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RESEARCH ARTICLE

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Beaver dam failures: Reconciling science, perception and policy for sustainable river management in Quebec (Canada)

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Abstract

Beavers (*Castor fiber*, *Castor canadensis*) are recognized as key ecosystem engineers, influencing river hydrology and geomorphology through dam construction. While their structures are associated with positive impacts like flood attenuation, increased biodiversity and water quality improvements, beaver dams are quickly blamed for exacerbating downstream flooding following their failure during extreme rain events. This study examines two Quebec Superior Court rulings (2008 and 2017) where beaver dam failures were considered responsible for significant property damage in the Port-au-Persil watershed, located in the Charlevoix region of Quebec, Canada. Using hydrological and hydraulic modelling (HEC-HMS and HEC-RAS), we assessed the downstream impacts of beaver dam failures during extreme rainfall events caused by Hurricane Katrina (2005) and Irene (2011). The results reveal that the failure of beaver dams had minimal impact on peak discharge and water levels downstream. For the Irene 2011 event, a 1D hydraulic model showed incremental flow increases of 11–15% and water level rises of up to 0.23 m near the area affected by the damage. A revised 2D model, incorporating a hypothetical four-fold increase in dam retention volume, demonstrated only minor changes in water levels (0.05 m), confirming that the observed flooding would have occurred even without dam failure. The 2D simulations further highlight that dam height, rather than retention volume, controls downstream flood wave propagation. These findings challenge the negative perception of beaver dams and emphasize the importance of robust scientific assessments in flood-related liability cases. The legal implications of Article 105 of Quebec's Municipal Powers Act, which holds municipalities liable for flood damage caused by "obstacles" in rivers, create a risk of widespread beaver dam removal. This study advocates for evidence-based management practices and public education to recognize the ecological benefits of beaver dams while addressing concerns over their perceived flood risks.

KEYWORDS

Beavers, court cases, dam breach, floods, hydraulic modelling

1 | INTRODUCTION

Beavers (*Castor fiber*, *Castor canadensis*) are well known to heavily influence river corridor hydrology through dam construction (Larsen, Larsen, & Lane, 2021; Stoll & Westbrook, 2020). They are important geomorphic agents affecting mainly first- and second-order streams, often described as "ecosystem engineers" (Brazier et al., 2021; Butler, 1995; Gurnell, 1998; Larsen, Larsen, & Lane, 2021; Westbrook, Cooper, & Butler, 2013; Wohl, 2021).

There is generally a scientific consensus on the positive impact of beaver dams, for example by creating and maintaining wetlands at landscape scales (Hood & Bayley, 2008; Naiman, Johnston, & Kelley, 1988), increasing biodiversity and generating beneficial heterogeneity for many species (Brazier et al., 2021; Hood & Larson, 2014; Spyra, Cieplok, & Krodkiewska, 2024). They represent an important passive restoration approach to enhance the quality of aquatic systems (Brazier et al., 2021; Pollock et al., 2023; Puttock et al., 2017; Roper, 2022), improving water quality and controlling riparian hydrology in a context of climate change (Dewey et al., 2022). Wetlands associated with beaver dams are known to be a cause of flow attenuation, particularly when they occur in a series (Gurnell, 1998; Nyssen, Pontzeele, & Billi, 2011; Puttock et al., 2017), and can therefore reduce the potential for flooding of properties downstream (Brazier et al., 2021; Ronnquist & Westbrook, 2021). Controlled experiments showed an increase in lag time of 59% (Graham et al., 2022) and reduced peak discharge of 30% (Puttock et al., 2017), although it remains challenging to predict the effect of beaver dams during extreme events (Graham et al., 2022). Some studies concluded that flow attenuation is in fact greatest during the largest events (Nyssen, Pontzeele, & Billi, 2011; Puttock et al., 2021) while others have found that the retention effects are only small or even negligible during larger events, and that their impact is only significant in areas of low channel slope (Neumayer et al., 2020; Wohl, 2021).

Extreme events are often associated with beaver dam failures, but their hydrological consequences are currently poorly understood (Brazier et al., 2021; Wohl, Scott, & Yochum, 2019). The common assumption that beaver dams fail during large floods was challenged by a study in the Canadian Rocky Mountains near Calgary (Alberta, Canada) (Westbrook, Ronnquist, & Bedard-Haughn, 2020), which also showed that water storage behind beaver dams (even failed ones) delayed flood peaks downstream. In fact, several widely cited papers attributing significant damage to beaver dam failures provide little scientific evidence to isolate the role of beaver dam failure from the damage that a flooding stream can cause to floodplain homes and infrastructure. For example, Hillman (1998) stated: "it was clear that most of the water contributing to the flood wave came from the larger, upstream pond, which was now completely empty" (p. 21) but recognized that "catastrophic beaver dam failures are usually preceded by unusually large rainfalls or result from high spring runoff" (p. 24). Overall, there is also a paucity of studies on beaver dams that used hydraulic modelling, with the exception of Neumayer et al. (2020), who used a 2D hydrodynamic model coupled with a hydrological model to investigate several beaver dam scenarios in Bavaria (Germany). However, to the best of our knowledge, no study has used hydraulic modelling to investigate beaver dam failure during an extreme rain event.

There are many cases of human-wildlife conflicts with beaver dams (Auster, Barr, & Brazier, 2021; Butler & Malanson, 2005; Parker et al., 1985; Stoll & Westbrook, 2020; Swinnen et al., 2019; Yarmey & Hood, 2020), with several private and corporate landowners considering beavers to be a "destructive pest, responsible for massive dollar amounts of timber destruction and flooding of cropland" (Butler, 1989, p. 30). The negative perception of beavers is particularly strong in Quebec (Canada), where beavers are abundant and therefore quickly blamed when a failure is observed on a stream that has caused damage to infrastructure. This negative perception is reinforced by the problem of blocked culverts linked to the construction of beaver dams. This often leads to flooding of logging roads. As will be illustrated in this paper, this negative perception also has legal implications that have a profound influence on river management practices in Quebec. Indeed, following a major flood that caused considerable damage in the Charlevoix region in August 2011, the owners of a heavily damaged inn located in Port-au-Persil (PAP) sued the Charlevoix-Est Regional County Municipality (RCM), the entity responsible for river management in the province of Quebec, holding it liable for failing to dismantle an upstream beaver dam that failed during the flood. Under Article 105 of Quebec's Municipal Powers Act (Municipal Power Act, 2005), "If informed of the presence in a watercourse of an obstacle that threatens the safety of persons or property, a regional county municipality must carry out the work required to restore normal water flow." Large wood in rivers is considered an "obstacle" under Article 105, and so are beaver dams.

The objectives of this study are 1 to illustrate the negative perception of beaver dams through two Quebec Superior Court rulings (in 2008 and 2017), both of which assumed that the failure of beaver dams was responsible for the damage suffered by the inn owners in the PAP watershed during the floods that occurred in 2005 and 2011 and 2 to discuss the legal implications of these rulings for beaver dams and river management. For the 2017 court case, the RCM's defence lawyers hired a firm of consulting engineers to carry out hydrological and hydraulic simulations in order to reconstruct the hydrograph of the August 2011 flood and to determine whether it was possible for the failure of the beaver dam to cause a flood wave destructive enough to damage the inn located more than 2 km downstream. We will present and discuss the results of these models as well as those of new numerical simulations based on different beaver pond volumes, heights and model parameters to improve our understanding of the downstream impacts of beaver dam failures, which we hope will ensure that the future management of beaver dams in Quebec (and elsewhere) is based on more robust science.

2 | METHODOLOGY AND METHODS

This section will first describe the PAP study area and then provide information on the two rain events (in 2005 and 2011) that resulted in damage to the Port-au-Persil inn. The two court cases on beaver dam failure in the PAP watershed will then be summarized, followed by information on hydrological and hydraulic modelling used to assess the downstream impact of beaver dam failures.

2.1 | Study area

The PAP watershed is located in the Charlevoix region (Quebec, Canada), 170 km north-east of Quebec City, and has a drainage area of 25.6 km^2 (Figure 1). The PAP River is a gravel-bed stream characterized by very steep slopes (up to 14%) in the downstream portion (where the inn is located) with a series of waterfalls and cascades. It has an average channel slope of 4.3% from the confluence with the Ruisseau du Canton, where a beaver dam failed in 2011, to the mouth (Figure 2a). The Ruisseau du Canton also has a steeper slope (3%) in its downstream reaches (Figure 2b), with an average slope of 1.8%.

