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Numerical Simulation and Field Test of River Ice Conditions in The Yukon River

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As part of a study of ice processes in the Yukon River at Whitehorse, for the Yukon Energy Corporation (YEC), KGS Group developed a numerical model of the river downstream of the Whitehorse Rapids Dam. The model was prepared with KGS Group in-house program VARY-ICE. The study included a field test to evaluate the integrity of the ice cover and border ice under flow fluctuations and to confirm performance of the numerical model. The test was carried out between February 13 and 15, 2007 and involved variations in the discharge from the Whitehorse Rapids Dam that gradually increased during the test up to 35 m^3/s. It was accompanied by frequent measurement of water levels at selected locations over a distance of about 9 km below the plant. In addition, nearly continuous visual observations of the river ice were carried out to monitor its reaction, as well as to serve as an early warning of potentially adverse conditions. This paper centers on the comparison between the test results and the numerical simulations.

The test results showed that pre-test simulations predicted well both the peak water levels and the magnitude of the variation in water levels at only some locations in the study reach. Based on the test results, a combination of ice thickness reduction (consistent with observations by Environment Canada in 1984-86) and reduction in hydraulic roughness, subsequent to conditions at ice cover formation, were incorporated in the modeling, that allowed better reproduction of the observed conditions. The field tests confirmed that VARY-ICE reliably estimated the hydraulic conditions for unsteady flow along the river.

1. Introduction

In February of 2007, a series of field tests were conducted on the Yukon River at Whitehorse by KGS Group and Yukon Energy Corporation (YEC). These tests consisted of measurements of water levels at various locations during three days, in which river flows were changed upstream at the Whitehorse Rapids Generating Station.

The tests were part of a study of winter conditions in the Yukon River and were intended to evaluate the integrity of the ice cover and border ice under rapid fluctuations of flow. They also allowed calibration of a numerical model of the river prepared with KGS Group's in-house program VARY-ICE. This paper describes the tests and how the results were used to calibrate the VARY-ICE model.

2. Background

The Yukon River downstream of the Whitehorse Rapids Hydroelectric Generating Station (WRGS) has a gravel/sand bed with a relatively mild slope of approximately 1 m in 1800 m. This paper focuses on the 4 km reach of the river at Whitehorse from the Robert Campbell Bridge to the Marwell Sewage Lift Station (MSLS). The river and key locations in the study area are shown in Figure 1. The average velocity of flow in the open water ranges from approximately 0.75 to 1.5 m/s. The process of ice cover development is always dominated by accumulation of slush ice pans that are generated in the exposed open water, accompanied by advancement of border ice from the river banks where velocities are low. The advance of the ice cover front is by juxtaposition, and commences typically in November or December, depending on weather. The ice front normally advances up to the Robert Campbell Bridge (Figure 1) by January; but the area between the WRGS and the bridge typically remains open during the winter, featuring border ice and anchor ice development at some locations. The ice thickness in the river downstream of the bridge is believed to reach an average of between 0.5 and 2 m during the accumulation process. Subsequent thickening can occur due to frost penetration, where the initial ice thickness is relatively thin (i.e. less than 0.5 m). Conversely, at locations of maximum thickness at formation, the ice cover can be subjected to consolidation, thinning and smoothing of the underside as the winter progresses. These changes in the ice cover are consistent with known processes in other rivers, and attested by the results of Environment Canada's detailed river ice observations from 1984 to 1986 (Alford and Carmack, 1985, 1987, 1988). The changes are also reflected in a gradual reduction of the daily water levels as time progresses, provided that flows remain constant or decline.

3. VARY-ICE Program

KGS Group selected their proprietary software called "VARY-ICE" for the development of a numerical model of the river and the formation of river ice cover. The objective of the modeling was to examine the potential fluctuations in water level that would occur with daily variations in flow and to foresee whether ice cover breakup could ensue and cause damage to the infrastructure close by.

