

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

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12

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

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

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31 **1 Introduction**

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

41 For Lake Kenogami, the estimated maximum inflow was 2780 m³/s,
42 exceeding the outflow and causing the reservoir to rise to
43 unprecedented levels. The water level reached a maximum level of
44 166.08 m, exceeding the crest of the concrete dams, 165.7 m
45 (Environnement et Faune Quebec, 1996a). As a result, a number of
46 dykes and all three dams (two discharging in Aux Sables River)
47 controlling the reservoir level were overtopped by Lac Kenogami
48 waters (Environnement et Faune Quebec, 1996a). The outflow spills
49 primarily into Aux Sables and Chicoutimi Rivers.

50 The four sections of this paper deal with flood mitigation and
51 environmental impact assessment in Aux Sables River. Section 2

52 presents first, the consequences of the 1996 flood on the Aux Sables
53 River, then the proposed solutions to reduce them, for a similar flood,
54 are reviewed and the retained option is explained. Section 3 deals with
55 the suspended sediment impact assessment of suspended sediment in
56 Aux Sables River during the implementation of the retained solution.
57 The results and discussion are presented in section 4, followed by a
58 conclusion.

59

60 **2 Aux Sables River flood mitigation**

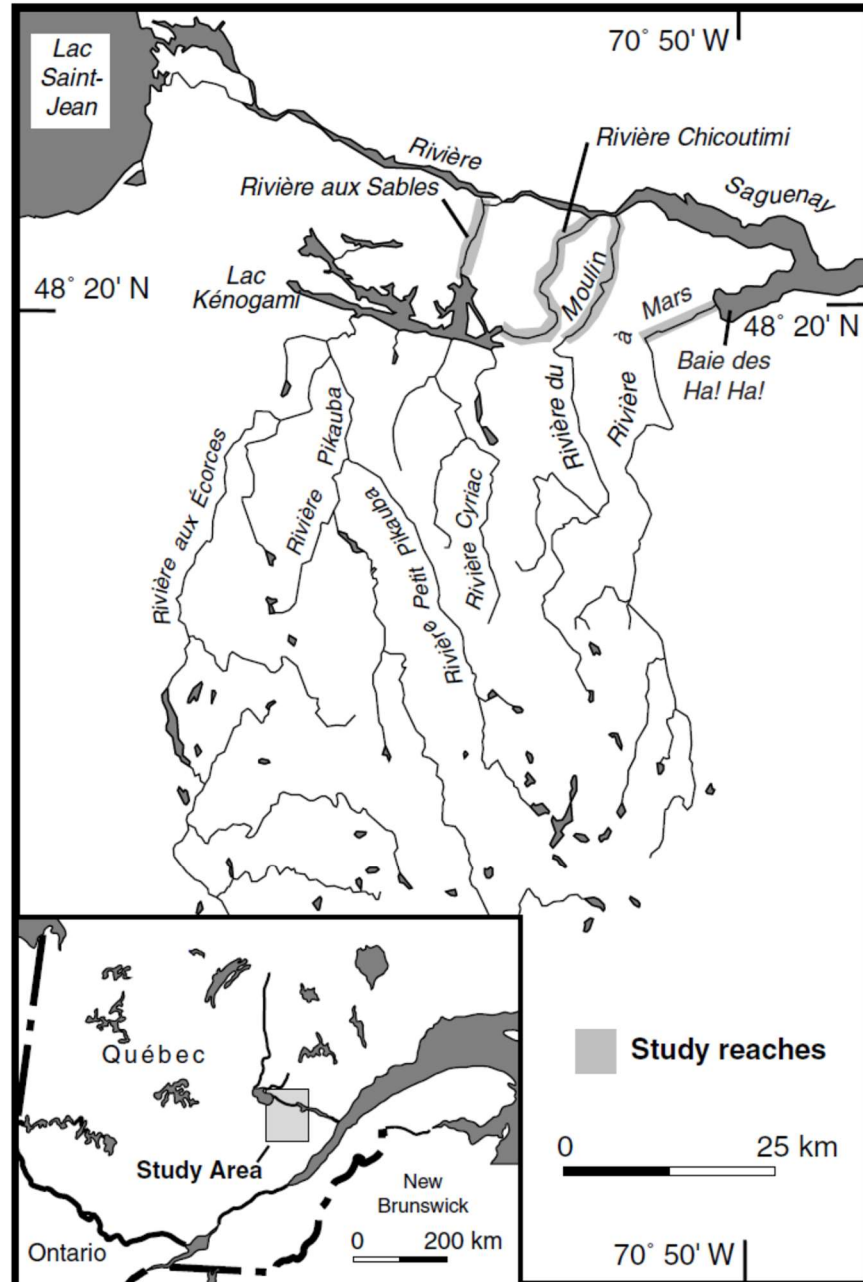
61 **2.1 Study reach**

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

68

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

72



73
 74 Figure 1. Location map depicting Lake Kenogami, Chicoutimi and
 75 Aux Sables Rivers (Brooks and Lawrence, 2000).

