CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Numerical Model Studies of Ice Conditions During the Design and Construction of the Keeyask Generating Station

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The proposed Keeyask Generation Project is a 695 megawatt hydroelectric generating station (GS) currently under construction at Gull Rapids on the Lower Nelson River. This project is located about 725 km northeast of Winnipeg, Manitoba. Given its northern environment, the management of river ice has been a key factor in the design of the station, and in the development of river management strategies to facilitate its construction.

Various pre-construction field and engineering studies have been undertaken to help establish an environmental winter baseline for the project, to assist in finalizing river management strategies for construction of the project, and to assess during construction and post project impacts on the ice regime both upstream and downstream of the project. The work involved the setup and calibration of Hatch's ICESIM and ICEDYN computer models to simulate the formation of an ice cover at this site – a cover which can often generate massive ice jams and ice dams along the reach. Water level increases at the project site were predicted and observed to be upwards of 9 m or more due the formation of this ice cover and the related complex river ice processes. The project is currently under construction, and important construction design support had to be provided during an early winter failure of the project ice boom which occurred in the initial winter of construction (2014/2015). The ICESIM model was used to track and forecast how high water levels would rise, and an innovative cofferdam design was used to allow it to be raised by several meters in the middle of winter. This paper provides an overview of the project ice conditions and summarize numerical modeling studies undertaken during the project construction highlighting the model adjustments required during the construction period when compared to the pre-construction studies.

1. Introduction

The proposed Keeyask Generation Project is a 695 megawatt hydroelectric generating station (GS) currently under construction at Gull Rapids on the Lower Nelson River. This project is located approximately 725 km northeast of Winnipeg, Manitoba and involves the construction of nine separate cofferdams and two rockfill structures to facilitate river management during the construction process. The project is currently in the first phase of diversion, shown schematically in Figure 1. It is important to note that many construction activities are seasonally sensitive and rely heavily on the integrity of these cofferdams, and delays of even a few weeks during critical work periods have the potential to delay the in-service-date by up to a year. Also, given its northern environment, the management of river ice has been a key factor in the design of the station, and in the development of river management strategies to facilitate its construction.

Various ice studies were carried out during the design phase for this project to assist in identifying appropriate design elevations for cofferdams during construction, and to identify any changes to the long term ice regime both upstream and downstream of the project. These studies have relied heavily on the collection of comprehensive winter field data and on calibrated numerical ice models. These ice models were also used to provide important construction design support during an early winter failure of the project ice boom which occurred in the initial winter of construction (2014/2015).

2. Overview of Ice Processes – Natural/Pre-Project Condition

As shown in Figure 2, the Keeyask Project is located on the Lower Nelson River in northern Manitoba. The reach of the lower Nelson River located within the Keeyask G.S. project area begins at the outlet of Split Lake and ends at the inlet to Stephens Lake. Overall it is a fast flowing river with reaches that are separated by rock controls, rapids, and lakes. The river drops approximately 26 m along its 56 km course between Split Lake and Stephens Lake, and experiences average winter flows of approximately 3300 m^3/s.

Ice formation on the lower Nelson River within this reach is a relatively complex process, and has been studied for many years by Manitoba Hydro. Under the pre-project winter regime, a thermal cover usually develops first on the reach's bounding lakes (Split Lake and Stephens Lake), while other faster sections of the river remain open, generating large volumes of frazil ice. As a result, two distinct ice covers typically develop over the course of a winter season in this reach:

i. a large hanging ice dam forms immediately downstream of Gull Rapids, at the inlet to Stephens Lake, and
ii. once sufficient border ice has formed, the ice will eventually bridge upstream of Gull Rapids, and advance upstream by juxtaposition/mechanical thickening.

Each reach is described briefly below.

Gull Rapids to Stephens Lake

In this reach, the Nelson River drops 13 m, from an elevation of approximately 153 m on Gull Lake to an elevation of 140 m (typical) on Stephens Lake. The majority of this head drop occurs within Gull Rapids over a distance of approximately 4 km. Although the rapids contain three separate channels (north, centre, and south) the majority of flow remains in the south channel of the river. Velocities in this branch are high, as flows cascade downstream over a series of rock controlled shelves. In this reach of the river, an ice cover initially forms on Stephens Lake in the early fall, typically around November 1st. Once Stephens Lake freezes over, all ice generated in the upstream reach passes through Gull Rapids, and collects on the leading edge of the cover, and causes the cover to begin to advance upstream. However, the opportunity for upstream progression is limited and the ice front typically stalls at the site of the proposed Keeyask G.S. due to the high velocities in these rapids. Any incoming ice is submerged and deposited under the ice cover resulting in the formation of a large hanging ice dam at the foot of Gull Rapids. The growth of this ice dam is initially very rapid, but slows considerably when and if an ice bridge forms upstream in Gull Lake. The ultimate size of the ice dam in any given winter is therefore very dependent on when and where the ice cover may eventually bridge upstream of Gull Rapids. Once the cover bridges, the supply of frazil ice being passed from the upper reach into the lower reach drops considerably.

