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Level Increase due to the Presence of a Hanging Dam during Early Spring Floods

Isabelle Thériault[1] and Wael Taha[2]
[1]Hydro-Québec, 855, rue Ste-Catherine Est , Montréal, Québec H2L 4P5
Theriault.isabelle@hydro.qc.ca

[2]LaSalle Consulting Group, 9620, rue Saint-Patrick, LaSalle, Québec H8R 1R8
wtaha@gcl.qc.ca

Muraille basin is an enlargement of the Romaine River located downstream from a 7 kilometers stretch of rapids which generates an important quantity of frazil ice that accumulates under the ice cover in the basin forming a hanging dam. In late fall 2010, a cofferdam was built, considering a 40 years return period flood. Since water levels increased by more than 4 m in the winter of 2011 due to frazil accumulations, overtopping the cofferdam became a prime cause for concern, especially in the case of an early spring flood. Therefore, an existing one-dimensional numerical model of the area was used to form the hanging dam in order to study the increase in water level during an early spring flood. A typical hydrograph of such a flood, along with the corresponding water temperatures, were set as input to the model simulations. Results showed that the hanging dam melted completely at the beginning of the flood event because of thermal erosion. Thawing occurred at a much greater rate than the increase in water level, ruling out any risk of overtopping the cofferdam. During the two following winters, aerial surveys and water level measurements showed that a tunnel had formed across the hanging dam. It gradually developed into a wide channel decreasing the water level despite large quantities of frazil remaining inside the basin. However, during springs of 2011 and 2012, with the combined rise in water temperature and discharge, the presence of ice didn't influence the water level as soon as the discharge reached the meltdown value obtained from numerical modeling. The model did not reproduce the breaches in the hanging dam, which govern the changes in water level during winter, but it proved to be a valuable tool in demonstrating the vulnerability of the accumulations to thermal erosion.

1 Introduction and problematic

Hydro-Quebec began in May 2009 the construction of the Romaine complex, on the Côte Nord, which includes four hydroelectric powerhouses. The Romaine River is a tributary of the St. Laurence River, it drains a watershed with an area of 14,500 km² at its mouth, and the mean annual flow is 327 m³/s. Under natural conditions, the flow gradually decreases from 200 m²/s at the beginning of December until a minimum value of 35-85 m³/s at the end of March. The peak spring flood occurs in mid-May and reaches an average value of 1500 m³/s. The average winter freezing index is 1400°C–days. Winter usually starts in mid-November and ends in mid-April.

The Romaine-2 powerhouse releases water into the Muraille basin, which is an enlargement of the Romaine River. This basin is located downstream from a 7 kilometer stretch of rapids which is characterized by a 60 m height difference and remains free of ice all winter long. Another 25 km stretch comprises of several open water reaches without areas between them to store the generated frazil. Under natural conditions, all this frazil generated is transported downstream and an important part of it accumulates in the Muraille basin.

In late fall 2010, a cofferdam was built on the right bank of the basin in order to protect the powerhouse area site from overflow. The water level associated to the 1:40 years return period flood was selected as the design criteria for the cofferdam crest elevation. The water level associated with this flood was calculated with backwater curves, calibrated with measurements during the spring period. No reliable measurements were available during winter.

As soon as the cofferdam was finished, an important water level increase occurred during the winter. The maximum water level occurred in mid-February and reached 87,7 m, which correspond to an increase of 4,5 m to the open water level associated to that same flow.

It was clear that this water level increase was due to the frazil ice accumulation and formation of a hanging dam in the basin. Hydro-Québec became concerned with the effect of the ice accumulation on the head loss across the basin and the water level increase , specially in the case of an early spring flood.

A numerical model was used in order to verify if the ice accumulation would continue to cause significant water level increase during the spring flood and if there was a risk of exceeding the design water level. The results assisted Hydro-Québec in the decision to raise or not the cofferdam. Field observations later confirmed and complemented the numerical model results.

2 Numerical Model

An existing one-dimensional numerical model of the downstream reach of the Romaine-2 generating station was used to form the hanging dam inside the Muraille Basin in order to study the increase in water level due to an early spring flood. The objective of the modeling study was to rapidly verify, considering a tight timeframe of a couple of months before spring, the hydraulic response of a reach with a severe constriction using an existing MIKE11-ICE model of the area.

