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Flooding of the Saguenay region in 1996: Part 2- flood mitigation and environmental impact assessment on Aux Sables River.

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Abstract. After the flooding of the Saguenay region in July 1996, several rivers, including the Aux Sables River, experienced unusual water discharges causing flooding and morphological damages. This paper deals with flood mitigation and environmental impact assessment in Aux Sables River following the July 1996 flooding. The consequences of the flood are summarized, followed by different proposed solutions for a similar flood are reviewed. For Aux Sables River, the option of digging the river to increase the discharge without causing flooding brings the issue of suspended sediment concentration since the intake water at Jonquiere will be at risk. Thanks to a newly developed software, UMHYSER-1D, suspended sediment impact assessment in Aux Sables River provides the maximum permissible sediment discharge to be released in the river to avoid any risk pollution for the population of Jonquiere city. Using UMHYSER-1D to mitigate water pollution risk confirms the important role of numerical modeling in solving complex engineering problems.

Keywords: Saguenay flood July 1996, Aux Sables River, Flood mitigation, Suspended sediment impact assessment, UMHYSER-1D.

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1 Introduction

During the July 1996 Saguenay flood, several rivers experienced unusual water discharges causing flooding and morphological damages. On top of the impacts to the Ha! Ha! River (Brooks and Lawrence, 1999; Lapointe et al., 1998), the most extreme flooding occurred along the rivers Aux Ecorces, Pikauba, and Cyriac, which flow into Lac Kénogami, and are tributaries of the Aux Sables and Chicoutimi rivers, Du Moulin and A Mars Rivers (Figure 1). The Chicoutimi and Aux Sables Rivers, two outlets of the Kenogami reservoir, were particularly affected by the flooding.

For Lake Kenogami, the estimated maximum inflow was 2780 m^3/s, exceeding the outflow and causing the reservoir to rise to unprecedented levels. The water level reached a maximum level of 166.08 m, exceeding the crest of the concrete dams, 165.7 m (Environnement et Faune Quebec, 1996a). As a result, a number of dykes and all three dams (two discharging in Aux Sables River) controlling the reservoir level were overtopped by Lac Kenogami waters (Environnement et Faune Quebec, l996a). The outflow spills primarily into Aux Sables and Chicoutimi Rivers.

The four sections of this paper deal with flood mitigation and environmental impact assessment in Aux Sables River. Section 2 presents first, the consequences of the 1996 flood on the Aux Sables River, then the proposed solutions to reduce them, for a similar flood, are reviewed and the retained option is explained. Section 3 deals with the suspended sediment impact assessment of suspended sediment in Aux Sables River during the implementation of the retained solution. The results and discussion are presented in section 4, followed by a conclusion.

2 Aux Sables River flood mitigation

2.1 Study reach

Flowing northwards into the Saguenay valley, the Aux Sables River is a tributary of the Saguenay River (Figure 1). The study reach is situated along the lower 11.1 km of the Aux Sables River, from the Lake Kenogami to the Saguenay River, with three run-of-the-river dams: Jonquière dam, Ville-de-Jonquière dam and Chute-à-Besy dam (Figure 2).

The longitudinal profile of the river is shown in figure 3 where the gentle river gradient steepens markedly along the last 3 km, characterized by the presence of bedrock.

