CGU HS Committee on River Ice Processes and the Environment
12th Workshop on the Hydraulics of Ice Covered Rivers
Edmonton, AB, June 19-20, 2003

Ice Consolidation on the Peace River: Release Patterns and Downstream Surge Characteristics

David Andres and Gary Van Der Vinne
Trillium Engineering and Hydrographics Inc.
210 4812 87 Street Edmonton, Alberta, T6E 5W3
dandres@trilliumeng.ab.ca
ginne@trilliumeng.ab.ca

Bill Johnson
Canadian Hydro Developers Inc.
500, 1324 17 Avenue Calgary, Alberta, T2T 5S8
bill@mail.canhydro.com

Gordon Fonstad
Alberta Environment
9820 106 Street Edmonton, Alberta, T5K 2J6
Gordon.Fonstad@gov.ab.ca

Ice consolidations during freeze-up on the Peace River can produce local flooding due to either the attendant surge of ice and water or the resulting over-thickened ice accumulation. These consolidation events occur very quickly, they affect the ice cover over a relatively short domain of the river, but produce surges that are felt a long distance downstream. Although the impacts of such events have been measured, there is limited knowledge of how the secondary consolidations are initiated, about the release pattern of water from channel storage, and of the characteristics and implications of the resulting surge.
In 2000-01, a consolidation event was detected on the Peace River between Town of Peace River and Dunvegan. The response of the Dunvegan gauge upstream of the consolidation provided an indication of the rate at which the ice cover collapsed, and three gauges downstream of the consolidation measured the resulting water wave. This paper summarizes the gauge records and the supporting background observations of the ice conditions, identifies the release pattern and the timing of the consolidation, and compares simulated and measured water levels downstream of the consolidation. Inferences about the effects of the surge on the stability of the downstream ice cover are also made.

1. Introduction

The stability of an ice cover on regulated rivers in western Canada is an issue at least on the Bow, North Saskatchewn, Peace, and Nechako Rivers. On these rivers, regulation for hydropower production has lead to an increase in discharge at freeze-up, resulting in a more dynamic freeze-up than would occur naturally. Observations indicate that consolidation events (the collapse and thickening of a newly formed ice cover) produce some of the highest winter water levels. These consolidation processes are most evident on the Peace River, where regulation has had the most dramatic effect on winter flows – discharge at freeze-up has been increased by about 400%, relative to the pre-regulated condition.

Neill and Andres (1984) documented one significant consolidation event that occurred on the Peace River in 1981 when almost 100 km of ice collapsed into about 40 km of ice and increased water levels at the Town of Peace River (TPR) to near record levels. Their analysis showed that the stage increase at the town was due to an increase in the thickness of the ice cover and the effects of a surge of water that was released as water was taken out of channel storage during the collapse. While the effects of the water surge were short lived, the effects of the thicker ice cover persisted for the entire winter.

It is evident from the literature that little quantitative information is available on this type of phenomenon. To quantify the effects of a consolidation and to forecast the likelihood and the outcome of its occurrence requires an understanding of at least the following phenomena:

(1) triggering of the event,
(2) release of water from the collapse,
(3) characteristics of the water surge downstream of the moving ice,
(4) downstream translation and thickening of the ice cover, and
(5) arrest of the consolidation against a solid ice cover downstream.

When all these processes are aggregated into one event, its analysis becomes somewhat of a daunting task due to the extensive coupling and nonlinearity of the processes. However, an understanding of the individual processes, (i.e. when does a collapse occur, how does a collapse occur, what are the release characteristics of the water in storage under the ice cover, what stops the collapse, etc.) is possible even with scarce data or imprecise measurements.

This paper will address one of the simpler of the above issues: the pattern of release of water from a consolidation event that was observed on the Peace River between Dunvegan and TPR (Figure 1). The outflow of water from the consolidation event will be inferred from considerations of the characteristics of the water wave downstream of the consolidation. In addition conclusions will be drawn about the stability of a thin ice cover during the passage of the water wave.

2. General Freeze-up Processes and Consolidation Occurrences

Under the current regulated conditions, freeze-up is dominated by the outflow of warm water from Lake Williston. Under cold late autumn or early winter air temperatures, the water is cooled as it travels down river from Bennett Dam. Frazil forms at some point, followed by the formation of ice pans whose surface concentration increases along the ice formation reach. The mild channel gradients and the subsequent low velocities in the reach downstream of the Vermilion Chutes promote the first formation of a stable ice cover in that part of the river. After that the ice cover advances systematically upstream by an accumulation-type of process, and a stable ice cover forms by either juxtaposition or consolidation. Downstream of Manning the ice cover generally forms by juxtaposition due to the very mild slopes. In the reaches between the Manning and Taylor, where the channel slopes are higher, either a juxtaposed or consolidated ice cover can form, depending upon flows and local air temperatures (Andres, 1999).

