The Yukon River at the White River was clear of ice.

Although there was still ice in this reach of the river, it had sufficiently deteriorated that additional flying costs were not warranted to observe the last run of ice.

7. Water Temperature

Terroux et al, 1981, have shown that in conditions of low discharge which occurred on the Mackenzie River during the 1980 and 1981 break-up periods, high water temperatures (between 8°C and 9°C) contributed significantly to the rate at which the ice cleared out of the river.

As was the case in 1982, an attempt was made to collect water temperatures along the Yukon River during the 1983 break-up season. However due to logistical problems and difficulties of safe access to open water, only two temperature readings were obtained. On May 3, the water temperature on the White River at the Yukon River was 1°C, while on May 8, the water temperature of the Yukon River at Minto was 4°C. Although these readings indicate that there was some heat (stored in the water) available to melt ice, there is not a sufficiently large sample of water temperatures to determine the significance of heat transfer as a mechanism of break-up.

The ideal way of collecting water temperatures is to use a helicopter equipped with floats so that landings can be made in open water, in the middle of the channel, upstream of ice covers.

8. Summary

Break-up along the Yukon River in 1983 was unspectacular in nature. There were no major ice jams, no significant flooding occurred, and the ice pans were for the most part small and composed of relatively thin, but competent ice. The ice jams which did occur were loosely packed, of little strength and of short duration. There were no hanging dams or ice jams composed of large thick ice pans and subsequently no significant flooding occurred. None of the Yukon River communities were flooded.

As previously indicated, the 1983 break-up was not a sequential event. Although there was a general south to north trend in the progression of ice clearance, this progression was not consistent. The progression of break-up from Lake Laberge downstream to the Canada-U.S. border is described in the following:

a) Ice first cleared on the reach of the river downstream of Lake Laberge through to Carmacks. Ice at Carmacks started to move on April 25 and had cleared out of that community on April 27.

b) The area downstream of the confluence of the Yukon and Klondike Rivers broke up and cleared of ice over a three day period from May 1 to May 3. Ice break-up occurred at Dawson City on May 1, 7 days earlier than mean break-up date of May 8 calculated by Orecklin, (1981). The Klondike River broke up on April 27, 4 days before break-up occurred on the Yukon River.

c) The reach of the river between the White River and Dawson City began to run on May 2, at approximately the same time as the Stewart River confluence cleared of ice. It would appear that increasing discharge on both the White and Stewart Rivers triggered break-up along this reach of the river.

d) Ice was running in the reach of the river between Carmacks and the

Pelly River by May 4. There are no major tributaries (of the importance of the Pelly and Stewart Rivers) and therefore there can be no sudden increases in discharge contributing to the mechanical break-up of the ice cover. As was the case in 1982, it would appear that break-up in this portion of the river is a continuation of the sequential process beginning in the upper reaches of the river.

e) As was the case in 1982, the reach of the Yukon River between Fort Selkirk and the White River was the last to clear of ice. Although the ice cover was moving in places along this reach of the river during the break-up period, ice did not clear out of the reach until May 8. Again it appears that ice clearance in this section is a continuation of the break-up process beginning in the upper reaches.

9. Conclusions

a) Break-up of the Yukon River ice cover between Carmacks and the Canada-U.S. border took place over a period of approximately 14 days from April 25, when the ice cover moved at Carmacks, to May 8 when the whole river was clear of ice.

b) Break-up on the Yukon River in 1983 was not a sequential event. The upper reaches are the first to clear of ice followed by the lower sections and finally the middle portion. It should be noted, however, that Stewart, White and Klondike Rivers appear to trigger break-up downstream of the White-Yukon confluence, accelerating the event in this area.

c) Release of ice at and below Dawson City seems to facilitate break-up upstream, between Dawson City and the Sixty Mile River.

d) No major flooding occurred along the Yukon River, no communities suffered flooding, no major ice jams occurred.

e) Ice on the Yukon River immediately prior to break-up appeared to be relatively thin.