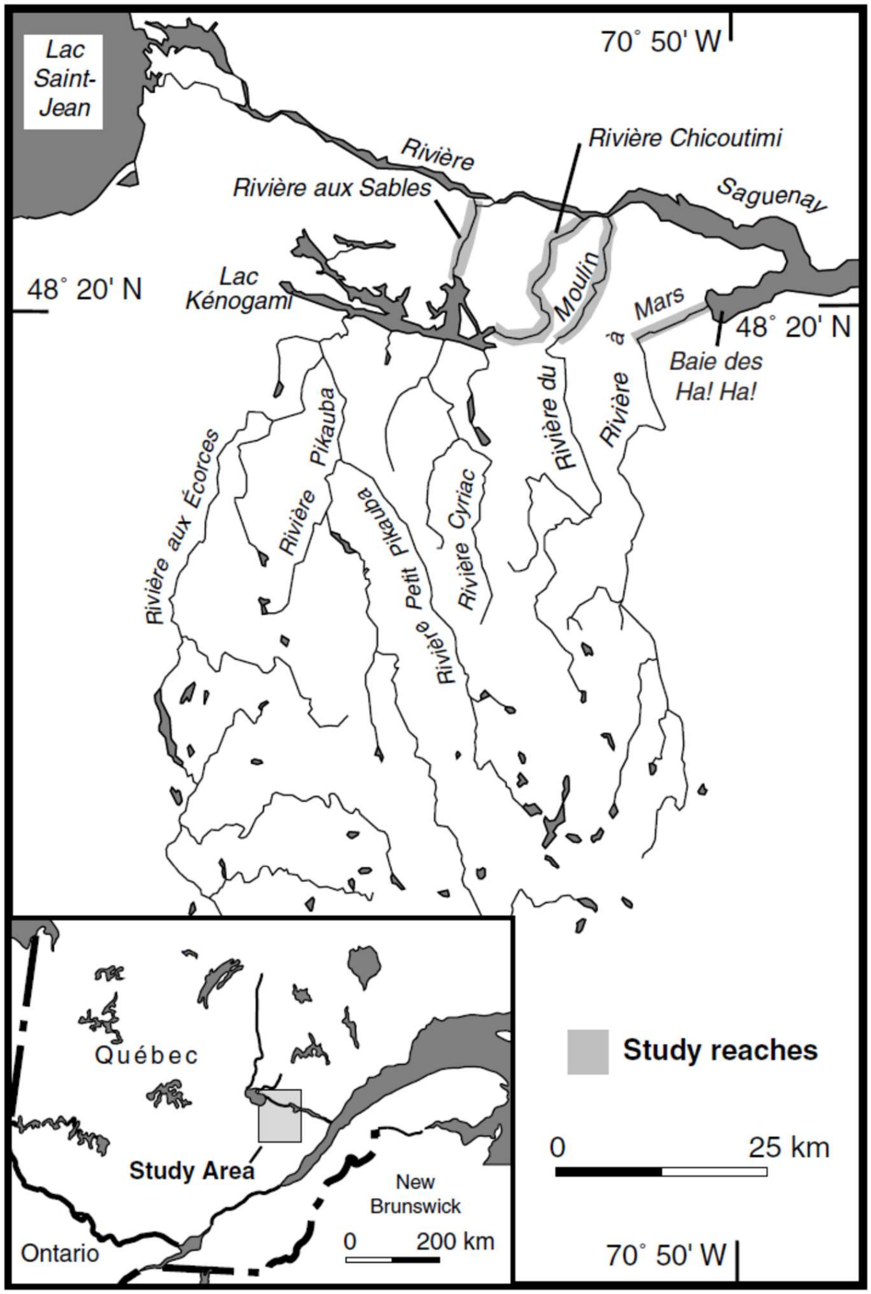

Figure 1. Location map depicting Lake Kenogami, Chicoutimi and Aux Sables Rivers (Brooks and Lawrence, 2000).

