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Climate and Ice Impacts on Great Slave Lake Levels and Flows in the Mackenzie River, Northwest Territories

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At the head of the Mackenzie River in the Northwest Territories, streamflow, lake level, ice cover, and climate are all part of a complex system. Conceptually, the formation of an ice cover on the Mackenzie River reduces outflows from Great Slave Lake by changing the hydraulic properties of the receiving channel, which in turn reduces drawdown of the lake during the winter months, when inflows to the lake are generally low. In warmer than average years, the duration of the ice covered season may be reduced, which in turn may result in higher lake outflows and seasonal drawdown of the lake. This paper will build on existing analysis of the lake outflow hydraulics to provide better insights into the effects of climate warming trends on long-term Great Slave Lake levels and discharge in the Mackenzie River. Results of comparative model simulations will be presented to better quantify the relationship between ice cover, lake level, and flow into the Mackenzie River.

1. Introduction

The effects of climate and human influences on surface waters in the Mackenzie River Basin are of importance to the people of the Northwest Territories for various ecological and social reasons. For example, a long-term decline in water levels on Great Slave Lake could have negative impacts on the navigability of the Mackenzie River through corresponding reduced streamflow and shallower depths. Outflows from Great Slave Lake are governed largely by lake level and inflows during the open water period; however, river ice is a significant factor in the seasonal variations in lake level, by increasing resistance and reducing flow area at the head of the Mackenzie River (Hicks et al., 1995a).

Inflows to Great Slave Lake via the Slave River are influenced by hydropower regulation on the Peace River. Under regulated conditions, a larger proportion of the annual flows occur in the winter months compared to the summer months and the mean annual flood magnitude has been reduced from its pre-regulation value (Church, 2015). Lake level changes in response to the water balance of the lake, and the river inflow and outflow volumes are a major component of this system. Precipitation and evaporation are also components of the lake water balance, but to simplify the analysis are not considered in this work.

The complexity of this system is increased by feedback mechanisms, which work to maintain a balance in lake levels. In a typical lake routing system, reductions in river inflow (due to summertime flow regulation or drought conditions) will tend to reduce outflows by means of a natural (or in some cases engineered) hydraulic outlet control. For Great Slave Lake, the outlet control is determined by the natural channel capacity of the Mackenzie River under variable hydraulic conditions. The objective of this paper is to investigate the potential climate and river ice impacts on Great Slave Lake water levels and outflows. More specifically, under warmer climate conditions, to what extent would a thinner ice cover or shorter ice-affected season alter seasonal lake levels and outflows.

Climate warming projections for the current century have the potential to dramatically affect river ice processes by prolonging freeze-up and delaying the formation of a stable ice cover. For example, Andrishak and Hicks (2008) found that the number of days an ice bridge could be sustained on the Peace River at the Shaftesbury Ferry site (upstream of the Town of Peace River) could decrease by up to 78%.

2. Modelling Approach

An existing, calibrated HEC-RAS model, used by Pietroniro et al. (2011) to develop a set of stage-fall rating relationships for the outlet of Great Slave Lake, was applied to examine the sensitivity of Great Slave Lake water levels and outflows to ice thickness and duration of ice-affected season on the Mackenzie River near Fort Providence, Northwest Territories. Previous work done by Hicks et al. (1992, 1995a,b) included field data collection, hydraulic model development and calibration, and analysis of the effects of river ice on flows in the Mackenzie River near Fort Providence, particularly as it pertains to the breakup period when conditions are most dynamic and potentially most severe. The approach taken for the present study was to build upon the previous work to better understand how an ice cover on the Mackenzie River may influence Great Slave Lake water levels in a warming climate.

Figure 1 shows the location of the study area and the modelled reach, which extends from the outlet of Great Slave Lake to Fort Providence. The downstream boundary, following the South Channel down to Fort Providence along the right side of Meridian Island, is approximately 100 km from Great Slave Lake. The Big Snye channel along the left side of Meridian Island was not included in the existing model; however, the North Channel which connects the Mackenzie River to Great Slave Lake was included in the model, albeit with very limited geometry. Based on the information available, the North Channel is considerably shallower than the South Channel, so it tends to be most active during periods of high lake level.