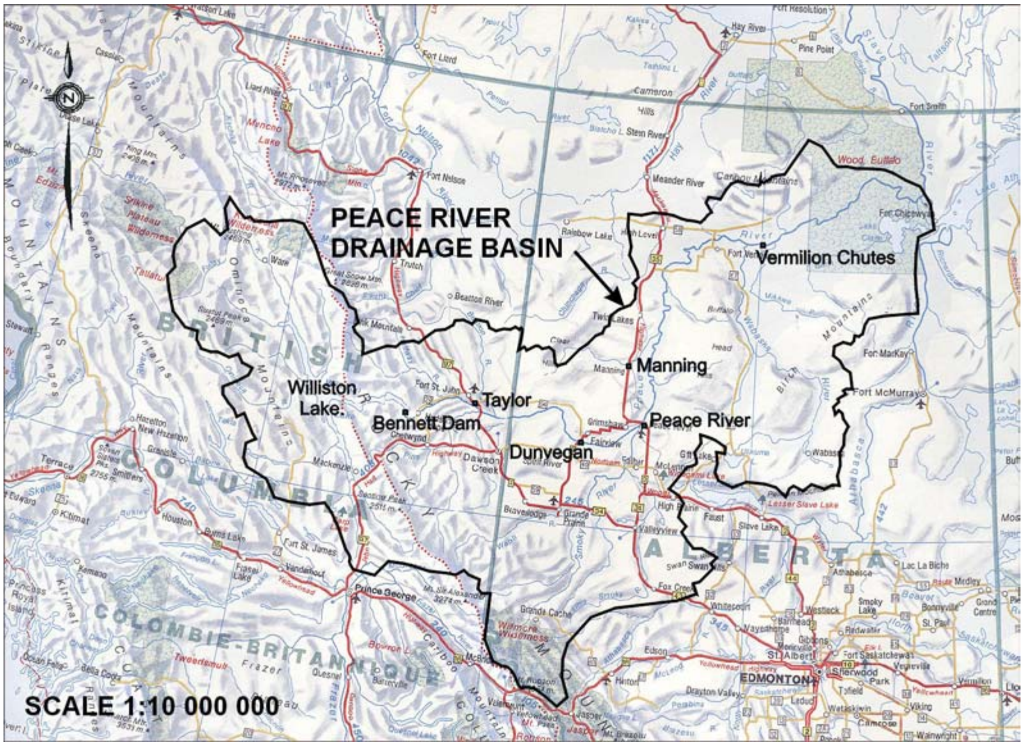

Figure 1 Location plan

In some years, secondary consolidations (collapse of an existing consolidated or juxtaposed ice cover) occur after the formation of the ice cover. The term is used to differentiate between a shove or collapse that occurs a few days after initial freeze-up and affect tens of kilometers of ice and a "primary" shoving event that occurs while the ice cover stabilizes very early during its formation before significant interstitial freezing develops. In terms of the processes – dynamic thickening of the ice cover and release of a water wave from channel storage – there is no difference between primary and secondary consolidations.

Secondary consolidations have produced the highest measured freeze-up levels along the river because of the effects of a high transient, surge-related discharge and the subsequent over thickening of the ice cover. For example, secondary consolidations in 1981-82 and 1991-92 produced extremely high water levels at TPR - 318.13 and 319.90 m respectively at the WSC gauge. These levels were two to four metres above the typical freeze-up elevation range of 314 to 316 m. The water level during the 1991-92 event came within 0.6 m of the top of dike.

The triggering of secondary consolidations is not well understood, but there is consensus about conditions that lead to secondary consolidations. Some of these conditions are:

(1) very rapid advances of the ice cover leading to a large increase in the forces on the ice cover without the attendant growth of thermal ice at the surface of the ice cover,
(2) sudden increases in discharge that violate the previously established equilibrium conditions, and
(3) sudden and dramatic temperature changes that can deteriorate the thermal ice on the surface of the ice cover.

Observations indicate that when a secondary consolidation occurs, there is failure within the cover somewhere downstream of the head of the cover (ice front), the ice front moves downstream in response to this failure, water is extracted from channel storage (adding to the flow in the river), and the additional flow increases the forces on the ice cover, thereby adding to the level of instability. Numerical models have not yet generally been developed to quantify/predict the transient discharges and the water level fluctuations within a secondary consolidation.

Freeze-up observations (mainly the documentation of ice front locations) have been carried out on a routine basis at TPR since about 1980. Thus, there are about 20 years of data from which some empirical understanding can be gained about the secondary consolidation issue in the reach upstream of the town. Table 1 summarizes the basic freeze-up characteristics germane to the stability/secondary consolidation issue. For each year, the table summarizes the period over which the observations were made, the average celerity of the ice front (rate of upstream advance of the head of the ice cover), the mean daily temperature at TPR during the period, and the discharge. The table also notes if a consolidation occurred any where in the reach.

