



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

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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 discharge, causing flooding and morphological damage. This paper addresses flood mitigation and environmental impact assessment of the Aux Sables River following the July 1996 flooding. The consequences of the flood are summarized followed by a review of various proposed solutions for a similar flood. The option of dredging the Aux Sables River to increase discharge without causing flooding raises the issue of suspended sediment concentration, since the intake water at Jonquiere would be at risk. Utilizing newly developed software, UMHYSER-1D, the suspended sediment impact assessment for the Aux Sables River enables the maximum permissible sediment discharge to be released into the river while avoiding any risk of pollution for the population of Jonquiere city. Using UMHYSER-1D to mitigate this 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 software

1 Introduction

During the July 1996 Saguenay flood, several rivers experienced unusual water discharge, causing flooding and morphological damage. In addition to the impact to the Ha! Ha! River, the most extreme flooding occurred along the Aux Ecorces, Pikauba, and Cyriac Rivers, which flow into Lake Kenogami and are tributaries of the Aux Sables, Chicoutimi, Du Moulin, and A Mars Rivers (Fig. 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 m³/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 165.7 m crest of the concrete dams

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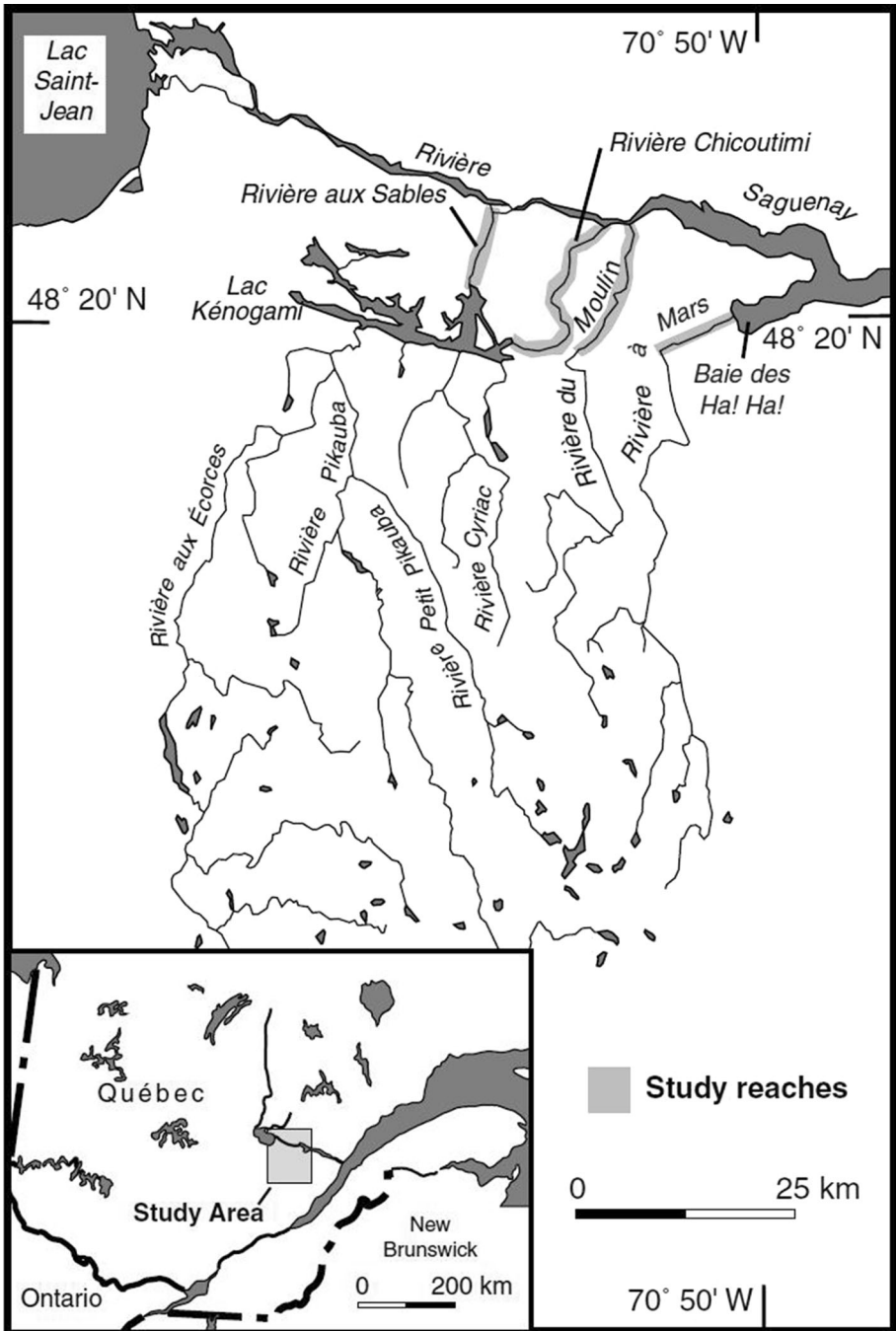