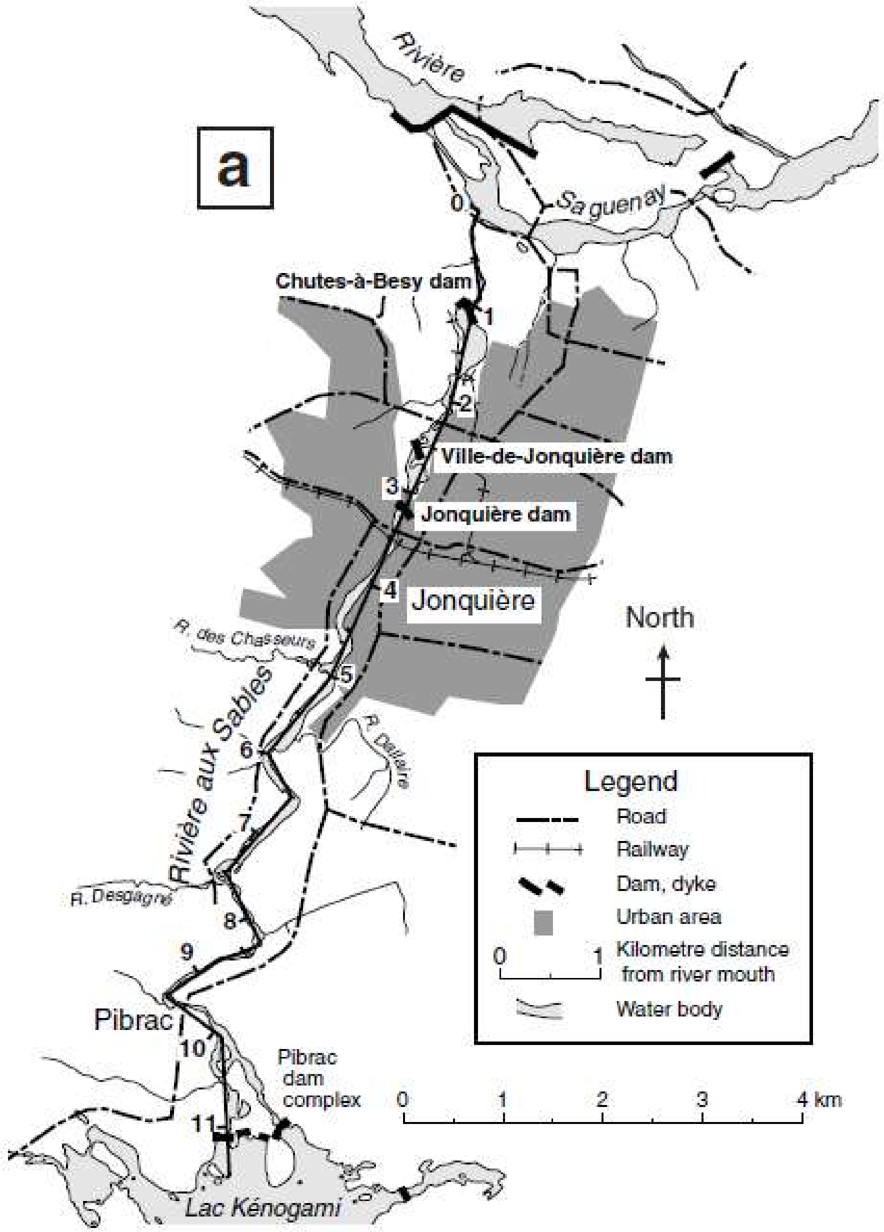

FIGURE 2. Aux Sables River: Pre-flood maps depicting the study reach along with the location of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

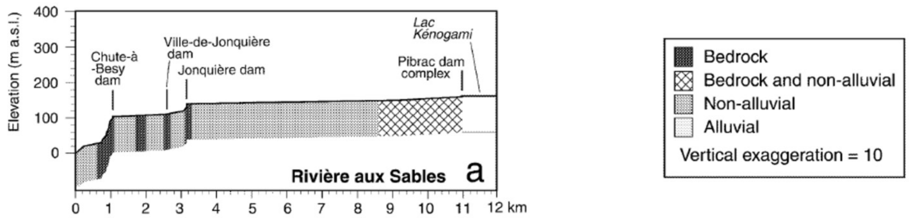

FIGURE 3. Longitudinal profiles and channel morphologies along the Aux Sables River (Modified after Brooks and Lawrence, 2000).

2.2 Discharge

The discharges on the two rivers, Aux Sables and Chicoutimi, outlets of the reservoir Kenogami, are regulated by control dams at the reservoir. The rainstorm of July 18 to 21, 1996, produced the hydrograph in figure 4, on Aux Sables River where two control dams and two dikes form the Pibrac dam complex (Figure 2).

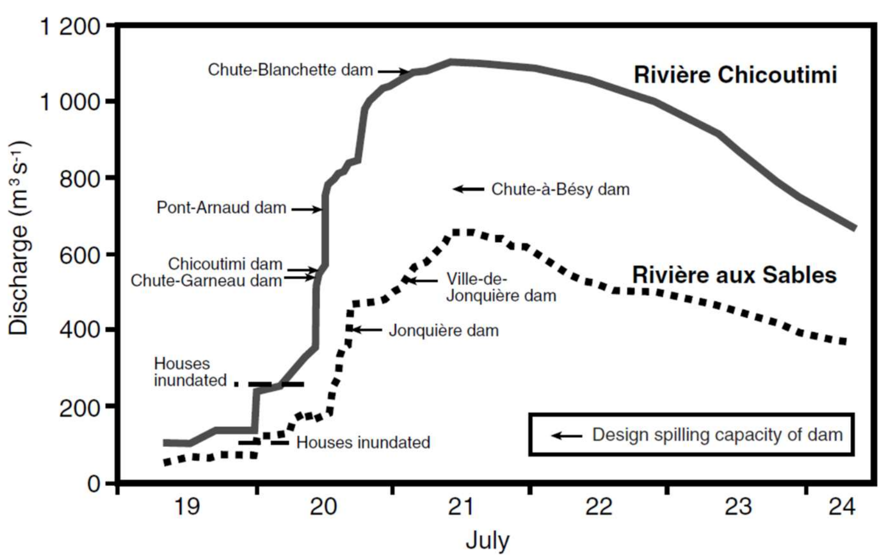

FIGURE 4. Aux Sables River's storm hydrograph (July 19-24, 1996; CSTGB, 1997). Note the minimum discharge beyond which houses begin to be flooded and the maximum spilling capacities of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