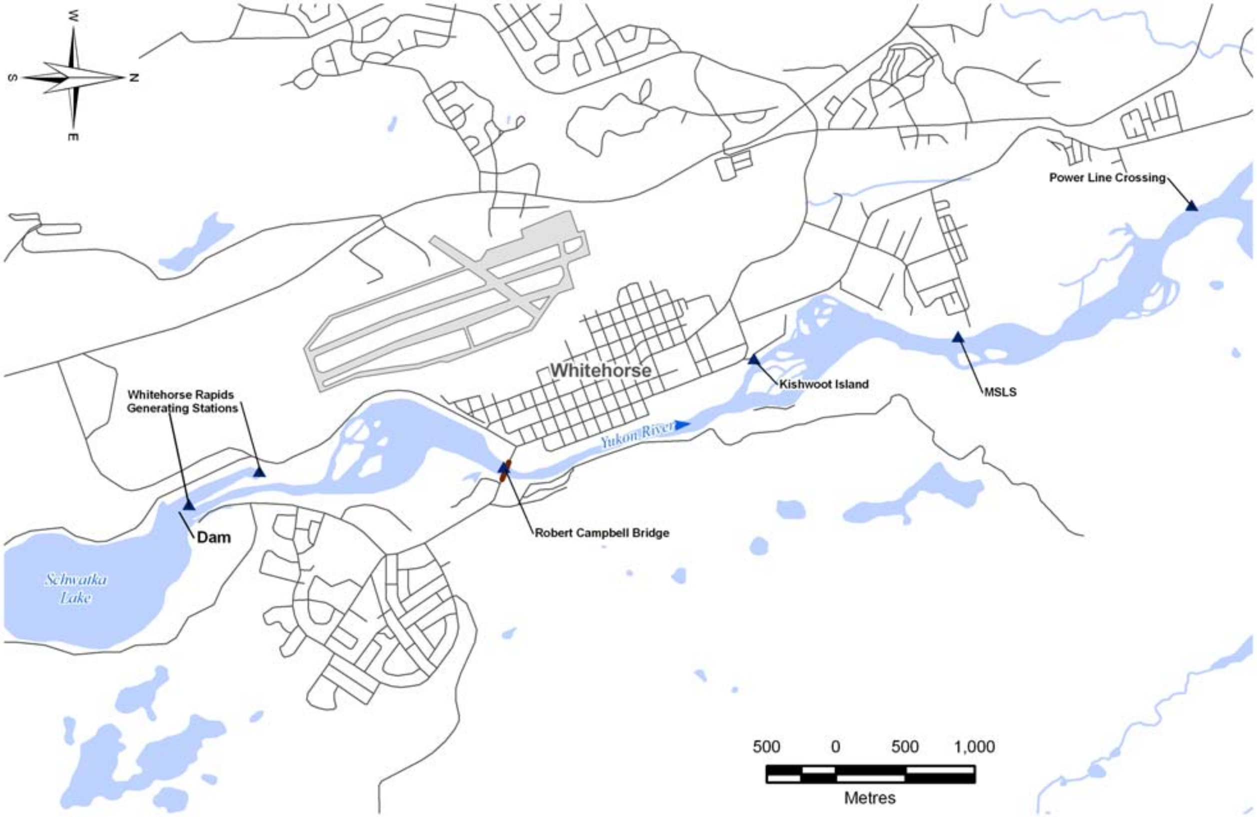

Figure 1. Study area and key locations

The principles used by the computer model VARY-ICE were originally developed in the early 1970's to investigate river ice in the design of hydroelectric power plants on the Nelson River in Manitoba. KGS Group has expanded and improved that concept, building on the experience gained by numerous applications of the methodology for over 10 rivers in North America.

The VARY-ICE computer model considers, in discrete time steps, the various processes that affect the water surface profile along a river, including

- Rate of ice generation
- Ice cover advancement by juxtaposition.
- Ice deposition and transport, Ice erosion
- Border ice growth
- Ice retreat by shoving
- Variation in flow and water level, using a full solution of the St. Venant equations.

4. Field Tests

The purposes of the test were to:

- Confirm that the ice cover downstream of the bridge will remain intact during temporary flow increases (peaking operations)
- Observe and if possible quantify the effects of the water level fluctuations on the border ice upstream of the bridge
- Confirm the performance of the numerical model developed by KGS Group (program VARY-ICE).