Fig. 1 Location map depicting Lake Kenogami, Chicoutimi and Aux Sables Rivers. (Reproduced with permission from Brooks and Lawrence 2000)

(Environnement et Faune Quebec 1996). As a result, a number of dikes and all three dams (two discharging in Aux Sables River) controlling the reservoir level were overtopped by Lake Kenogami waters (Environnement et Faune Quebec 1996). The outflow spilled primarily into the Aux Sables and Chicoutimi Rivers.

The four sections of this paper address flood mitigation and environmental impact assessment for the Aux Sables River. Section 2 presents first the consequences of the 1996 flood on the Aux Sables River and the proposed solutions to reduce the consequences of a similar flood are reviewed and the retained option is explained. Section 3 addresses the suspended sediment impact assessment for the Aux Sables River during implementation of the retained solution. The results and discussion are presented in Sect. 4 followed by the study's conclusions.

2 Aux Sables River flood mitigation

2.1 Study reach

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

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

2.2 Discharge

The discharge of the Aux Sables and Chicoutimi rivers, which are outlets of the Kenogami Reservoir, is regulated by control dams. The rainstorm of July 18 to 21, 1996, produced the hydrograph in Fig. 4, on the Aux Sables River where two control dams and two dikes form the Pibrac dam complex (Fig. 2).

2.3 Consequences

When the discharge along the Aux Sables River reaches $150 \text{ m}^3/\text{s}$, property inundation occurs, and when $170 \text{ m}^3/\text{s}$ is exceeded, flooding of homes begins (Environnement et Faune Quebec 1996). During the July 1996 flooding, not only was the peak flow discharge $653 \text{ m}^3/\text{s}$ (CSTGB 1997), overtaking these critical values, but flood discharge also exceeded the available spilling capacity at the Jonquière and Ville-de-Jonquière dams, which are two run-of-the-river dams (Fig. 4). Table 1 summarizes the spilling capacities and the eventual consequences for the three dams. Between 8.6 and 8.4 km, 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 0.6 km and the river mouth (0 km), the channel was widened from 20–30 m to 60–130 m. Between 11 and 3.5 km numerous homes were inundated on the gently sloping upper portion of the river (Brooks et al. 1997).