2.3 Consequences

Along Aux Sables River, when the discharge reaches 150 m³/s, the inundation of property occurs and when 170 m³/s are exceeded, flooding of homes begin (Environnement et Faune Quebec, 1996a). During the July 1996 flooding, not only was the peak flow discharge 653 m³/s (CSTGB, 1997), overtaking these critical discharges, but also flood discharges exceeded the available spilling capacity at Jonquière dam and Ville-de-Jonquière dam, two run-of-the-river dams (figure 4). Table 1 summarizes the spilling capacities and the eventual consequences of the 3 dams. Between km 8.6 to 8.4, up to 20 m of lateral bank erosion occurred along the left bank, while a series of sand and gravel mid-channel, side, and point bars were aggraded between 8.3 and 7.2 km, and between km 0.6 and the river mouth (0 km), the channel was widened from 20-30 m to 60-130 m. Between km 11 and 3.5, the gently-sloped upper portion of the river, along which numerous homes were inundated (Brooks et al., 1997).

Table 1. Aux Sables River's run-of-the-river dams and impacts from flooding (modified after CSTGB, 1997 and Brooks and Lawrence, 2000).

Dam (Year)	Type (foundation)	Dam height (m)	Dam length (m)	Spilling capacity* (m^3/s)	Impacts of flooding
Jonquière (1943)	Concrete gravity (bedrock with soil abutments)	8	93	530	- abutment breached, lateral valley side erosion, reservoir drained, river flow diverted away from dam
Ville-de-Jonquière (1996)	Concrete gravity (bedrock)	< 15	~105	455	- concrete wing-wall breached, partial drawdown of reservoir
Chute-à-Besy (1911)	Concrete gravity (bedrock) and earthen dike (soil)	< 15	~220	770	- dike breached, incision and lateral erosion of valley side, reservoir drained, river flow diverted away from dam

* spilling capacity at maximum working level of reservoir

2.4 Flood mitigation

Mitigation options

The flooding events along the Aux Sables River, among other rivers, were analyzed by the ``Commission scientifique et technique sur la gestion des barrages`` (CSTGB, 1997). Afterward, Hydro-Quebec, Ministère de l'Environnement and a consortium of consultants assessed various options to mitigate flood, resulting from extreme conditions, in Lake Kenogami, Chicoutimi and Aux Sables Rivers (Ministère des Ressources Naturelles et Hydro-Québec, 2002a, 2002b, 2002c, 2002d, 2002e; Hydro-Québec, 2001, 2002a, 2002b and Groupe-Conseil GÉNIVAR, 2002).

The options were analyzed according to the following criteria:

1. A flood comparable to the one of July 1996 should not exceed the major flood levels on the Chicoutimi and Aux Sables Rivers, corresponding to the discharge beyond which a home begins to be flooded;
2. For a maximum probable flood, water level of Lake Kenogami must be less than 166.67 m;
3. All existing, or new, structures must conform to the Dam Safety Act ;
4. During the summer, the water level of Lake Kenogami must be stabilized at 163.86 m ± 0.1 m.

Different scenarios were proposed. The first one proposed raising and consolidating the retaining structures of the Kenogami Lake, raising the flood levels on the rivers downstream and implementing an improved flood forecasting system.

The second scenario suggested the construction of a reservoir upstream of Kenogami Lake on the Pikauba River, the consolidation and modernization of existing structures of Kenogami Lake, and the construction of a sill in the Aux Sables River. In addition to the implementation of an improved flood forecasting system.

Finally, the third scenario involved the construction of two reservoirs on the Pikauba and the Aux Ecorces Rivers, the consolidation and modernization of existing structures of Kenogami Lake and the implementation of an improved flood forecasting system.

Digging a sill in Aux Sables River

Relevant to this paper, only the flood mitigation option directly related to Aux Sables River will be reviewed. The following options were considered to increase Lake Kenogami's discharge capacity (Ministère des Ressources Naturelles, de la Faune et des Parcs, 2003):

5. Digging 600 m along the Aux Sables River;
6. Digging several kilometers along the Chicoutimi River;

7. Building an outlet toward Lake Saint-Jean along several kilometers via Belle-Rivière;
8. Building a canal in the Jean-Dechêne stream which flows for several kilometers before reaching the Saguenay;
9. Digging a tunnel several kilometers long toward the Saguenay.