2.1 Software Description

The MIKE11-ICE software simulates ice formation in a stretch of river throughout an entire winter season. At every time step and at every point on the river, it makes a full balance of thermal exchanges between the water, the atmosphere, and stationary or moving ice. The net balance between the gain and loss of heat brings about a change in water temperature, and then frazil ice grains are produced and drift in suspension.

As described in detail in (Thériault and al., 2010), the model integrates the formulations describing every process responsible for the ice cover dynamics, which are the:

- Supercooling of the water and production of frazil ice downstream from the point where water temperature reaches 0°C;
- Rising of frazil ice grains and formation of ice pans on the surface;
- Upstream progression of the leading edge due to the juxtaposition of ice pans;
- Transportation of various types of ice under the stationary covers, deposition and formation of hanging dams;
- Border ice cover progression from the banks towards the centreline based on the cooling rate in contact with cold air, and flow velocity;
- Static ice cover thickness variations;
- Openings in the ice cover due to flow velocities in the presence of “warm” water (water temperatures higher than 0°C) and/or during warm trends (air temperature and solar radiation);
- Increase in water levels due to thermal covers and hanging dams.

Of particular interest to this study, the extent of a static ice cover is controlled by several processes. The thickness varies based on heat exchanges with the atmosphere and with the underlying water when its temperature exceeds 0°C (thermal erosion). The leading edge may progress upstream due to juxtaposition of ice pans. The leading edge is defined as the transition between cross-sections completely closed by ice covers, and other partially open sections.

Border ice can progress towards the river centre depending on the cooling rate and local flow velocity. Conversely, border ice can retreat towards the shore due to thermal erosion where water temperature is above 0°C and local velocity is too high.

Border ice progression and retreat determine the area of openings at free surface flow, which allow for the production of frazil ice grains where water temperature is 0°C. The grains then rise to the surface and form ice pans, which then drift further downstream.

Once an ice cover is closed, whether closure happened due to juxtaposition of ice pans or due to border ice progression, frazil ice is transported under the ice cover. It can deposit under the cover forming a hanging dam if the flow velocities falls below a specified limiting velocity of deposition, typically between 0.4 to 0.6 m/s. A Manning number is assigned to the hanging dam to take into account an increased roughness of the flow section. An exponential decrease is also imposed on the value of this Manning number to reproduce the smoothing effect in aging hanging dams.

The heat flux lost to the atmosphere is calculated by the model based on the weather conditions (air temperature, short- and long-wavelength solar radiation, wind speed, etc.). As for thermal erosion, the heat flow transmitted by warm water to ice is computed using a relation of the type Dittus-Boelter:

$$\Phi_{water} = A \frac{V^{0.8}}{R_H^{0.2}} T \qquad \textbf{[1]}$$

where V is the local flow velocity at the limit between open water and border ice, R_H is the hydraulic radius, T is the water temperature and A is a constant.

2.2 Numerical Model

The one-dimensional model reproduced the reach between the exit of the Romaine-2 (KP 84) and the reservoir of the Romaine-1 (KP54) generating stations. The model was developed within the scope of the environmental evaluation studies performed for the Romaine Hydro-Electric Project. It should be mentioned that the model did not reproduce the frazil ice generating surface located upstream from Romaine-2. The frazil ice generation feature was therefore not used in the following simulations. Instead, frazil ice concentrations were injected at the upstream limit of the model and transported with the flow.

Model Calibration was performed for the winters of 2003-2004, 2004-2005 and 2010-2011. The quantities of frazil ice injected at the upstream limit of the model, the deposition limit velocities and the roughness of the hanging dam were adjusted in the model to match the water levels provided by Hydro-Quebec from their hydrographic stations located in the area. The resulting hanging dam thicknesses are presented on figure 1 and show that the dam is comprised of three sections with peak thicknesses of roughly 2-5 m, 6-9 m and 13-16 m. The most severe accumulations, namely the hanging dam formed during the winter of 2010-2011 was selected for the early flood simulation.

