Prediction of Ice Jam Water Levels in a Multi-Channel River: Fort Albany, Ontario

Paul Grover[1], Catriona Vrkljan[2], Spyros Beltaos[3], David Andres[4]

[1] *Senior Water Resources Engineer, AGRA Earth & Environmental Limited, Calgary, (Formerly with Klohn-Crippen), pgrover@agraee.com*
[2] *Water Resources Engineer, Klohn-Crippen Consultants, Calgary, cvrkljan@klohn.com*
[3] *Research Scientist, National Water Research Institute, Burlington, spyros.beltaos@cciw.ca*
[4] *President, Trillium Engineering and Hydrographics, Edmonton dandres@trilliumeng.ab.ca*

This paper describes the hydraulic analysis and methods used to estimate ice jam water levels and associated return periods on the Albany River at Fort Albany. The analysis was complicated by the presence of multiple channels in the study reach. Estimates of the flow splits amongst the channels were made using the MIKE 11 model for both open water and ice covered channels. The flow split estimates were checked independently by using a simplified spreadsheet model which assumed equilibrium jams in the connecting channels. The RIVJAM model was used to estimate ice jam levels in the channels that affected the community. Because RIVJAM applies only to single-channel reaches, it was applied sequentially within sub-reaches of constant flow, assuming common junction values of ice thickness and water level. Stage-frequency curves were developed for various ice jam events, by taking into account the joint probability of an "equilibrium" ice jam occurring in combination with a given flow.

1. Introduction

Fort Albany is a First Nation community of about 1000 people, located on the south bank of the Albany River about 15 km upstream of James Bay (Figure 1). The community has a history of flooding due to ice jams that occur during spring breakup, and to a lesser extent, during the fall freeze-up. This flooding not only inundates the community, but it also causes substantial structural damage due to the influx of large ice floes. The only road into the community is a winter road. Consequently, during a major flood, the community has to be evacuated by air. During severe floods, the airstrip has even been inundated, necessitating evacuation by helicopter.

With reference to Figure 1, ice floes and flood waters generally enter the community via two main avenues: the Dry Channel and Lake St. Anne. Three dykes were constructed in 1997 and 1998 to reduce the damage to the community from ice floes. The dykes are called the Main Spill Dyke, Lake St. Anne North Dyke, and Lake St. Anne South Dyke (Klohn-Crippen, 1998). These dykes are the first phase of a flood control scheme for the community that is planned to be implemented in the coming years.

This paper describes the breakup process at Fort Albany, summarizes the hydrologic and ice jam data collected at the site, and describes the methodology used to develop ice jam stage-frequency curves that were used to set the crest elevations of the dykes.

2. Ice Jam Processes

The Albany River in the vicinity of Fort Albany is composed of multiple channels. The North and South Channels are the largest channels and flow in an easterly direction (Figure 1). In some reaches the North and South Channels split into two or more sub-channels that are narrower than the parent channel, but have approximately the same slope. The Dry Channel, which separates the Mainland from Anderson and Sinclair Islands, also flows in an easterly direction, but it only flows during high river stages. There are numerous smaller connecting channels that run north and south between the North and South Channels. These connector channels have much flatter slopes and have sills at the entrance with a higher bed elevation than the North and South channels so they flow only when water levels are high. The flows in these connecting channels are driven by water level differentials between the North and South channels. Typically, the main and secondary eastward flowing channels have slopes of about 0.001 while the north-south connecting channels have almost negligible slope.

The flow distribution between the channels varies depending on the total discharge in the river and the ice conditions. During the winter, the North Channel carries more flow than the South Channel and there is no flow in the Dry Channel.

The breakup front (downstream limit of ice rubble) moves from upstream to downstream along the Albany River. Usually the front enters the North Channel first, and there is a consequent increase in water levels due to both the surge of water that accompanies the breakup front and the additional flow resistance caused by the accumulation of broken ice. As a result, water and ice are diverted into the South Channel via the numerous connecting channels. This triggers breakup in the South Channel and ice jams can form if the supply of ice is sufficient and the hydraulic conditions are appropriate. The prime jamming location in the South Channel is near Willow Island. The slope of the river flattens out at this location as James Bay is approached and the ice cover remains intact longer than on the steeper reaches of river upstream.

The thickness of the ice jam and the increase in flow resistance of the ice cover causes water levels on the South Channel to rise. The increase in water levels results in water and ice being diverted into the Dry Channel at the location of the Main Spill Dyke. The Dry Channel initially conveys large flows until it fills up with water and ice.