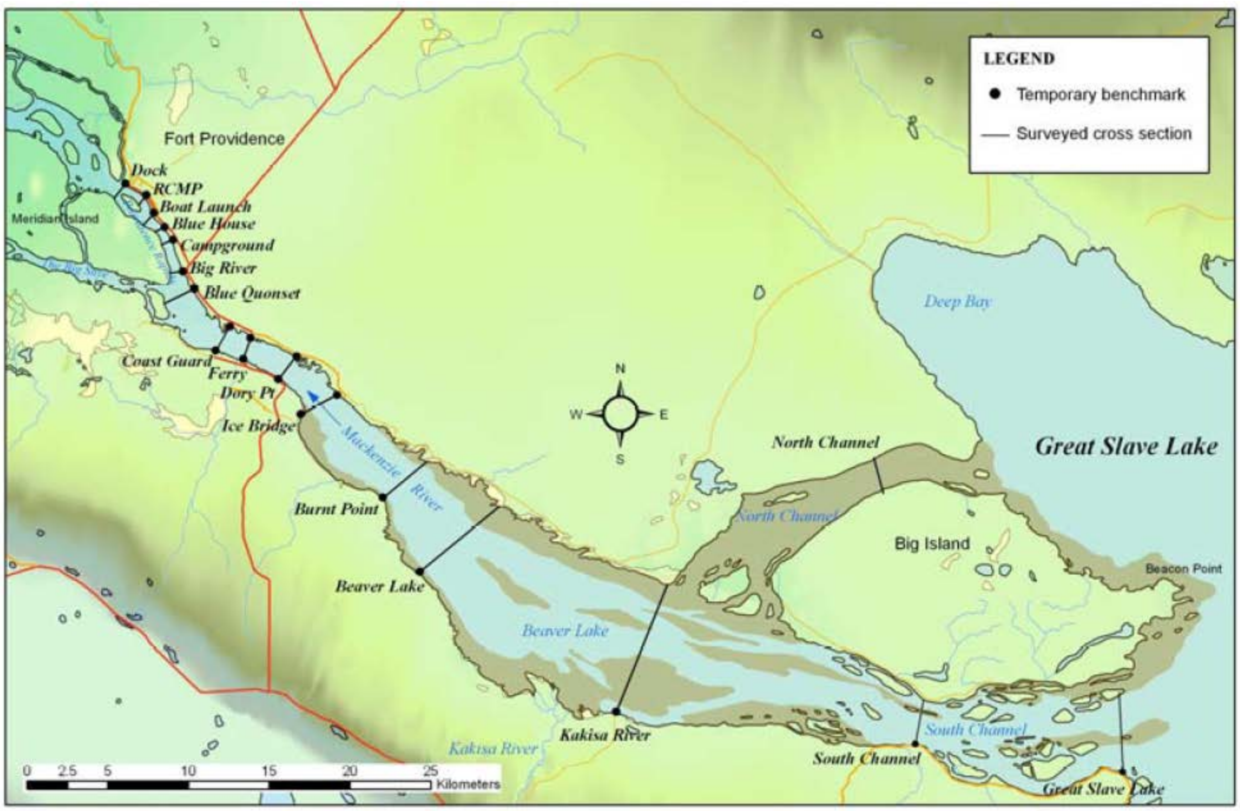

Figure 1. Study area and modelled reach showing the location of surveyed cross sections used in the numerical hydraulic model. (Source: Pietroniro et al. 2011)

Two sets of scenarios were run: first, a series of rating curves were developed for varying ice thicknesses and lake levels using steady state assumptions; second, the rate of lake level increase due to the formation of a stable ice cover on the Mackenzie River was analyzed using level-pool routing and unsteady assumptions for lake outflow. For the latter scenario, inflow to Great Slave Lake was held constant at 4,000 m^3/s (a moderate winter flow, based on the historical gauging records on the Slave River) to examine lake level change without the effect of fluctuating inflows.

Several other factors adding to the complexity of the outlet hydraulics were not considered, including: wind effects on Great Slave Lake water levels, partial ice covers during freeze-up, ice thickening by consolidation or breakup, and ice cover roughness changes in response to varying ice conditions. Although the above variables and parameters may be quite significant to the annual outflow and water level hydrographs for Great Slave Lake, there is substantially limited data available to reliably capture these aspects in the present work.

3. Results and Discussion

Figure 2 compares simulated discharge from the Mackenzie River Basin Hydraulic Model to the observed for the Mackenzie River at Strong Point (250 km downstream of Great Slave Lake, above the mouth of the Liard River), using the stage-fall lake outflow relationships derived from the existing HEC-RAS model. These continuous simulation results are based on fixed dates of freeze-up and breakup described by Pietroniro et al. (2011) and ice cover thickness measurements made by Hicks et al. (1995a). Considering the limited complexity of the model in terms of variable ice-affected conditions, the discharge hydrograph is reasonably well represented in these years; however, distinct differences between simulated and observed values such as those seen in late 1993 and early 1994 are most likely due to a delayed freeze-up which was not captured in the model. Likewise, at breakup, the model was unable to capture peak discharges such as those in the spring of 1992 and 1993 that are most likely associated with ice jam formation and release in the reach between Great Slave Lake and Strong Point.