Figure 2 shows the relationship between the ice front celerity and the air temperature. It is evident that the celerity of the ice front is almost linearly proportional to the temperature, for discharges in the range between 1300 and 1800 m^3/s. Furthermore, the celerity of the ice front is close to zero when temperatures at TPR are above -10 ^0C.

Figure 2 also shows the years when a secondary consolidation occurred. The occurrence of such an event was defined on the basis of either direct observations or from interpretation of the ice front position data. The celerity of the ice front between TPR and Dunvegan has ranged from 0.02 m/s (1.4 km/day) to 0.67 m/s (57 km/day). Secondary consolidations were apparent in five years, and occurred over the entire range of measured ice front celerity. A secondary consolidation occurred in 1981-82 due to a discharge increase of about 60% following a period of rapid upstream advance. In 1991-92 a secondary consolidation occurred during a brief but severe warm spell that followed a more or less normal freeze-up between TPR and Dunvegan.

Table 1 Summary of ice front celerity and secondary consolidation events

Year	Start Date of Period	End Date of Period	Average Discharge at Hudson Hope during Period (m^3/s)	Average Air Temperature at TPR during Period (^0C)	Average Ice Front Celerity (m/s)	Comments
1975/76	12-Dec	16-Dec	1316	-30.3	0.28	
1979/80	24-Dec	28-Dec	454	-5.0	0.13	consolidation
1981/82	31-Dec	6-Jan	1358	-33.8	0.30	consolidation
1982/83	4-Jan	6-Jan	1273	-15.6	0.11	
1983-84	14-Dec	23-Dec	1450	-26.6	0.14	
1984/85	21-Dec	24-Dec	1533	-30.6	0.19	
1985/86	2-Dec	6-Dec	1698	-15.4	0.10	
1986/87	20-Jan	30-Jan	1681	-9.0	0.03	
1987-88	29-Jan	8-Feb	1793	-28.5	0.20	
1988/89	29-Dec	12-Jan	1265	-18.1	0.12	consolidation
1989/90	9-Jan	19-Jan	1630	-8.8	0.02	
1990/91	20-Dec	28-Dec	1847	-25.7	0.13	
1991/92	18-Feb	23-Feb	1795	-18.6	0.07	consolidation
1992-93	29-Dec	31-Dec	1563	-41.2	0.67	consolidation
1993/94	12-Jan	14-Jan	1553	-24.5	0.18	
1994/95	3-Jan	13-Jan	1879	-17.8	0.01	
1995-96	10-Dec	15-Dec	1731	-20.6	0.14	
1996-97	20-Dec	26-Dec	1399	-30.3	0.29	
1997-98	12-Jan	16-Jan	1642	-25.5	0.21	
1998-99	4-Jan	15-Jan	1578	-19.1	0.11	

Also of interest is 1979-80, when a secondary consolidation occurred when discharges at Hudson Hope increased from an ambient freeze-up discharge of about 450 m^3/s to over 1500 m^3/s. In 1992-93 the ice cover consolidated near Dunvegan without any apparent perturbation in either discharge or temperature, except that it had advanced upstream at a very rapid rate just prior to the secondary consolidation. In 1988-89 a consolidation was preceded by about a 20% increase in discharge in combination with a slight warming trend.

3. The 2000-01 Consolidation Event – February 27, 2001

The most recent significant consolidation occurred during the winter of 2000-01. Although not a particularly major event, it occurred in a reach where continuous water level information was available from four functioning hydrometric stations and the characteristics of the ice cover were being monitored by aerial reconnaissance. Thus there is a relatively good data set that describes both (1) the disposition of the ice cover before and after the event and (2) the characteristics of the water wave that resulted from the release of water from under the collapsing ice cover. The following provides a brief description of the consolidation event.