10. REFERENCES

Fenco Engineering, 1976, Yukon Flood Study, Department of Indian and Northern Affairs, Whitehorse, Yukon.

Kent, T.D., A Survey of the Timing and Progression of the Ice Break-up on the Yukon River, 1982, prepared for Environment Canada, Inland Waters Directorate, 1982.

Orecklin, M., 1981, Dawson Flood Study, ice jam of May 3, 1979; 1980 and 1981, break-up, Department of Indian and Northern Affairs, Whitehorse, Yukon.

Terroux, A.C.D., D.A. Sherstone, T.D. Kent, J.C. Anderson, S.C. Bigras, and L.A. Kriwoken, 1981, Ice Regime of the Lower Mackenzie River and Mackenzie Delta, Inland Waters Directorate, Environment Canada, Hull, Quebec.

Note: Photographs and Videotapes

Several hundred 35mm slides were taken during the course of the survey. These are available for viewing at Water Planning and Management Branch, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C.

The ice cover as occurred on each day of the survey was mapped on 1:250,000 scale NTS maps. These maps are available for study at Water Planning and Management Branch, Inland Waters Directorate, Pacific and Yukon Region, Vancouver, B.C.

APPENDIX 3

ESTIMATION OF ICE-RELATED STAGE-DISCHARGE CURVES, YUKON RIVER AT DAWSON

The following calculations assume steady uniform flow in a prismatic channel with approximately the cross-section of that at the WSC gauge on the Yukon River at Dawson given by UMA (1983). The geometry assumed was

Stage (m)	Mean depth (m)	Surface width (m)
312	2.8	360
313	4.0	360
314	5.4	360
315	6.8	360
316	8.2	360

From Figure 1 in the main body of the report, the slope in this vicinity is approximately 0.00036. FENCO (1974) quote "approximately 1 foot per mile," or 0.00019. The basis for this is not given. Although not conservative in the present context, the former value was used.

Based on the discharge of 7200 m^3/s at a stage of 316 m given by the WSC rating curve (UMA, 1983), an open water bed roughness k_b = 0.32 m was calculated. A value of 0.3 m was used in the ice-covered rating curve calculation. The solid ice cover was assumed 1 m thick with an hydraulic roughness of 0.3 m; the ice jam roughness was taken as 3 m.

The rating curve calculations used the procedures and equations given by Gerard and Calkins (1984). Because of the data limitations the resultant ice-covered rating curves given in Figure 6 are very approximate. However, they should be adequate for their role in this report, which is simply to filter out those flood events that would likely not be compatible with the steady, more or less uniform, flow assumptions on which such rating curves are based. It should be noted that the procedure used to determine the ice jam rating curve is quite different from that used by UMA (1983), and the results are likewise quite different.

Reference

Gerard, R. and Calkins, D.J. 1984. "Ice-related flood frequency analysis: application of analytical estimates," CSCE/ASCE Cold Regions Specialty Conference, Edmonton, Alberta, April, 1984.

APPENDIX 4

RECOMMENDATIONS FOR FURTHER INVESTIGATION

From the review summarized in the main body of the report it is evident that, with regard to the natural ice regime:

(a) There is almost a surfeit of historical information on ice-related stages at Dawson upon which to base a decision about the worth of flood protection at Dawson (presumably a levee and associated internal drainage facilities).

(b) There is a better than usual (for a northern river) understanding of the general ice regime of the river below Lake Laberge.

Hence, in the absence of a firm development proposal such as flood protection at Dawson or hydro-power development in the upper Yukon River basin, major investigations of the natural ice regime would be difficult to justify from an engineering point of view. Nevertheless, one or more of the following relatively minor efforts may be justified in the interim. An attempt has been made to put them in an order that reflects both significance and required effort or expense.

1. Water temperature measurements and ice regime observations at three or four selected sites along the Yukon River from Lake Laberge to Dawson prior to and during freeze-up, and during and after break-up at each site. The frequency of observation and measurement during these periods should be no greater than weekly. The program should continue for about five years in the first instance, after which analysis, and the development situation at that time, will indicate if they should continue.