Prior to planning and carrying out the field tests, numerous simulations of the river ice were carried out to examine potential variations in water level, and their effect on the ice cover stability, as well as the potential for increased stresses on the ice cover and assessment of whether those increase could cause breakup. It was concluded from the preliminary modeling that the variations in flow that were planned to be tested would be safely tolerated by the ice cover.

The test program consisted of three consecutive days of increasing the duration of a peak outflow of approximately 195 m^3/s from a starting basic flow of 165 m^3/s. Day 1 (Feb 13 2007) was planned to consist of 2 hours of peak outflow, Day 2, of 4 hours of peak flow, and Day 3 of 6 hours of peak flow. Table 1 shows the flows during the tests as measured at the WRGS.

The test was accompanied by frequent measurement of water levels at selected locations over a distance of about 9 km below the plant. Recorded water levels were also available from the Marwell Sewage Lift Station (MSLS). In addition, nearly continuous visual observations of the river ice were carried out to monitor its reaction, as well as to serve as an early warning of potentially adverse conditions. Unfortunately the ice conditions were unsafe for access to measure ice thicknesses. Observations of the reservoir ice cover condition were also carried out. To limit the extent of this paper, only the water levels at the following three locations are reported:

- Marwell Sewage Lift Station (MSLS)
- Kishwoot Island
- Robert Campbell Bridge

These are shown in Figure 1 and their corresponding water level measurements for the tests are included in Tables 2, 3 and 4.

Table 1. Hourly Discharges

2-hour Peaking Operation		4-hour Peaking Operation		6-hour Peaking Operation	
Time (h)	Upstream Flow (m^3/s)[1]	Time (h)	Upstream Flow (m^3/s)[1]	Time (h)	Upstream Flow (m^3/s)[1]
11:00	170.9	8:00	178.9	8:00	164.6
12:00	164.1	9:00	176.3	9:00	165.7
13:00	179.5	10:00	175	10:00	185.3
14:00	197.5	11:00	199.3	11:00	197.7
15:00	197	12:00	197.3	12:00	198.8
16:00	170.4	13:00	198.3	13:00	197.5
17:00	166.2	14:00	189.2	14:00	198.7
18:00	166.6	15:00	157.1	15:00	197.6
		16:00	164.2	16:00	198.8
		17:00	166.9	17:00	145.9
				18:00	144.5
				19:00	145.5

[1] Outflow from Whitehorse Rapids Generating Station (m^3/s)

Table 2. Measured Water Levels 2-hour peaking test

Robert Campbell Bridge		Kishwoot Island		MSLS - surveyed		MSLS - recorder	
Time	W.S. El. (m)	Time	W.S. El. (m)	Time	W.S. El. (m)	Time	W.S. El. (m)
13:05	632.41	12:22	631.84	11:25	630.20	11:15	630.23
13:25	632.47	13:18	631.91	13:36	630.22	11:30	630.23
13:43	632.50	14:16	631.98	14:38	630.33	11:45	630.22
14:07	632.53	15:25	631.99	15:43	630.37	12:00	630.22
14:30	632.53					12:15	630.21
14:57	632.55					12:30	630.21
15:18	632.55					12:45	630.20
15:40	632.49					13:00	630.20
						13:15	630.22
						13:30	630.24
						13:45	630.28
						14:00	630.29
						14:15	630.31
						14:30	630.32
						14:45	630.33
						15:00	630.33
						15:15	630.36
						15:30	630.36
						15:45	630.35