The vast majority of the PAP watershed is used for forestry, except for a sector on either side of road 138 (identified in Figure 1c), which is used for agricultural purposes. There is a bridge at the crossing with the Chemin de Port-au-Persil (also identified on Figure 1c) that was reconstructed in December 2023 to be wider as it has overflowed on several occasions in the last few years, including during the 2005 and 2011 floods.

There are no gauging stations in the watershed, and the nearby gauging stations are for much bigger watersheds (La Malbaie, ID: 051502, area of 1707 km^2; Du Gouffre, ID: 051301, area of 865 km^2).

2.2 | Rain events of 2005 and 2011

The two major rain events of 2005 and 2011 were analysed in great depth in an expert report submitted to the Court in April 2014 (Armstrong & Gauthier, 2014) – see section 2.3– and are summarized here.

On August 30, 2005, a post-tropical depression originating from the remnants of Hurricane Katrina hit the Charlevoix region. Based on the weather station located in Saint-Siméon (ID: 7047735, Figure 1b), 174.8 mm of rain fell in 24 hours, starting at 18:00 on August 30, with flooding noted at the Chemin Port-au-Persil bridge around 18:30 on August 31. This event was well in excess of a 100-year rainfall event (140.4 mm).

On August 28–29, 2011, the tail of Hurricane Irene hit the Charlevoix region, dropping 126.4 mm of rain in 24 hours, with 123 mm falling between 16:00 on August 28 and 4:00 on August 29. This rainfall event has a return period of 50 years over a 24-hour period and over 100 years over 12- and 6-hour periods. A landslide located just upstream from the confluence between the PAP River and the Ruisseau du Canton resulted from this rain event, with massive erosion and deposition zones and the presence of large wood

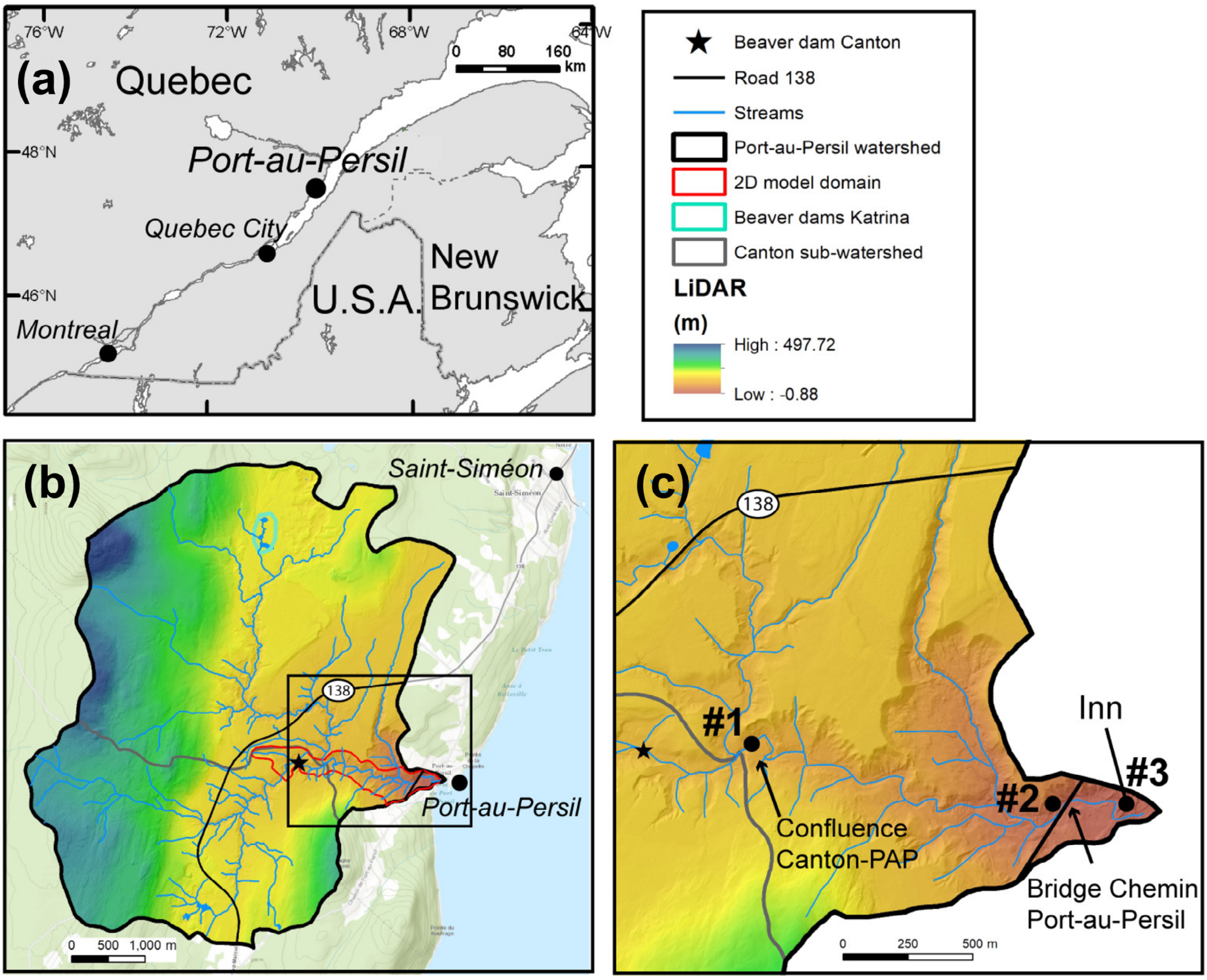

FIGURE 1 The Port-au-Persil (PAP) watershed with the beaver dams that failed in 2005 (Katrina flood) and in 2011 (Irene flood, beaver pond located on the Ruisseau du Canton) identified in b). The numbers in the downstream zones in c) correspond to the location described in the caption of Figure 3.

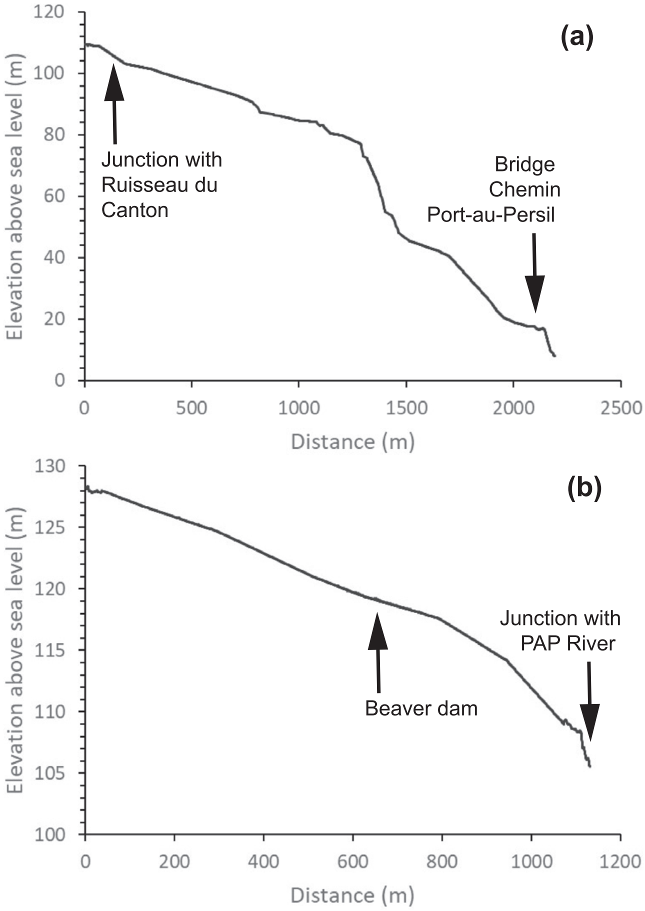

FIGURE 2 Longitudinal profile of a) the PAP River and b) the Ruisseau du Canton, where the beaver dam that failed in 2011 was located.

that was noted by one of the authors in many places in the PAP River (Figure 3). Note that it was precisely at the point where wood accumulated upstream of the bridge (Figure 3a) that the river overflowed its banks in 2011, causing damage to the inn property (Figure 3c). There was also a significant accumulation of sediments in the river in this sector, where the gradient is lower, which could have contributed to the river leaving its bed in the section immediately upstream of the Chemin de Port-au-Persil bridge.