After several studies, the retained option was digging a single sill in the Aux Sables River to ensure the protection of homes that are susceptible to flooding on either side of the river upstream of Pibrac Bridge (Ministère des Ressources Naturelles et Hydro-Québec, 2002a, 2002b, 2002c, 2002d, 2002e). In 2009, GENIVAR (2009) proposed a new concept by eliminating the Pibrac Bridge's pillar (figure 5) which acts as an obstruction to the flowing water at high discharges.

Figure 5. Pibrac Bridge: for high discharges, the pillar is an obstruction to the flow, increasing the water level upstream. Note the cofferdam installed to limit suspended sediment release.

The proposed concept (figure 6) consists of:

1. Increase the flow section downstream of the bridge (downstream of km 10.29) by excavating the left bank for a length of about 60 m;
2. Increase the flow section to the right of the bridge by excavating the river bed of about 2 m and excavating on the left bank;
3. Replace the Pibrac Bridge with a span of 50 m (without central pillar);
4. Increase the flow section upstream of the bridge by excavating a channel of 440 m length, with a maximum width of 60 m, requiring an excavation of the river bed varying from 0.5 to 2 m;

According to the above, Aux Sables River will be able to carry a discharge of 650 m^3/s without flooding the riparian houses.

Figure 6. Excavation limits from the Pibrac Bridge: yellow limits correspond to option replacing the bridge with a longer one with no pillar (Modified after GENIVAR, 2009).

3 Suspended sediment impact assessment

3.1 Site description

The study area (figure 7) is about 5.8 km long, from the Pibrac Bridge (km 10.32) to the Jonquiere water intake (km 4.9). The outlet of the small shallow lake, just after the bridge (steep 400 m long reach), Rapid du CEPAL, forces suspended sediments mixing (figure 8). The tributaries to this river reach do not contribute significantly to the discharges of the river, except tributary C located at km 5.4, 500 m from the water intake station. As it can be seen in figure 9, the color difference between the water of this tributary and river's water, suggests that it provides substantial suspended sediment.

Figure 7. Study area from Pibrac Bridge to the Jonquiere water intake (courtesy of GENIVAR)

Figure 8. CEPAL rapid at km 9.7, looking upstream. Suspended sediment mixing allows adopting one-dimensional approach.

Figure 9. Suspended sediment inflow from tributary C (km 5.4) (Courtesy of GENIVAR)

3.2 Problematic

The excavation of the river involves suspended sediment release. Depending on the concentration of these sediments at the filtration plant, in the city of Jonquiere, can be harmful, which eventually leads to a significant risk of drinking water pollution and therefore a health risk for the population.

Suspended sediment concentration at the Jonquiere water intake should be less than 19.29 mg/l to ensure delivering drinkable water. To minimize suspended transport downstream the Pibrac Bridge, cofferdams were installed just after the bridge (figure 5). The question to be answered is, for a given constant discharge controlled by the Pibrac dam, km 11.1, what is the maximum sediment concentration released at the bridge to ensure that the suspended sediment concentration at the Jonquiere water intake is less than 19.29 mg/l?

3.3 Available data

Some data are easily retrieved such as river bathymetry, upstream and downstream boundary conditions, river bed composition, and geometry of cross-sections describing the river. All these data were secured by GENIVAR thanks to the field campaigns carried out on the site.

Turbidity

Turbidity surveys were done at various locations along the river. A turbidity probe was installed in Aux Sables River near Highway 70, 1 km upstream of the Jonquiere water intake. Moreover, turbidity measurements took place at three sites (figure 7), Jonquiere water intake (site A), near the CEPAL rapids (site B) and just upstream of the Pibrac bridge (site C).

Boundary condition

The upstream condition is located just after the Pibrac Bridge, km 10.3, were the discharge will be specified. The discharge in the river is controlled by the Pibrac dam, km 11.1. During the work period, the released discharge from Lake Kenogami is quasi-permanent, varying between 5 m^3/s and 50 m^3/s. For the downstream boundary condition, at the Jonquiere dam, km 3 (figure 2), the water level is maintained constant by the dam at 140.2 m.

There is no internal boundary condition for the water phase. For the suspended sediment, a concentration, depending on the water discharge, will be specified at km 5.4.

Riverbed composition

The armored riverbed is made of large pebbles with the exception of rapids, where water flows over bedrock. There would be no bed load sediment transport. During riverbed excavations, the cohesive sediment, beneath the armored layer, was release and transported downstream.

Cross-sections

The river reach from the Pibrac Bridge, km 10.3, to the Jonquiere dam, km 3.0, is discretized into 86 cross-sections provided by GENIVAR.

Water lines

GENIVAR provided the water lines corresponding to the following discharges: 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 m^3/s.