Such measurements are needed for an assessment of the role played by warm water at break-up, and to calibrate a numerical model of the temperature regime of the river for calculation of possible changes in ice production at freeze-up and the environmental impact of changes in the flow regime.

2. Extend the period of reliable continuous WSC stage measurements on the Yukon and Klondike Rivers at Dawson such as to encompass freeze-up and break-up. Something more than the regular WSC installation will be required to do this, but it is difficult to imagine it is not possible. At the very least, maximum stages near Dawson at freeze-up and break-up on both rivers should be determined each year.

3. Discharge and temperature measurements, by whatever means, for the White River prior to and during break-up of the White River-Dawson reach of the Yukon River for a period of, say, five years (which do not have to be sequential, but should be coordinated with 4). Also, although they are of less consequence, similar measurements might be made prior to and during freeze-up.

4. If they are not already taken, temperature measurements should be made over the same periods on each of the gauged tributaries below Lake Laberge, at the nearest station to the Yukon.

5. Continue aerial reconnaissance of freeze-up along the reach of interest for another two or three years to identify:

(a) Time and location of lodgement in the reach;

(b) Location and progression of the upstream limit of ice production;

(c) General development of the morphology of the frazil pans produced;

(d) General development of shorefast ice, particularly at and near likely lodgement locations;

(e) Rate of accumulation progression and, if possible, some indication of the nature of the accumulation (e.g. smooth or rough).

The primary intent is to confirm and extend the observations of the past two seasons, and to provide sufficient data to assess, in a general and likely empirical way, how items such as lodgement and accumulation progression are related to discharge and meteorological variables. This, and the other information collected, would be needed to calibrate the numerical simulation of freeze-up needed to assess the impact of development.

6. Continue for another two or three seasons aerial reconnaissance of progression of break-up along the reach to:

(a) Confirm and better define the apparent role of the White and Stewart Rivers in triggering break-up of the Yukon River ice cover to Dawson and beyond and, if possible, whether this role may be significantly effected by increased discharges in the Yukon at break-up. Of particular interest is the source and cause of the major surges and ice runs that seem to originate in this reach, and pose the major flood threat in Dawson;

(b) Define the general progression of ice deterioration in the various reaches, and how this is related to discharge, incoming water temperature, meteorological variables and the geomorphic characteristics of the reaches;

(c) Better define progression of break-up in the reach between Carmacks and the White River, and significant events that occur in the final stages such as the "Coffee Creek jam." It is possible that such progression will occur through the Stewart River-Dawson reach if the present "triggering" action of the White and Stewart Rivers is mitigated by a controlled and increased discharge on the Yukon.

(d) Determine if break-up at Eagle and beyond depends on break-up near Dawson, or whether, in the early absence of this due to regulation, break-up in that reach would be triggered by other early events between Dawson and Eagle (as suggested by the 1982 break-up observations). If this was so, the major influence of regulation on the break-up regime would be confined to Canadian territory.

(e) Continue, for the same period as item 6, a mid- to late-winter aerial reconnaissance of the ice cover to define open water areas and the state of the ice cover in general.

8. Investigate the general influence of an ice cover and/or water temperature on the aquatic fauna in the river. (Investigations under the Fisheries and Wildlife components of the Yukon River Basin Study may provide results sufficient for this item.)

9. Define the hydraulic geometry (4-5 cross-sections distributed over some 20 river widths; water surface slope; bed and bank material; and thalweg profile) of the two rivers near Dawson to allow development of synthetic stage-discharge curves. This would also be useful at possibly two or three other sites between Dawson and Lake Laberge, and one downstream, perhaps near Eagle or Fortymile.

10. Review the historical record for information on freeze-up along the Yukon and its tributaries.

11. Based on the DCM (1981) review of historical information, extend and verify the compilation prepared by FENCO (1974) of stages, and, where possible, the likely range of mean daily discharges.