2.3 | Court rulings on flood damage following the rain events of 2005 and 2011

Unusually, two Quebec Superior Court rulings (in 2008 and 2017) have been delivered concerning the PAP watershed for damage caused by the two rain events described above (Katrina in 2005 and Irene in 2011), both times by the same plaintiffs (inn owners) and both times invoking the RCM's liability following beaver dam failures (with different beaver dams in 2005 and 2011). The inn is located just downstream of the bridge of the Chemin Port-au-Persil (Figure 1c).

The 2008 ruling (Tremblay c. MRC Charlevoix-Est, 2008), hereafter called Ruling_2008, concerned the accumulation of wood at the Chemin du Port-au-Persil bridge that was linked to the failure of three beaver dams located 6.6 km upstream of the inn, in the northern part of the watershed (the beaver dams and the inn are identified on Figure 1b and c, respectively). The Court ordered the RMC to pay plaintiffs the amount of CA$450 K as it concluded that there was a "preponderance of the evidence establishing a causal link between the [large wood] debris accumulated on the bridge due to poor maintenance of the river and the flooding that occurred on the plaintiffs' property" (Ruling_2008, para. 100, translated from French). In court, the expert engineer hired by the plaintiffs' lawyers, hereafter called EEP, stated that: "the mandate given to [his company] was to assess the causal link between the damage suffered by the inn and the wood jam at the bridge on Chemin Port-au-Persil and the lack of maintenance of the watercourse, and more specifically the presence of beaver dams, prior to the flooding that occurred on August 31, 2005" (Ruling_2008, para. 67). The judge was clearly convinced that the wood that accumulated at the bridge came from the failure of the 3 beaver dams located more than 6 km upstream and stated that "a bridge must let water through, not trees and debris of all kinds. Had it not been for the lack of maintenance of the river, trees and debris would not have accumulated and the bridge had the capacity to receive and let through the flow resulting from the heavy rains of August 31, 2005, according to the two experts in the case" (Ruling_2008, para. 99).

The 2017 ruling (Tremblay c. MRC Charlevoix-Est, 2017), hereafter called Ruling_2017, concerned the failure of a single beaver dam located in a tributary of the PAP River called the Ruisseau du Canton (9.5 km^2 drainage area, Figure 1b,c), 2.5 km upstream of the inn during the Irene 2011 flood. The Court ordered the MRC Charlevoix-Est to pay plaintiffs the amount of CA$620 K. This ruling cites Ruling_2008 on several occasions, in particular concerning the role of beaver dam failures (even if these beaver dams were in different locations, see Figure 1b). It should be noted that the Quebec Municipal Powers Act and its Article 105 described above only came into force in 2006, so it was not taken into account in Ruling_2008 as the flood occurred in 2005, but was taken into account in Ruling_2017. The same expert engineer (EEP) was hired by the plaintiffs. As the mandate received was similar to that of the 2005 flood, EEP told the Court that "he had to check whether the same conditions had caused the flooding, whether the beavers had rebuilt a dam" (Ruling_2017, para. 110). He was informed by a resident that a beaver dam was seen in the Ruisseau du Canton so he visited it in September 2011, 2 weeks after the Irene flood. The judge states that EEP "uses the term "LUNAR ZONE" [*note*: upper-case in the Court ruling] to describe the area; there is no longer any vegetation" (Ruling_2017, para. 111). For EEP, "it is clear that something recent has happened here", that "beaver dams failed here not long ago. This is a washed-out area" (para. 111). EEP further states that: "based on his training and the literature, a beaver dam is "a time bomb". If it doesn't rain, the dam resists, but a heavy rain can wash it away" (Ruling_2017, para. 115). "Having walked around the former beaver pond to get an idea of its surface area, taking into account the approximate height of the lake (4.5 to 5 feet [1.4 to 1.5 m]), EEP estimated the volume of water in the pond at 15,000 m^3" (para. 116). "He notes that for a smaller rainfall in 2011, the damage was similar to or worse than in 2005" (para. 117). He also states that "the discharge generated by the rainfall of 28 and 29 August 2011 alone still does not explain the backflow and flooding" and therefore "another element is needed to cause the damage with the same amount of rain" (Ruling_2017, para. 119).

FIGURE 3 a) Photo taken one day after the Irene event showing accumulated wood upstream of the bridge of Chemin de Port-au-Persil (#2 in Figure 1c); b) Erosion and deposition in the PAP River immediately downstream from the confluence with the Ruisseau du Canton (#1, Figure 1c); c) Damage at the PAP inn (#3, Figure 1c) following Irene flood event (photo: https://www.lecharlevoisien.com/2020/02/04/une-riviere-sous-haute-surveillance/); d) Accumulated wood around 20 m upstream of the bridge of Chemin de Port-au-Persil (#2, Figure 1c); e) Erosion and deposition in the PAP River immediately downstream from the confluence with the Ruisseau du Canton (#1, Figure 1c).

The defence lawyers hired the expert engineer Jean Gauthier, co-author of this paper. He filed an expert report in April 2014 (Armstrong & Gauthier, 2014), which presented a detailed analysis of the impact of the beaver dam failures on the water levels at the bridge for both the 2005 and 2011 events based on a combination of hydrological and hydraulic modelling, described in section 2.4. As will be seen in the Results section, the judge raised doubts on the modelling results, including on the estimated beaver pond volume of 2,500 m^3 used to run flood wave attenuation simulations for the 2011 event.

2.4 | Numerical modelling

Since there are no gauging stations in the PAP watershed, the first step of the court case expert report (Armstrong & Gauthier, 2014) was to set up a hydrological model to estimate discharge on the PAP River during the two major rain events of 2005 and 2011, which was then used in a 1D hydraulic model. This section presents a summary of the parameters used in these two models, as well as those of a new 2D hydraulic model, based on the bathymetry data collected in 2013 by Armstrong & Gauthier (2014) and the LiDAR (Light Detection And Ranging) elevation data acquired by the province of Quebec in the fall of 2013 (i.e. after the acquisition of the field data in the expert report), which analyses in more detail the impact of the beaver dam failure on the Ruisseau du Canton as a function of a range of volumes, heights and breaching times of the beaver pond.

2.4.1 | Hydrological modelling

On April 4, 2013, a team from the engineering firm of Jean Gauthier installed piezometric probes, linked to a telemetry system, at the bridge on Chemin de Port-au-Persil, to measure water levels. They also measured discharge that day, which corresponds to the baseflow level for the hydrological model (0.515 m^3/s). On April 25, 2013, the team returned to the site after the snow had melted to measure a higher discharge (8.34 m^3/s) and to install a rain gauge near the centroid of the watershed. Another discharge measurement was made on May 26 (9.89 m^3/s), which was used to produce a rating curve at the

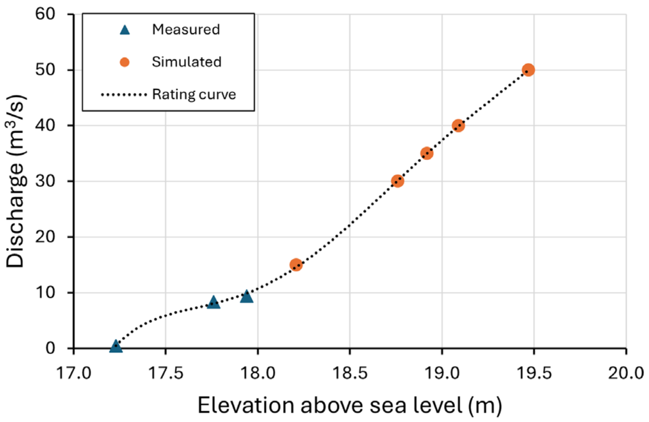

FIGURE 4 Rating curve for the PAP River at the Chemin du Port-au-Persil bridge based on measurements and hydrological model simulations of (Armstrong & Gauthier, 2014).

bridge (Figure 4). Water levels were continuously measured until July 17, 2013, which included a major rain event on June 28–29, with 103.8 mm of rain over 48 hours. The discharge estimated from the rating curve for this event was 18.9 m^3/s (maximum water level of 18.38 m).

A hydrological model (HEC-HMS, version 3.5) was calibrated using both the low-flow (April 4) and high-flow (June 28–29) events. The model HEC-HMS was based on the widely used SCS (Soil Conservation Service) Curve Number (CN) method that estimates precipitation excess/loss that takes into account land use and soil types (Zema et al., 2017). The PAP watershed was divided into 23 sub-watersheds that were characterized based on 2009 soil maps from IRDA (Institut de Recherche et de Développement en Agronomie). The hydrological classification for each soil type was obtained from the Ministry of Transportation culvert manual (Ministère des Transports du Québec [MTQ], 2004). Land use information was obtained from Natural Resources Canada (2009 data).