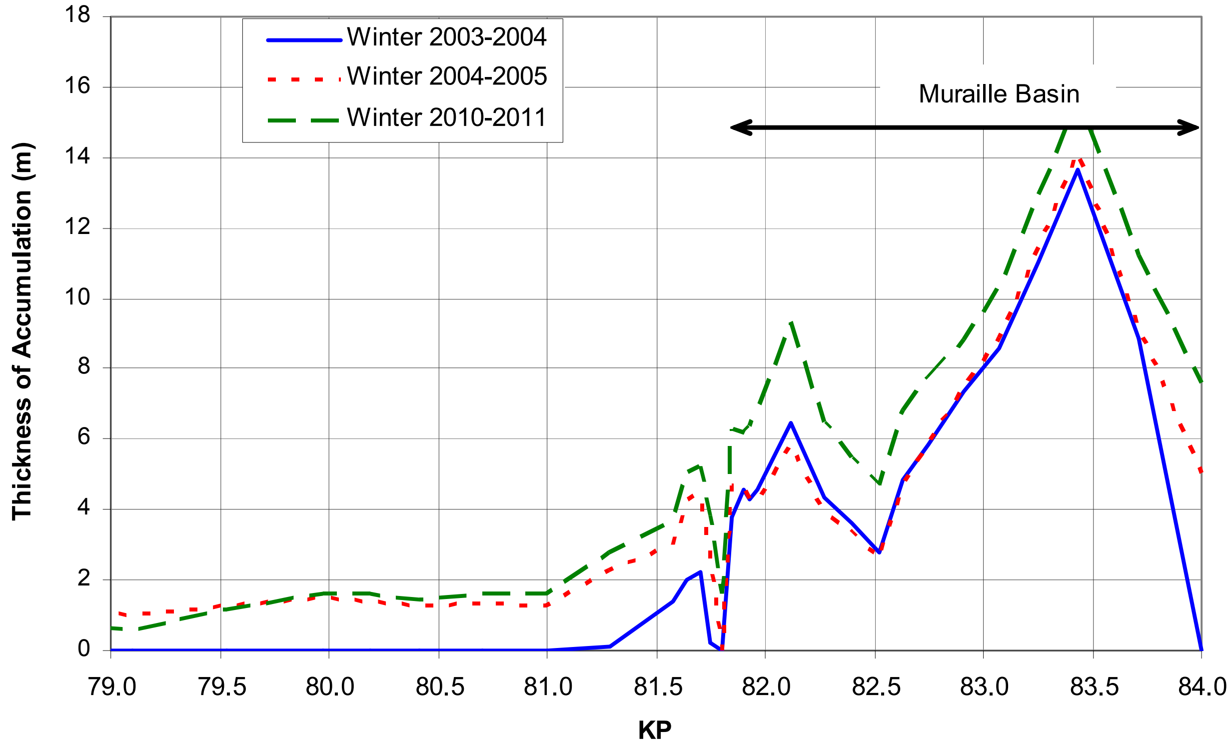

Figure 1: Comparison of Maximum Thicknesses of Frazil Ice Accumulations.

A hydrograph of a typical early flood, along with the corresponding water temperatures, were set as input to the model simulations after formation of the hanging dam. Figure 2 presents a plot of the hydrograph and water temperature profile used for the simulation combining two sets of boundary conditions. The first half of the simulation from November 1st till February 14th is to form an extreme hanging dam and it uses data from the winter of 2010-2011, while the second half from February 14th to May 15th is to simulate an early flood and it uses data from an early flood scenario. According to Figure 2 the early flood actually starts on April 22nd.