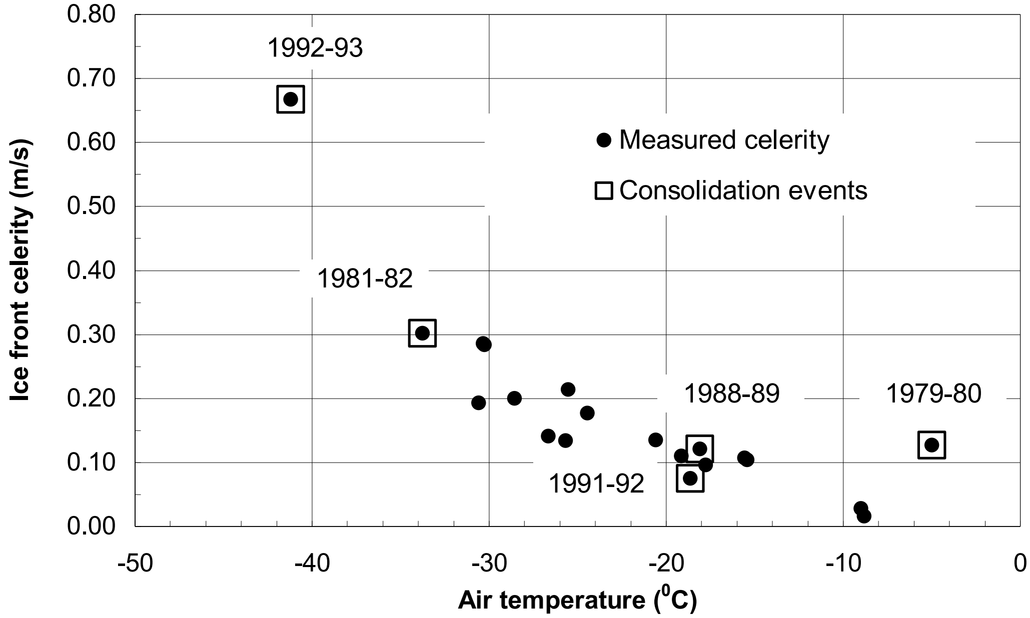

Figure 2 Ice front celerity and consolidation events in study area

The advancing ice cover approached the gauge at TPR (km 939) toward end of January, at which time BC Hydro adopted a controlled flow release to provide relatively steady flows during the freeze-up period at the town. Flows at Peace Canyon were set to about 1400 m^3/s, which, due to local inflows, resulted in flows at the ice front of about 1600 m^3/s. Warmer weather then ensued, which caused the head of the ice cover to retreat downstream until the resumption of more seasonal weather in early February, at which time the head of the ice cover re-advanced toward TPR. A stable ice cover formed there February 10 (Figure 3) with a stage increase of 3.29 m above the nominal open water stage. The head of the ice cover continued to advance upstream, reaching the gauge at Peace River Correctional Centre (PRCC) at km 855 on February 12 and the Elk Island gauge (km 901) on February 23 (see Figure 4 for locations). The stage increase at freeze-up at these two locations was 4.98 m and 5.60 m respectively, at a discharge of about 1600 m^3/s and at air temperatures that varied between -12 ^{0}C and -20 ^{0}C. The ice cover continued to advance upstream, approaching to near km 936, about 4 km downstream of the Dunvegan gauge (km 940) on February 27. The river level at Dunvegan rose by some 4.11 m under the influence of the approaching ice cover (Figure 5).

Mean daily temperatures at Dunvegan increased from –23.6 ^{0}C on February 25 to –3.0 ^{0}C on February 27 and to +4 ^{0}C on February 28. The warmer weather apparently caused the young, weak, ice cover to collapse. About 27 km of ice was consolidated into about 13 km of ice. After the collapse, the head of the ice cover was located at km 923, and the toe of the new over-thickened accumulation was located at km 910, or about 9 km upstream of Elk Island. From the gauge record at Dunvegan it is evident that the collapse occurred at 1930 hrs and lasted until 0130 hrs on 28 February, with the stage at Dunvegan dropping by about 3.2 m over a period of six hours. Since a typical rise in the gauge when the ice cover forms at the gauge is 5.0 m – due to about 2.7 m of ice below the water level and about 2.3 m of additional water depth due to the increased resistance of the ice cover – a rise in water level of 4 m indicates that the ice front had advanced to within about 4 km of the gauge just before it collapsed. The subsequent decrease in water level of 3.2 m indicates that the ice front had receded downstream a distance of about 13 km. This more or less corroborates subsequent observation of the ice conditions. (Simulations indicate that the backwater effects at Dunvegan are almost linear, so that for the local slope of 0.00025, every 1 m increase or decrease in water level represents about a 4 km change in the position of the ice front relative to the gauge.)