The first stage of hydrological calibration aimed to reproduce the volume of runoff by adjusting the effective impermeability and the fraction of rain contributing to runoff (CN). Secondly, by modifying the delay coefficient, the Manning coefficients and the baseflow and flood parameters of the sub-watersheds modelled by the SCS method, Armstrong & Gauthier (2014) adjusted the value of the maximum discharge and the peak time (synchronism with the maximum discharge measured). The calibration aimed to achieve the following degrees of accuracy: ± 20% for runoff volumes; ± 15% on maximum discharges; ± 15 min on the timing of the maximum discharges. For the June 28–29 event, the calibration results showed that the hydrological model underestimated the volumes generated at the very start of the event and during the falling limb. However, the peak flow and the timing of the event were very well simulated, with only 1.4% difference between the simulated (18.7 m^3/s) and measured discharge (18.9 m^3/s) and a 12-minute difference between the simulated and actual peak.

The model was then applied to the Irene event of August 28–29, 2011, using the rain data from the provincial weather station 7,047,735 located in Saint-Siméon (Figure 1b), 5 km from the bridge of Chemin du Port-au-Persil. This resulted in a peak discharge of 39.2 m^3/s at the bridge.

2.4.2 | Initial 1D hydraulic modelling of beaver dam failure

Between June 10 and 13, 2013, bathymetry measurements were taken by the engineering firm on 66 cross-sections in the PAP watershed over a length of 7.1 km, including the Ruisseau du Canton. This was used by Armstrong & Gauthier (2014) to develop a HEC-RAS 1D model (version 4.1), which is a widely used model for dam-break flood routing (Mo et al., 2023). The cross-sections were surveyed every 100 m or so and interpolated every 10 m to stabilize the model during unsteady simulations using SCS hydrographs obtained from the methodology described above. The bed elevation of these interpolated sections was then adjusted on the basis of the longitudinal profiles of the surveyed stream sections. The modelling was carried out in two sections. The first section began at the foot of the waterfall at the Chemin du Port-au-Persil bridge and covers a total length of 5.1 km (up to approximately 1.5 km downstream of the Katrina beaver dams identified in Figure 1c). The second begins at the mouth of the Ruisseau du Canton in the PAP River and covers a total length of 2.0 km. Manning's coefficients were assigned on the basis of field information gathered during the survey campaign and theoretical tables (Ward & Trimble, 2004). They were then adjusted through calibration, which aimed to reproduce the measured water levels of the June 28–29 event (± 0.10 m), which gave Manning's n values of 0.035 in the channel except for the downstream sections (from the bridge at Chemin du Port-au-Persil), where they were increased to 0.045.

An unsteady modelling approach (time step = 1 s) was used based on the flood hydrograph derived from hydrological simulations for each of the 23 sub-watersheds using the HEC-HMS software described above. The beaver dam that failed in the Ruisseau du Canton is located 491 m upstream of the confluence with the PAP River. The dam's maximum elevation at the centre of the stream is 2.15 m, based on field survey data collected in 2013, corresponding to the height between the crest of the beaver dam (elevation above sea level of 121.42 m) and the bottom of the stream. The volume of the reservoir was calculated below the elevation of 121.42 m, and the retention volume was estimated at 2,500 m^3 based on survey data.

An important parameter to consider in a dam failure flood is the timing. Since no information was available on the timing of the failure (start time and failure time), two scenarios for the 2011 (Irene) flood have been modelled (Figure 5a,b). In the first scenario, the dam fails at the maximum of the flood hydrograph (2:00 on August 29). This scenario makes it possible to assess the maximum impact of a failure. In the second scenario, failure occurs at 22:45 on August 28, just before the overflows observed at the Chemin de Port-au-Persil bridge at around 23:00. This second scenario makes it possible to assess the impact of a potential dam failure on simulated flow at the bridge at the time the overflows began.

The breach parameters were estimated on the basis of observations made in the field. The modelled breach has a height of 2.15 m, a base width of 4 m, side slopes of 1:1 and a weir coefficient of 1.90 to maximize breach flow (Marangoz, Anılan, & Karasu, 2024). The time taken for the breach to form was set at 10 minutes. This is a relatively short formation time, close to the instantaneous failure parameters of 6 minutes used in dam safety studies (Marche, 2008). This formation time was used because it allows the breach to form completely without lowering the reservoir level too much, generating maximum

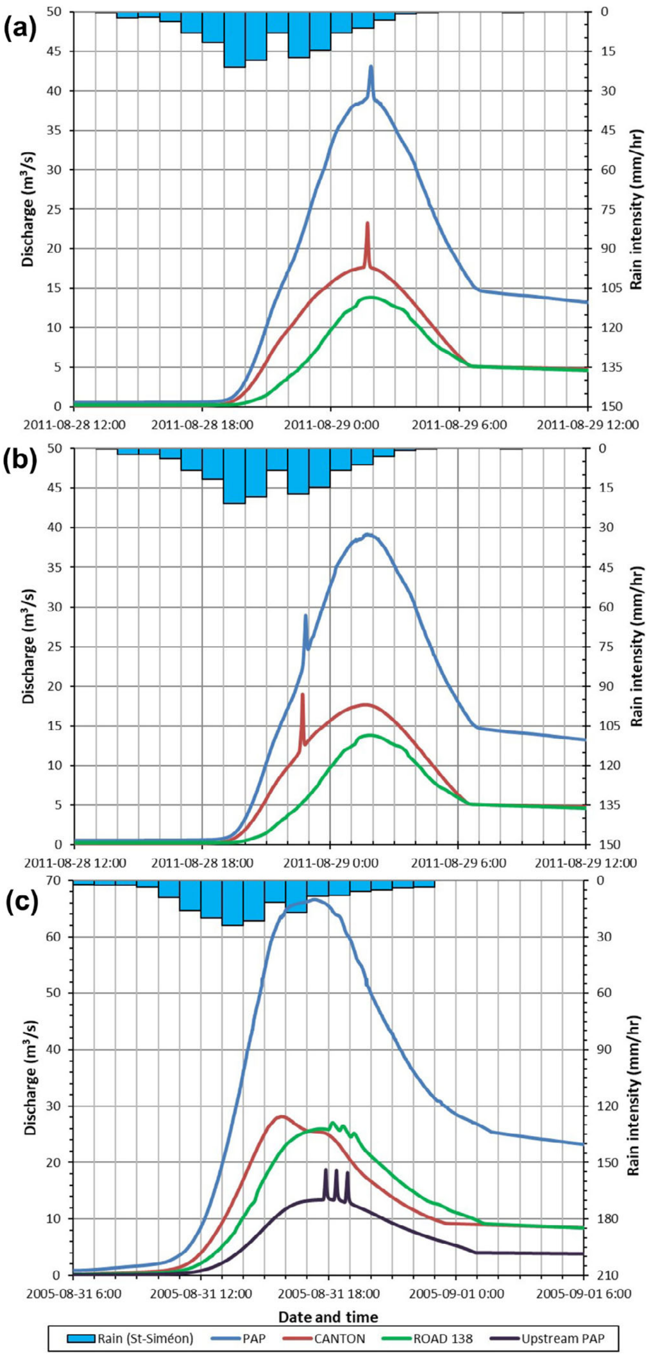

FIGURE 5 : Flood hydrographs of the Irene event for two beaver dam failure scenarios with a) failure at the peak of the flood hydrograph (at 2:00 on August 29) (scenario 1); b) failure just before the PAP river overflowed its banks in the area of the bridge on Chemin de Port-au-Persil (at 22:45 on August 28) (scenario 2); c) Flood hydrograph of the Katrina event with a cascade of 3 beaver dam failures. From Armstrong & Gauthier (2014).

breach flow. In reality, the breaching can be quite long (Nyssen, Pontzeele, & Billi, 2011), and it is very likely that failure time would be closer to (or even longer than) that for earth dams, which is 30 minutes (Marche, 2008).