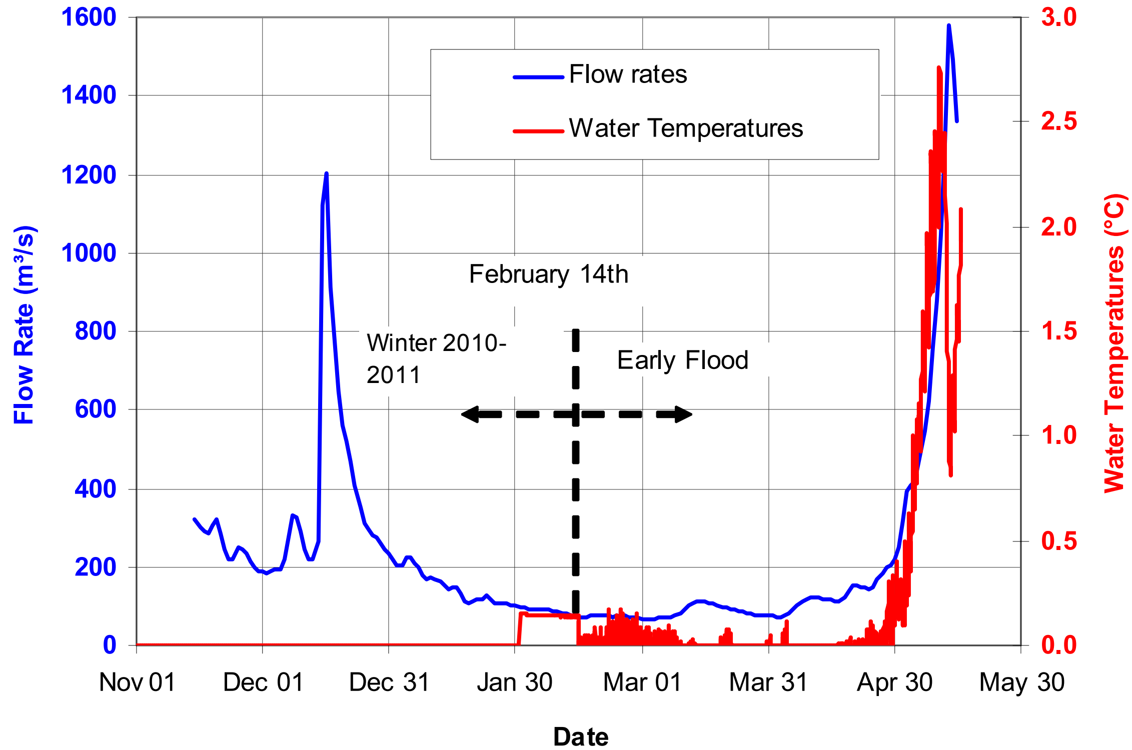

Figure 2: Upstream Boundary Conditions Set for Early Flood Simulation.

2.3 Modeling results

Figure 3 presents the water level variations resulting from the early flood simulation described in section 2.2. The same simulation was run without any ice interfering with the flow in order to compare the results in ice conditions with free surface flow conditions. The free surface water levels are also plotted on figure 3.

The following phases can be observed in the water level profile:

- From January 13th to February 12th, the water level increases due to the build-up of the hanging dam in spite of a gradual reduction of the flow rate (figure 2) in this period. The maximum increase in water level that can be attributed to the presence of the extreme hanging dam is 4.5 m.

- From February 14th to March 30th, the flow rate is almost constant while the water level decreases by a few centimetres du to the smoothing of the aging hanging dam.

- From March 31st to April 21st , the flow rate gradually increases and the free surface water levels follow the same trend. However, the water levels with ice conditions keep decreasing due to thermal erosion of the hanging dam. At this time of the year, solar radiation penetrates the ice cover and heats the water during daylight hours.

- From April 22nd to May 9th , the early flood begins with a steep increase of flow rate from 150 to 750 m3/s, while the water temperatures also increase from a little above freezing temperatures to 2 ºC. The combination of increased flow velocities and increased water temperatures is the driving force for severe thermal erosion. The hanging dam, and all remaining ice in the modeled stretch of river is completely melted in this phase.
- From May 9th to May 15th , the water level variation in the simulation with ice becomes identical to the free surface flow simulation because all ice has disappeared from the river at this point in time.