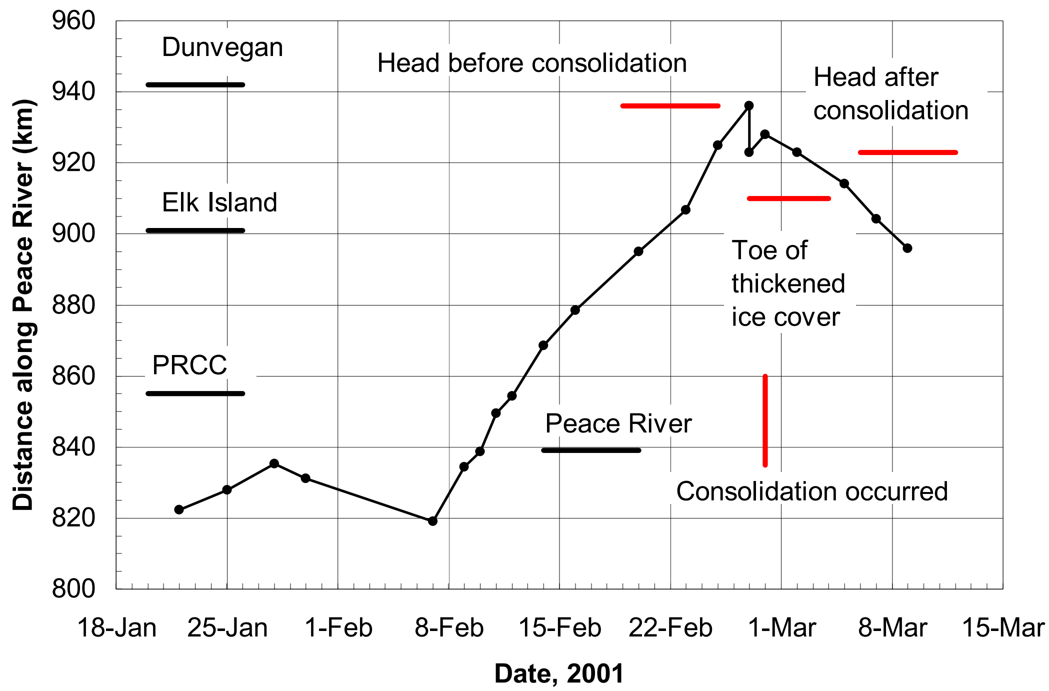

Figure 3 Position of the head of the ice cover, 2001

The water wave released by the consolidation reached the Elk Island gauge at about 2200 hrs, February 27 (Figure 5), or three hours after the start of the consolidation movement. The water levels increased by about 1.31 m over a period of about three hours. The tail end of the surge passed the gauge at 0700 hrs on 28 February. The duration of the event at Elk Island was about seven hours. By the time the water wave reached PRCC it had attenuated significantly over the nine hour travel time between Elk Island and there. The stage increase at PRCC was only about 0.53 m and the length of the wave was about 24 hours (Figure 5).

The water wave had a similar shape at TPR, but with a peak of only about 0.35 m above ambient water levels (Figure 5). Table 2 summarizes the salient information about the water wave at each of the three gauging stations. It should be noted that the water waves observed at PRCC and TPR were superimposed on top of other waves with longer periods that were generated from other unsteady flow processes in the river (discharge fluctuations at Bennett Dam, residual effects of varying ice front advancement rates, varying tributary inflows, etc.).