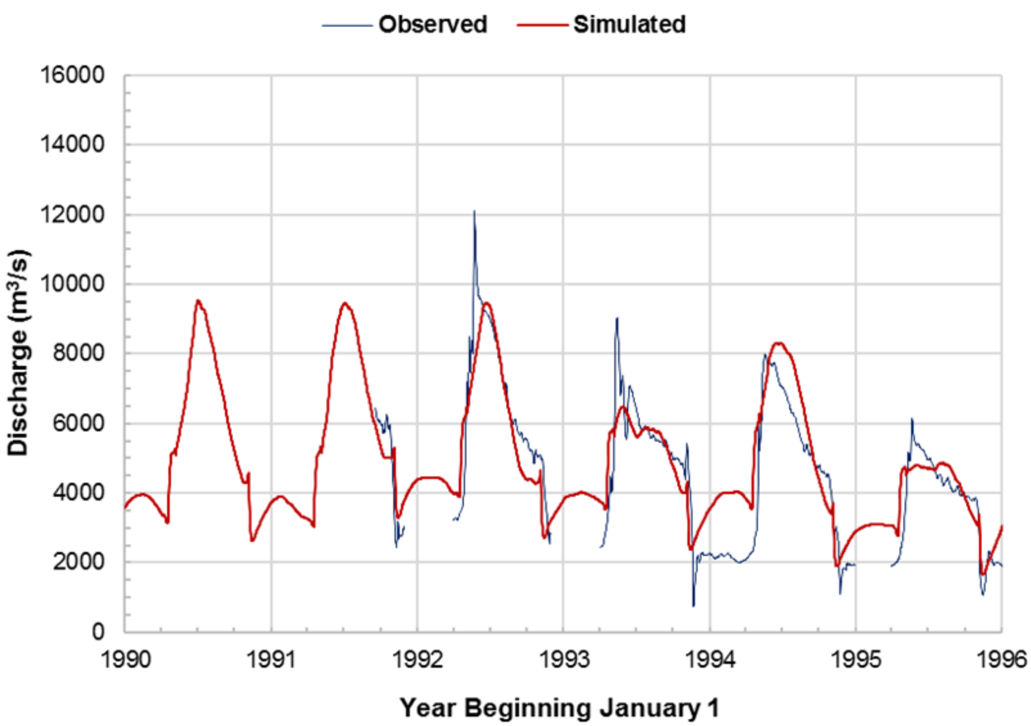

Figure 2. Comparison of simulated and observed hydrographs for Mackenzie River at Strong Point based on the Mackenzie River Basin Hydraulic Model.
(Source: Amec Foster Wheeler, 2016)

Figure 3 compares the simulated and observed water levels on Great Slave Lake for the same years shown in Figure 2. The results are similar in terms of overall agreement, and of note is that the simulated water levels consistently agree with the observed around the end of the open water season (i.e. late-September through end of November), just prior to the onset of freeze-up. This also suggests that the timing of ice cover formation and differences in the rate of ice growth from year to year are significant to the amplitude of the annual lake level hydrograph.