Normally, the increase in water level stage due to the accumulating ice dam is limited to perhaps 3 or 4 m. However, during extreme years involving cold winter temperatures and delayed upstream bridging, the winter water level may increase by 8 or 9 m over the open water level. The ice front has not been observed to directly progress up through the south channel of Gull Rapids into Gull Lake, even during such an extreme year. Although the ice front does not progress, under natural conditions, ice constrictions can begin to form in parts of the rapids, and this can lead to some local staging, and help to facilitate the initiation of an ice front near the head of the rapids.

Split Lake to Gull Rapids

In this river reach, the Nelson River drops 13 m, from an elevation of approximately 166 m on Split Lake, down to an elevation of approximately 153 m at Gull Lake. The majority of this head drop occurs over a relatively steep section of the river located between the outlet of Clark Lake down to a point which is approximately 15 km upstream of Gull Rapids. The higher velocities in this reach have a significant impact on overall ice formation processes.

Each year, a competent ice cover first forms on Split Lake, usually beginning sometime between mid-October and mid-November. At the same time, frazil ice is generated in the open water sections of the river, and these generated flocs agglomerate into ice floes and eventually, into larger ice pans and sheets. These pans gradually grow in size with time of exposure, and distance travelled downstream. Figure 4 shows a reach of the river near Gull Rapids, and gives an indication of the density and size of some of these pans. Border ice also begins to grow from each bank (where velocities are low enough) gradually reducing the open water width of the river. As the open water width narrows and generated ice pans become larger and larger, these ice sheets eventually lodge, or arch at a narrow section of the river, creating an ice bridge. This bridge typically forms within the vicinity of Gull Lake, and thus permits the progression or advancement of an upstream ice cover. The date at which this ice bridge may form is quite variable. Typically, bridging occurs by mid-December, but it has been known to occur as early as mid-November, and in other years, has not been observed to occur until late in the winter (if at all).

Once initiated, this cover advances upstream through a juxtaposition process. The typical cover in the downstream reach of Gull Lake (i.e. up to 10 km upstream of Gull Rapids) is relatively thin, and smooth, as the cover is able to advance quickly and easily against the lower velocities in this area. However, the cover in the upstream reach of the lake is considerably thicker and rougher, as it must periodically shove and thicken to support the advancing ice cover. The cover typically grows to be between 5 m and 8 m thick in the upper reaches of Gull Lake. The advancing ice cover typically stalls either temporarily or for the season at the foot of Birthday Rapids, owing to the higher velocities present at this location. These high velocities cause ice pans to submerge and be carried under the leading edge, leading to the formation of a hanging ice dam downstream of the rapids. As the hanging ice dam grows downstream of Birthday Rapids, it leads to increases in water levels at the foot of Birthday Rapids. Eventually, water levels may rise to a point that is high enough to “drown out” the rapids, lowering flow velocities, and allows the cover to begin advancing upstream again. This does not occur every year, but if it does, the cover eventually stalls at a location which is approximately 5 km upstream of Birthday Rapids.

Anchor ice also typically forms just downstream of the outlet of Clark Lake, and also at the immediate outlet of Split Lake. These accumulations slowly restrict the conveyance of the channel in this area, at times leading to water level staging upstream along both Clark Lake and Split Lake.

3. Ice Management Strategy

Given the northern location of this project, management of the challenging river ice processes described above is key to the success of the project. As noted in section 2, winter stage increases at the project site can be quite variable, and quite large in the natural environment, prior to construction of the dam.

The diversion strategy developed to allow construction of the project relies on the performance of an ice boom, which has been installed upstream of the project site and is used to initiate and encourage the formation of an early upstream ice cover. This boom forms the subject of another paper at this workshop (Morris, 2017), but by promoting the early development of the upstream ice cover, it prevents ice that would normally be generated in the long river reach upstream the project site from forming and passing through Gull Rapids and collecting in a massive ice dam at the base of the rapids. The reduction in this ice volume allows cofferdam elevations to be lowered, saving considerable construction costs for these temporary structures, as well as minimizes additional river management challenges (i.e., increased seepage due to higher water levels) that have the potential to affect planned construction activities during the winter period.

4. Numerical Model

Sophisticated numerical models have been developed over the years to help better understand and predict ice conditions on river reaches like these. A robust and comprehensive model, ICESIM, was developed and calibrated to represent the steady growth of the ice cover over a typical winter period [KGS Acres, 2009). This model was used to predict ice conditions in the vicinity of the proposed Keeyask G.S. for use in the design and construction of the Project. In addition, a fully hydrodynamic ice model, ICEDYN, was setup and used to dynamically route projected daily discharges the thereby predict forebay and tailwater level variations associated with the project.