If the water levels on the South Channel continue to rise, a portion of the flow leaves the South Channel and overflows into the Lake St. Anne watershed at the location of the Lake St. Anne North and South Dykes. There are no trees along the waterway that connects the South Channel with the lake, suggesting that these overflows have historically transported large volumes of water and ice into Lake St. Anne. The outflow from Lake St. Anne occurs in a small creek that runs through the Mainland Community and empties into the Dry Channel. The ice floes that entered the community via Lake St. Anne caused much damage in the 1985 flood, the worst flood on record.

An ice jam can cause water levels to rise rapidly- several meters in a matter of hours. The present knowledge of ice jam mechanics is not advanced enough to accurately forecast if and when a jam will occur. However, observations and numerical hydraulic modeling indicate that the events leading up to the formation of an ice jam are similar from year to year and that certain factors must be satisfied before ice-related flooding can occur at Fort Albany. For example, the modeling work demonstrated that a jam must already be in place in the North Channel in order for Fort Albany to experience flooding from the South Channel. If there were no jam in the North Channel, most of the flow in the South Channel would be diverted to the North Channel since that would be the path of least resistance. Water levels on the South Channel at Fort Albany would then be unlikely to reach flood stage.

Fort Albany also experiences ice jams during freeze-up. These tend not to be as severe as spring floods but can still disrupt the community, by cutting off access between the Mainland and Sinclair Island.

3. Historical Flood Levels

Kriwoken (1988) examined the historical incidence of flooding in Fort Albany. The 1985 flood was the most severe since the community moved to its present location in 1933. During the 1985 flood, ice flowed through the community causing extensive damage. Power poles were knocked down and about 17 homes were moved off their foundations. The depth of flooding was reported to be at least one meter everywhere in the community.

Figure 2 shows the historical flood levels at Fort Albany for the period of record. The data is plotted within the context of perception levels, i.e. water levels that were noted by members of the community as being significant for some reason or another. The minimum perception level corresponds to el. 113 m, which is approximately the elevation of the top of banks in Fort Albany. If the water level in a particular year did not exceed 113 m, residents did not perceive that a significant flood occurred that year. Residents are still inconvenienced by water levels below the minimum perception level because access is cut off between the Mainland and Sinclair Island. This is disruptive as most of the homes are on Sinclair Island, but the school, hospital, administrative offices, and Northern Store are on the Mainland.

There were no high water level data available upstream of the community where the three dykes were to be constructed. Accordingly, surveys were made of the vegetation types along the banks of the channels to develop some information about historic flood levels. Figure 3 is a sketch illustrating the vegetation types at the Main Spill Dyke and the Lake St. Anne South Dyke. Three distinct zones of vegetation were observed:

- Coniferous trees that were in excess of 60 years old;
- Deciduous trees that were about 30 years old;
- Willows and alders that were less than 15 years old.

The age of all trees were determined by ring counts. There was a well-defined transition between these three zones of vegetation.

These data suggest that ice frequently encroaches into the lower zone where the willows and alders are the dominant species. Ice has encroached into the middle zone of deciduous trees at least once within the last 30 years. It is surmised that many of the trees in the middle zone were knocked down during a previous severe ice jam, probably the 1966 or 1985 events. The coniferous trees higher up the bank have been affected by ice very infrequently as evidenced by the limited ice scarring in the trees closest to the channel.

The information on vegetation types was used in the calibration of the hydraulic models, as will be discussed subsequently in Section 5.2.

4. Hydrology

The closest Water Survey of Canada gauge on the Albany River is at Hat Island, about 230 km or two days travel time, upstream of Fort Albany. Figure 4 shows the peak annual flows at Hat Island from 1965 to 1996. The annual flood peaks are all snowmelt events and thus have a direct affect on spring flood conditions at Fort Albany.

It is interesting that the worst flood on record at Fort Albany occurred in 1985, but as Figure 4 shows, the flow that year was not the highest on record. Conversely, the years of highest flow (1992 and 1996) did not result in major flooding. The reason for the poor correlation between peak flows and stages is due to the influence of ice jams that raise the water level substantially.

Table 1 summarizes the estimated discharges on the Albany River, for various return periods. This analysis is based on 31 years of data (1965-1996). The peak annual flows at Fort Albany were estimated by increasing the flows at Hat Island by a factor of 1.103 to account for the differences in drainage areas between the two sites.