The Katrina beaver dam failures were also simulated with the hydraulic model. As hourly rainfall data were not available for this event, the twice-daily data from weather station 7,047,735 (in Saint-Siméon) were adjusted on the basis of the hourly rainfall recorded at weather station 701S001 managed by Environment Canada and located in Quebec City. In order to simulate the scenario of the failure of the three beaver dams in the upstream sector of the PAP River (see Figure 1c), a synthetic failure hydrograph was generated using HEC-HMS software for reservoirs of around 2,500 m^3 each, as field observations showed that the beaver dams in the upstream part of the PAP River were of the same order of magnitude or smaller than the one observed on the Ruisseau du Canton. The same breach formation hypotheses were used. This hydrograph representing the breach flow of a beaver dam was added to the flood flow of the river at three (3) different locations at 30-minute intervals, representing a cascading failure of three successive dams (Figure 5c).

2.4.3 | New 2D hydraulic modelling of the beaver dam failure

We revisited the initial model to run a HEC-RAS 2D (version 6.6) unsteady flow model (time step of 0.25 s) for the Irene event of August 28–29, 2011. The full momentum equations (Shallow Water Equations, Eulerian–Lagrangian Method) were applied, but no turbulence model was incorporated, as the main purpose of the 2D model was to compare different scenarios rather than to obtain highly accurate water surface elevations (WSE) across the study area. Furthermore, as the digital elevation model (DEM) was derived from the interpolated surveyed cross-sections from the 1D model, it did not accurately represent the real bathymetry everywhere in the 2D domain. Thus, adding the turbulence model using a DEM that does not represent the bed well at all points was not considered relevant in this study. The same beaver dam geometry as for the 1D simulations was used, without taking into account the leaky nature of beaver dams as in [Neumayer et al., 2020] who used culverts in their 2D model to include permeability, in order to maximize the potential damage caused downstream by the failure. This model used the 1-m LiDAR DEM acquired by the Quebec Government in the fall of 2013 to obtain more accurate data in the floodplain, with a mesh size of 8 m. The 2D model started upstream from the confluence with the Ruisseau du Canton, which was also included (see 2D domain limits in Figure 1c). The cross-sections of the 1D model were used to interpolate the bathymetry on a 2-m mesh in the channel bed. The same Manning's n values (0.035) as for the 1D model were used in the channel.

As with the initial model, we ran simulations for this event firstly without any beaver dam failure, and then with the worst-case failure scenario, at the peak of the flood hydrograph (scenario 1, Figure 5a), for the same breach parameters described above (including a failure time of 10 minutes).

To assess the hydraulic impact of the volume of the reservoir created by the beaver dam, we also ran a simulation with a much larger retention volume of 10,000 m^3. This required to "dig" (numerically) the DEM upstream of the dam to accommodate this large volume, as in reality only a volume of around 2,100 m^3 could be retained with the existing topography.

Since it is well known that dam height is a key controlling factor for flood wave propagation (Marche, 2008), we also ran a simulation that added 1 m to the dam height (so 3.15 m instead of 2.15 m). This is an arbitrary value that was chosen to represent a significant increase in the height of the dam. Most beaver dams are less than

1.5 m in height (Hafen et al., 2020; Majerova, Neilson, & Roper, 2020; Neumayer et al., 2020), so this value is considered close to a maximum height that could be found in nature, which is around 5 m (Neumayer et al., 2020). The corresponding retention volume of 8,500 m^3 with the existing topography was used for these simulations. Additionally, we investigated the impact of the time taken for the breach to form by testing both the original time (10 minutes) and a longer time (30 minutes), which corresponds to the failure time of earth dams (Marche, 2008).

3 | RESULTS

The results will first present the main findings from the beaver dam simulations related to both floods (Irene in 2011 and Katrina in 2005), followed by a description of how the scientific evidence was interpreted by the judge, and the legal implications of this court case.

3.1 | Beaver dam simulations

3.1.1 | Irene event (2011) initial report

The 1D model of (Armstrong & Gauthier, 2014) showed that the beaver dam failure on the Ruisseau du Canton during the Irene event triggered a flood wave that spread as far as the mouth of the PAP River.

For scenario 1 (Figure 5a), the discharge calculated immediately downstream of the beaver dam on the Ruisseau du Canton was 23.5 m^3/s, approximately 9 minutes after the start of the breach formation (Table 1). This discharge is 6.3 m^3/s higher than the maximum discharge calculated at the same point without a break, i.e. 17.2 m^3/s, and thus corresponds to the additional discharge resulting from the breaching of the beaver dam. This results in an increase in the water level of around 0.16 m in this reach (Table 1). The average increase in flow velocity was around 0.60 m/s in the centre of the channel, 0.16 m/s near the right bank and 0.19 m/s near the left bank.

At the mouth of the Ruisseau du Canton, located 491 m downstream of the beaver dam, the discharge calculated following the breach was 23.4 m^3/s, around 11 minutes after the breach began (Table 1). An estimated time lag of 3 minutes between the arrival times of the wave front at the dam and at the mouth of Ruisseau du Canton allowed Armstrong & Gauthier (2014) to estimate the propagation speed of this front at 2.73 m/s. The beaver dam break discharge at this section is 5.7 m^3/s, which represents a 9.5% reduction compared to the discharge increase of 6.3 m^3/s immediately downstream of the dam, indicating that there was very little flood wave attenuation between the beaver dam and the mouth of the Ruisseau du Canton, where the increase in water level was around 0.15 m following the dam failure (Table 1).

The additional discharge from the Ruisseau du Canton was taken over by the PAP River and conveyed to its mouth along with the rest of the discharge generated by the entire watershed area. In scenario 1, the maximum discharge calculated downstream of the junction of the Ruisseau du Canton and the PAP River is 40.8 m^3/s, approximately 12 minutes after the breach began to form (Table 1). This is 5.5 m^3/s higher than the maximum discharge modelled without a break, i.e. 35.3 m^3/s, resulting in an increase in water level of 0.09 m. The corresponding increase in flow velocity is less than for the Ruisseau du Canton, in the order of 0.16 m/s in the centre of the channel and 0.07 m/s along the banks. The flood wave travel time between the beaver dam and the mouth of the PAP River was very rapid, around 21 minutes (Table 1), due to the steep gradient of the river between these two points (Figure 2), with an estimated propagation speed of 3.31 m/s. This travel time is faster than in the Ruisseau du Canton due to the steeper slope.

For scenario 2 (Figure 5b), the maximum discharge calculated downstream of the dam on the Ruisseau du Canton was 19.6 m^3/s, 9 minutes after the breach began to form (Table 2). This discharge is 7.9 m^3/s higher than the maximum discharge observed without a failure, i.e. 11.7 m^3/s, and the water level increased by 0.25 m after the breach. This increase in discharge corresponds to an average increase in flow velocities of around 0.71 m/s for the centre of the channel, 0.17 m/s for the right bank and 0.22 m/s for the left bank. These relative increases are greater than those observed for scenario 1, given the lower initial discharge before the dam failure in the Ruisseau du Canton.

For scenario 2, the discharge calculated following the beaver dam failure immediately downstream of the junction with the Ruisseau du Canton was 26.2 m^3/s, 12 minutes after the start of the breach (Table 2). This is 5.9 m^3/s higher than the maximum discharge observed in the model without a breach, i.e. 20.3 m^3/s, and corresponds to a water level increase of 0.12 m. The average increase in estimated velocities is on the order of 0.20 m/s in the centre of the channel and virtually zero along the banks.

The modelling results illustrate how the flood wave is attenuated during its journey and represent an incremental flow varying between 4.3 and 6.0 m^3/s at the Chemin de Port-au-Persil bridge, depending on the scenario, which corresponds respectively to 11% and 15% of the peak discharge with no failure (Tables 1, 2). The increase in discharge caused by the dam failure would have been observable over a

TABLE 1 Difference in discharge, water level for scenario 1 immediately downstream of the beaver dam on the Ruisseau du Canton, at the mouth of the Ruisseau du Canton (491 m from the beaver dam), in the PAP River just downstream (135 m) from the junction with the Ruisseau du Canton and at the bridge of Chemin du Port-au-Persil (Armstrong & Gauthier, 2014).

Location	Peak discharge with no failure (m^3/s)	Peak discharge with failure (m^3/s)	Difference in discharge (m^3/s) (% of peak discharge)	Increased level due to failure (m)	Arrival time of the flood wave (min)
Immediately downstream of the beaver dam	17.2	23.5	6.3 (26.8%)	0.16	9
Mouth of the Ruisseau du Canton	17.7	23.4	5.7 (24.3%)	0.15	11
PAP after confluence with Ruisseau du Canton	35.3	40.8	5.5 (13.5%)	0.09	12
Bridge Chemin du Port-au-Persil	39.2	43.5	4.3 (9.9%)	0.23	21

TABLE 2 Difference in discharge, water level for scenario 2 immediately downstream of the beaver dam on the Ruisseau du Canton, at the mouth of the Ruisseau du Canton (491 m from the beaver dam), in the PAP River just downstream (135 m) from the junction with the Ruisseau du Canton and at the bridge of Chemin du Port-au-Persil (Armstrong & Gauthier, 2014).