The ICESIM model was developed by Acres International Limited (now Hatch Ltd.) in the late sixties to facilitate the design of hydroelectric plants on the Nelson River in Manitoba, Canada. The ICEDYN model is nearly identical in its ability to simulate the various ice formation processes, but is a fully dynamic model rather than a steady state model. This allows the program to route time varying hydrographs through the river system.

Both models consider, in discrete time steps, the various ice processes that affect the water surface profile along a river, namely

- rate of ice generation
- ice cover advancement by frontal progression using a Froude number criterion
- ice deposition and transport
- ice erosion
- border ice growth
- ice retreat by shoving

Separate models were setup for the areas upstream of the project site, and downstream of the project site. Cross sections for each model were derived directly from existing backwater datasets of the reach. These cross sections were surveyed as a part of earlier hydrometric surveys, and are consistent with those sections utilized in concurrent open water studies. Additional interpolated cross sections were added to the two models as needed to ensure model stability.

Following its initial setup, the models were calibrated to match open water rating curves previously derived at a number of specific locations along the river reach based on measured field data. After obtaining a suitable match under open water conditions, the models were then used to simulate the development of an ice cover on the two study reaches for winters in which ice observation data was available. Ice parameters for the models were initially selected based on judgement, and these parameters were then adjusted as necessary to obtain a good match between simulated levels and those measured in the field for a number of past winters. Final parameters for the originally calibrated ice models are summarized in Table 1 below.

Table 1. Summary of Ice Parameters

Parameter	Value	
Ice Erosion Velocity:	1.5	m/s
Ice Deposition velocity:	1.0	m/s
Limiting Froude Number:	0.12	
Maximum roughness of ice cover:	0.05	manning n
Roughness of bed:	0.03	
K1 tan Φ :	0.18	
K2 :	8.5	

The upstream boundary condition of the models consisted of user defined flows, while the downstream boundary condition consisted of a user defined stage hydrograph. Air temperature sequences utilized in the models were based on meteorological data collected at the Gillam airport (MSC, 2015).

Under open-water conditions, the models were calibrated to within 0.25 m of the open-water rating curves derived at the key location in the study area. Under winter conditions, a good overall match was achieved between measured and modeled water level data. Figure 5 illustrates a sample water surface profile for the upstream reach of river between Spilt Lake and Gull Rapids. As shown in Figure 5, the first 10 km (i.e. within Gull Lake) of the ice profile consists of a relatively thin, juxtaposed cover. Upstream of this, the cover is considerably thicker, and consists of a much rougher, mechanically thickened profile.

The upstream model was able to reproduce winter water levels at key locations upstream of Gull Rapids to within 0.5 m, on average, of those observed during the freeze-up period. Downstream of Gull Rapids, the downstream model was able to reproduce observed freeze-up water levels to within 0.75 m on average.

Figure 6 shows the results of a simulation for the 1991/1992 flow year for the reach of river downstream of the Gull Rapids. Also shown for comparison on this figure are a number of surveyed water levels that were taken for this period. As discussed earlier, a large hanging ice dam typically forms in this area, and the significant size of this hanging ice dam is well demonstrated in this profile plot. Again, the reasonable match obtained between observed and computed water levels demonstrates the ability of the numerical model to represent the complex ice conditions along the reach.

5. Model Application - Construction Support

Once calibrated, the numerical models were used for a variety of things – to help set cofferdam heights required for winter protection, to help establish base line conditions for environmental studies, and to help predict how ice conditions on the river would change in the post-project environment. Likely the most important role played to date however involved use of the model to provide real time construction support, which was required during the winter of 2014/15.

As noted in other papers (Abdelnour 2016, 2017), (Morris, 2017), a potentially disastrous situation occurred during the first winter of the Stage 1 diversion program. In November, 2014, unprecedented high river flows, and unseasonably cold temperatures, caused a section of the upstream ice boom to break, allowing travelling ice sheets to continue flowing towards the project site, accumulating in a very large ice dam just downstream of the project site (Figure 7). The water levels began to rise steadily and relentlessly and threatened to overtop and/ or end run a kilometer-long cofferdam that was constructed to allow the powerhouse excavation to proceed. Failure of the cofferdam, and inundation of the work area, would have been devastating, resulting in up to a year’s delay to the project and many millions of dollars in losses. A contingency plan was immediately triggered and the top-up of these cofferdams was started. Of critical importance to the contingency plan was the prediction of how high water levels could ultimately rise due to the accumulating ice. This information was needed in order to select a new, target crest elevation for the powerhouse cofferdam under the most severe winter scenario contemplated. In order to provide this critical information, the developed ice models were remobilized and converted for use in a forecasting role. The team, working closely with Manitoba Hydro's engineers, carefully reviewed expected flow forecasts and historical temperature records to select an appropriate design condition for the winter period. The model was then used to simulate the expected winter condition, and to provide final water level projections to the geotechnical design team.