Table 1 Albany River Flows at Hat Island and Fort Albany

RETURN PERIOD (years)	ALBANY RIVER FLOWS (m^3/s)	
	At Hat Island	At Fort Albany
2	4,390	4,840
5	5,670	6,250
10	6,580	7,260
20	7,500	8,270
50	8,760	9,660
100	9,770	10,800

5. Hydraulic Modeling

This section describes the methodology used to estimate ice jam water surface profiles at Fort Albany. The following three steps were performed:

1. Estimates of the flow splits amongst the various channels were made using the MIKE 11 model. The model was run for both open water and assumed ice covered conditions. Flow splits were calculated for the 1985 flood and for river discharges having return periods between 2 and 100 years. To verify the MIKE 11 results, the flow splits were also estimated using a simplified spreadsheet model that was based on equilibrium ice jam occurrence within a simplified network of channels and sub-channels. The flow splits calculated using both procedures were very similar, and the MIKE 11 results were selected for further analysis.

2. The RIVJAM model (Beltaos, 1993,1996) was set up to model ice jams along the South Channel using the flow splits calculated from MIKE 11. The RIVJAM model was calibrated to match the observed 1985 high water marks in Fort Albany and the information on vegetation zones upstream at the Main Spill Dyke and Lake St. Anne Dykes. The calibrated model was

then used to estimate ice jam water surface profiles along the South Channel for flows having the return periods listed above.

3. Stage-frequency curves were developed at key locations. The return periods on the stage-frequency curves were adjusted by a factor to reflect the joint probability of an equilibrium ice jam occurring in combination with that particular flow.

These three steps are described in more detail below.

5.1 Estimation of Flow Splits

A model network of the various channels in the Fort Albany area was developed. The model was used to simulate the flows in the complex arrangement of connecting channels between the North and South channels. These connecting channels are important since they provide additional conveyance to the North and South Channels when water levels are high, and serve to equalize water levels across the entire network. Some of the connecting channels convey little or no flow except during high river stages. This is consistent with the aerial photos and observations made during the site visits.

Estimates of the flow splits amongst the various channels were made using the MIKE 11 model for both open water and assumed ice-covered conditions. The MIKE 11 model was calibrated to match the available water level data for open water flow conditions. The upstream boundary was placed upstream of the junction of the North and South Channels, where the total river discharge was input to the MIKE 11 model as a constant upstream discharge. The downstream boundary condition was the water level in James Bay, which is representative of a constant sea level. A sensitivity analysis indicated that, at high discharges, the river levels and flow splits in the area of interest were insensitive to tidal influence. Water levels and flow splits for open water conditions were simulated reasonably well with a Manning's bed roughness coefficient of 0.035.

A Manning's n value of 0.16 was used in MIKE 11 to simulate the water levels that might be caused by ice jams. This extreme value was deemed appropriate, since MIKE 11 is an open-water flow model that cannot directly account for (a) the resistance to flow produced by the rough underside of an ice jam, and (b) the submerged portion (about nine-tenths) of the ice-jam thickness, which must be added to the under-ice flow depth in order to arrive at the total water depth. As a check of the MIKE 11 results, a second method for calculating flow splits was applied, as indicated next.

A simplified flow network of channels and nodes was formulated and analysed using a custom spreadsheet model. Water levels and flows at each of the nodes were calculated by assuming that equilibrium ice jams existed in each of the channels downstream of each node. Flow out of each of the channels at each node was determined by equalizing the total energy (comprised of the velocity head, flow depth under the ice cover), and the equilibrium ice jam thickness on the basis of the flow in each of the channels.

Flow splits were calculated for the 1985 flood (19 year return period) as well as for river discharges having return periods of 2, 5, 10, 30, 50 and 100 years. The flow splits calculated using both procedures were very similar, and the MIKE 11 results were selected for further analysis.

5.2 Ice Jam Modeling with RIVJAM

RIVJAM was used to estimate the ice-jam water surface profiles along the South Channel using the flow splits calculated from MIKE 11. RIVJAM is a numerical model that computes the non-uniform ice jam thickness and water level along a jammed river reach. The model is based on the equations of flow continuity and momentum and on a differential equation that expresses the balance of stresses within an ice jam.