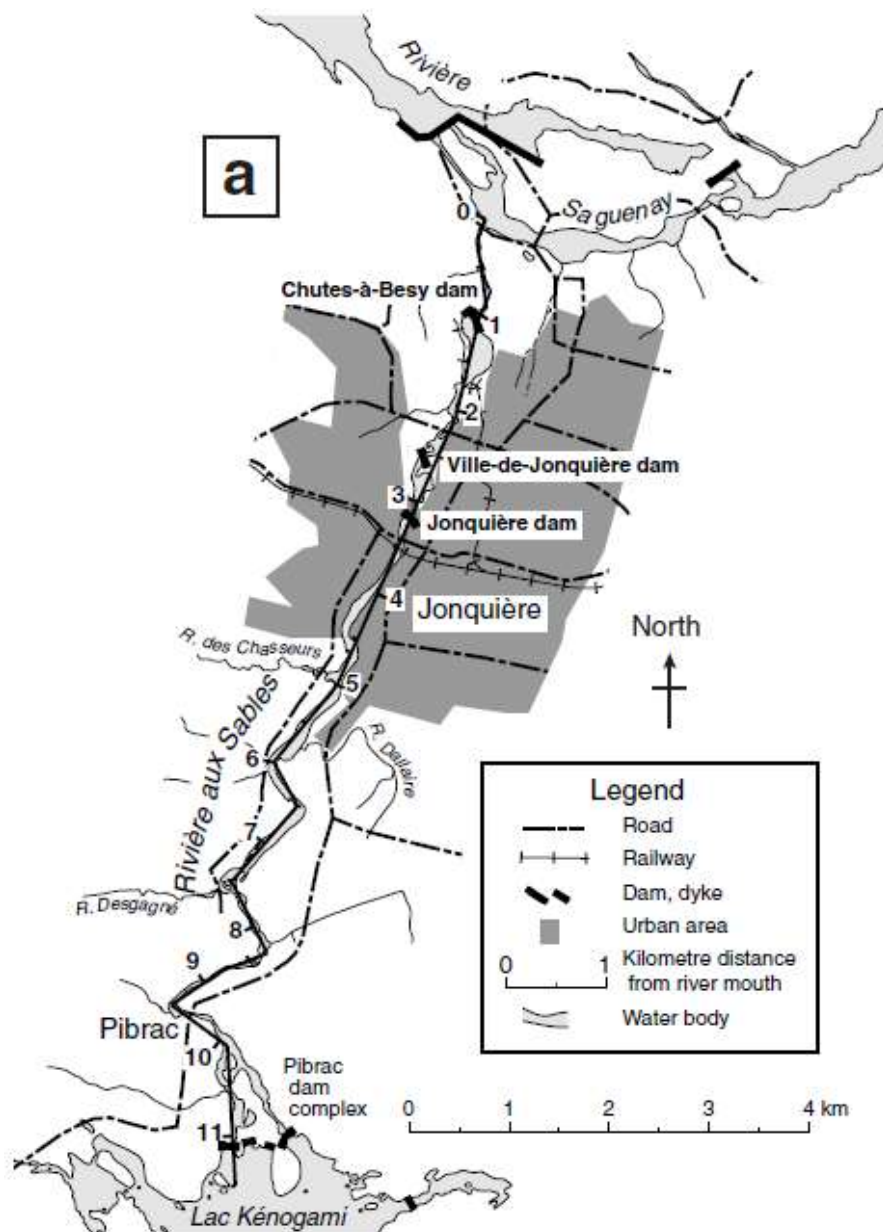


FIGURE 2. Aux Sables River: Pre-flood maps depicting the study reach along with the location of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

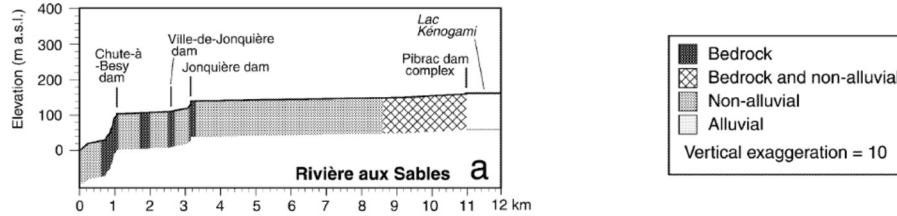


FIGURE 3. Longitudinal profiles and channel morphologies along the Aux Sables River (Modified after Brooks and Lawrence, 2000).

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).

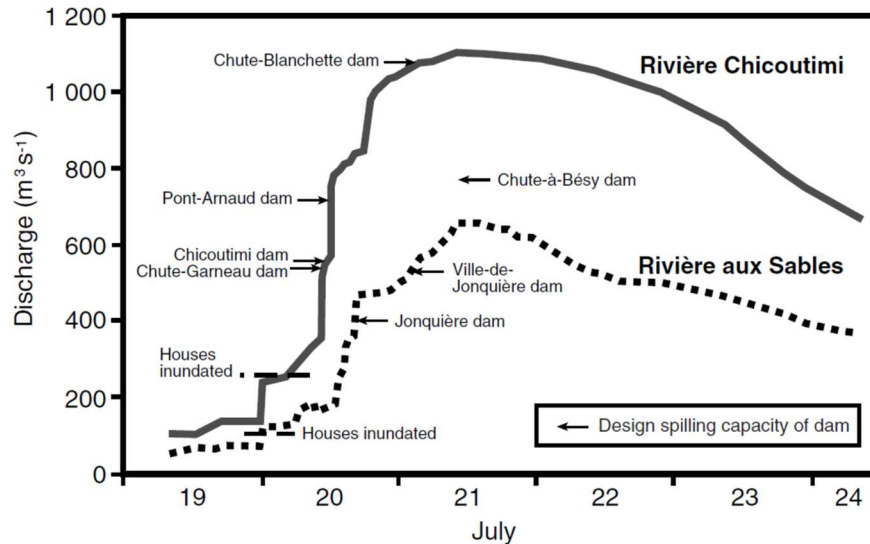


FIGURE 4. Aux Sables River's storm hydrograph (July 19-24, 1996; CSTGB, 1997). Note the minimum discharge beyond which houses begin to be flooded and the maximum spilling capacities of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

98 **2.3 Consequences**

99 Along Aux Sables River, when the discharge reaches 150 m³/s, the
100 inundation of property occurs and when 170 m³/s are exceeded,
101 flooding of homes begin (Environnement et Faune Quebec, 1996a).
102 During the July 1996 flooding, not only was the peak flow discharge
103 653 m³/s (CSTGB, 1997), overtaking these critical discharges, but
104 also flood discharges exceeded the available spilling capacity at
105 Jonquière dam and Ville-de-Jonquière dam, two run-of-the-river dams
106 (figure 4). Table 1 summarizes the spilling capacities and the eventual
107 consequences of the 3 dams. Between km 8.6 to 8.4, up to 20 m of
108 lateral bank erosion occurred along the left bank, while a series of
109 sand and gravel mid-channel, side, and point bars were aggraded
110 between 8.3 and 7.2 km, and between km 0.6 and the river mouth (0
111 km), the channel was widened from 20-30 m to 60-130 m. Between
112 km 11 and 3.5, the gently-sloped upper portion of the river, along
113 which numerous homes were inundated (Brooks et al., 1997).