The model results were sobering, as they indicated the 15 m thick ice dam would result in a formidable increase in level at the powerhouse cofferdam site – increases in level of more than 6 m above the previous winter design levels which assumed the ice boom was in place, and more than 10 m above open water levels at this location. Of equal importance was the expected rate of rise of these winter levels. The construction team required this information in order to assemble the operator and equipment fleet that would be needed to stay ahead of these rising water levels. This information was relayed to the rest of the design team, and during the course of the winter, the model results were updated frequently based on actual atmospheric conditions and flows. Figure 8 illustrates the rough nature of the ice dam, as it forms along and interacts with the powerhouse cofferdam. Figure 9 illustrates the ICESIM model representation of the ice dam and how it correlated with empirical site information. Of interest, the figure shows both the simulated or predicted profile along with the observed water level measurements taken on that date. The good correlation between model results and observed levels provided good confidence in the ability of the model to simulate a very complex physical ice process.

The modelling team did find that some modifications were needed to the calibrated ice parameters to better represent the severe ice conditions associated with this ice dam during the construction period. Predicted ice levels using the originally calibrated ice parameters tended to underestimate the rate and amount of staging the team was seeing early in the winter period. It was found that results were most sensitive to changes in both the ice deposition and ice erosion velocities set for the ice dam in the model, and to the maximum roughness adopted for the cover. The original calibration values used in the model for the deposition and erosion velocities were 1.0 and 1.5 m/s respectively. It was necessary to raise each of these values by 0.1 m/s (to 1.1 and 1.6 m/s) in order to better match field data, and to increase the maximum roughness value of the cover to 0.08 to reflect the increased roughness expected for the thicker cover. These adjustments were considered to be reasonable – and are certainly within the range of possible values based on previous work by Michel (1971) and Nezhikhovskiy (1964). It was rationalized that the very cold temperatures being experienced (one of coldest winters on record) resulted in the development of relatively large, thick ice sheets upstream of Gull Rapids. This ice would be broken up to a large extent as it passed through Gull Rapids, but the resulting ice chunks and pans would still be quite competent and buoyant as they passed under the ice dam. One would expect that this type of ice may lodge more easily under the dam than ice generated in other years (i.e. during less severe winters), and conversely it may take a greater force to dislodge and erode this ice once it is in place. In addition, the high flows being experienced would have slowed normal border ice growth, and delayed or in this case prevented the formation of an upstream ice cover that would have normally cut off the frazil ice supply. The Stage 1 Diversion strategy, in which all flow was contained in the south channel of the rapids, appeared to exacerbate this delay in a natural bridging event by concentrating flow in the center of the channel. The border ice development was therefore limited, and the open channel width remained too large for incoming pans to arch naturally. This raised the risk that an ice cover was not going to be initiated naturally. Considering all of these things, the trend to higher deposition and erosion velocities and a higher ice roughness value made good sense to better match field observations.

Conversely, in subsequent years of diversion, in which the ice boom has been functional and was successful in developing an upstream cover, water level increases downstream of the project have been very small. This implies that ice volumes collecting in the reach downstream of the project are very small. For these years, it was found that it was necessary to reduce the ice deposition velocity to 0.9 m/s (from the originally calibrated value of 1.0 m/s) in order match the observed staging patterns. Again, this can be rationalized based on the modified character of the ice pans that are now formed downstream of the ice boom. Given the shortened reach available for generation of ice downstream of the boom, these pans tend to be very small, thin, and slushy when they pass through Gull Rapids. Since the resulting ice matrix is almost neutrally buoyant, one would expect that deposition velocities would be correspondingly lower.

6. Summary and Conclusions

The proposed Keeyask Generation Project, a 695 megawatt hydroelectric generating station (GS), is currently under construction at Gull Rapids on the Lower Nelson River. Various pre-construction field and engineering studies have been undertaken to help establish an environmental winter baseline for the project, to assist in designing river management strategies for construction of the project. The work involved the setup, calibration, and application of sophisticated numerical ice models to simulate the formation of an ice cover at this site. Important construction design support had to be provided during an early winter failure of the project ice boom which occurred in the initial winter of construction (2014/2015). The numerical model was used successfully to track and forecast how high water levels would rise, providing important real time support to the construction team. However, it was found that small adjustments to some of the calibrated ice parameters were necessary in order to better match field data for events that may be considered to bracket the range of possible levels.

6. Acknowledgments

The authors would like acknowledge and thank Manitoba Hydro for supplying all data used in this assessment, and for allowing the team to publish the results of these studies.