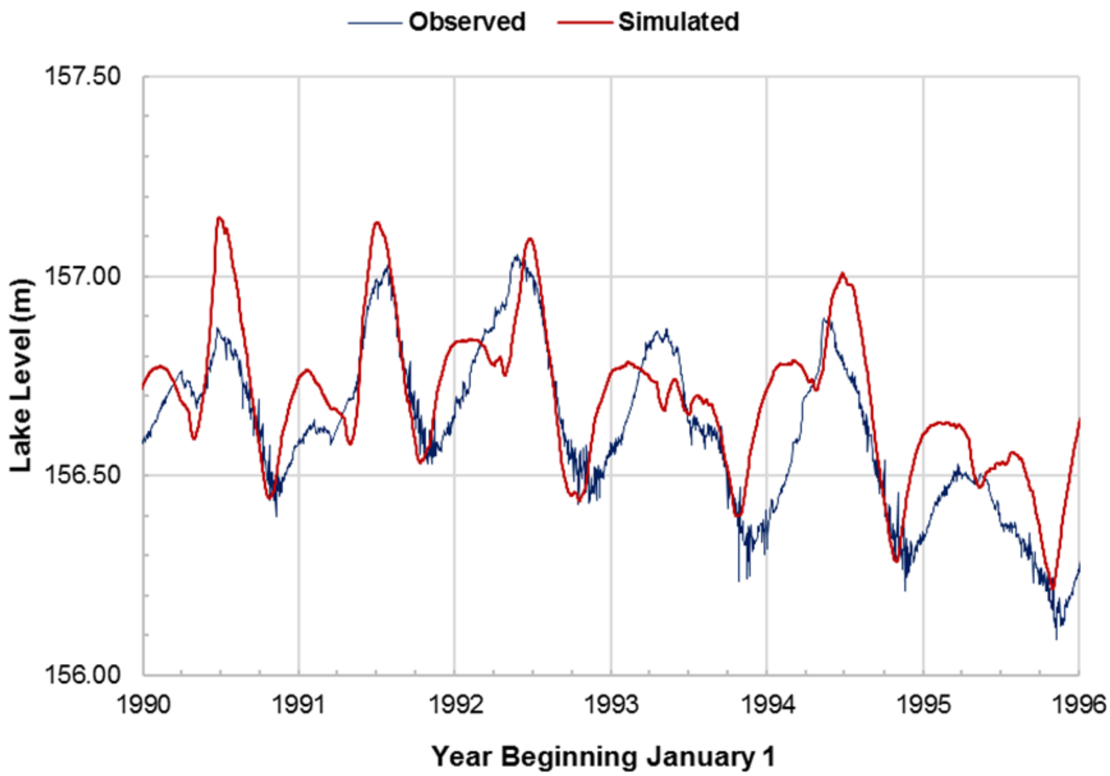

Figure 3. Comparison of simulated and observed water level hydrographs for Great Slave Lake based on the Mackenzie River Basin Hydraulic Model.
(Source: Amec Foster Wheeler, 2016)

Figure 4 presents simulated rating curves for the Mackenzie River at the outlet of Great Slave Lake for open water and four fixed, fully-developed ice cover profiles. The previously calibrated 1992 ice profile reported by Hicks et al. (1995a) was used to represent what could be considered "typical" winter ice conditions based on the available data (Pietroniro et al., 2011). To examine the sensitivity of ice thickness, 50% and 150% of the 1992 ice thickness profile were simulated for comparison. Also shown is a curve representing 1% of the 1992 ice thickness profile to illustrate the hypothetical lower envelope of the ice-affected rating curves controlling the lake outflows.

The approximate Water Survey of Canada (WSC) observed normal range of water levels on Great Slave Lake is 156.5 to 156.8 m, with infrequent lows of about 156.0 m and highs of about 157.3 m occurring in the historical record from 1938 to present (at Yellowknife Bay). Based on WSC gauging records for the Slave River, the approximate normal winter discharge (under regulated conditions), which is the largest river flowing into Great Slave Lake, is in the range of 3,000 to 5,000 m^3/s. From Figure 4, under steady state conditions and a lake inflow discharge of

4,000 m^3/s, the expected lake level would be 156.26 m under open water conditions, 156.63 m for 50%, 156.93 m for 100%, and 157.23 m for 150% of the 1992 ice thickness profile, respectively. Note that the 1 m range in water levels from open water up to 150% of the 1992 ice thickness profile at this representative winter discharge could potentially account for more than 75% of the observed variability in lake levels.

