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Geomorphic Effects of Flooding Along Reaches of Selected Rivers in the Saguenay Region, Québec, July 1996
Les conséquences des inondations de juillet 1996 sur la géomorphologie de certaines rivières de la région du Saguenay, au Québec
Auswirkungen der Überflutungen im Juli 1996 auf die Geomorphologie am Beispiel von ausgewählten Flüssen in der Saguenay-Region, Québec

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Résumé de l'article

Du 18 au 21 juillet 1996, des pluies torrentielles ont entraîné le débordement de nombreuses rivières dans le sud du Québec, en particulier d'affluents du Saguenay s'écoulant vers le nord. Dans les tronçons d'étude des rivières aux Sables, Chicoutimi, du Moulin et à Mars, les effets de la crue sur la géomorphologie fluviale ont varié considérablement selon la morphologie des lits, l'énergie de l'écoulement et l'interaction entre les eaux de crue et certaines infrastructures. La rivière à Mars, le long du tronçon étudié, a subi un élargissement excessif de son lit et un remodelage de sa plaine d'inondation, la rivière à méandre devenant réticulée. La puissance unitaire de l'écoulement de crue a ainsi dépassé le seuil minimal d'érosion (300 Wm^{-2}) sur la plus grande partie du tronçon étudié. Des observations morphologiques et empiriques indiquent qu'avant la crue le lit de la rivière à Mars présentait une configuration de transition, donc susceptible de changer pendant une crue extrême. Dans les tronçons étudiés des rivières aux Sables et Chicoutimi, les effets les plus importants se sont produits à un certain nombre de barrages au fil de l'eau. Les eaux de crue qui débordaient de quatre de ces barrages ont profondément érodé des sédiments adjacents non consolidés, formant ainsi de nouveaux chenaux qui ont canalisé le cours des rivières. Les eaux qui ont débordé du cinquième barrage ont affouillé des matériaux non consolidés, érodé des assises de routes et endommagé ou détruit des bâtiments. Ailleurs, le long des deux rivières et le long du tronçon d'étude de la rivière du Moulin, l'érosion a été locale et les conséquences géomorphologiques ont été limitées, sinon négligeables, en raison de substrats résistants ou de la faible puissance unitaire de l'écoulement de crue.

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GEOMORPHIC EFFECTS OF FLOODING ALONG REACHES OF SELECTED RIVERS IN THE SAGUENAY REGION, QUÉBEC, JULY 1996

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ABSTRACT A severe rainstorm from July 18 to 21, 1996, caused widespread flooding along many rivers in southern Québec, particularly in the Lac-Saint-Jean–Chicoutimi area, along north-flowing tributaries of the Rivière Saguenay. Along study reaches located on the Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin and Rivière à Mars, the fluvial geomorphic effects of flooding varied considerably, reflecting differing channel morphologies (alluvial, non-alluvial and bedrock), flow energy, and the interaction of floodwaters and infrastructure. Catastrophic channel widening and floodplain reworking occurred along the Rivière à Mars study reach, transforming the river from a meandering to braided planform. Consistent with this, unit stream power of the flood flow exceeded the minimum erosive threshold (300 Wm^{-2}) along most of the study reach. Morphological and empirical evidence indicates that the pre-flood Rivière à Mars channel exhibited a transitional planform, and thus was vulnerable to a planform transformation during an extreme flood. The most significant geomorphic effects along the Rivière aux Sables and Rivière Chicoutimi study reaches occurred at a number of run-of-the-river dams. Floodwaters overtopped four dams and eroded deeply into unconsolidated sediments adjacent to the dams, forming new channels that captured the flow of the river. Floodwaters also overtopped a fifth dam, scouring overburden and road beds, and damaging and destroying buildings within an urban subdivision. Elsewhere along these two rivers, as well as along the Rivière du Moulin study reach, there were localized erosional problems, particularly at bridges, but the geomorphic effects generally were limited or negligible, reflecting either low unit stream power or resistant substrates.