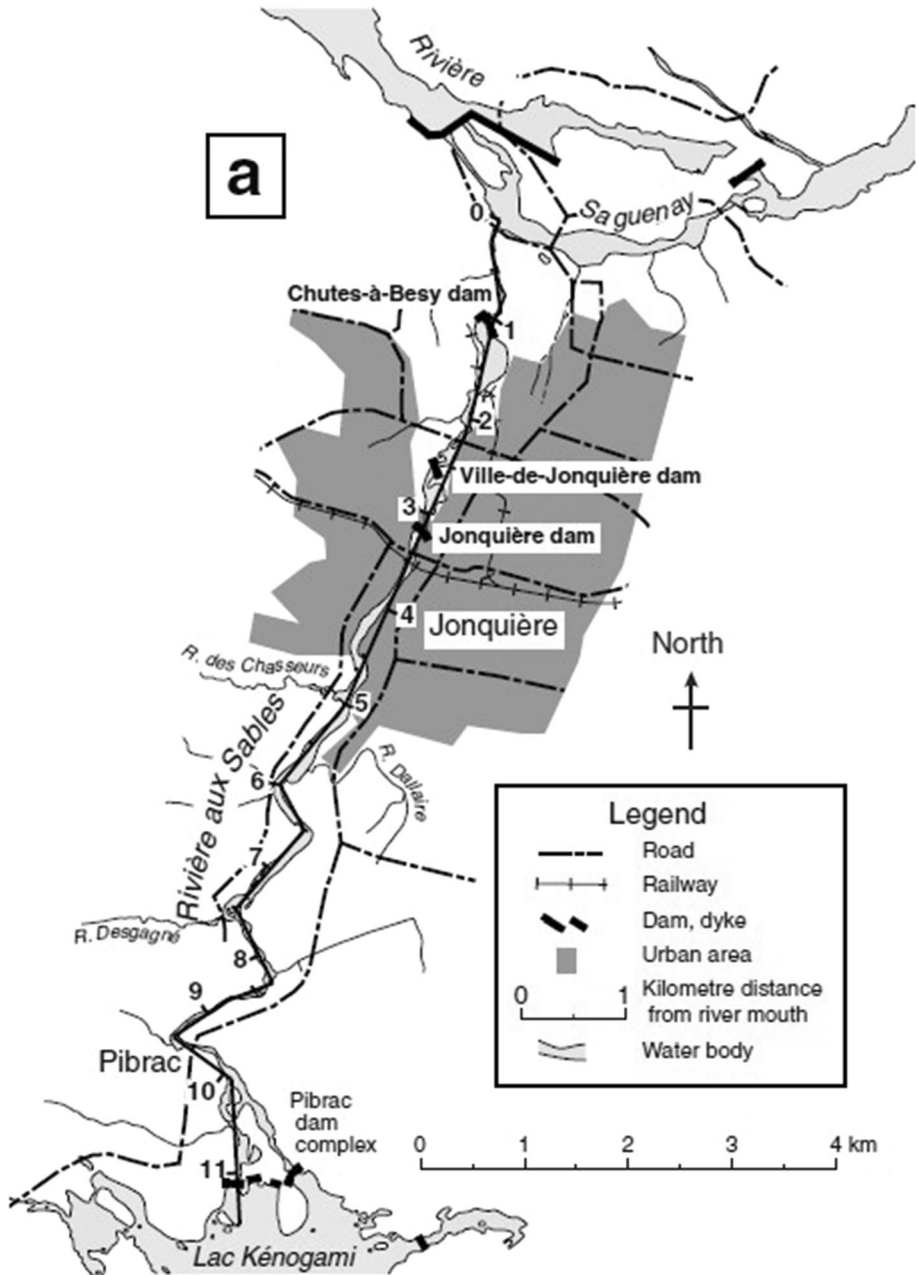


Fig. 2 Aux-Sables River: Pre-flood maps depicting the study reach along with the location of the run-of-the-river dams. (Modified after Brooks and Lawrence 2000)

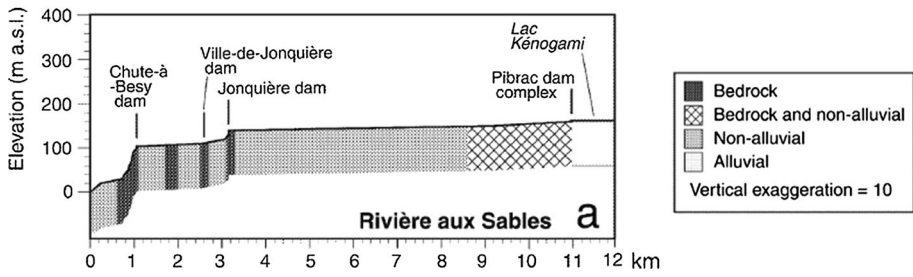


Fig. 3 Longitudinal profiles and channel morphologies along the Aux Sables River. (Modified after Brooks and Lawrence 2000)