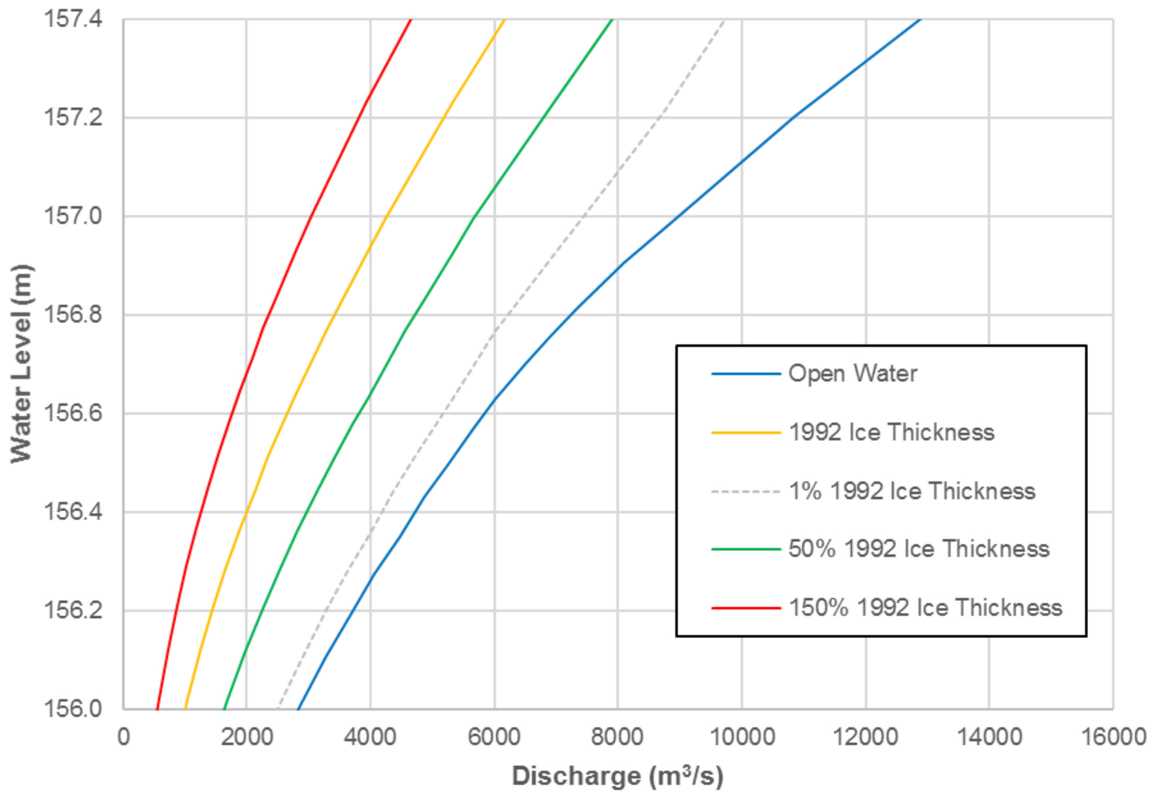

Figure 4. Simulated rating curves for varying ice thicknesses, Mackenzie River South Channel outlet from Great Slave Lake.

Unsteady flow routing using a level-pool assumption for Great Slave Lake was used to further assess the effect of ice on lake levels. Figure 5 compares the response for a constant inflow discharge of 4,000 m^3/s over the winter period. The open water case is shown strictly as a control condition, where the outflow would remain equal to the inflow when starting from an initial lake level of 156.26 m. Table 1 summarizes the key water levels of interest to quantify the effect of ice thickness and duration of ice-covered season.

Table 1. Effect of ice-affected season duration on Great Slave Lake water levels.

Duration of ice-affected season	**Water Level at End of Period (m)**		
	50% 1992 Ice Cover	**1992 Ice Cover**	**150% 1992 Ice Cover**
6 months	156.61	156.87	157.12
5 months	156.59	156.83	157.07
4 months	156.56	156.78	156.99