7. References

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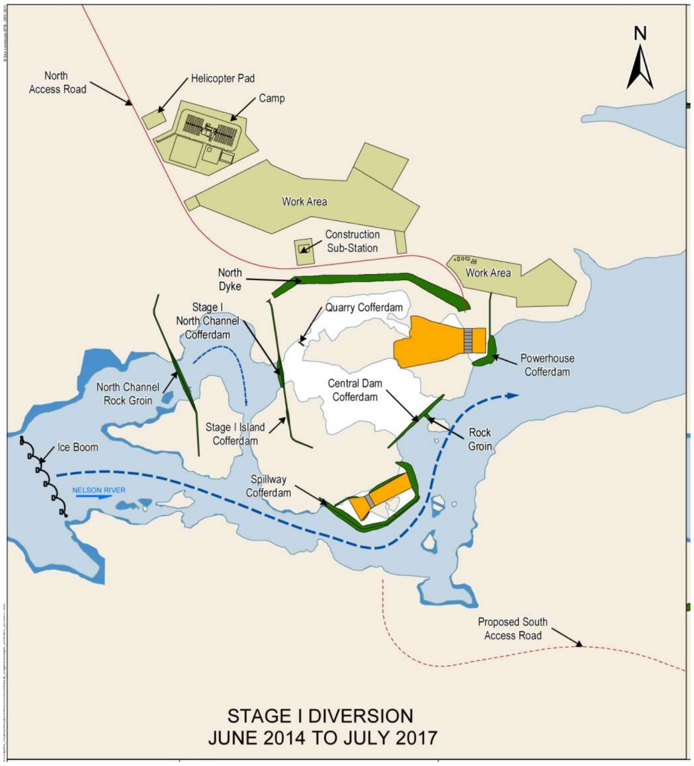