RÉSUMÉ *Les conséquences des inondations de juillet 1996 sur la géomorphologie de certaines rivières de la région du Saguenay, au Québec.* Du 18 au 21 juillet 1996, des pluies torrentielles ont entraîné le débordement de nombreuses rivières dans le sud du Québec, en particulier d'affluents du Saguenay s'écoulant vers le nord. Dans les tronçons d'étude des rivières aux Sables, Chicoutimi, du Moulin et à Mars, les effets de la crue sur la géomorphologie fluviale ont varié considérablement selon la morphologie des lits, l'énergie de l'écoulement et l'interaction entre les eaux de crue et certaines infrastructures. La rivière à Mars, le long du tronçon étudié, a subi un élargissement excessif de son lit et un remodelage de sa plaine d'inondation, la rivière à méandre devenant réticulée. La puissance unitaire de l'écoulement de crue a ainsi dépassé le seuil minimal d'érosion (300 Wm^{-2}) sur la plus grande partie du tronçon étudié. Des observations morphologiques et empiriques indiquent qu'avant la crue le lit de la rivière à Mars présentait une configuration de transition, donc susceptible de changer pendant une crue extrême. Dans les tronçons étudiés des rivières aux Sables et Chicoutimi, les effets les plus importants se sont produits à un certain nombre de barrages au fil de l'eau. Les eaux de crue qui débordaient de quatre de ces barrages ont profondément érodé des sédiments adjacents non consolidés, formant ainsi de nouveaux chenaux qui ont canalisé le cours des rivières. Les eaux qui ont débordé du cinquième barrage ont affouillé des matériaux non consolidés, érodé des assises de routes et endommagé ou détruit des bâtiments. Ailleurs, le long des deux rivières et le long du tronçon d'étude de la rivière du Moulin, l'érosion a été locale et les conséquences géomorphologiques ont été limitées, sinon négligeables, en raison de substrats résistants ou de la faible puissance unitaire de l'écoulement de crue.

ZUSAMMENFASSUNG *Auswirkungen der Überflutungen im Juli 1996 auf die Geomorphologie am Beispiel von ausgewählten Flüssen in der Saguenay-Region, Québec.* Ein heftiger Regensturm vom 18. bis 21. Juli 1996 verursachte ausgedehnte Überflutungen an vielen Flüssen in Süd-Québec, vor allem im Gebiet Lac-Saint-Jean-Chicoutimi, entlang den nordwärts fließenden Nebenflüssen des Saguenay-Flusses. In den untersuchten Abschnitten von Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin und Rivière à Mars sind die Auswirkungen der Überflutungen auf die Fluss-Geomorphologie von beträchtlichem Unterschied und spiegeln unterschiedliche Flussbettmorphologien (alluvial, nichtalluvial und anstehendes Gestein), Fließenergie und Interaktion zwischen Überflutungswasser und Infrastruktur. Im untersuchten Abschnitt von Rivière à Mars kam es zu einer exzessiven Flussbetterweiterung und einer Umformung seiner Überschwemmungsebene , so dass der mäandernde Fluss in eine verwilderte Form umgewandelt wurde. Übereinstimmend damit überstieg die Stärke der Strömung des Flutwassers die unterste Erosionsgrenze (300 Wm^{-2}) auf dem größten Teil des untersuchten Abschnitts. Morphologische und empirische Belege zeigen, dass das Flussbett des Rivière à Mars vor dem Hochwasser eine Übergangsform zeigte und also während eines extremen Hochwassers anfällig für Veränderungen war. Die wesentlichsten geomorphologischen Veränderungen entlang der studierten Abschnitte von Rivière aux Sables und Rivière Chicoutimi fanden an einigen Staudämmen entlang des Flusses statt. Das Hochwasser überflutete vier Dämme , grub sich tief in nichtbefestigte angrenzende Sedimente ein und bildete neue Flussbetten, welche das Flusswasser auffingen. Das Hochwasser hat auch einen fünften Damm überflutet, schürfte nicht befestigtes Material und Straßenläufe aus und beschädigte und zerstörte Gebäude eines Stadtteils. Anderswo entlang dieser zwei Flüsse sowie im untersuchten Abschnitt von Rivière du Moulin kam es zu örtlichen Erosionsproblemen, vor allem an Brücken, aber die geomorphologischen Auswirkungen waren im Allgemeinen begrenzt oder geringfügig, sei es weil die Fließenergie gering oder weil der Untergrund widerstandsfähig war.