Table 3. Measured Water Levels 4-hour peaking test

Robert Campbell Bridge		Kishwoot Island		MSLS - surveyed		MSLS - recorder	
Time	W.S. El. (m)	Time	W.S. El. (m)	Time	W.S. El. (m)	Time	W.S. El. (m)
10:00	632.43	9:41	631.86	9:20	630.23	9:00	630.25
10:30	632.51	10:54	631.92			9:15	630.25
10:49	632.53	11:30	631.95			9:30	630.25
11:00	632.55	12:02	632.00			9:45	630.25
11:30	632.58	12:33	631.99			10:00	630.25
11:49	632.58	13:03	632.01			10:15	630.25
12:00	632.59	13:38	632.02			10:30	630.25
12:25	632.60	14:09	631.98			10:45	630.26
12:45	632.60	14:35	631.93			11:00	630.29
12:59	632.60					11:15	630.31
13:20	632.61					11:30	630.31
13:30	632.61					11:45	630.33
13:50	632.61					12:00	630.34
14:15	632.55					12:15	630.35
14:25	632.53					12:30	630.35
14:31	632.51					12:45	630.37
14:41	632.46					13:00	630.37
						13:15	630.38
						13:30	630.38
						13:45	630.38
						14:00	630.38
						14:15	630.37

Table 4. Measured Water Levels 6-hour peaking test

Robert Campbell Bridge		Kishwoot Island		MSLS - recorder	
Time	W.S. El. (m)	Time	W.S. El. (m)	Time	W.S. El. (m)
10:00	632.47	9:17	631.82	9:00	630.20
10:30	632.50	11:03	631.96	9:15	630.20
11:00	632.54	13:09	632.00	9:30	630.21
11:30	632.58	13:41	632.00	9:45	630.21
12:00	632.58	14:22	632.01	10:00	630.23
12:30	632.59	15:03	631.99	10:15	630.24
13:00	632.59	15:36	632.02	10:30	630.27
13:30	632.61	16:07	632.01	10:45	630.29
14:10	632.62			11:00	630.29
14:30	632.62			11:15	630.31
15:00	632.62			11:30	630.32
15:30	632.62			11:45	630.34
16:00	632.61			12:00	630.34
				12:15	630.35
				12:30	630.36
				12:45	630.36
				13:00	630.36
				13:15	630.37
				13:30	630.37
				13:45	630.37
				14:00	630.38
				14:15	630.38

5. Numerical Model

Prior to the field test, the conditions that were to be tested were simulated with VARY-ICE, based on the observations made early in the winter. The peak water level of El. 630.9 m at the Marwell Sewage Lift Station that occurred on November 16, 2006, was used to select the Manning-n value for the ice cover. The parameters used in the model included:

Manning n-value of the river bed: 0.03
Manning n-value of the ice cover at time of formation: 0.035
Maximum Froude number for advancement of the ice front : 0.11
Minimum velocity for erosion of the ice cover: 1.5 m/s
Maximum velocity for ice deposition under the ice cover: 1.1 m/s

This Manning-n value for underside of the ice cover was considered representative of the peak winter water levels in 2006-2007. It is important to note that these water levels have been observed to vary from year to year, such that the Manning-n values for the ice that were required to reproduce the wide variation in historical conditions ranged from a lowest value of 0.034 to a highest value of 0.06. No systematic explanation was found to this variability, although a wide variety of contributing factors were identified. The authors have found similar situations in other rivers such as the Nelson River in Manitoba and the Peace River in Alberta.

Later in the winter, the water levels are known to recede in the Yukon River as a result of consolidation, thinning and smoothing of the underside of the ice cover. Figure 2, which shows water levels at the MSLS and Yukon River flows for the 2006-2007 winter, illustrates this situation. To represent this condition, the VARY-ICE program was modified so the Manning-n value of the ice was reduced by a factor (less than 1.0) that was input to the program. The model applies this factor after a selected time step, at which the user determines that peak winter conditions have been achieved at the MSLS. Application of the factor is reduced linearly from its full value at the downstream location to zero at the location of the ice front.