The South Channel was divided into seven sub-reaches extending from Willow Island to upstream of Lake St. Anne South Dyke. The boundaries between the reaches were chosen so that there would be approximately uniform discharge within each sub-reach. From on site observations, it is known that the toe of the jam normally forms near Willow Island. The RIVJAM model was applied starting at the toe of the jam at Willow Island, and working upstream. Each sub-reach was modeled sequentially using the results for water level and ice thickness from the previous reach as the starting point. The starting ice thickness at the toe of the jam was varied until a condition approximating an equilibrium jam profile was obtained. In an equilibrium jam condition, the ice thickness remains constant and the slope of the water surface is approximately parallel to the channel invert.

The RIVJAM model was calibrated to match the observed 1985 high water marks in Fort Albany and the information on vegetation zones upstream at the Main Spill Dyke and Lake St. Anne Dykes.

Table 2 lists the model calibration coefficients which were within ranges defined by previous applications, and generally close to default values (Beltaos, 1996).

Figure 5 shows the calibrated RIVJAM profile for the 1985 flood. Calibration was achieved by varying the ice thickness at the toe of the jam. The estimated river levels at the Main Spill Dyke and Lake St. Anne South Dykes were el. 116.7 and 118.0 respectively. These predicted levels are consistent with the vegetation in the area (Figure 3) and would be high enough to cause overflows of water and ice from the South Channel into Lake St. Anne watershed (as was known to have occurred in 1985).

Table 2 Calibration Coefficients for RIVJAM Model

PARAMETER	VALUE
Specific gravity of ice	0.92
Porosity of jam	0.4
Friction factor ratio $f_i/2f_o$	0.50
Seepage parameter, lambda	2.5 m/s
Rubble normal-strength coefficient K_x	12.0
Rubble normal/shear-strength coefficient, C_o	2.0
Constants used to calculate composite friction factor:	
C	0.40
m_1	1
m_2	1
Manning's n, minimum	0.033
Manning's n, maximum	0.100
Water depth at toe of jam	2.0 m
Ice thickness at toe of jam	7.5 m (1:2 Year Discharge) to 10.9 m (1:100 Year Discharge)

The calibrated RIVJAM model was then used to predict water levels along the South Channel for river discharges having return periods of 2, 5, 10, 30, 50 and 100 years. The thickness of ice at the toe of the jam was varied until a condition was obtained which approximated an equilibrium profile.

5.3 Stage-Frequency Curves

Figure 6 is a stage-frequency curve that summarizes the estimated ice jam water levels at three key locations. The values on the X-axis correspond to the return period of the river discharge shown in Table 1. For example, if an equilibrium ice jam were to occur during a 1:50 year flow of 9660 m^3/s, the estimated water level at the Main Spill Dyke would be about el. 118.8. However, this is not indicative of a 1:50 year water level at the Main Spill Dyke since it does not consider the joint probability of an equilibrium ice jam forming and a 1:50 year flood occurring.

The joint probability can be estimated by considering the historical flood data. First, it is noted that the 1985 flood levels were the worst in the 66 years of recorded data (1933 to 1998). The 1985 peak flow had a return period of 19 years. Therefore the probability of the flow (1/19) would have to be multiplied by a factor of about 1/3.5 to yield the correct joint probability, 1/66 (i.e. 1/19 times 1/3.5 is approximately 1/66). Next, it is shown that the historic flood level data suggest a higher factor during smaller flood events. Referring to Figure 2, the water level equaled or exceeded el. 113 m seven times in 55 years (1933 to 1987). Therefore, el. 113 approximately represents the 1/8-year ice jam level at Sinclair Island prior to the construction of the Phase 1 Dykes. Using RIVJAM, the flow that would be capable of producing this water level was determined to be about 6200 m^3/s, or about a 1/5-year event. Therefore, the adjustment factor for the joint event was calculated to be about 1/1.5. The adjustment factor value was interpolated for intermediate events.

Figure 7 is a stage-frequency curve that considers the joint-event probability. This curve was obtained by shifting the curves from Figure 6 to the right. The probability factors and the joint probabilities are shown in Table 3. Keeping the probability factor constant at higher flows is likely conservative since there is less probability of an equilibrium ice jam remaining intact as the river discharge increases. This is consistent with the concept of the ice clearing discharge as described by Beltaos (1995). Ice jams cannot remain intact at very high discharges because the hydrodynamic forces become high enough to break up the intact ice sheet downstream of the toe of the jam.