3.4 Numerical model

UMHYSER-1D

For a constant water discharge, released from Lake Kenogami, the convection-diffusion equation is solved to determine the concentration of suspended sediments at the Jonquiere water intake. To this end, the software UMHYSER-1D (AlQasimi and Mahdi, 2018), presented in a companion paper, is used. For unsteady sediment transport, UMHYSER-1D solves the convection-diffusion equation with source term from sediment erosion/deposition:

$$\frac{\partial AC}{\partial t} + \frac{\partial (\xi QC)}{\partial x} = \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \Sigma \qquad (1)$$

where: C = depth averaged concentration; A = cross section area, Q = flow rate, D = longitudinal diffusion coefficient, a calibration parameter, ξ = velocity of sediment relative to the water (Greimann et al., 2008). Σ = source (erosion, excavation, lateral inflow) and sink (deposition) terms for one sediment class.

To discretize the convective term, the Lax-Wendroff TVD scheme is used, and a central difference scheme is used to for the diffusion term (Tannehill et al., 1997). The source term is discretized according to the procedure used for the BASEMENT model (Vetsch et al., 2017).

4 Results and discussion

Numerical modeling of the Aux Sables River should answer the following question: under which hydraulic conditions (flows) the concentration of the sediments, released at Pibrac bridge, would be lower than 19 mg/l at the filtration station (water intake) of the city of Jonquiere?

To answer this question, the following numerical simulations are made:

- Permanent flow modeling without sediment transport: this step is necessary for the determination of the Manning coefficients,
- Modeling of suspended transport (released sediments): first, calibrate the model to determine the right diffusion coefficient. Then, the validation of the model is undertaken.
- Use of the model to assess suspended sediment transport and answer the previous question.

4.1 Calibration and validation

Liquid phase

Knowing the flow discharges and the corresponding water lines, simulations are carried out for a steady flow at different discharges and the results are compared to measurements of water lines. For each of the available discharges (5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 m^3/s), the maximum difference between observed and simulated water lines does not exceed 3 cm for the Manning's coefficients listed in table 2. Figure 10 shows an example of the calibration for a discharge of 30 m³/s.

Table 2. Calibrated Manning's coefficients

River km	Right bank	River	Left bank
0 - 5.3	0.08	0.03	0.08
5.3 - 6.2	0.08	0.03	0.04
6.2 - 9.0	0.06	0.03	0.04
9.0 - 10.0	0.08	0.05	0.08
10.0- 10.3	0.06	0.02	0.06

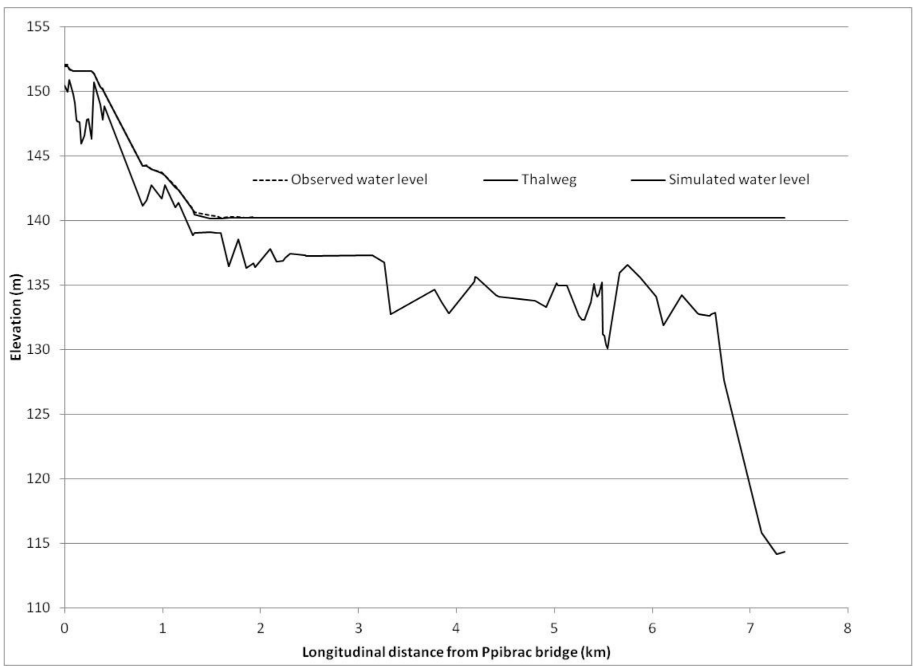

Figure 10. Example of calibration results for a discharge of 30 m³/s.