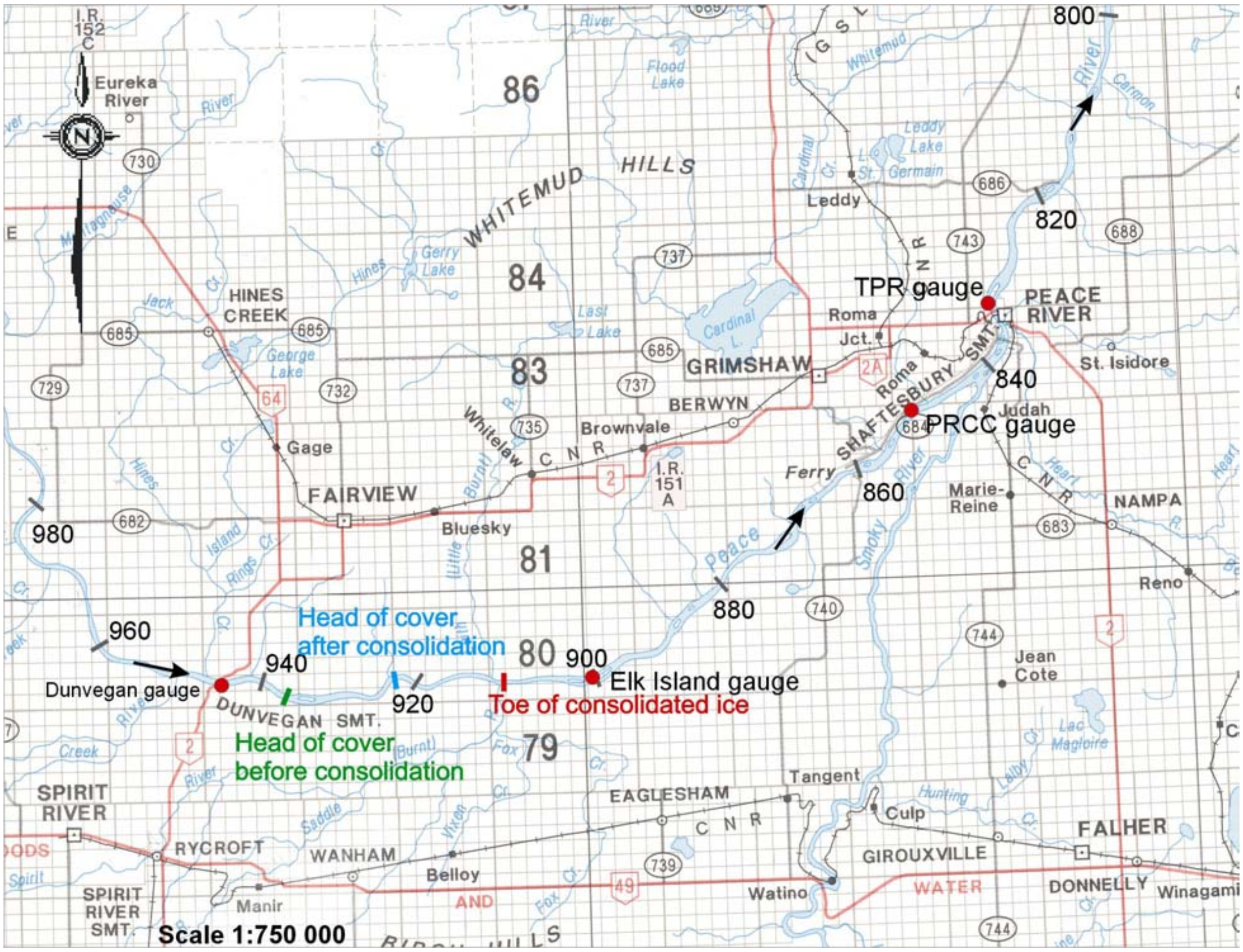

Figure 4 Study area showing gage locations and ice front locations

4. Analysis

The unsteady flow model CDG1D (Hicks, 1996) was used to simulate the water levels measured downstream of the collapse event. Although this model was not developed to be used for situations with an ice cover, a pseudo ice covered condition was simulated by adjusting the open water roughness to represent the composite roughness of both the bed and the ice cover. Given a dearth of cross section data, the river was assumed to be rectangular with a width of 410 m, and a slope of 0.00028. A bed roughness of 0.023 and an under-ice roughness of 0.05 were obtained from previous calibration to water levels measured during ice formation near Dunvegan in 2001-02 (Trillium Engineering, 2002).

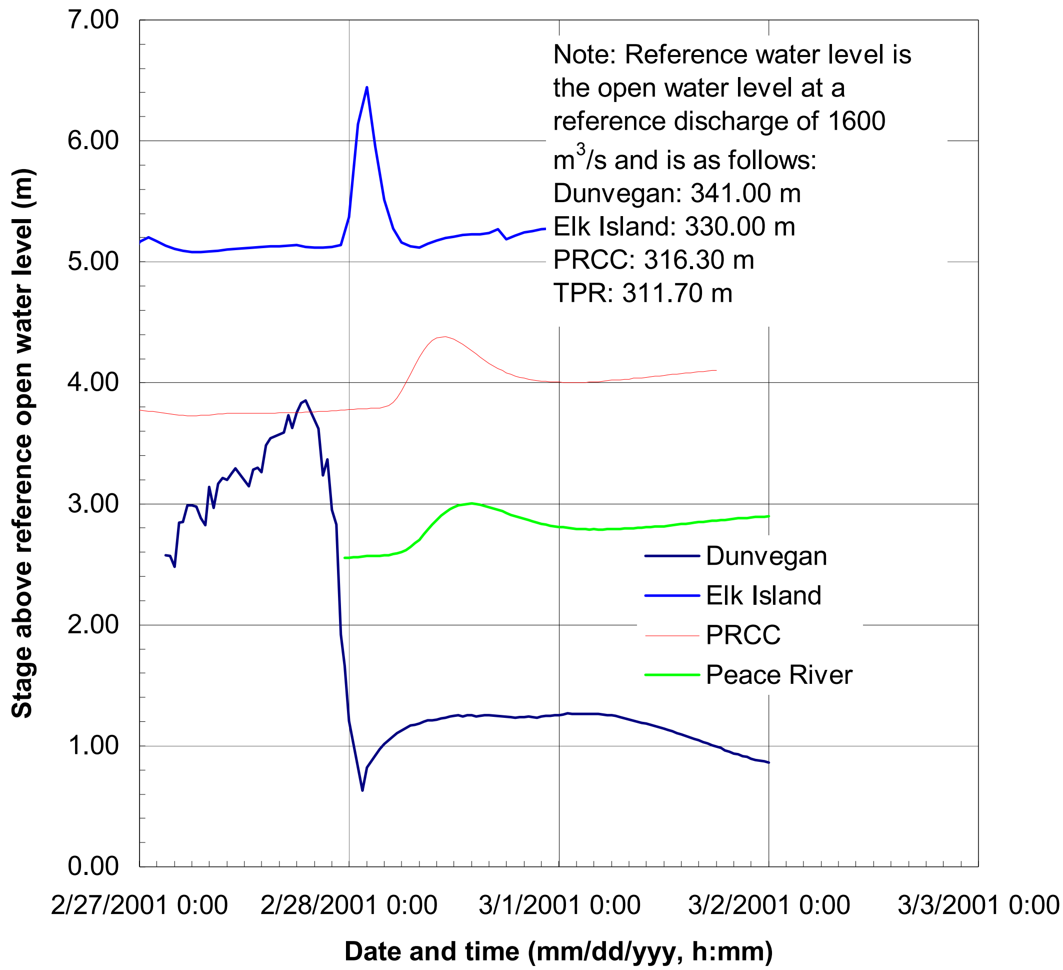

Figure 5 ***Gauge heights along the Peace River during the consolidation event***