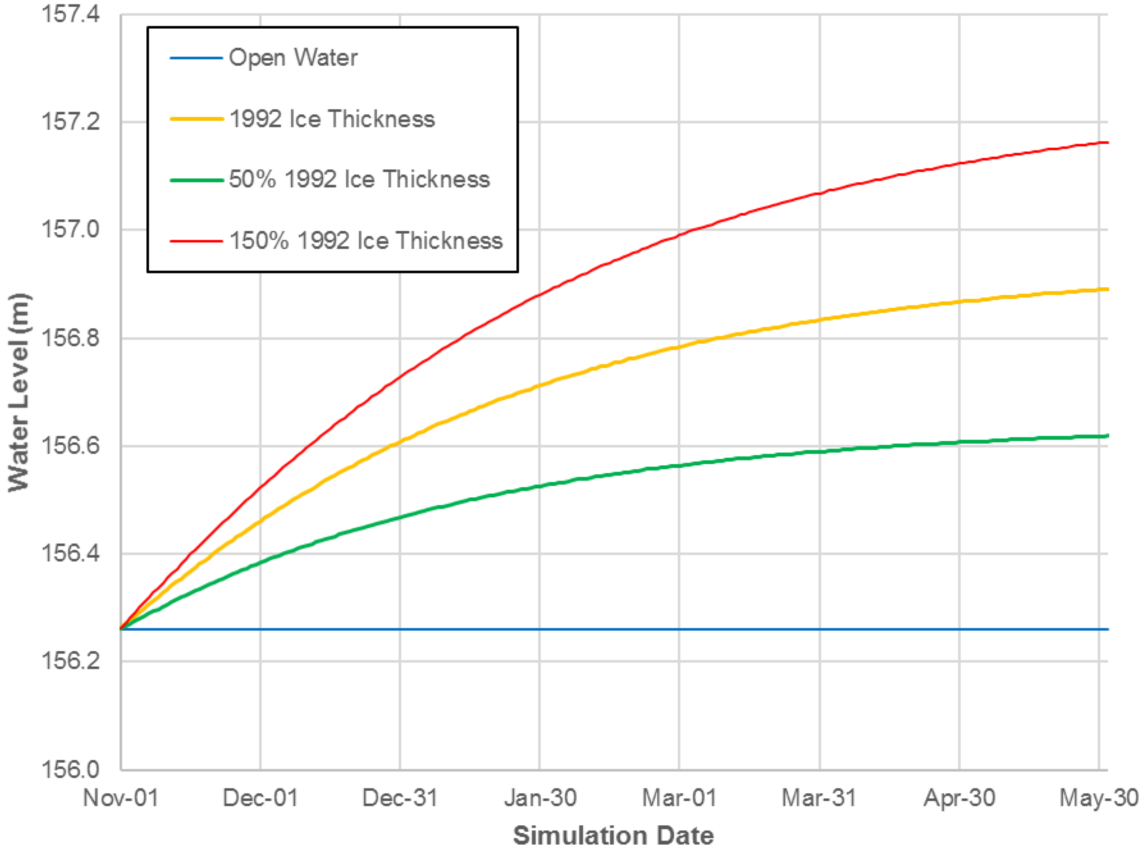

Figure 5. Comparison of Great Slave Lake water level hydrographs for hypothetical constant ice conditions on the Mackenzie River and constant inflow discharge. (Note: open water case shown as a control scenario.)

These results suggest that shortening of the ice-affected season is unlikely to have as significant an impact on lake levels as changes in ice thickness. However, the timing of freeze-up and the duration of ice-affected season could influence ice thickness for a variety of reasons. Further examination of the data would be required to quantify these effects. A thermal river ice growth model developed by Trillium (2002) for the Mackenzie River at Fort Providence was used to estimate the effect of warmer air temperatures on ice thickness, using historical data from the winter of 1992 as a baseline for comparison. Figure 6 shows the modelled ice thickness over the winter period for historical 1992 and 1°C, 3°C, and 5°C warmer than historical. The largest difference in ice thickness occurs in the month of February, with a reduction of 0.02, 0.07, and 0.09 m for the 1°C, 3°C, and 5°C warmer scenarios, respectively. The initial ice thickness of 0.90 m used by Trillium (2002) was kept the same in each scenario.

To illustrate the impact of this, Figure 7 shows the simulated rating curves for open water and 1992 ice cover (from Figure 4) together with a curve corresponding to a 0.09 m ice thickness reduction, as in the 5°C warmer climate scenario. Since the magnitude of this change in ice thickness is much less than the percentage changes in ice thickness shown in Figure 4, the deviation from the 1992 ice thickness curve is also relatively small.

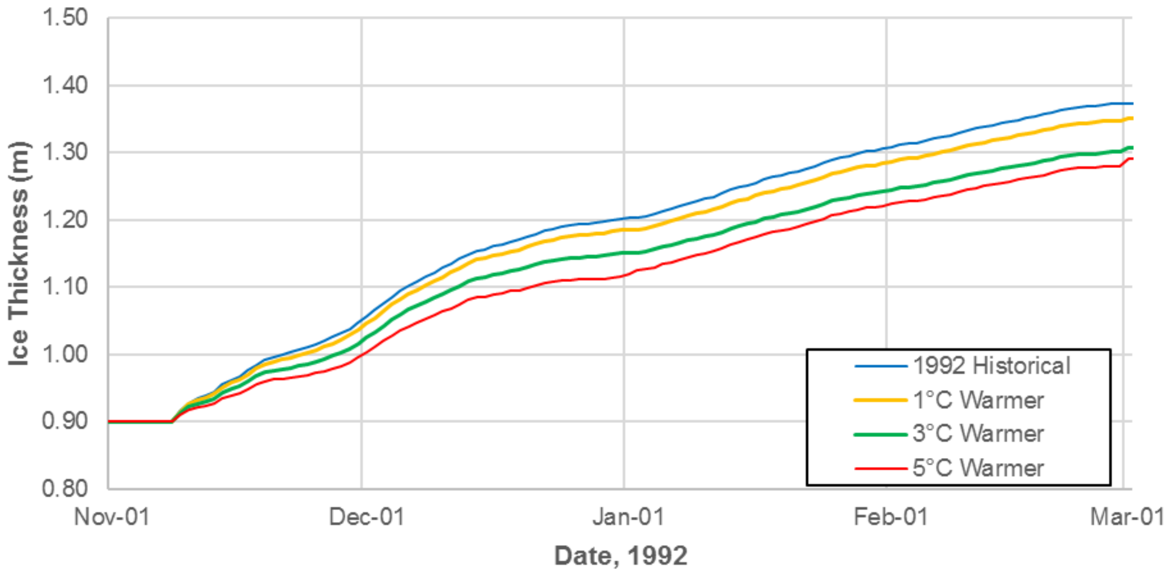

Figure 6. Results of river ice growth model for Mackenzie River near Fort Providence under historical and warmer climate conditions.