114

115

116

117

118 Table 1. Aux Sables River's run-of-the-river dams and impacts from
 119 flooding (modified after CSTGB, 1997 and Brooks and Lawrence,
 120 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

133 **Mitigation options**

134 The flooding events along the Aux Sables River, among other rivers,
135 were analyzed by the ``Commission scientifique et technique sur la
136 gestion des barrages`` (CSTGB, 1997). Afterward, Hydro-Quebec,
137 Ministère de l'Environnement and a consortium of consultants
138 assessed various options to mitigate flood, resulting from extreme
139 conditions, in Lake Kenogami, Chicoutimi and Aux Sables Rivers
140 (Ministère des Ressources Naturelles et Hydro-Québec, 2002a, 2002b,
141 2002c, 2002d, 2002e; Hydro-Québec, 2001, 2002a, 2002b and
142 Groupe-Conseil GÉNIVAR, 2002).

143 The options were analyzed according to the following criteria:

- 144 1. A flood comparable to the one of July 1996 should not exceed
145 the major flood levels on the Chicoutimi and Aux Sables
146 Rivers, corresponding to the discharge beyond which a home
147 begins to be flooded;
- 148 2. For a maximum probable flood, water level of Lake Kenogami
149 must be less than 166.67 m;
- 150 3. All existing, or new, structures must conform to the Dam
151 Safety Act ;
- 152 4. During the summer, the water level of Lake Kenogami must be
153 stabilized at $163.86 \text{ m} \pm 0.1 \text{ m}$.

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

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

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

167

168 **Digging a sill in Aux Sables River**

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

173 5. Digging 600 m along the Aux Sables River;

174 6. Digging several kilometers along the Chicoutimi River;

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

180

181 After several studies, the retained option was digging a single sill in
182 the Aux Sables River to ensure the protection of homes that are
183 susceptible to flooding on either side of the river upstream of Pibrac
184 Bridge (Ministère des Ressources Naturelles et Hydro-Québec, 2002a,
185 2002b, 2002c, 2002d, 2002e). In 2009, GENIVAR (2009) proposed a
186 new concept by eliminating the Pibrac Bridge's pillar (figure 5) which
187 acts as an obstruction to the flowing water at high discharges.



188

189 Figure 5. Pibrac Bridge: for high discharges, the pillar is an
190 obstruction to the flow, increasing the water level upstream. Note the
191 cofferdam installed to limit suspended sediment release.
192
193 The proposed concept (figure 6) consists of:

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

203 According to the above, Aux Sables River will be able to carry a
204 discharge of 650 m³/s without flooding the riparian houses.





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)

239 **3.2 Problematic**

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

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

253

254 **3.3 Available data**

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

260

261 **Turbidity**

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

268

269 **Boundary condition**

270 The upstream condition is located just after the Pibrac Bridge, km
271 10.3, where the discharge will be specified. The discharge in the river is
272 controlled by the Pibrac dam, km 11.1. During the work period, the
273 released discharge from Lake Kenogami is quasi-permanent, varying
274 between 5 m³/s and 50 m³/s. For the downstream boundary condition,
275 at the Jonquiere dam, km 3 (figure 2), the water level is maintained
276 constant by the dam at 140.2 m.

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

280

281

282

283 **Riverbed composition**

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

289

290 **Cross-sections**

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

294

295 **Water lines**

296 GENIVAR provided the water lines corresponding to the following
297 discharges: 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 m³/s.