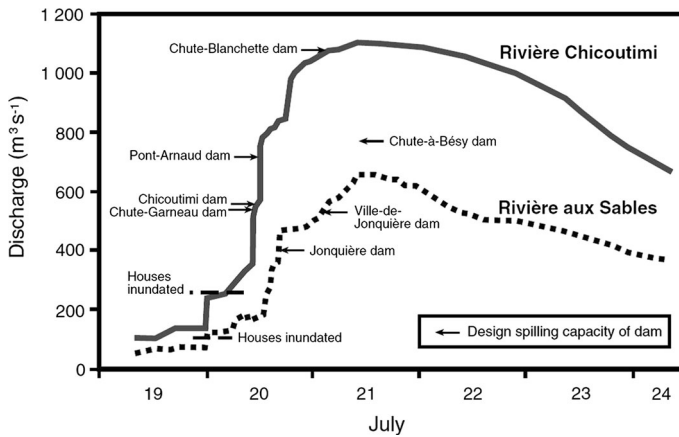


Fig. 4 Aux Sables River's storm hydrograph (July 19–24, 1996; CSTGB 1997). Note the minimum discharge beyond which houses begin to be flooded and the maximum spilling capacities of the run-of-the-river dams. (Modified after Brooks and Lawrence 2000)

Table 1 Aux Sables River 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 ^a (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

^aSpilling capacity at maximum reservoir working level

2.4 Flood mitigation

2.4.1 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 floods resulting from extreme conditions in Lake Kenogami, and the Chicoutimi and Aux Sables Rivers (Ministère des Ressources Naturelles et Hydro-Quebec 2002a, b, c, d, e; Hydro-Quebec 2001, 2002a, b and Groupe-Conseil GENIVAR 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, the 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 summer the water level of Lake Kenogami must be stabilized at 163.86 m \pm 0.1 m.

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

The second scenario suggested the construction of a reservoir upstream of Lake Kenogami on the Pikauba River, the consolidation and modernization of existing Lake Kenogami structures, 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 Aux Ecorces Rivers, the consolidation and modernization of existing Lake Kenogami structures, and the implementation of an improved flood forecasting system.

2.4.2 Digging a sill in the Aux Sables River

In this paper only the flood mitigation option directly related to the 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):

Digging 600 m along the Aux Sables River;

1. Digging several kilometers along the Chicoutimi River;
2. Building an outlet toward Lake Saint-Jean along several kilometers via the Belle-Rivière;
3. Building a canal in the Jean-Dechêne stream that flows for several kilometers before reaching the Saguenay;
4. 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-Quebec

2002a, b, c, d, e). In 2009, GENIVAR (2009) proposed a new concept by eliminating the Pibrac Bridge pillar (Fig. 5), which acts as an obstruction to flowing water at high discharges.

The proposed concept (Fig. 6) consists of

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

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

3 Suspended sediment impact assessment

3.1 Site description

The study area (Fig. 7) is approximately 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 sediment mixing (Fig. 8). The tributaries to this river reach do not contribute significantly to the river discharge except tributary C at km 5.4, 500 m from the water intake station. As can be seen in Fig. 9, the color difference between the water of this tributary and the river water suggests that it provides substantial suspended sediment.



Fig. 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



Fig. 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)

3.2 Problem presentation

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

The suspended sediment concentration at the Jonquiere water intake should be less than 19.29 mg/l to ensure drinkable water. To minimize suspended transport downstream from the Pibrac Bridge, cofferdams were installed just after the bridge (Fig. 5). The question is the following: for a given constant discharge controlled by the Pibrac dam at 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, riverbed composition, and geometric cross sections describing the river. All these data were secured by GENIVAR thanks to the field campaigns carried out on the site.