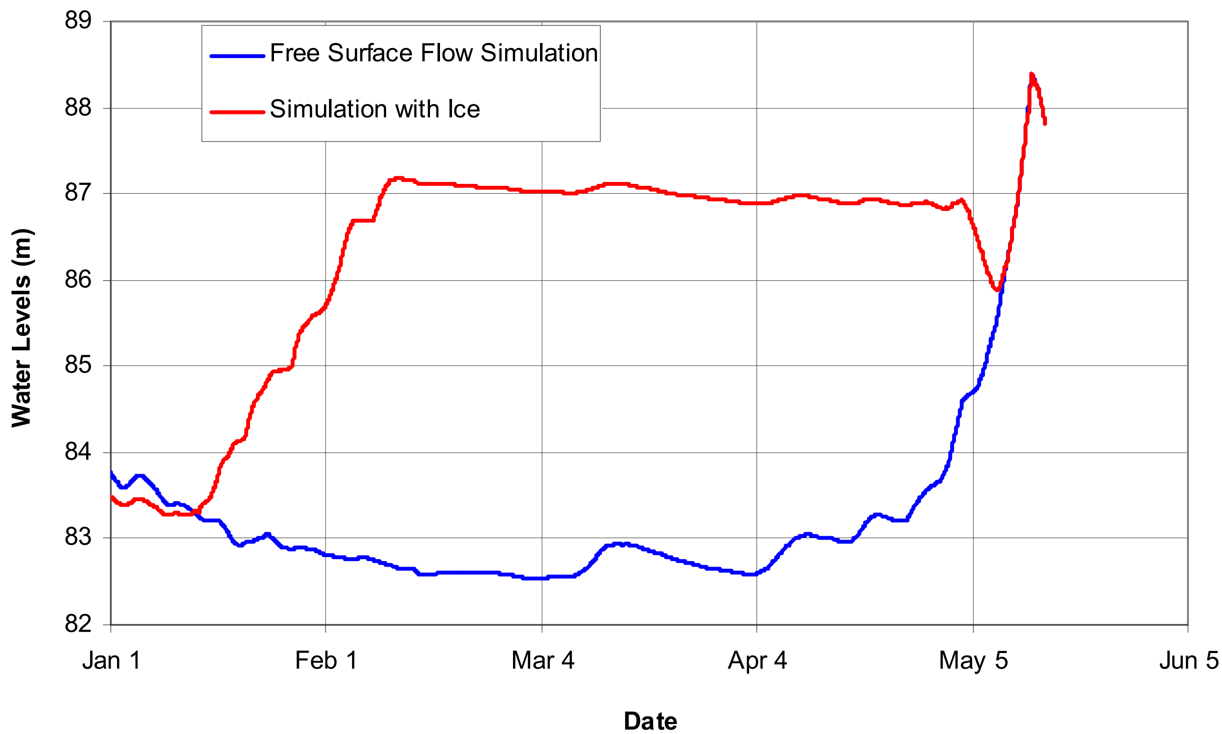

Figure 3: Water Levels at KP 83,43 for Simulation of an Early Flood in the Presence of a Hanging Dam.

As a result, the heat flux transported by the flow managed to eliminate the hanging dam and its induced water level increase half-way through the flood event before the flow rate reached 750 m^3/s, which is half of the flood peak value of 1500 m^3/s.
Therefore, thawing occurred at a much greater rate than the increase in water level, ruling out any risk of overtopping the cofferdam.

3 Observations

Many field observations were made during the following winters. The water level was measured weekly at the upstream end of the basin by traditional surveying. A gauging station was installed near the cofferdam and the manual measures were used to validate the continuous measures. The water level gauge was still susceptible to be moved by ice, but sufficient reaction time was provisioned if a difference between manual and the level gauge measures was observed. Figure 4 shows the water level measured during the three winters following the cofferdam construction.