Figure 1. Keeyask Project Stage 1 River Diversion Strategy

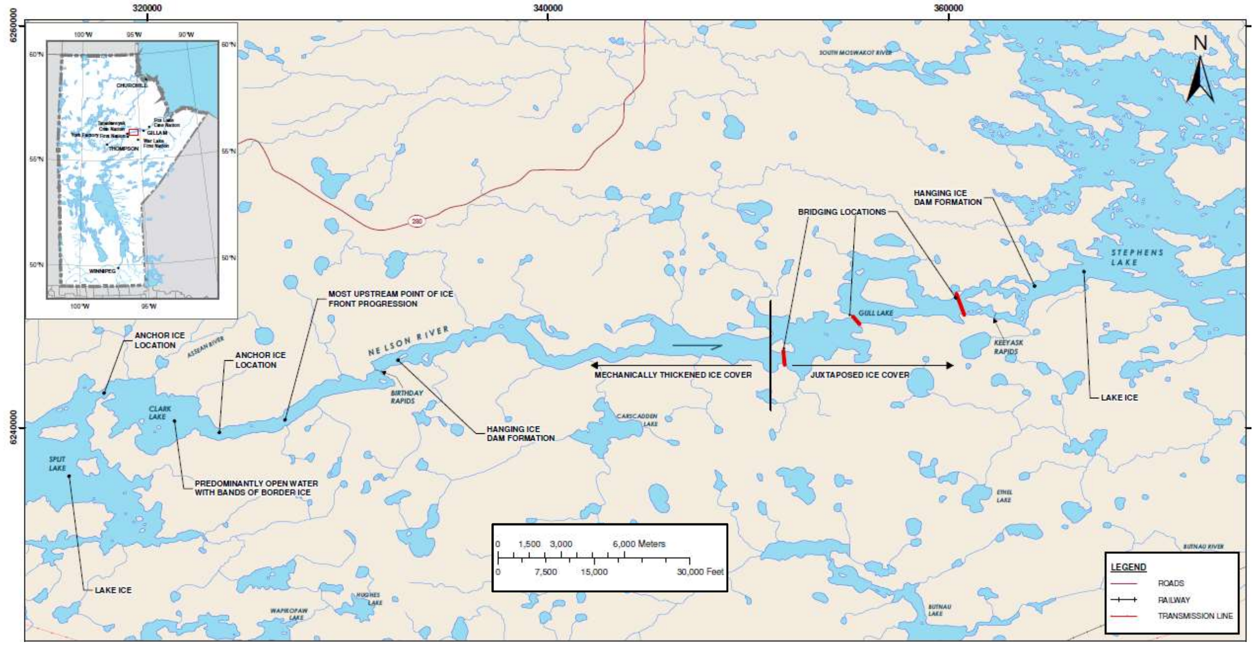

Figure 2. Keeyask Reach – Major Ice Processes

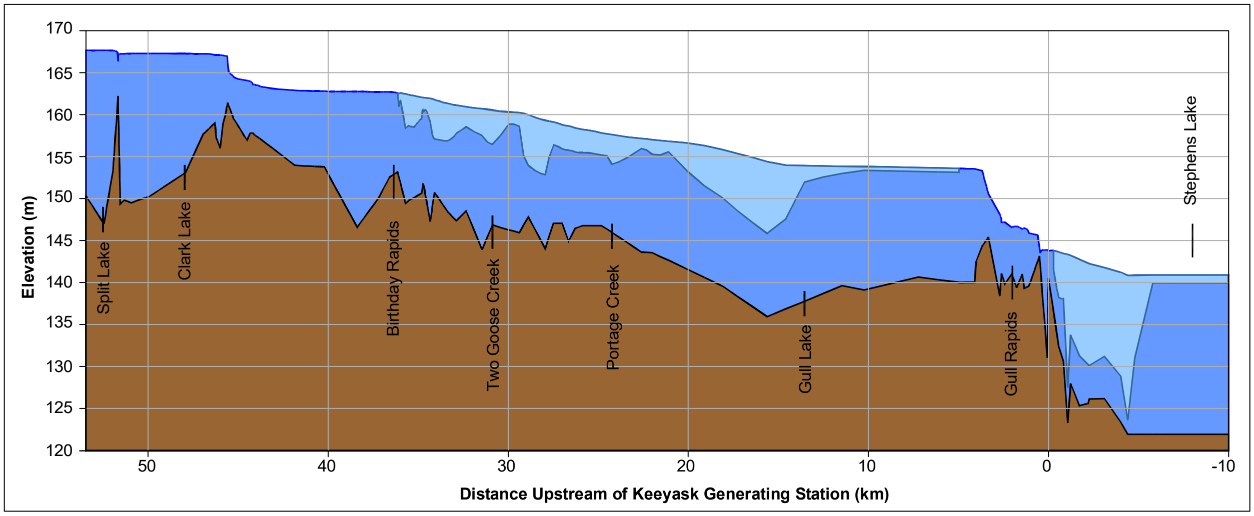

Figure 3. Keeyask Pre-Project Ice Regime – Typical End of Winter Profile

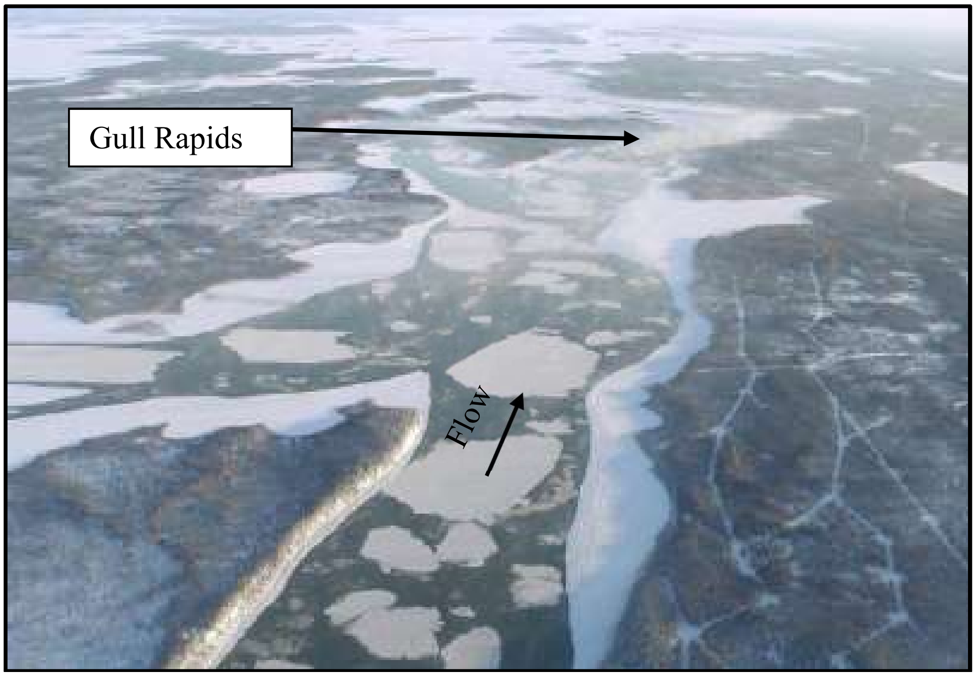