Table 3 Ice Jam Probability Analysis

Annual Probability of River Discharge	Annual Probability of Equilibrium Ice Jam Forming	Annual Joint Probability of Equilibrium Ice Jam Forming for a Given River Discharge
1:2	1:1.5	1:3
1:5	1:1.5	1:8
1:10	1:2.5	1:25
1:19	1:3.5	1:67
1:30	1:3.5	1:105
1:50	1:3.5	1:175
1:100	1:3.5	1:350

6. Summary and Conclusions

To reduce the damages in Fort Albany caused by ice floes, three flood protection dykes have been constructed and others are under consideration. The design elevations of the dykes are governed by ice jams that occur during breakup. There are limited historical data on high water levels at the study site. Accordingly, numerical modeling was used to derive ice jam stage-frequency curves at critical locations near the community.

The Albany River at Fort Albany has a complex multi-channel configuration. As there are no ice-jam models that can simulate ice jam formation and propagation in a multi-channel reach, the single-channel RIVJAM model was applied sequentially within subreaches of constant flow. The ice thickness and water level predicted by the model at the end of a subreach were used as the starting boundary condition for the next subreach.

The flow splits amongst the various channels were estimated using the MIKE 11 model and verified using a simplified spreadsheet application, assuming equilibrium jams in the connecting channels. The two methods produced similar results.

RIVJAM was calibrated to reproduce the available data on water levels and vegetation zones for the worst flood event on record. The calibrated model was then used to estimate ice jam levels for flows of varying return periods. Stage-frequency curves were developed at key locations. The return periods on the stage-frequency curves were adjusted by a factor to reflect the joint probability of an equilibrium ice jam occurring in combination with a particular flow. The adjustment factors, which varied from 1:1.5 for lower flows to 1:3.5 for higher flows, were estimated by examining historic flood levels and data on vegetation types.

Acknowledgements
The authors wish to thank the Chief and Council at Fort Albany for permission to publish this paper, Cal Lockhart at Indian Affairs for funding the project and Brian Feherty for managing the project.

References

Beltaos, S., 1993. "Numerical Computation of River Ice Jams", Can. J. of Civ. Eng., 20(1), 88 - 89.

Beltaos, S., 1995, "Breakup of River Ice", National Water Research Institute Contribution 95-125, Burlington, Canada.

Beltaos, S., 1996, "User's Manual for the RIVJAM model", National Water Research Institute Contribution 96-37, Burlington, Canada.

Klohn-Crippen, 1998,"Fort Albany First Nation, Flood Protection Plans, Design Basis Memorandum".

Kriwoken and Associates, 1988, "Review of Historical Flooding in Northern Ontario Indian Communities".