Solid phase

From March 13-16, 2009, no rain was observed, thus the sediments input from the tributary at km 5.4 is assumed nil. The river discharge is almost constant, varying between 24.7 m³/s and 26.4 m³/s, and the observed turbidity, at km 6.15, varies between 1.43 and 1.95 NTU. The calibration is achieved by varying the diffusion coefficient given by Fischer's equation (Fisher, 1975). The best results (Figure 11) are obtained by changing the proportionality constant of Fisher's equation from 0.011 to 0.0135. Note that the simulated concentration starts at 0 mg/l since the model's computations start with a nil concentration. Figure 12 shows a validation example for the period March 2-3, 2009.

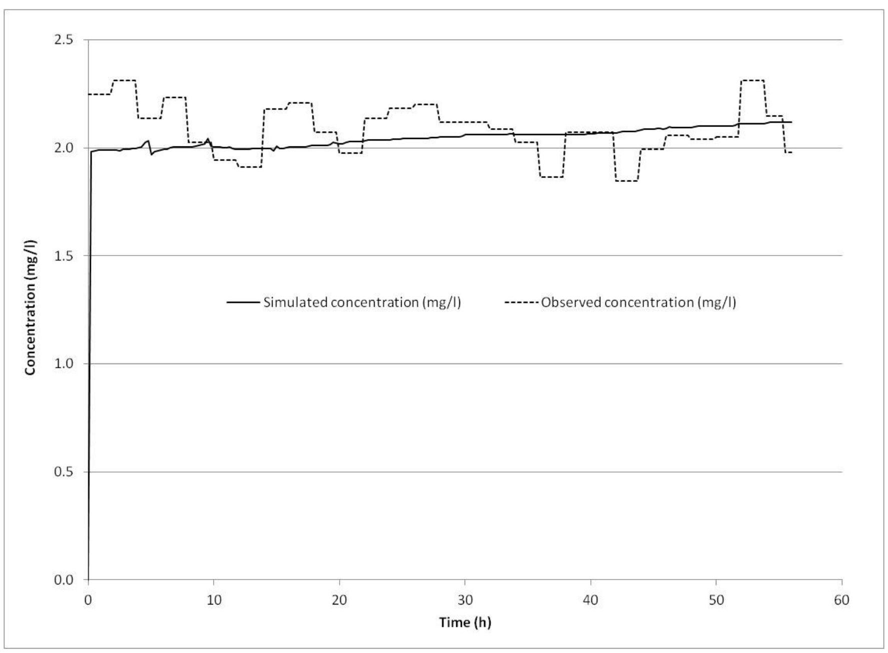

Figure 11. Calibration of the diffusion coefficient for a liquid discharge varying between 24.7 m³/s and 26.4 m³/s during the period March 13-16, 2009.

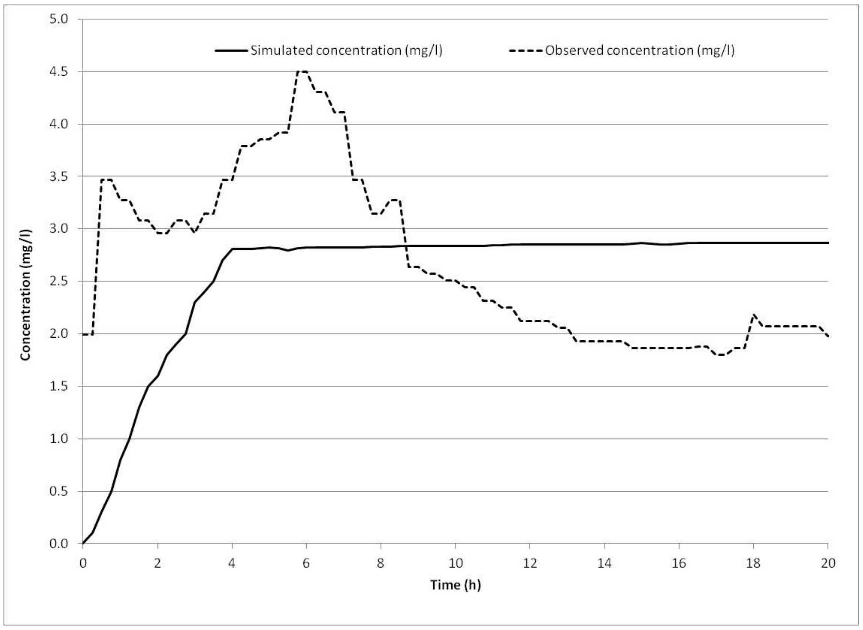

Figure 12. Validation of the calibrated model. Observed and simulated concentration from March 2, 22:00 to March 3, 18:00.