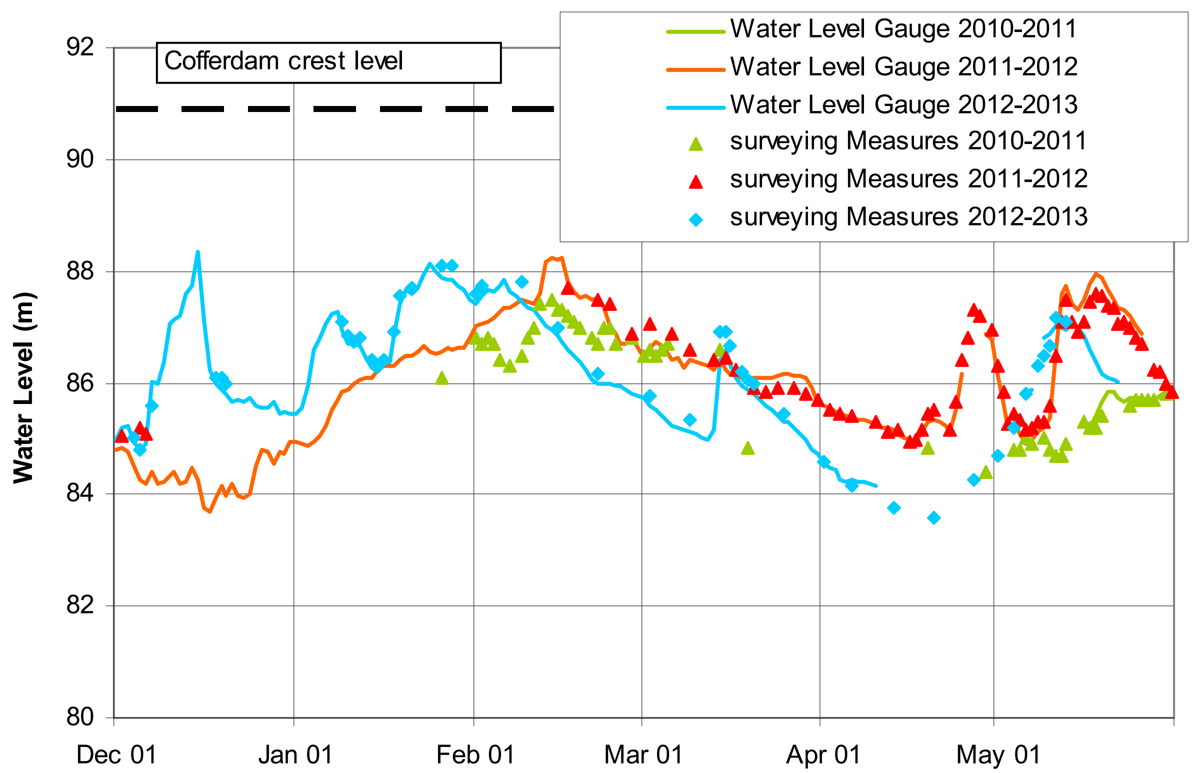

Figure 4: Water Level Measurements.

For the documented winters, aerial surveys were performed at the beginning, middle and end of winter. Unfortunately, the frazil accumulation thickness couldn't be measured since the presence of cracks on the ice cover due to staging resulted in a dangerous accessibility. The water temperature is measured in the Romaine Sud-Est river, which is a tributary of the Romaine river that drains into the Muraille basin. Past observations indicated that the water temperature warms at a similar pace in spring.

The ice cover forms on the Muraille basin as soon as winter begins. Most of the frazil ice generated in the open area upstream settles under the ice cover and raises rapidly the water level (picture 1). At this moment, the water level increase can reach 5,2 m at the upstream part of the Muraille basin . The water level slope in the dune formed by frazil accumulation can reach 2,5m/km temporarily and stabilizes at 1,2m/km. A smaller part of the frazil escapes from beneath the ice cover (picture 2) and drifts in the river downstream from the basin, where the ice cover isn't formed yet. Drifting frazil ice rises to the surface and forms ice pans.

Picture 1: Hanging Dam in the Muraille Basin, December 13th, 2012.

Picture 2: Frazil Drifting Downstream from Muraille Basin, December 9th, 2011.

Further in the winter, the ice cover progresses from downstream by ice pan juxtaposition on a leading edge and eventually reaches the outlet of the basin. The frazil generated in the rapids upstream of the basin can now settle under the ice cover in this part of the river downstream from the basin. It raises the water level in this part of the river, which causes another water level increase in the basin.

In mid-February, frazil continues to be generated in the rapid upstream, but at a lower rate because the generating surfaces are reduced and solar radiation is increased. The water level slowly starts to decrease. ,No visual sign can explain this decrease except for the smoothing of the hanging dam. In March, small tunnels appear inside the hanging dam, which originate from the cracks present in the ice cover. These tunnels act as preferential paths for the flow (picture 3). Slowly, the tunnels become channels. They gradually enlarge and extend downstream (picture 4). At the end of April, an important amount of frazil remains in the basin, but the major part of the flow seems concentrated in these channels. The water level increase due to ice effect is now reduced to a value between 2 and 3 m compared to open water stage discharge relations. These conditions prevail in the river when the spring flood arrives.