Figure 4. Typical Concentration of Ice Pans and Sheets Upstream of Gull Rapids

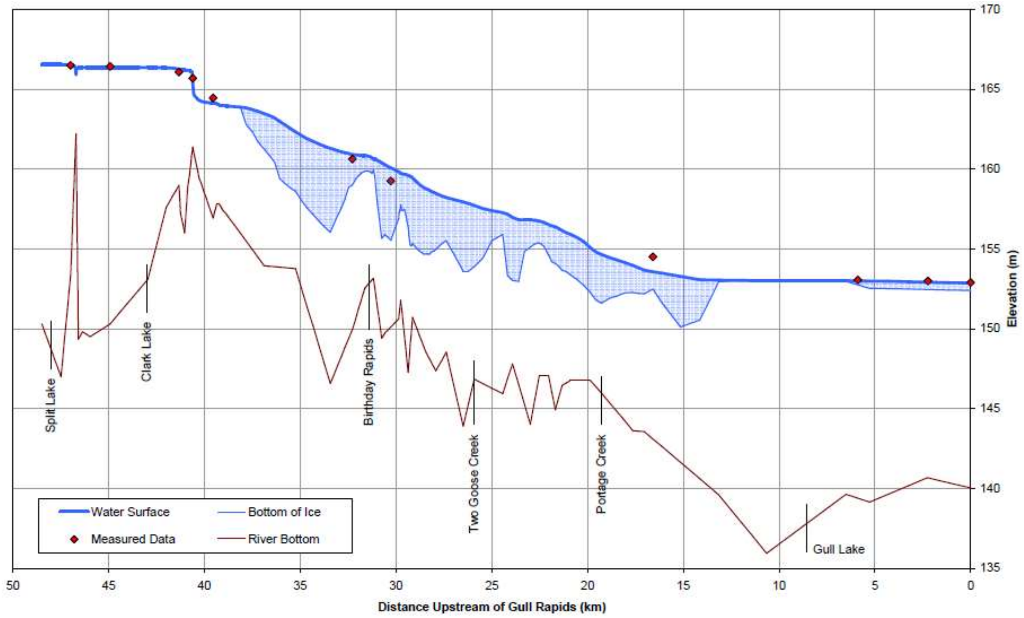

Figure 5. Example Calibration Year for Upstream Reach (2003/2004)

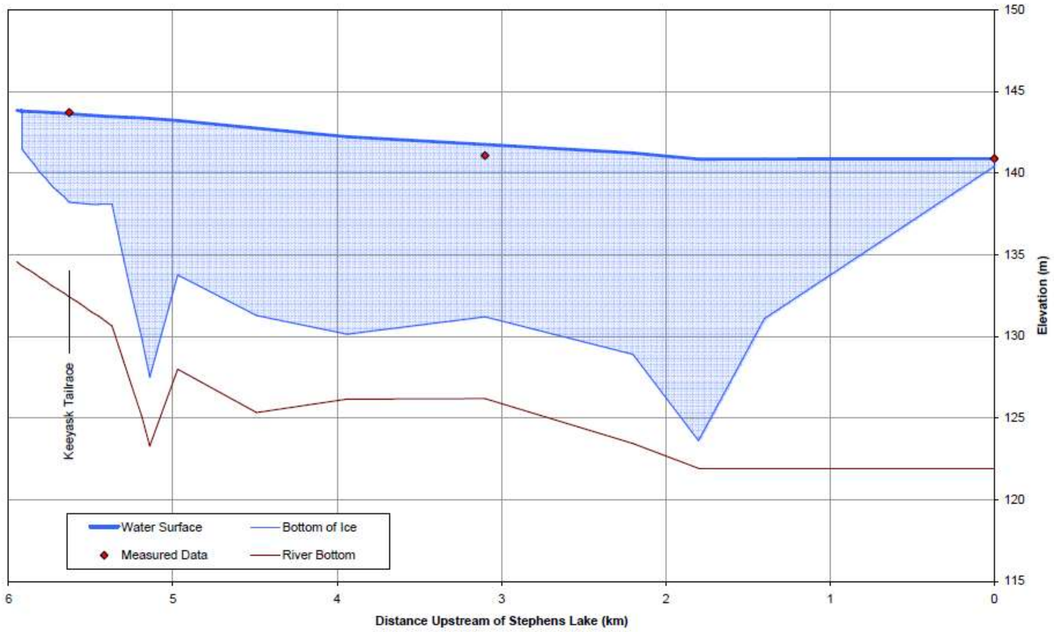

Figure 6. Example Calibration Year for Downstream Reach (1991/92)