4.2 Suspended sediment assessment

To find the maximum sediment concentration to be released at the bridge to ensure that the suspended sediment concentration at the Jonquiere water intake is less than 19.29 mg/l, the calibrated and validated model will be used.

According to the available means on the site, the maximum possible quantity of suspended sediment to be released at the Pibrac bridge is 53.80 tons per day. If we report this over an hour of work, that's

2.2419 tons dumped. It is therefore considered that during the works, the maximum sediment discharge released does not exceed 2.5 tons per hour.

A series of simulations are performed as follow:

a- The sediment discharge is constant equal to 2.5 tons/h;

b- Several simulation are performed, each with a different water discharge, looking for the minimum water discharge giving a concentration at the water intake, at Jonquiere, of 19.29 mg/l.

c- Redo step b) with a smaller sediment discharge (2, 1.5. 1, 0.5 tons/h) looking for the corresponding minimum water discharge

Table 3 and Figure 13 summarize the results. According to the available river discharge, controlled by the Pibrac dam, one can decide what's the maximum quantity to be released into the river.

Table 3. Maximum tolerable released sediment load into the Aux Sables River

Upstream released sediment (ton/h)	Minimum water discharge (m^3/s)	Concentration at water intake (mg/l)
0.5	5	19.15
1.0	10	19.10
1.5	18	19.13
2.0	25	19.08
2.5	32	18.96

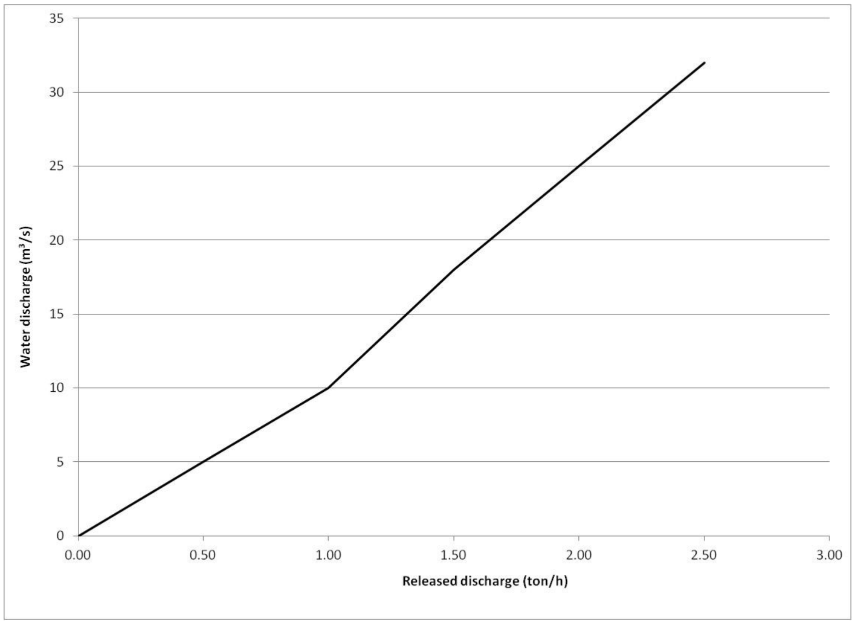

Figure 13. Maximum sediment load released upstream corresponding to the minimum water discharge of the Aux Sables River.

5 Conclusion

The severe rainstorm of July 1996, caused extreme flooding in the Saguenay region, Quebec. Among its numerous consequences, along the Aux Sables River, the flood discharges exceeded the design or available spilling capacity at two run-of-the river dams. Flooding in an urban area damaged or destroyed buildings and infrastructures. The inundation threshold discharge was exceeded by a factor of 3.8.

The retained option for flood mitigation on Aux Sables River consists of increasing the flow section downstream of Pibrac bridge by excavating the left bank for a length of about 60 m; increasing the flow section to the right of the bridge by excavating the river bed of about 2 m and excavating on the left bank; replacing the Pibrac Bridge with a span of 50 m (without central pillar) and increasing the flow section upstream of the bridge by excavating a channel of 440 m length, with a maximum width of 60 m, and requiring an excavation of the river bed varying from 0.5 to 2 m.

This option raised pollution risk at the water intake at Jonquiere city, located a few kilometers downstream the work area. Thanks to a newly developed software, UMHYSER-1D, suspended sediment impact assessment in Aux Sables River provides the maximum permissible sediment discharge to be released in the river to avoid any pollution risk for the population of Jonquiere city. Using UMHYSER-1D to mitigate water pollution risk confirms the important role of numerical modeling in solving complex engineering problems.

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