Location	Peak discharge with no failure (m^3/s)	Peak discharge with failure (m^3/s)	Difference in discharge (m^3/s) (% of peak discharge)	Increased level due to failure (m)	Arrival time of the flood wave due to failure (min)
Immediately downstream of the beaver dam	11.7	19.6	7.9 (40.4%)	0.25	9
Mouth of the Ruisseau du Canton	12.1	19.3	7.2 (37.3%)	0.15	11
PAP after confluence with Ruisseau du Canton	20.3	26.2	5.9 (22.5%)	0.12	12
Bridge Chemin du Port-au-Persil	23.2	29.2	6.0 (20.5%)	0.20	20

period of ± 16 min. However, the value of the peak flow (an increase of up to 6 m^3/s for scenario 2) would only have been observable over a period of ± 6 min. The impact on the observable water level in the bridge area caused by this additional water inflow for scenario 1, was 0.23 m higher than the maximum level with no failure (Table 1) (19.32 m compared to 19.09 m). Considering that the level at which overflow would begin on the left bank at the bridge is at elevation 19.52 m (from the topographical survey), the incremental flow related to the failure of the beaver dam cannot explain the problem of overflow and flooding that occurred in August 2011.

One of the possible hypotheses raised by Armstrong & Gauthier (2014) to explain the overflow is the presence of obstructions creating a hydraulic restriction in the river in the area of the bridge. According to the information they obtained, there were no obstructions directly in line with the bridge. The water overflowed slightly upstream of the river's last bend. Analysis of the photos taken the day after the events (Figure 3a) shows the presence of large wood that may have created an obstruction to the flow in a section located slightly upstream of the bridge (around 20 m). This caused the water to overflow an old wooden bridge at this point. There was no reliable information on the nature and extent of the wood accumulation in the river. However, high-water marks were observed in the trees where the wood had accumulated. The elevation of these high-water marks shows that the water level reached a maximum elevation of around 19.75 m (0.45 m above the level of the left bank at this point). The simulations at the position where there was overflow indicate that the rise in water level attributable to a beaver dam failure is of the order of 0.15 to 0.18 m for scenarios 1 and 2, respectively, so the river would have overflowed at this point even if the beaver dam had not failed.

3.1.2 | Irene event (2011) new 2D simulations

The 2D model, ran with a retention volume 4 times larger (10,000 m^3 instead of 2,500 m^3) revealed that with scenario 1, the discharge increase near the Chemin du Port-au-Persil bridge was 1.2 m^3/s, corresponding to a difference of 3.3% compared to the maximum discharge of 36.9 m^3/s with a retention volume of 2,500 m^3 (Table 3). The impact of this marked increase in retention volume on the simulated water levels is also very slight (Figure 6), with a maximum increase of just 0.05 m near the bridge (peak of 19.37 m compared with 19.32 m). The impact of (artificially) raising the beaver dam by 1 m is much larger (grey line in Figure 6; Table 3). The maximum discharge at the bridge in this case would be 50.1 m^3/s, an increase of 36% compared to the scenario with a volume of 2,500 m^3 and a dam

TABLE 3 Impact of pond volume, height and breach time on discharge and water level at the bridge of Chemin du Port-au-Persil for scenario 1 beaver dam failure simulated with the 2D model. The original 2D simulation used a pond volume of 2,500 m^3, a dam elevation of 2.15 m and a breach time of 10 min.

2D model runs	Peak discharge (m^3/s)	Peak water level (m)
No dam failure	32.2	19.13
Original simulation with dam failure	36.9	19.32
Increased pond volume (10,000 m^3)	38.1	19.37
Raised dam elevation (3.15 m)	50.1	19.72
Raised dam elevation with longer breach time (30 min)	43.8	19.56

height of 2.15 m, with a maximum elevation near the bridge 0.35 m higher than in the scenario with a volume of 10,000 m^3 (Figure 6b). However, when this case of raising the dam was run with a longer failure time (30 minutes instead of 10 minutes), it reduced the maximum elevation by 0.16 m (19.56 m instead of 19.72 m) (Table 3). For all the scenarios, the simulated rise in water level associated with the beaver dam failure had a very short duration (15–20 minutes).

3.1.3 | Katrina event (2005)

For the Katrina flood, where the beaver dams were located much further upstream (Figure 1c), the beaver dam failure (Figure 5c) was estimated by Armstrong & Gauthier (2014) to have increased discharge by 5.3 m^3/s, corresponding to 29% of the peak discharge of 18.7 m^3/s in the upstream part of the watershed (Table 4). At the road 138 culvert, about 2 km downstream of the beaver dam failure sites, the river discharge reaches a value of around 27.1 m^3/s. The portion attributable to the failure of the beaver dams is only 1.1 m^3/s because of the peak flow attenuation in lower gradient sections of the river in this sector. At the bridge of the Chemin du Port-au-Persil, the estimated discharge was 63.7 m^3/s, with only an additional 0.1 m^3/s that resulted from the three beaver dam failures (Table 4). This had no impact on the simulated water level at the bridge, which was 20.34 m.

The modelling scenarios of Armstrong & Gauthier (2014) therefore suggest that the failure of the beaver dams during the 2005 event in the upstream part of the watershed did not contribute in any perceptible way to the overflow problems observed at the Chemin Port-au-Persil bridge. Large wood was found just upstream of that bridge, severely restricting the flow at this point. According to the

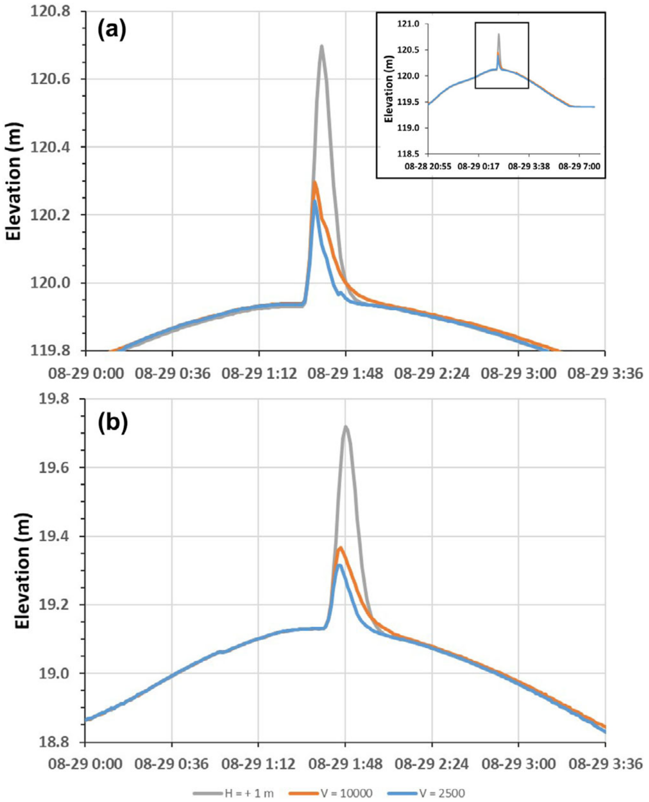

FIGURE 6 Water levels simulated with the 2D model for the August 2011 flood peak with beaver dam scenario 1 (Figure 5a) a) close to the beaver dam, immediately downstream of the junction with Ruisseau du Canton in the PAP River (with the full duration of the flood event represented in the top right inset) and B) at the Chemin du Port-au-Persil bridge. Blue line: simulation with a retention volume of 2,500 m^3; orange line: retention volume of 10,000 m^3; Grey line: hypothetical case of a beaver dam elevation increased by 1 m, with a retention volume of 8,500 m^3.

assessment of Armstrong & Gauthier (2014), the river would have overflowed at this point, even without obstruction, since the estimated water level without obstruction at the bridge was 20.34 m, and there is overflow on the left bank from an elevation of 19.52 m. The very high discharge (well in excess of the Q100 of 26 m^3/s) alone generated sufficient velocities and water levels to erode the banks and transport large wood.