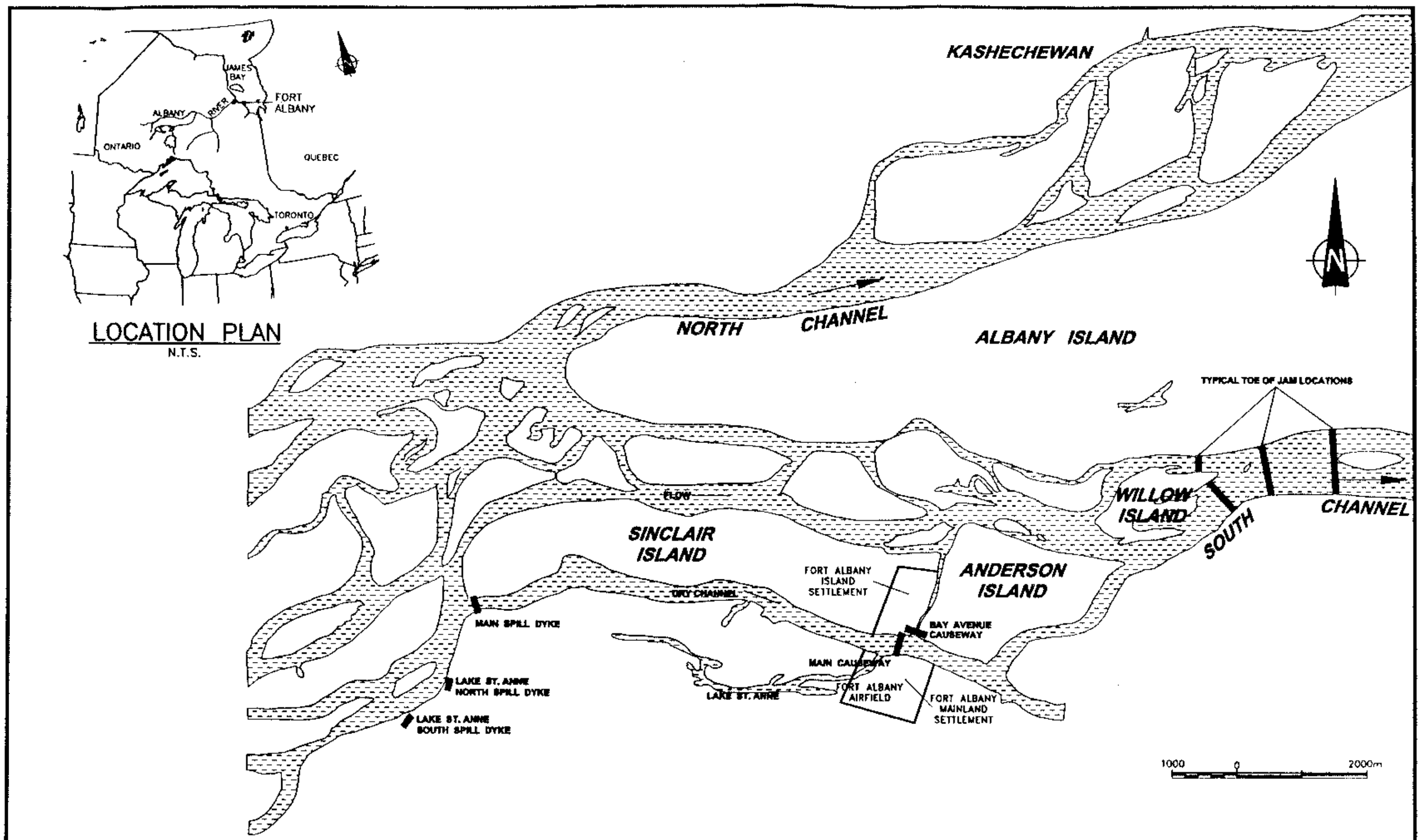
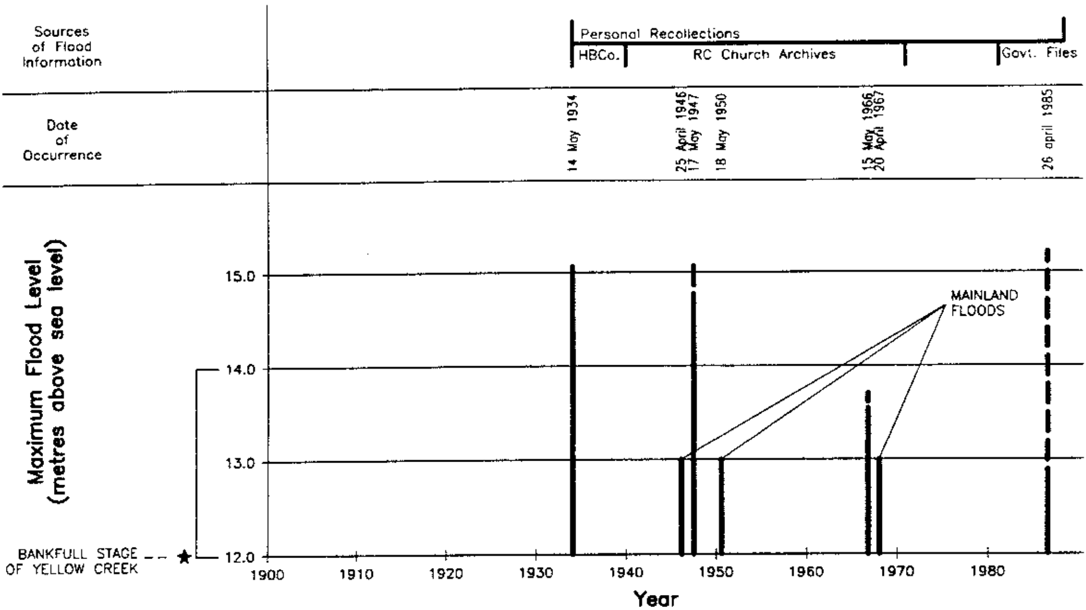


FIGURE 1: LOCATION PLAN AND GENERAL ARRANGEMENT

FROM "FORT ALBANY FIRST NATION, FLOOD PROTECTION PLANS, DESIGN BASIS MEMORANDUM", KLOHN–CRIPPEN, OCTOBER 1998.