Picture 3: Opening in the Frazil Dune, March 12th , 2012.

Picture 4: Channel in the Basin at the End of the Winter (2012-04-20).

Field observations associated with the passage of three spring floods are available. The flow increase occurs at the same time as the warming of the water temperature. During the first days of the spring flood, the water level increases, mainly due to the flow increase, and staging from the presence of frazil ice is still in effect. However, head losses do not increase with the flow increase. For the past three years, all staging due to ice disappeared before the flow reached 600 m^3/s and the water level only varied as a function of the flow in free surface conditions . It was also observed that when this moment occurred, the daily water temperature was between 1,4 and 2,9°C and the maximum temperature between 2,0 and 3,5°C . When the peak flow arrived, all the ice effects had disappeared (Figure 5).

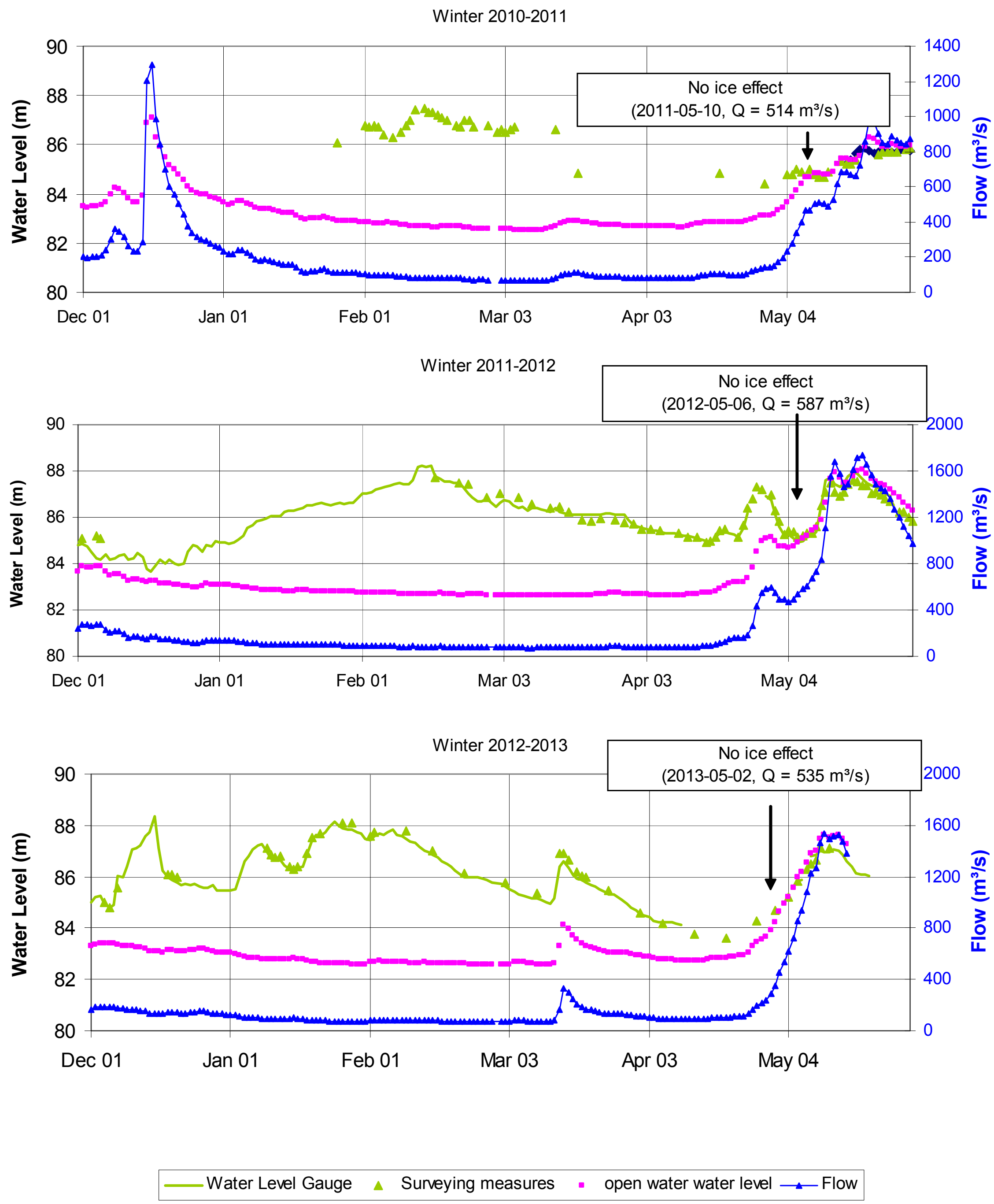

Figure 5: Flow, Water Level Measures and Open Water Levels.

4 Comparisons between Numerical Model and Observations

The model used to predict the behavior during spring flood is a one dimension model, but it clearly came to our attention that three-dimensional effects were controlling the hanging dam evolution and water level variation during the second part of winter. The formation of tunnels and channels in the hanging dam and its effect on the water level haven't been predicted by the model. Therefore, for the three observed winters, the water level at the end of winter was much lower that the level predicted by the model. At the end of the winters 2011 to 2013, water level varied from 83,6 m to 85,0 m and the level predicted was 86,9 m. It should be mentioned that the water levels recorded during the first half of the past three winters were close to the maximum water level simulated with the numerical model. Therefore, it implies that the actual hanging dam during those winters was quite similar to what was simulated in the numerical model. Table 1 compares the water level increase predicted to the one observed for different flows in the basin.

Table 1: Comparison between Water Level Increased observed and predicted by the Model at the end of the Winter.

Flow in Muraille basin (m³/s)	Calculated water level increase (m)	Observed water level increase (m)		
		2011	2012	2013
75	4,5	unavailable	2,66	2,90
150	3,7	1,29	2,13	2,50
300	2,75	1,04	2,56	3,08
500	1,09	0,30	0,57	0,48
600	0,80	0	0	0
750	0	0	0	0