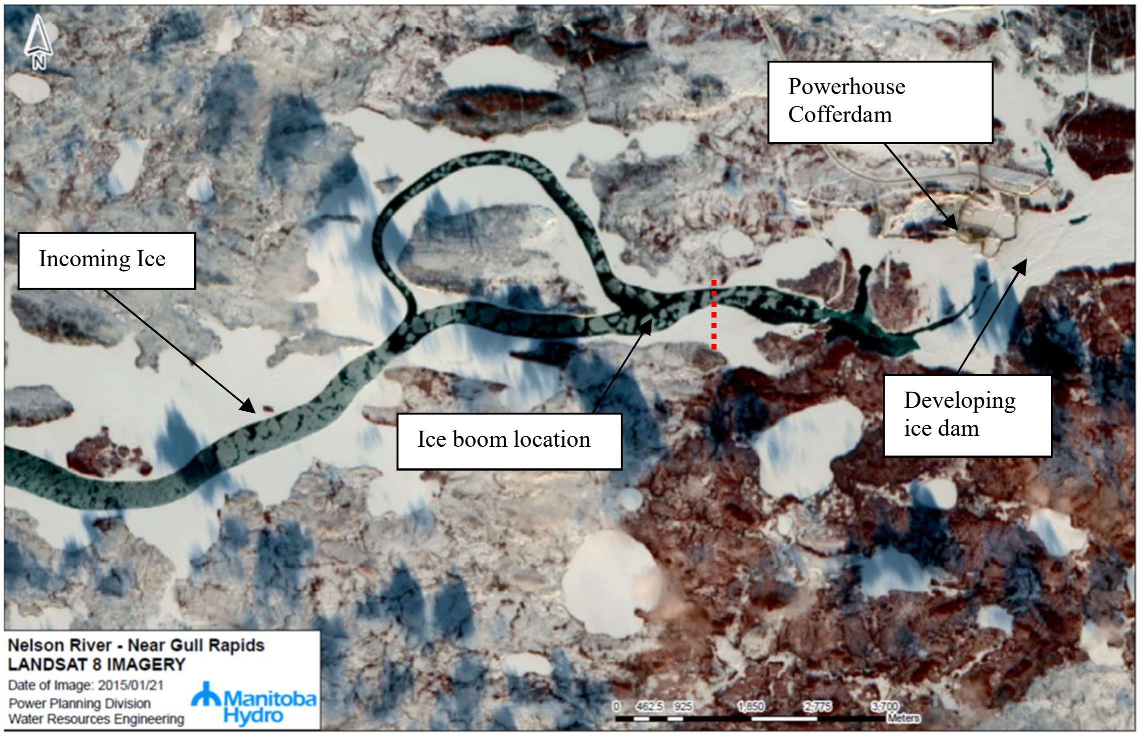

Figure 7. Frazil ice generation and ice dam buildup at Powerhouse Cofferdam (Jan, 2015)

Figure 8: Accumulating Ice at Crest of the Powerhouse Cofferdam

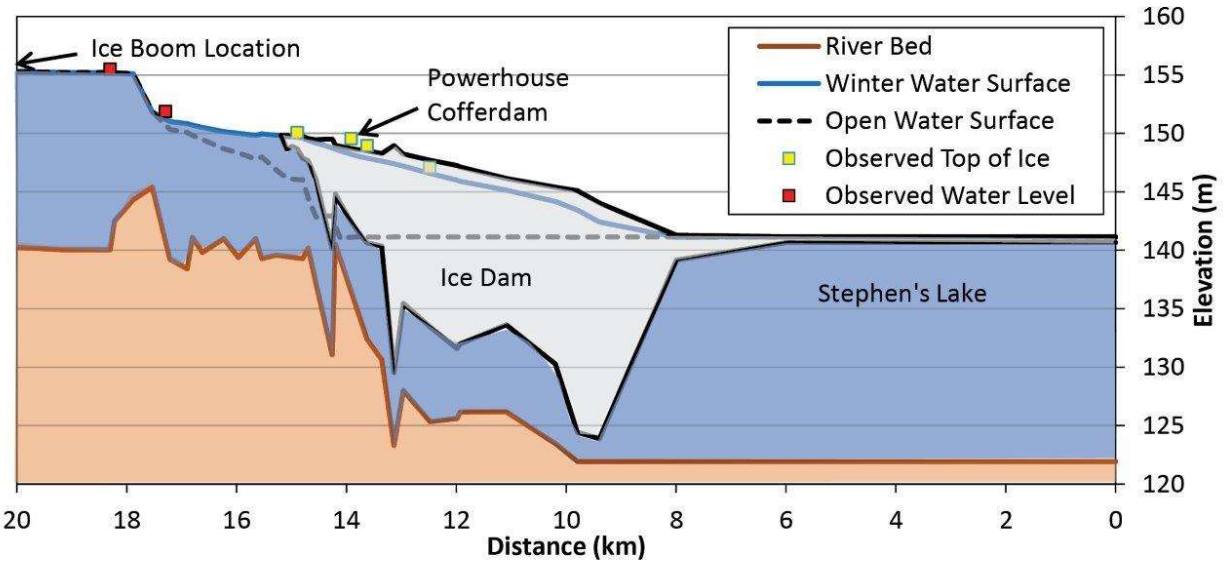

Figure 9. Example of ICESIM computed and observed ice profile (January 2015)