3.3.1 Turbidity

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

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





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



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

3.3.2 Boundary conditions

The upstream condition is located just after the Pibrac Bridge, at km 10.3, where the discharge will be specified. The river discharge is controlled by the Pibrac dam, at km 11.1. During the work period, the released discharge from Lake Kenogami is quasi-permanent,

varying between 5 and 50 m³/s. For the downstream boundary condition, at the Jonquiere dam and km 3 (Fig. 2), the water level is maintained constant by the dam at 140.2 m.

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

3.3.3 River bed composition

The armored riverbed is made of large pebbles with the exception of the rapids, where water flows over bedrock. There is no bed load sediment transport. During riverbed excavation cohesive sediments beneath the armored layer are released and transported downstream.

3.3.4 Cross sections

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

3.3.5 Water height

GENIVAR provided the water height corresponding to the following discharges: 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 m³/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, presented in a companion paper, is used. For unsteady sediment transport, UMHYSER-1D solves the convection–diffusion equation with source terms from sediment erosion/deposition:

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

where: C = depth averaged concentration; A = cross section area, Q = flow rate, D = longitudinal diffusion coefficient, a calibration parameter, and Σ = source (erosion, excavation, lateral inflow), and sink (deposition) terms for one sediment class.

4 Results and discussion

Numerical modeling of the Aux Sables River should answer the following question: under which hydraulic conditions (flows) would the concentration of sediments released at the Pibrac Bridge be lower than 19.29 mg/l at the Jonquiere filtration station (water intake)?

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

- Permanent flow modeling without sediment transport: this step is necessary for determining the Manning coefficients,
- Modeling of suspended transport (released sediments): first, calibrate the model to determine the right diffusion coefficient. Then, validate the model.

- Using the model to assess suspended sediment transport and answer the previous question.

4.1 Calibration and validation

4.1.1 Liquid phase

Knowing the flow discharge and corresponding water height, simulations are carried out for a steady flow at different discharge rates, and the results are compared to the water height measurements. For each of the available discharge rates (5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 m³/s), the maximum difference between observed and simulated water height 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