LEGEND:

- LOWEST RECORDED MAXIMUM FLOOD LEVEL
- RANGE IN RECORDED MAXIMUM FLOOD LEVELS
- ★ PERCEIVED MINIMUM FLOOD LEVEL
- ELEVATION RANGE OF SETTLED AREA

NOTES:

1. FROM "REVIEW OF HISTORICAL FLOODING IN NORTHERN ONTARIO INDIAN COMMUNITIES", KRIWORKEN AND ASSOCIATES, MARCH 1988.
2. TO CONVERT TO KLOHN-CRIPPEN LOCAL DATUM, ADD 100 m EVEN.

FIGURE 2: HISTORIC FLOOD LEVELS AT FORT ALBANY

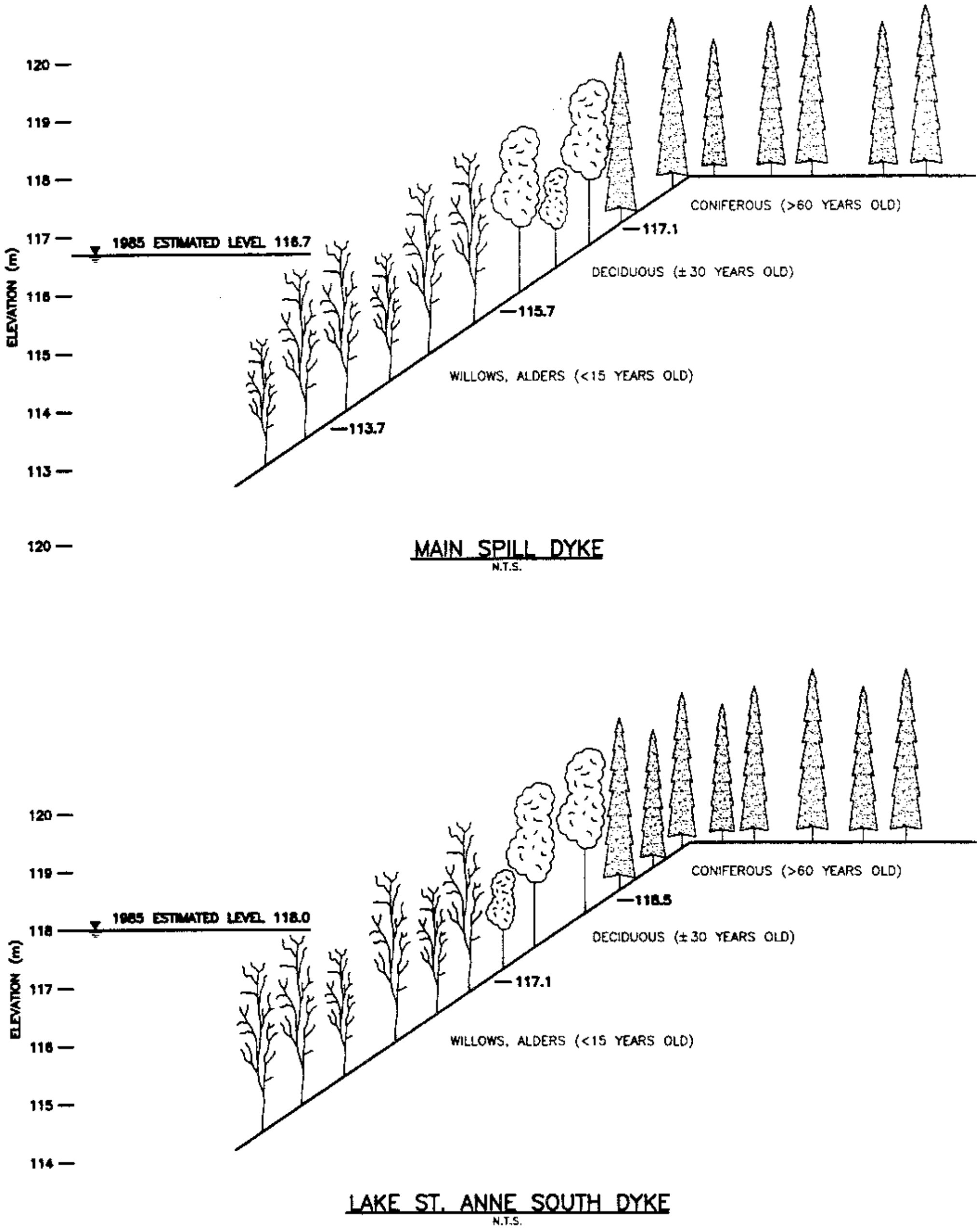
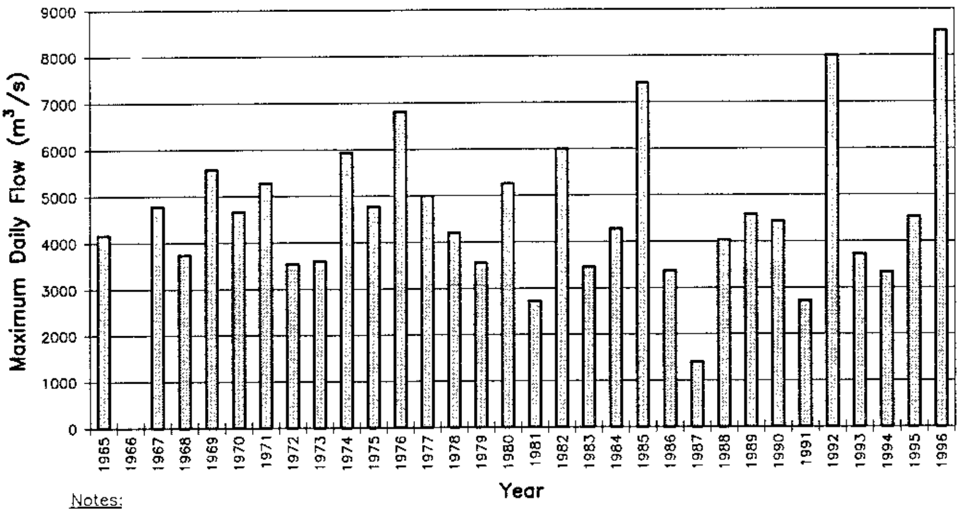