Table 2 **Summary of measured water wave characteristics**

Parameter	Elk Island	PRCC	TPR
Distance downstream of new ice front (km)	22	68	84
Travel time of leading edge of water wave from time of consolidation (hrs)	3	8	11
Travel time of peak of water wave from time of consolidation (hrs)	6	14	18
Duration of water wave (hrs)	7.5	25	28
Peak stage increase above ambient water levels (m)	1.31	0.53	0.35

Three main parameters had to be specified to define the initial conditions in the unsteady flow model: (1) the location of the upstream boundary in relation to Elk Island, (2) the duration of the outflow hydrograph that resulted from the consolidation, and (3) the shape of the outflow hydrograph. The location of the upstream boundary was arbitrarily selected to be the position of the new ice front. Since it is unlikely that the roughness had changed substantially under the newly consolidated ice cover (between km 910 and km 923), there would have been no change in channel storage of water in that section of the river. The duration of the hydrograph was selected on the basis of the signal provide by the Dunvegan gauge. The start of the collapse is evident in Figure 5 and can be taken as 1930 hours on February 27. The gauge begins to rise again at 0130 hours on February 28, indicating that the collapse had finished and the ice front was beginning to advance upstream again. Thus, it appears that the event lasted for about six hours – that is the release of stored water occurred over a period of six hours.

The least well defined parameter was the shape of the outflow hydrograph. For simplicity's sake, the shape of the hydrograph was assumed first to be triangular, with a time base of six hours and a volume that represented the volume of water released from storage. From this volume the water wave would have had a peak of about 1150 m^3/s above the carrier discharge. Three alternatives of the shape of the hydrograph were considered: the peak skewed to the front of the hydrograph, the peak centered within the hydrograph, and the peak skewed to the back of the hydrograph. However, none of these shapes produced water levels that matched the observed water levels downstream because the resulting peak discharge was too low.

As an alternative, a Gaussian-shaped hydrograph was adopted with its peak located at the centre of the hydrograph, and corresponding to the time halfway through the consolidation event. The peakedness of the hydrograph was adjusted until there was a reasonably good fit to the recorded stage at all three locations downstream. The most representative inflow hydrograph had a peak flow of 2250 m^3/s, with an effective time base of three hours, during which most of the flow was released from the consolidation. Figure 6 shows the results of the simulation for the optimally-shaped hydrograph. When the peak incremental discharge resulting from the release of water in storage is added to the background ambient steady discharge, a peak discharge of about 3850 m^3/s results – an increase in flow at the downstream end of the consolidation of about 140%.

Overall, the model slightly under-estimates the peak water level at Elk Island and PRCC, but slightly over-estimates the peak water level at TPR. The simulated durations are somewhat longer at all three sites, as well. However, given the simplifications and assumptions about the characteristics of the wave (dynamics of the secondary consolidation event) and the simplified hydraulic representation of the river, the model simulates the measured water levels reasonably well.

The water level information at Elk Island (Figure 6) is also of interest from the perspective of the stability of the ice cover and the magnitude of the water perturbations that are required to fracture the thermal ice and destabilize the ice cover. The ice cover at Elk Island would have been five or six days old. Given ambient air temperatures of between -13 and -24 ^{0}C over that period, the maximum thermal ice thickness would have been about 0.30 m. It is evident that a stage increase of 1.3 m was insufficient to destabilize the ice cover from the point of view of lifting the cover free of the banks – in spite of the stage increase being about 4.3 times the thickness of the thermal ice.