298

299 **3.4 Numerical model**

300 **UMHYSER-1D**

301 For a constant water discharge, released from Lake Kenogami, the
302 convection-diffusion equation is solved to determine the concentration

303 of suspended sediments at the Jonquiere water intake. To this end, the
 304 software UMHYSER-1D (AlQasimi and Mahdi, 2018), presented in a
 305 companion paper, is used. For unsteady sediment transport,
 306 UMHYSER-1D solves the convection-diffusion equation with source
 307 term from sediment erosion/deposition:

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

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

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

318

319 **4 Results and discussion**

320 Numerical modeling of the Aux Sables River should answer the
 321 following question: under which hydraulic conditions (flows) the
 322 concentration of the sediments, released at Pibrac bridge, would be

323 lower than 19 mg/l at the filtration station (water intake) of the city of
324 Jonquiere?

325

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

328 - Permanent flow modeling without sediment transport: this step is
329 necessary for the determination of the Manning coefficients,

330 - Modeling of suspended transport (released sediments): first, calibrate
331 the model to determine the right diffusion coefficient. Then, the
332 validation of the model is undertaken.

333 - Use of the model to assess suspended sediment transport and answer
334 the previous question.

335

336 **4.1 Calibration and validation**

337 **Liquid phase**

338 Knowing the flow discharges and the corresponding water lines,
339 simulations are carried out for a steady flow at different discharges
340 and the results are compared to measurements of water lines. For each
341 of the available discharges (5, 10, 15, 20, 25, 30, 35, 40, 45 and 50
342 m³/s), the maximum difference between observed and simulated water
343 lines does not exceed 3 cm for the Manning's coefficients listed in

344 table 2. Figure 10 shows an example of the calibration for a discharge
345 of 30 m³/s.