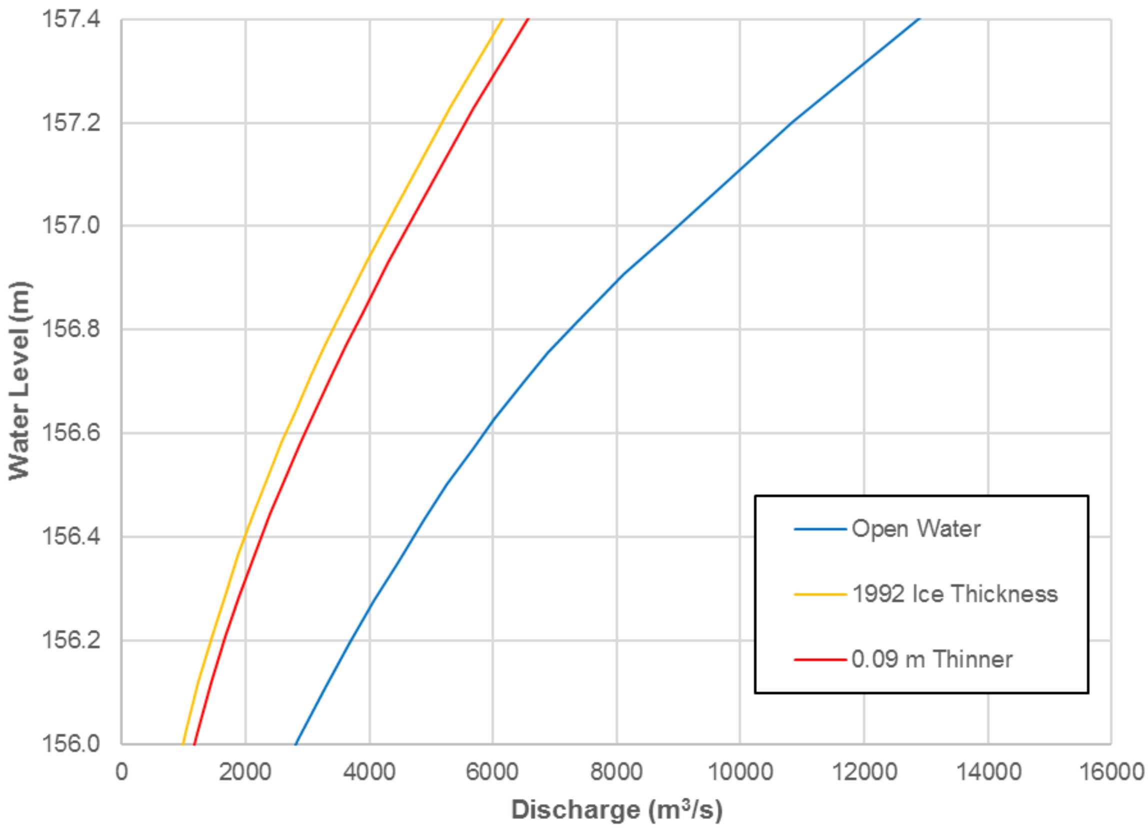

Figure 7. Simulated Great Slave Lake outlet rating curve for 0.09 m reduction in ice thickness under hypothetical 5°C warmer than 1992 climate scenario.