Despite significant differences, the model results agreed with the observations or conclusions for the following points:

- The ice cover was still present when the flow started to increase.
- At early spring, as soon as the flow increases, there is a rapid decrease of the water level staging.
- The model predicted properly that, when the peak flow occurs, there is no more water level enhancement due to the presence of frazil in the basin.
- The model predicted properly that the maximum water level that may cause the overtopping of the cofferdam with a 5% probability is due to the spring flood and not the presence of ice.
- There is no need to raise the cofferdam.

5 Conclusion

The cofferdam downstream from the Romaine-2 powerhouse has been designed to withstand a 1:40 year return flood. Each winter, an important hanging dam forms in the basin next to the cofferdam. The staging from this dam reaches more than 5 m at the beginning of winter and slowly decreases in the course of the winter.

A one-dimensional numerical model of the Romaine-2 downstream reach was used to verify the response of the water levels to the arrival of an early spring flood. The model and showed that the spring flood arrives with most of the frazil accumulation still present in the basin. The dam rapidly disappears because thawing occurred at a much greater rate than the increase in water level. The peak flow occurs without any ice present in the river.

Field observations confirmed all of the above but also showed that three-dimensional effects, namely the formation of tunnels and channels across the hanging dam, reduced the impact of the dam on water levels in the second half of winter. At the arrival of spring flood, a remaining staging of only 2 m was still recorded.

The field observations of the past three years showed that maximum water level occurred in winter. The water levels due to the presence of the hanging dam exceeded the levels reached for the majority of the springs. It should be pointed out that the 40 years return period flood would induce higher water levels at the cofferdam.

The model did not reproduce the breaches in the hanging dam, which govern the changes in water level in the second half of winter, but it proved to be a valuable tool in demonstrating the vulnerability of the accumulations to thermal erosion.

References

Thériault. I., Saucet. J.-P. Taha. W., 2010. Validation of the Mike-Ice model simulating river flows in presence of ice and forecast of changes to the ice regime of the Romaine river due to hydroelectric project. *20th IAHR Symposium on Ice*.