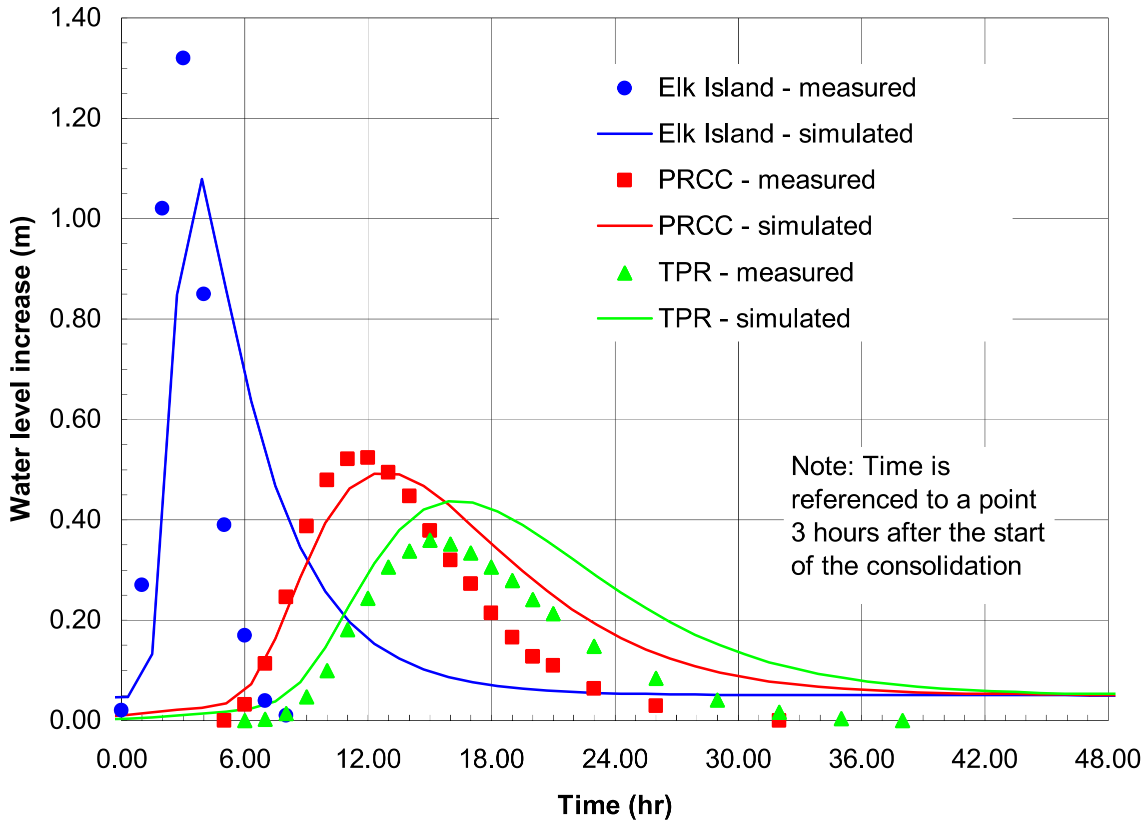

Figure 6 ***Comparison of measured and simulated stage levels downstream of the consolidation***

From the unsteady flow model, the peak discharge at Elk Island was about 2500 m^3/s. This occurred on the rising limb just prior to when the peak stage was recorded. The calculated slope at the time of maximum discharge was 0.00037 – an increase of about 30% over the steady state slope. This translates into an increase in the shear along the underside of the ice (relative to the pre-consolidation condition) of at least 60% - not an insignificant increase. This increase in shear also did not destabilize the ice cover. This indicates that the water wave itself is quite benign with respect to its ability to destabilize a frozen ice pack and only a passage of a surge that also contains ice can produce the high local uplift forces required to fracture an ice cover.

5. Conclusions

A consolidation event that occurred on the Peace River between Dunvegan and the Town of Peace River in 2001 was described, and the water wave that the consolidation produced was simulated. In spite of a lack of detailed cross section data and direct observations of the event, it was possible to back out the salient features of the consolidation and simulate the water wave that it produced reasonably well.

Reasonable simulations of the water levels downstream of the consolidation area could be achieved using a simple one dimensional unsteady flow model. The outflow hydrograph was represented by a Gaussian-shaped curve with a time base equivalent to the six hours over which the consolidation occurred, but with most of the volume concentrated within three hours of the time of the peak. The peak outflow from the consolidation was estimated to be about 3850 m^3/s, which was about 2.4 times greater than the background flow of 1600 m^3/s. It is evident that even relatively benign consolidations can significantly increase flows in the river, although these peaks appear to attenuate rather rapidly.

Analysis of the unsteady flows under the intact ice cover just downstream of the consolidation indicated that the shear stress on the underside of the ice cover increased to about 160% of the pre-consolidation value. In spite of this increase in shear, accompanied by a simultaneous stage increase of 1.3 m (4.3 times the thickness of the solid ice within the accumulation), the cover was not destabilized. Apparently the water wave itself does not have a significant impact on the stability of an ice cover.

Acknowledgements

Glacier Power Ltd. provided the funding to undertake the initial analysis, in support of on going work to better quantify ice process on the Peace River. Thanks also to Faye E. Hicks of the University of Alberta for providing the numerical unsteady flow model that was used in the simulations. Alberta Environment provided much of the background ice data and W. Granson, Alberta Environment, Peace River carried out the aerial observations to document the event.

References

Andres, D. 1999. The effects of freezing on the stability of a juxtaposed ice cover. Proceedings of the 10th Workshop on River Ice: River Ice Management with a Changing Climate: Dealing with Extreme Events. Committee on River Ice Processes and the Environment, Hydrology Section, Canadian Geophysical Union, Winnipeg, Manitoba.

Hicks, F.E. 1996. Hydraulic flood routing with minimal channel data: Peace River, Canada. Canadian Journal of Civil Engineering. Vol. 23, No. 2 pp. 524-535.

Neill, C.R. and D. Andres. 1984. Freeze-up flood stages associated with fluctuating reservoir releases. Third International Speciality Conference on Cold Regions Engineering, CSCE/ASCE, Edmonton, Canada.

Trillium Engineering and Hydrographics Inc. 2002. Observations of freeze-up on the Peace River, 2001-02. Appendix C-2 of Dunvegan Hydroelectric Project Information Update. Submitted by Glacier Power Ltd. to Alberta Energy and Utilities Board.