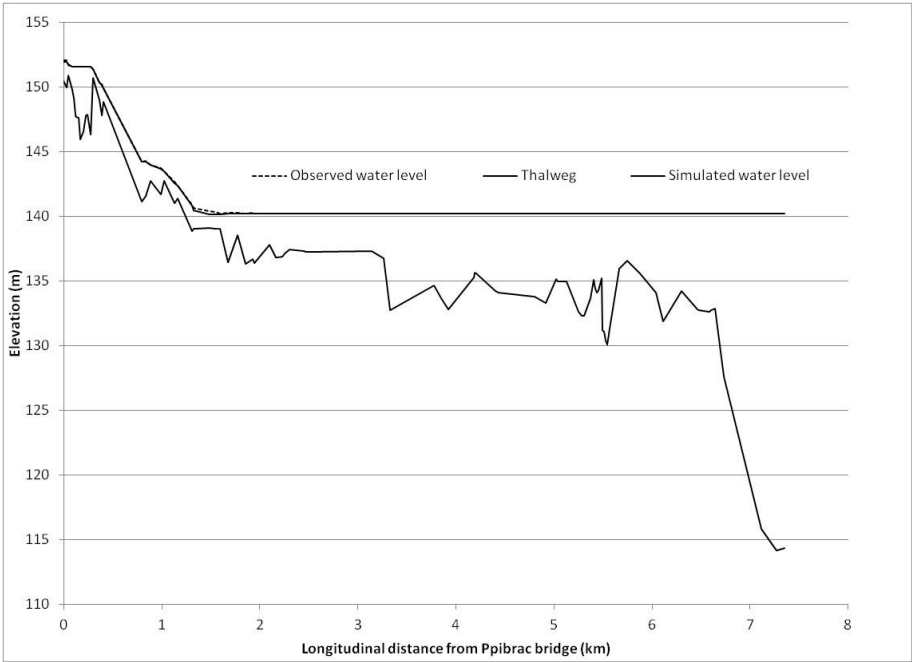
346

347 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

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350

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

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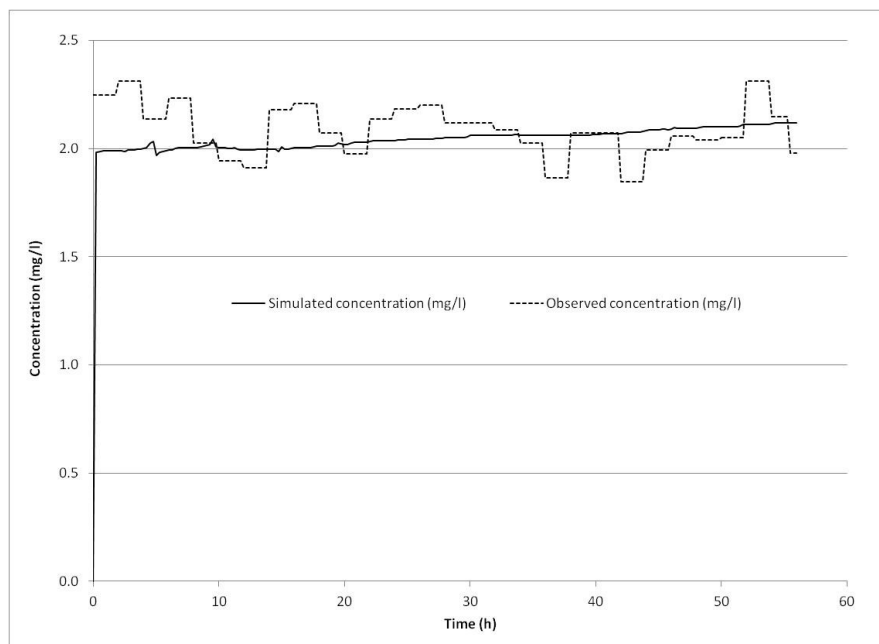
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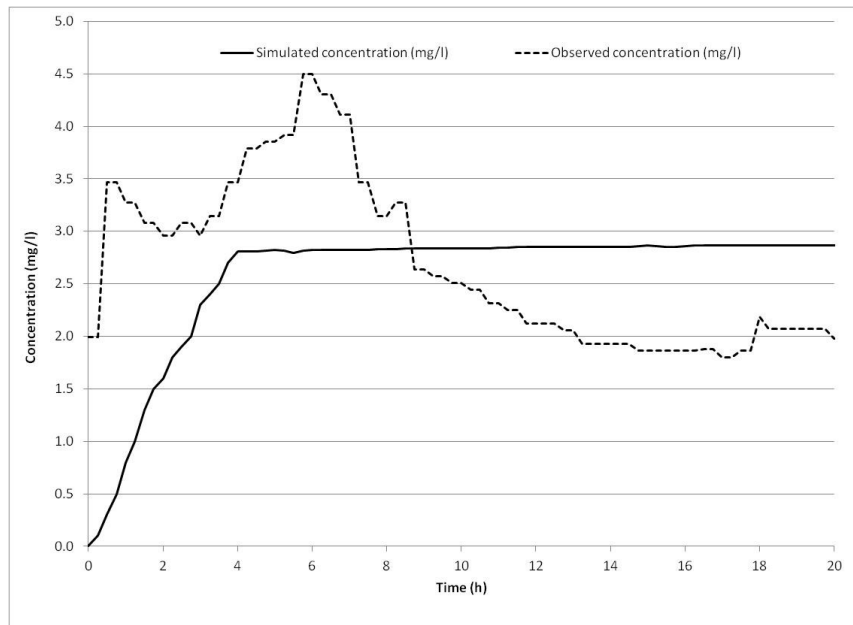
Solid phase

358 From March 13-16, 2009, no rain was observed, thus the sediments
359 input from the tributary at km 5.4 is assumed nil. The river discharge
360 is almost constant, varying between 24.7 m³/s and 26.4 m³/s, and the
361 observed turbidity, at km 6.15, varies between 1.43 and 1.95 NTU.
362 The calibration is achieved by varying the diffusion coefficient given
363 by Fischer's equation (Fisher, 1975). The best results (Figure 11) are
364 obtained by changing the proportionality constant of Fisher's equation
365 from 0.011 to 0.0135. Note that the simulated concentration starts at 0
366 mg/l since the model's computations start with a nil concentration.
367 Figure 12 shows a validation example for the period March 2-3, 2009.
368