3.2 | Court assessment of the scientific evidence for the 2011 flood

It is clear from the Ruling_2017 that the judge considered the testimony of EEP to be much more credible than that of the defence's expert engineer, even though EEP "stated that he himself was not qualified to use the "modelling" method, and even if he could hire someone to do this, he saw no need to do so because he had all the necessary data, information, documentation and testimony on the situation in 2011" (Ruling_2017, para. 121). EEP had estimated the volume of the beaver pond by "walking around the former beaver pond to get an idea of its surface area" whereas Armstrong & Gauthier (2014) actually surveyed the former beaver pond. Despite the rough methodology used by EEP to determine the volume of the beaver dam pond, the judge found it more credible and considered negatively the fact "The RMC expert [(Armstrong & Gauthier, 2014)] did not take into account the volumes of water at the dam put forward by the EEP expert" (Ruling_2017, para. 151). As revealed by our new 2D hydraulic model simulations, even if the (much larger) volume of water estimated by EEP had been used, the impact on the flow stage near the inn would have been very minor (Figure 6 and Table 3).

The two expert engineers (EEP and J. Gauthier) clearly had opposite views on the impact of the Ruisseau du Canton beaver dam failure. EEP stated in Court: "We can confirm that if the beaver dams on the Ruisseau du Canton had been dismantled before 28 August 2011, there would never have been any damage to the property" (para. 120), whereas J. Gauthier stated: "it can be seen that the river would have overflowed at this point even if the dam had not broken" (para. 134). EEP "testified that the modelling method could not be used in 2013 during [J. Gauthier]'s assessment because the river is no longer the same, it has been modified, and the conditions that existed on August 28 and 29, 2011 are not reflected by the modelling method" and raised doubts on models overall, i.e. "these models are designed for free-flowing rivers and do not take into account ice cover or other physical constraints (bridges, ice jams) that could significantly alter the flow. The many post-flood diagnoses, and unfortunately the randomness of disasters, call into question the effectiveness of statistical hydrology and hydrodynamic modelling, both in France and in Quebec" (para. 122). EEP also admitted "that he did not calculate the amount of water that escaped into the river when the dam burst. The damage he observed led him to conclude that it was the surge of water that amplified the flow and caused the damage" (Ruling_2017, para. 125).

Apparently, EEP was able to convince the judge that models were of little use, as the judge wrote: "the Tribunal is surprised by the opinion expressed by expert Gauthier when he speaks of a negligible incremental contribution due to the breaking of the beaver dam. The Tribunal is of the opinion that the description of the sudden arrival of an enormous volume of water by the people on the ground contradicts this statement by expert Gauthier" (para. 152). He further added: "All this description of the sudden arrival of a wave, of a mass of water causing destruction in its path, shows that there is more to it than even abundant rain. Such a volume of water arriving suddenly must have its source?" (para. 163), and "What else but the beaver dam on the Ruisseau du Canton that burst, releasing all of its water volume at once, which the preponderance of evidence establishes at between 10,000 m^3 and 15,000 m^3, with observations made in the autumn of 2010 and the spring of 2011. Mr [X, a resident witness] said that he had seen many beaver dams, but the one in question was impressive: "There really is a lot of water."" (para. 164).

3.3 | Legal implications

Article 105 of the Quebec Municipal Powers Act was cited on many occasions in Ruling_2017, as the RMC was informed in 2010 that there was a beaver dam in the Ruisseau du Canton. This Article is based on the concept (now widely challenged in the scientific literature – see Discussion) that "maintenance" of a river is needed to avoid flood damage. Once the RMC is informed of the presence of an obstacle (such as a beaver dam), then it must carry out the work

TABLE 4 Difference in discharge, water level for the 2005 Katrina flood downstream of the three beaver dams located upstream in the PAP watershed, at the junction between PAP River and road 138 (see Figure 1B) and at the bridge of Chemin du Port-au-Persil (Armstrong & Gauthier, 2014).

Location	Peak discharge with no failure (m^3/s)	Peak discharge with failure (m^3/s)	Difference in discharge (m^3/s) (% of peak discharge)	Increased level due to failure (m)	Arrival time of the flood wave due to failure (min)
Upstream PAP	13.4	18.7	5.3 (29%)	0.07	8
PAP at road 138	26.0	27.1	1.1 (4.1%)	0.10	27
Bridge Chemin du Port-au-Persil	63.7	63.8	0.1 (0.2%)	0.01	40

required to restore normal water flow, and it can then be held liable for the damage, as highlighted by the 2017 Court ruling. Indeed, the judge stated: “The Charlevoix-Est RMC has been duly informed of the obstruction in the Ruisseau du Canton caused by a beaver dam. RMC representatives have been informed of the danger of a beaver dam and the damage caused by the breaking of such a dam. The Charlevoix-Est RMC, by virtue of its legal obligation, had to carry out all the work required in a timely manner to eliminate the threat to the safety of people and property of which it had been duly notified” (Ruling_2017, para. 186). “Given its fault of omission, the defendant cannot plead a fortuitous event or force majeure as defined by the notions of unforeseeability and irresistibility. Inspector [X]'s report of October 18, 2010, not to mention the 2005 flood at the same location, clearly shows the RMC's fears that an event such as the one that occurred could happen” (para. 187).

The implications of the 2017 Court ruling are therefore significant for river management, because whenever a RMC is made aware of a beaver dam on its territory (even if it is located far upstream, as was the case with the Katrina flood in 2005), it is liable to prosecution for flood damage.

4 | DISCUSSION

To the best of our knowledge, this is the first study that uses a hydraulic model to study in detail the downstream impact of beaver dam failure during a large flood. Our findings, based on the original 1D hydraulic model as well as new 2D simulations with a four-fold increase in the beaver dam volume, confirm that the beaver dam failure cannot explain the damage that resulted from the Irene 2011 flood event. Only a beaver dam much higher than the one on the Ruisseau du Canton could have caused an overflow, as shown by the 2D simulations that added 1 m (47% increase) to the actual height of the beaver dam (Figure 6B), and even then only with a very short (and thus conservative) failure time (10 minutes), which may not be representative of the way beaver dams break down during floods, likely through loss of material, rendering it porous (Nyssen, Pontzeele, & Billi, 2011). As pointed out by EEP, there is inevitably some level of uncertainty in hydraulic models, particularly in torrential streams, which was not specifically addressed in Armstrong & Gauthier (2014). The findings from the 2D model on the relative (minor) impact of modifying the retention volume or the larger effect of dam height on flood wave propagation are therefore more useful than the actual precise water surface elevation values predicted by hydraulic models. As for the 2005 flood, with beaver dams located much further upstream in the PAP watershed, it is simply impossible for them to have had a significant impact at the mouth of the river.

Previous studies have also shown that breaches in beaver dam analogues during high flow events resulted in a lot of stream bank erosion, but only immediately downstream (Pearce et al., 2021). It therefore seems doubtful that damage located at considerable distances downstream of a beaver dam can be attributed to dam failure, which makes the two Superior Court judgments described in this paper all the more surprising and highlights the poor understanding of river dynamics during major flow events.

A hydrogeomorphological characterization of the PAP River was, in fact, included in the expert report (Armstrong & Gauthier, 2014), which highlighted the widespread problem of riverbank erosion following the exceptional flood events of August 2005 and 2011. Armstrong & Gauthier (2014) believed that the significant input of sediment and large wood was linked to these two events, which disrupted the river's equilibrium. Given the steep gradient of this section, flow velocities in the river are very high, reaching an average of around 3 m/s in the reaches upstream from the bridge, without a beaver dam failure. At the time of the August 2011 event (start of the overflow), the river had a discharge approaching or exceeding the estimated Q100 (of the order of 26 m^3/s) and the water velocities and levels observed were already likely to lead to problems of bank erosion and transport of large wood, especially in a context of hydro-sedimentary disequilibrium caused by the August 2005 event. Indeed, with a slope (S) in the area close to the bridge of around 2%, and a river width (W) of around 15 m, this discharge (Q) results in unit stream power ($USP = \rho\ g\ Q\ S/W$, where ρ is mass density (1,000 kg/m^3) and g is acceleration due to gravity (9.81 m/s^2)) over 300 W/m^2, clearly sufficient to result in massive erosion (Bizzi & Lerner, 2015). These flow conditions may also result in wood congestion that can create a steep front (Ruiz-Villanueva et al., 2019), which could explain the sudden arrival of flow near the Port-au-Persil bridge described by several eyewitnesses during the 2011 flood. As noted by Mohr et al. (2023) for the major flood of July 2021 in central Europe, the rapid rise in water level can also be due to backwater effects from floating debris trapped upstream of the bridge.