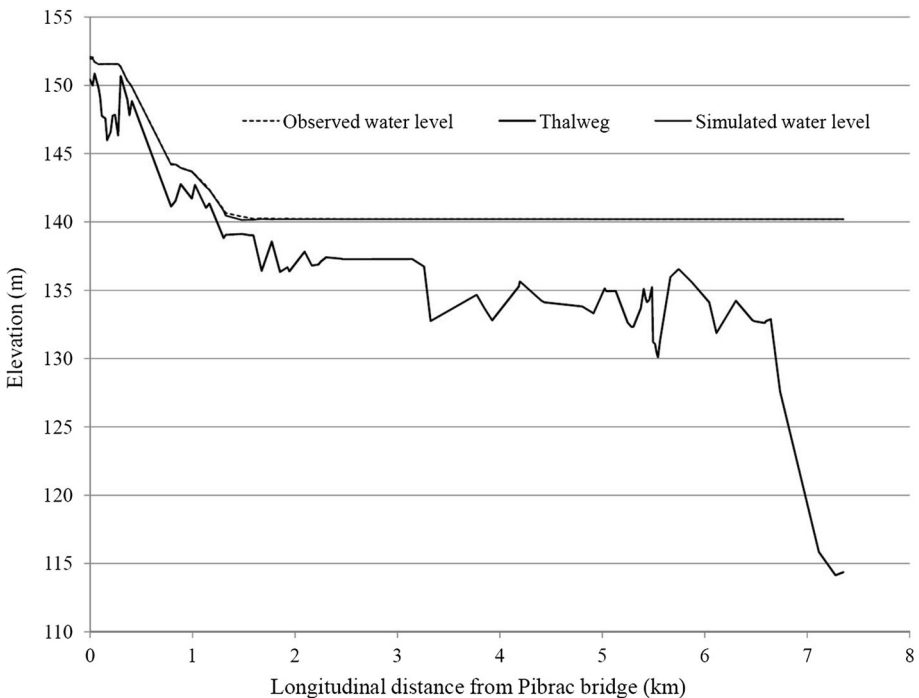


Fig. 10 Example of calibration results for a discharge of 30 m³/s

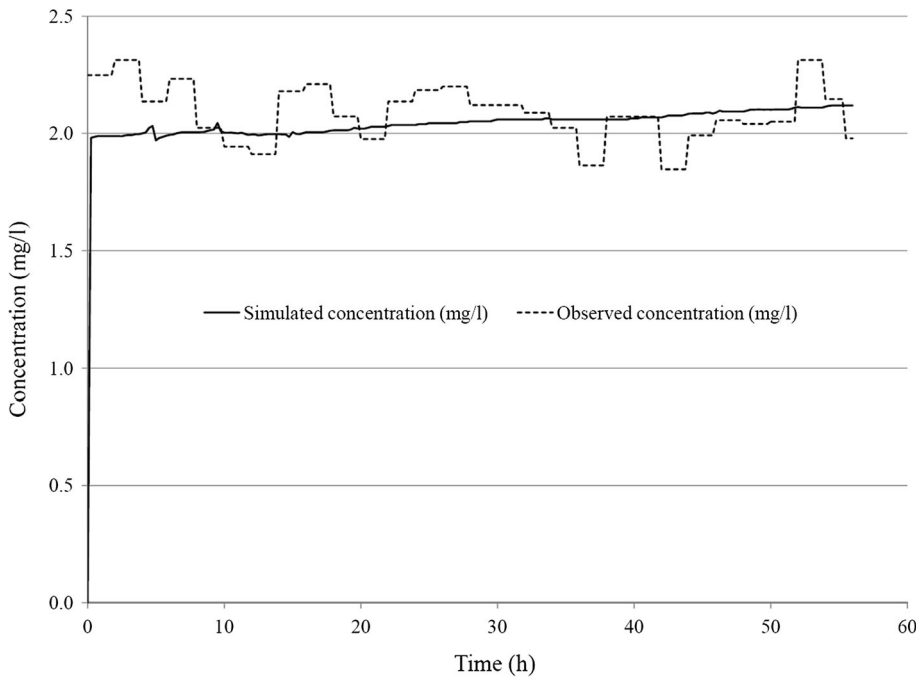


Fig. 11 Calibration of the diffusion coefficient for a liquid discharge varying between 24.7 and 26.4 m³/s during the period March 13–16, 2009

4.1.2 Solid phase

From March 13 to 16, 2009, no rain was observed, thus the sediment input from the tributary at km 5.4 is assumed nil. The river discharge is almost constant, varying between 24.7 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 (Fischer 1975):

$$D = 0.011 \frac{U^2 W^2}{HU^*} \tag{2}$$

where W = channel width, U = cross-sectional average velocity, H = water depth, and U* = shear velocity.

The best results (Fig. 11) are obtained by changing the proportionality constant of Fischer’s equation from 0.011 to 0.0135. Note that the simulated concentration starts at 0 mg/l since the model computations start with a nil concentration. Figure 12 shows a validation example for the period of March 2–3, 2009.