369

370 Figure 11. Calibration of the diffusion coefficient for a liquid
 371 discharge varying between 24.7 m³/s and 26.4 m³/s during the period
 372 March 13-16, 2009.
 373



374
 375 Figure 12. Validation of the calibrated model. Observed and simulated
 376 concentration from March 2, 22:00 to March 3, 18:00.
 377

378 4.2 Suspended sediment assessment

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

383 According to the available means on the site, the maximum possible
 384 quantity of suspended sediment to be released at the Pibrac bridge is
 385 53.80 tons per day. If we report this over an hour of work, that's

386 2.2419 tons dumped. It is therefore considered that during the works,
387 the maximum sediment discharge released does not exceed 2.5 tons
388 per hour.

389 A series of simulations are performed as follow:

- 390 a- The sediment discharge is constant equal to 2.5 tons/h;
391 b- Several simulation are performed, each with a different water
392 discharge, looking for the minimum water discharge giving a
393 concentration at the water intake, at Jonquiere, of 19.29 mg/l.
394 c- Redo step b) with a smaller sediment discharge (2, 1.5, 1, 0.5
395 tons/h) looking for the corresponding minimum water discharge

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

399
400 Table 3. Maximum tolerable released sediment load into the Aux
401 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

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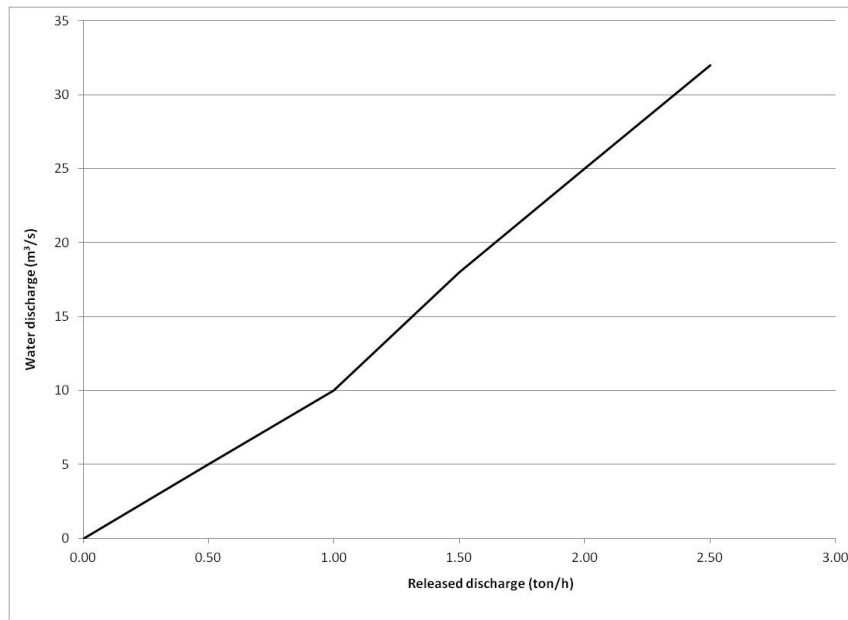


Figure 13. Maximum sediment load released upstream corresponding to the minimum water discharge of the Aux Sables River.

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

419 excavating the left bank for a length of about 60 m; increasing the
420 flow section to the right of the bridge by excavating the river bed of
421 about 2 m and excavating on the left bank; replacing the Pibrac Bridge
422 with a span of 50 m (without central pillar) and increasing the flow
423 section upstream of the bridge by excavating a channel of 440 m
424 length, with a maximum width of 60 m, and requiring an excavation
425 of the river bed varying from 0.5 to 2 m.

426 This option raised pollution risk at the water intake at Jonquiere city,
427 located a few kilometers downstream the work area. Thanks to a
428 newly developed software, UMHYSER-1D, suspended sediment
429 impact assessment in Aux Sables River provides the maximum
430 permissible sediment discharge to be released in the river to avoid any
431 pollution risk for the population of Jonquiere city. Using UMHYSER-
432 1D to mitigate water pollution risk confirms the important role of
433 numerical modeling in solving complex engineering problems.

434

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