Human-wildlife conflicts with beaver dams are common (Yarmey & Hood, 2020). In North America, the common approaches to mitigating potential impacts include removing beavers by trapping or shooting, removing beaver dams and fencing trees (Hood, Manaloor, & Dzioba, 2018; Jonker et al., 2006). Public perception of wood in rivers remains largely negative (Wohl, 2015), with a negative perception of beavers very often associated with widespread media attention following floods (Jonker et al., 2006). If local stakeholders, such as cities or private landowners, who play a key role in river management, continue to have such a negative perception, then wood will continue to be removed from river corridors (Wohl, 2015). It is worth noting that public perception can be bipolar, with some that "adore" beavers (Wohl, 2015) and others regarding beavers as rodents that need to be trapped and removed wherever they are present.

A survey conducted in 2023 among 13 river managers in eastern Quebec (Buffin-Bélanger et al., 2024) revealed that the vast majority of them considered that beaver dam failures can cause flooding likely to create damage. They were concerned about flooding upstream of the dam, which was also noted in other studies, for example, in a 2014 survey of key informants in Alberta (Canada) (Yarmey & Hood, 2020). In general, the most negative perception of beaver dam risk comes from farmers as they are worried they will lose income (Yarmey & Hood, 2020), with a recent survey in Germany showing overall very limited acceptance of beavers in forestry and agricultural areas (Hohm et al., 2024). However, in the Quebec survey, the impact on farmers was not a primary concern (and was not implicated at all in the PAP court rulings). The fact that Quebec river managers were concerned about flooding *downstream* of the beaver dam is somewhat unusual when compared to other countries, and is probably related to the 2017 PAP Court ruling, which confirms the (unsubstantiated) thesis that beaver dams have a direct impact on the damage suffered downstream. The scientific consensus is that hazards associated with beavers are predominantly in the immediate vicinity of the dam (Wohl, Scott, & Yochum, 2019). Standard mitigation measures for beaver dams include preventing beavers from damming intakes and limiting the water level of beaver ponds (Wohl, Scott, & Yochum, 2019), but we were unable to find any literature recommending the removal of beaver dams located as far away as in the PAP court cases.

The high primary productivity and diverse habitat of beaver meadows are known to create biotic resilience to disturbance in the river corridor (Brazier et al., 2021). Recognition of these functions is behind the reintroduction of beavers in the northern hemisphere (Auster, Barr, & Brazier, 2021), as well as the installation of structures designed to mimic the effects of beaver dams (Morizot & Husky, 2024; Pilliod et al., 2018; Wohl, 2024). The province of Quebec, therefore, appears to be going against the grain when it comes to beaver dam management, and this is clearly linked to Article 105 of the Municipal Powers Act, which affects the overall management of large wood in rivers with its outdated view that river "maintenance" is necessary and that wood in rivers is a nuisance. The strict application of Article 105 could mean that all beaver dams in Quebec would have to be dismantled as a preventive measure, since they would automatically constitute an obstacle to the normal flow of water, which is certainly not the legislator's primary objective. The basic premise in both court cases is that beaver dams are a threat to the safety of people and property, with no mention of the flood attenuation role of beaver dams that is widely recognized in the scientific community (Brazier et al., 2021; Graham et al., 2022; Puttock et al., 2017). This premise seems well established in the province of Quebec, where even some biologists also consider large wood and beaver dams to be problematic (Biron, Buffin-Bélanger, & Massé, 2018). For example, the guidelines from Fisheries and Oceans Canada (Fleury & Boula, 2012) for brook trout restoration state that "stream cleaning to improve brook trout habitat is a widespread activity in Quebec. It consists primarily of removing some of the riparian vegetation, woody debris, log jams or ancient beaver dams that contribute to a decrease in the overall habitat quality of the brook trout" (p. 22). The funding criteria for fish habitat restoration projects from Quebec's Fondation de la Faune (Fauna Foundation) are heavily based on these guidelines, and thus include the dismantling of beaver dams (https://fondationdelafaune.qc.ca/programmes-daide-financiere/amelioration-de-la-qualite-des-habitats-aquatiques-aqha/).

In the neighbouring state of Vermont (USA), where hurricane Irene caused severe damage in 2011, the previous practice was to remove wood from the river. However, with other extreme rain events such as in July 2023, they are now seeing the value of wood in rivers and are installing beaver dam analogues (Diamond, Allaire, 2023; Northern Woodlands, 2023). It is interesting to note the extent to which the two judges (in 2008 and 2017) paid little heed to scientific concepts, in particular the fact that major floods will inevitably cause bank erosion and lead to trees accumulating further downstream. It is particularly astonishing to note the extent to which the judge in 2017 brushed aside a rigorously conducted modelling study based on widely used software (HEC-HMS and HEC-RAS). This judgment is in fact a good example of a broader problem of judicial treatment of scientific evidence in civil liability cases, which is particularly problematic in the Quebec legal system where the defence and the plaintiff each have their own scientific expert who often contradict each other, leaving a judge with no scientific training to decide who is more credible (Vergès & Khoury, 2017).

In the context of property damage caused by extreme events, the search for someone to blame in legal cases has major economic consequences, prompting people to look for a means to recoup their losses. Natural processes such as logjams created by falling trees during floods do not attract media attention and do not make good culprits. In the particular legal context in Quebec, with Article 105 of the Municipal Power Act requesting that a regional county municipality restore "normal water flow" if informed of the presence of an obstacle (such as a beaver dam) that "threatens the safety of persons or property", the 2017 ruling creates a problematic jurisprudence.

More rigorous scientific assessments of the failures of beaver dams are needed to counter the deleterious effects of such court rulings, which contribute to maintaining a very negative perception of beavers. There is a recognized paucity of studies that used hydraulic modelling to investigate the role of beaver dams (Feng & Molz, 1997; Neumayer et al., 2020), and it is our hope that by publishing the detailed model presented in the 2017 Court case, more scientific evidence, including a hydrogeomorphological assessment, will be required in the future before concluding that there is a causal relationship between the presence of beaver dams and damage to buildings during major floods. Scientific studies should be accompanied by education campaigns on the positive role of beaver dams in the ecosystem.

5 | CONCLUSIONS

This study used a combined hydrological and hydraulic modelling approach to assess the impact of a beaver dam failure in a small tributary during an extreme flood event in 2011 that resulted in considerable damage at the mouth of the Port-au-Persil watershed. It is highly unusual for two court cases to have been filed following flooding in the same watershed, with both cases a beaver dam failure considered to have caused the damage observed. This exceptional situation explains why a remarkable amount of data is available, since an engineering firm was hired by the lawyers defending the municipal entity sued by the plaintiffs, resulting in a much more detailed analysis (Armstrong & Gauthier, 2014) than would otherwise have been possible.

The findings of this initial expert report, presented in court, that the river would have overflowed even if the dam had not broken, were dismissed by the judge in the 2017 court ruling. The main argument used by the judge was that this expert report underestimated the retention volume behind the beaver dam in their 1D hydraulic simulations. New 2D simulations run in this study, using a retention volume four times larger than in the original 1D model, reveal a minor (3.9%) increase in the maximum water level associated with the beaver dam failure, confirming that the damage caused by this flood could not be due to the beaver dam. These simulations also reveal that beaver dam height, not retention volume, is the most important controlling factor for downstream damage from beaver dam failure. As beaver dams are usually less than 1.5 m in height (Hafen et al., 2020; Majerova, Neilson, & Roper, 2020), and therefore much lower than the heights of 2.15 m and 3.15 m used in the numerical simulations in this study, it should not be concluded de facto that a breach or the mere presence of a beaver dam increases the risk of flooding downstream. Natural processes along rivers, such as landslides and large wood jams caused by fallen trees, are more likely to be responsible for the damage observed during high-magnitude floods. However, the potential effects of these natural processes are rarely taken into account in the flood maps, which makes it possible to build despite the high risk in these areas.

AUTHOR CONTRIBUTIONS

Pascale Biron: conceptualization; methodology; investigation; writing—initial draft, reviewing and editing; Jean Gauthier: methodology; investigation; resources; software; writing—reviewing and editing; Mathieu Dubé: methodology; investigation; resources; software; writing—reviewing and editing; Thomas Buffin-Bélanger: methodology; investigation; writing—reviewing and editing; Maxime Boivin: methodology; investigation; writing—reviewing and editing.

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DATA AVAILABILITY STATEMENT

The court rulings described in this paper are publicly available. The data for the 1D and 2D models are available upon request.

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