FIGURE 3: VEGETATION ZONES

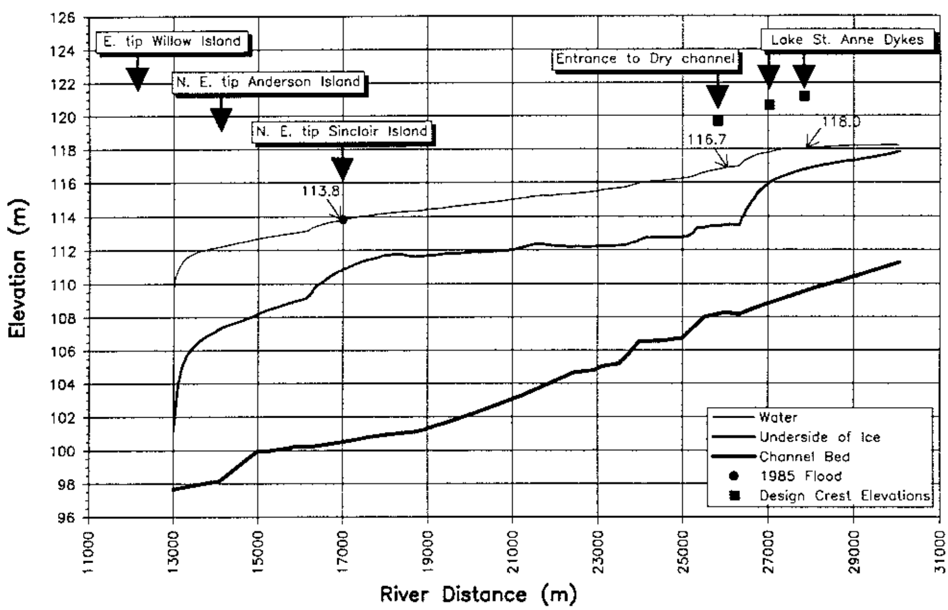
FROM "FORT ALBANY FIRST NATION, FLOOD PROTECTION PLANS, DESIGN BASIS MEMORANDUM", KLOHN-CRIPPEN, OCTOBER 1998.

FIGURE 4: MAXIMUM ANNUAL FLOWS, ALBANY RIVER AT HAT ISLAND



Notes:
1. Data source – Water Survey of Canada

FIGURE 5: RIVJAM CALIBRATION PROFILE, 1985 EVENT



FROM "FORT ALBANY FIRST NATION, FLOOD PROTECTION PLANS, DESIGN BASIS MEMORANDUM", KLOHN–CRIPPEN, OCTOBER 1998.