4.2 Assessment of suspended sediment deposition

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

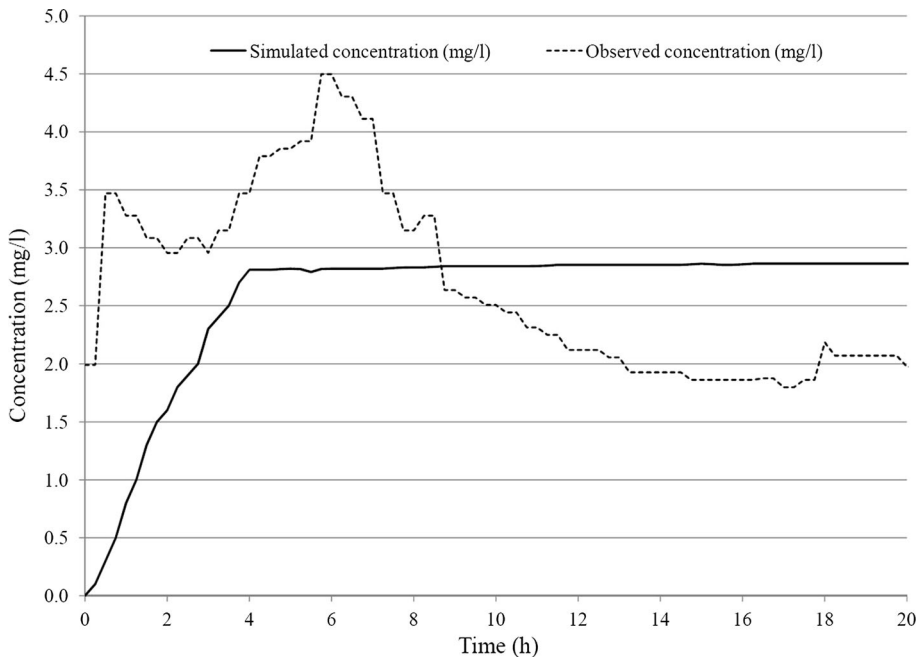


Fig. 12 Validation of the calibrated model. Observed and simulated concentration from March 2, 22:00 to March 3, 18:00

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

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 and 2.2417 tons is dumped per hour. It is therefore considered that during the work, the maximum sediment discharge released will not exceed 2.5 tons per hour.

A series of simulations are performed as follows:

- The sediment discharge is constant at 2.5 tons/h;
- Several simulations with different water discharge are performed looking for the minimum discharge giving a concentration at the Jonquiere intake of 19.29 mg/l.
- Redo step (b) with a smaller sediment discharge (2, 1.5, 1, 0.5 tons/h) looking for the corresponding minimum water discharge.

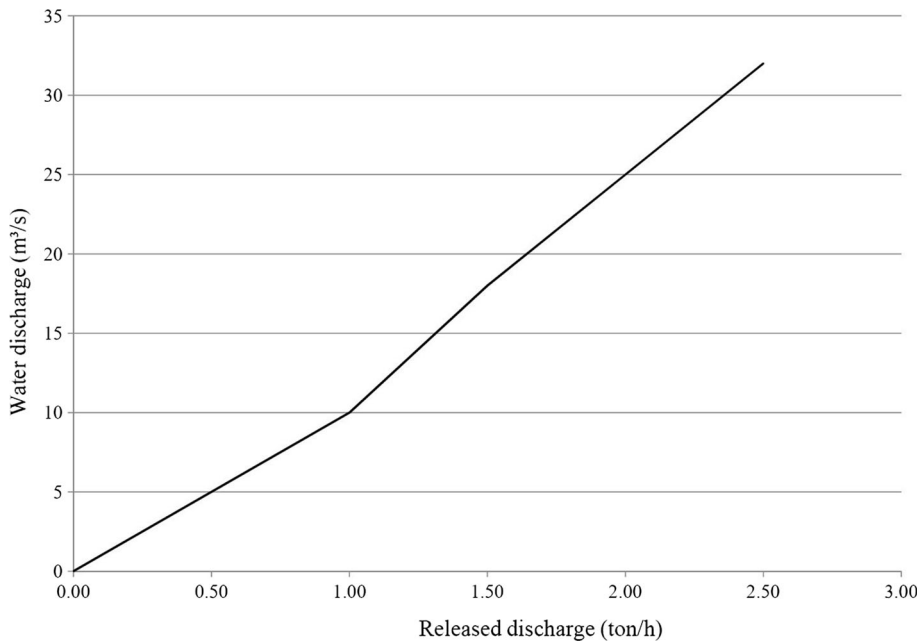


Fig. 13 Maximum sediment load released upstream corresponding to the minimum water discharge of the Aux Sables River

Table 3 and Fig. 13 summarize the results. According to the available river discharge capacity controlled by the Pibrac dam, one can choose the maximum quantity to be released into the river.

5 Conclusions

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

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

This option raised a pollution risk at the Jonquiere city water intake, located a few kilometers downstream from the work area. Thanks to a newly developed software, UMHYSER-1D, an Aux Sables River suspended sediment impact assessment provides the maximum permissible sediment discharge that will 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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