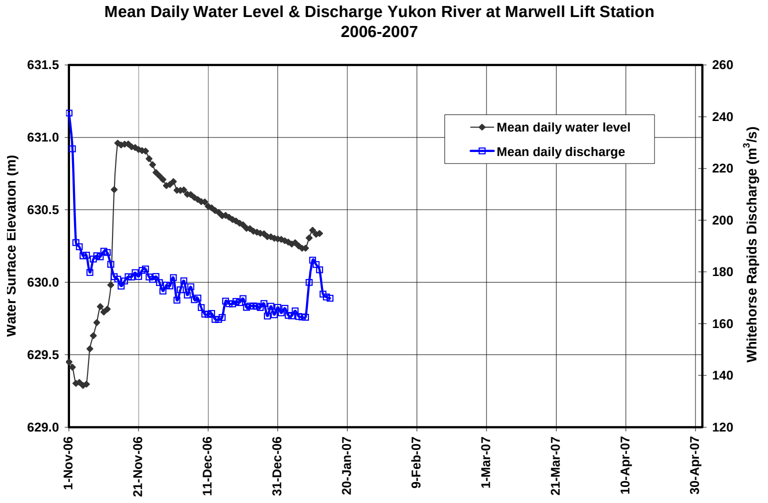

Figure 2. Yukon River Flows and Water Levels at the MSLS – 2006-2007 winter

The model with these adjustments predicted closely the simulated water level at the MSLS for the peak flow during the test. However, the model did not predict well the magnitude of water level fluctuations at that location. The simulated water levels at the Robert Campbell Bridge were overall higher than those measured during the field tests. Figure 3 shows a comparison of water levels at the MSLS between the model, as prepared prior to the field tests, and the measured values for day 2, using the actual flows measured during the test.

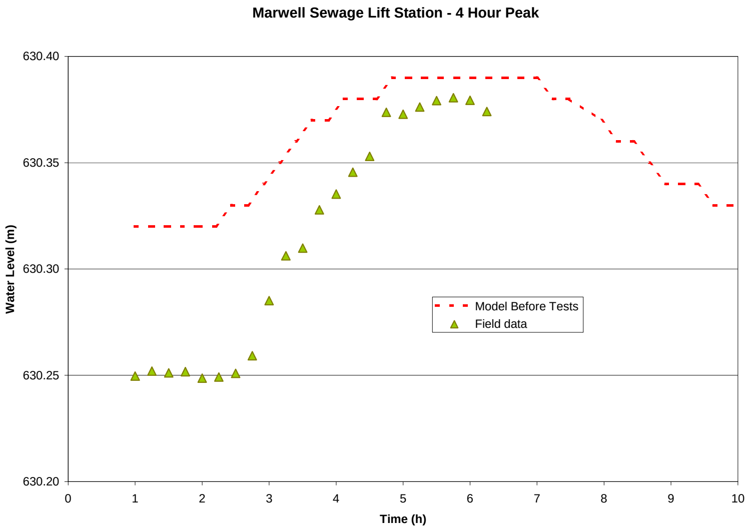

Figure 3. Comparison of field data with model results prior to calibration

To better fit the test data, a further adjustment was made to the VARY-ICE model. This time an algorithm was included that would reduce the ice thickness after peak winter conditions. The reduction factor was to be reduced linearly from its full value at the downstream location to zero at the location of the ice front, in a similar manner to the roughness reduction factor. The combination of the reduction in roughness and ice thickness allowed matching more closely the values observed during the tests. Figures 4 to 9 show the measured water levels and the model results for the 4-hour and 6-hour peaking tests at the three locations listed in Section 4.