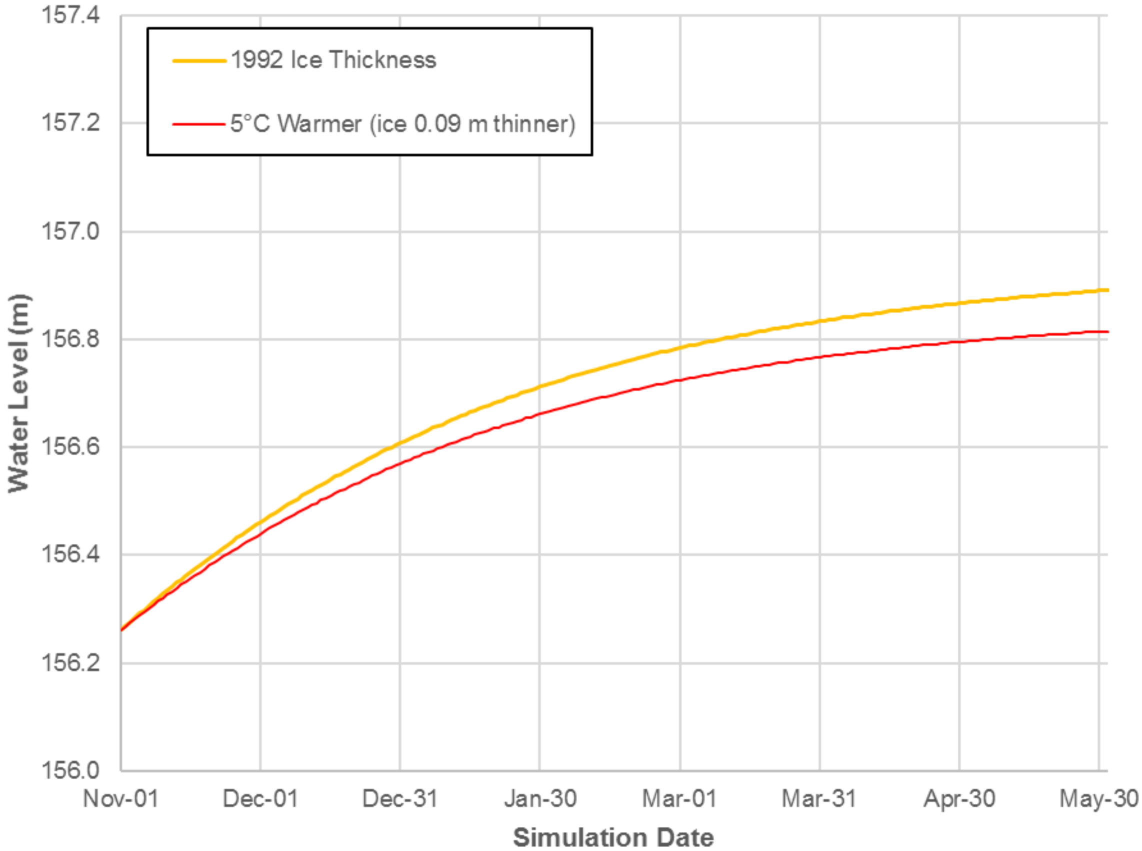

Figure 8. Comparison of Great Slave Lake water level hydrographs for hypothetical constant ice conditions on the Mackenzie River and constant inflow discharge for historical 1992 conditions and 0.09 m thinner ice corresponding to a 5°C warmer than 1992 climate.

Comparing the two curves quantitatively, the predicted increases in outflow discharge associated with this thinner ice cover scenario are in the order of 200 to 350 m^3/s, or 10 to 15% of the total. Figure 8 shows the impact of the thinner ice cover on Great Slave Lake water levels under the same conditions described earlier with reference to Figure 5. After six months, a 0.09 m thinner ice cover would correspond to a water level at the end of the period of 156.80 m versus 156.87 m for the 1992 historical base case. The difference in water levels is of approximately the same magnitude after four and five months' time, suggesting this result is not sensitive to shortening of the ice-affected season.

4. Conclusions and Recommendations

Results of this work suggest that, excluding the effects of changing inflows from coming from the upstream basin, a warmer climate and shorter ice season would potentially result in higher outflow discharges and lower lake levels in the late-fall/early-winter, depending on the timing of freeze-up. Outflows from Great Slave Lake are sensitive to changes in ice thickness, even relatively small reductions in ice thickness that are predicted by thermal ice growth and decay models. However, since outflows from Great Slave Lake are also dominated by responses in lake water level, an increase in outflow should be mitigated by a decrease in outflow associated with declining lake levels.

There is the potential for climate warming to result in lower annual minimum lake levels in the fall due to longer persistence of open water conditions. A thinner ice cover and shorter ice-affected season could also reduce the annual maximum water levels on the lake as well; however, conditions in the upstream basin would play a significant role in determining this.

To better understand the implications for climate warming on Great Slave Lake water levels and outflows, continued ice monitoring and collection of current channel bathymetry should be undertaken along the Mackenzie River near Fort Providence. Additional cross sections or detailed bathymetric mapping are needed for the North Channel as the current information is limited and suggests that this channel would freeze to the bed at typical winter lake levels. Updated survey information would confirm this and allow for an assessment of changes in channel cross sections since the existing surveys were completed in the early 1990s. These data and future improvements to the lake outlet hydraulic model could also be used to improve existing flow routing and hydrologic models developed for the Mackenzie River Basin.

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