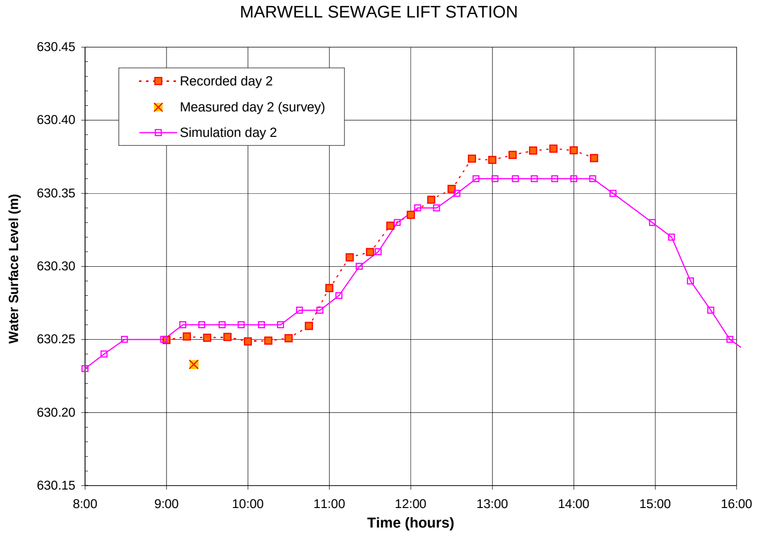

Figure 4. MSLS – 4-hour peak test

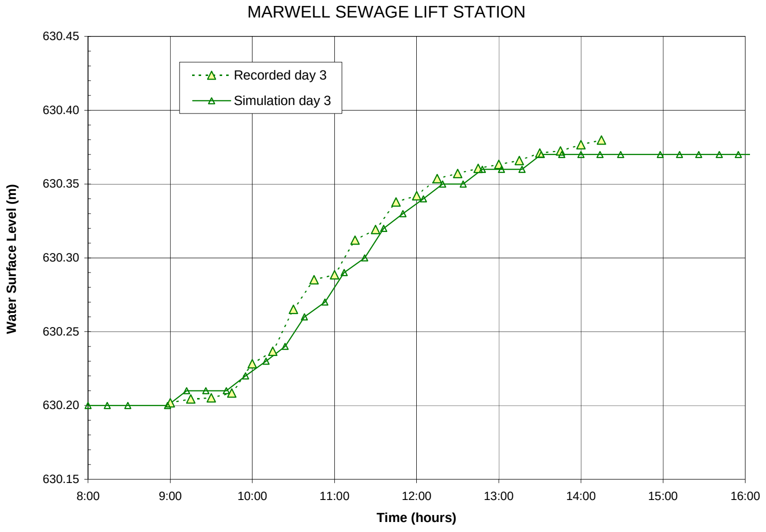

Figure 5. MSLS – 6-hour peak test

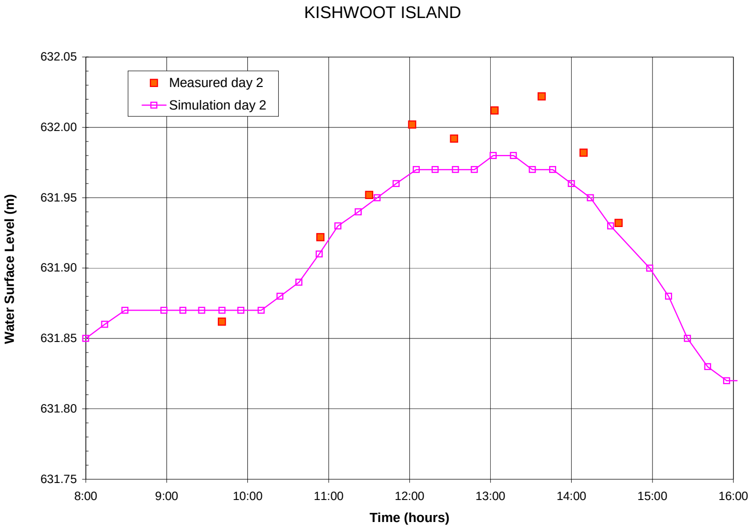

Figure 6. Kishwoot Island – 4-hour peak

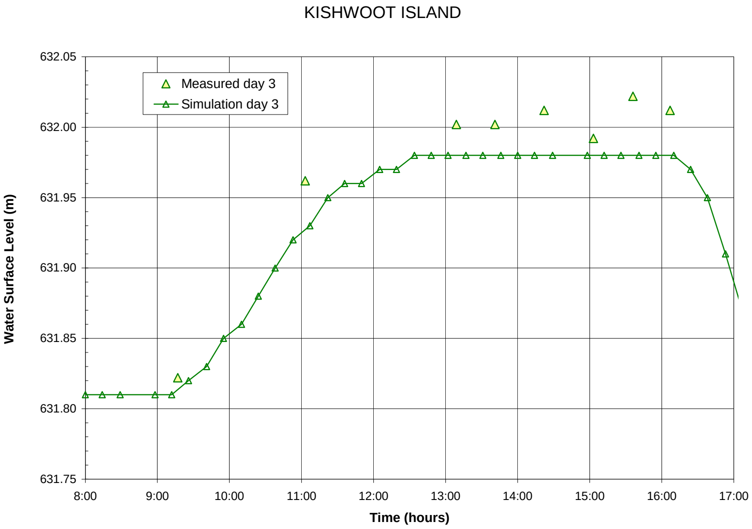

Figure 7. Kishwoot Island – 6-hour peak

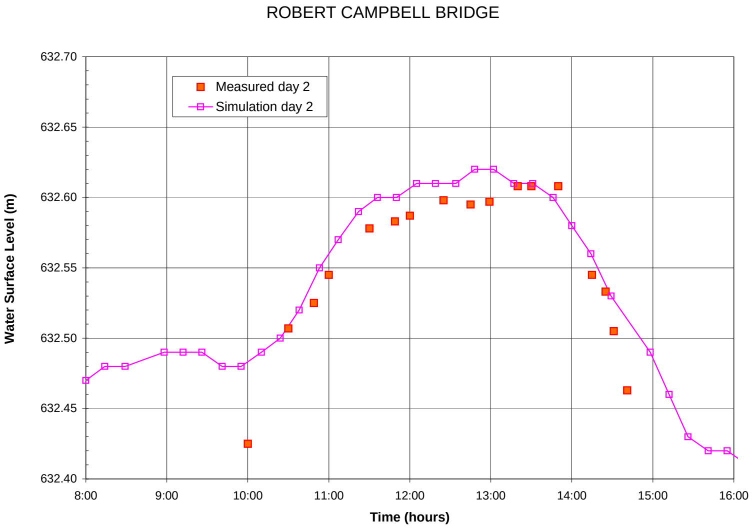

Figure 8. Robert Campbell Bridge– 4-hour peak

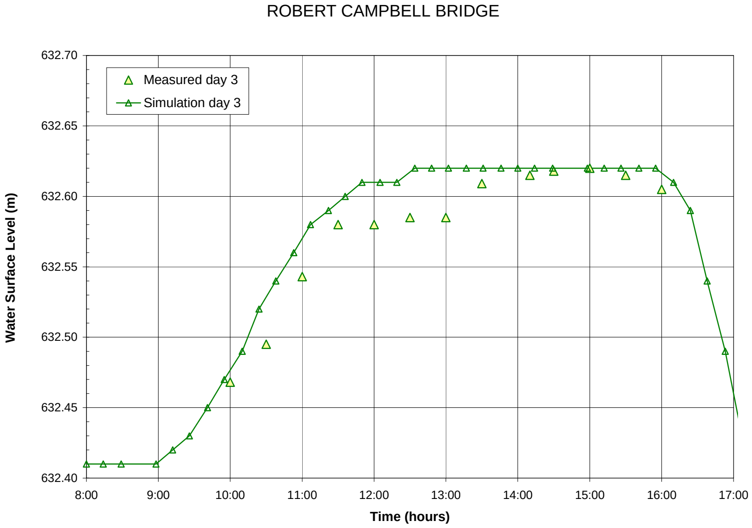

Figure 9. Robert Campbell Bridge – 6-hour peak

6. Conclusions

The field tests provided useful results. The key conclusions / observations were:

The field tests showed that the water level predictions from the original configuration of VARY-ICE significantly underestimated the actual fluctuations in the MSLS area and, in general, downstream of Kishwoot Island. This underestimation is believed to result from the numerical process that was used to represent the receding water levels in the downstream area subsequent to the early winter formation period. Means to improve the simulation of the receding water levels in this area were developed. A combination of ice thickness reduction (consistent with observations by Environment Canada in 1984-86, and reduction in hydraulic roughness were incorporated in the modeling.

The field tests confirmed that the model prepared with VARY-ICE is reliable in representing the response of the Yukon River at Whitehorse to peaking operations at the WRGS.

The field tests confirmed the theoretical analyses, including the VARY-ICE simulations, that breakup of the ice cover would not occur for a daily range of flows from 165 m^3/s to 200 m^3/s.

References

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