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INTRODUCTION

The geomorphic importance of “rare” high magnitude floods has long been debated in the fluvial geomorphic literature. Numerous papers document negligible to minor geomorphic effects resulting from extreme hydrometeorological flooding along rivers in humid climates of North America (*e.g.*, Wolman and Eiler, 1958; Gardner, 1977; Moss and Kochel, 1978; Hickin and Sichingabula, 1988). These results support the notion that most geomorphic work along rivers is done by flows of moderate magnitude occurring on a semi-annual basis (Wolman and Miller, 1960; Leopold *et al.*, (1964). However, it is also well documented that extreme floods can produce catastrophic geomorphic change, whereby large-scale erosion of a valley bottom (or at least sections of it) occurs and results in substantial widening of the channel and reworking of the floodplain (*e.g.*, Gupta and Fox, 1974; Clark *et al.*, 1987; Hickin and Sichingabula, 1988; Kochel, 1988; Miller and Parkinson, 1993).

This dichotomy of geomorphic effects from high magnitude flooding has become clearer by considering the energy of the flow rather than only the magnitude of the discharge (Baker and Costa, 1987). Widespread bank erosion and floodplain stripping can occur when the flow energy exceeds the erosive threshold of the valley bottom, otherwise the effects of the flood may be minimal or at least consistent with those of lesser flows (Baker and Costa, 1987). Other factors of importance are the interval between successive severe floods (*e.g.,* Wolman and Gerson, 1978; Desloges and Church, 1992) and the duration of the flood flow above threshold (Costa and O’Connor, 1995).

Flooding triggered by a severe rainstorm during July 18 to 21, 1996, caused a major disaster along the north shore of the St. Lawrence River between Trois-Rivières and Sept-Îles, and within the Saguenay Valley, Québec. The flooding, associated road wash-outs and landslides caused ten deaths, displaced thousands of people, damaged and destroyed property and infrastructure, overtopped numerous dams and dikes, and impaired the operations of many businesses and industries (Commission scientifique et technique sur la gestion des barrages (CSTGB), 1997; Ministère du Conseil exécutif Québec, 1997). The impacts of the flooding were especially severe in the Lac-Saint-Jean–Chicoutimi area along low-lying areas adjacent to the north-flowing tributaries of the Rivière Saguenay.

This paper documents the fluvial geomorphic effects of the extreme flooding triggered by the July 1996 rainstorm along selected reaches of four rivers in the Saguenay area, Québec (Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin, and Rivière à Mars; Fig. 1). The geomorphic effects are notable because of the variety of channel morphologies present along the study reaches and their different responses to the flooding. Also, at some locations, infrastructure was a critical factor accentuating erosion. In this case study paper, we review briefly the rainstorm that caused the flooding, summarize the flood discharges, and examine and discuss the fluvial geomorphic effects of flooding along channels of differing morphologies as well as the influence of dams and bridges.

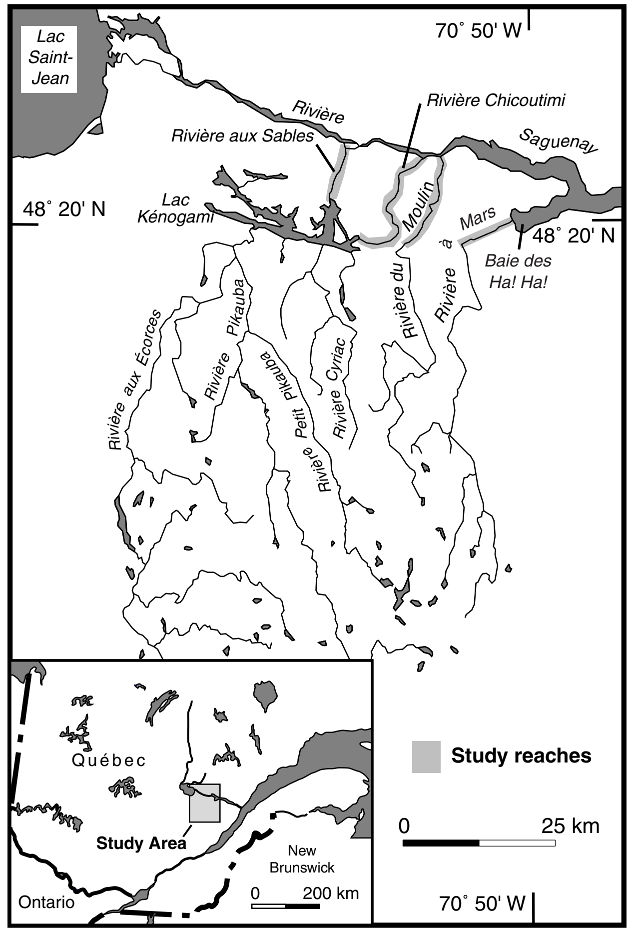
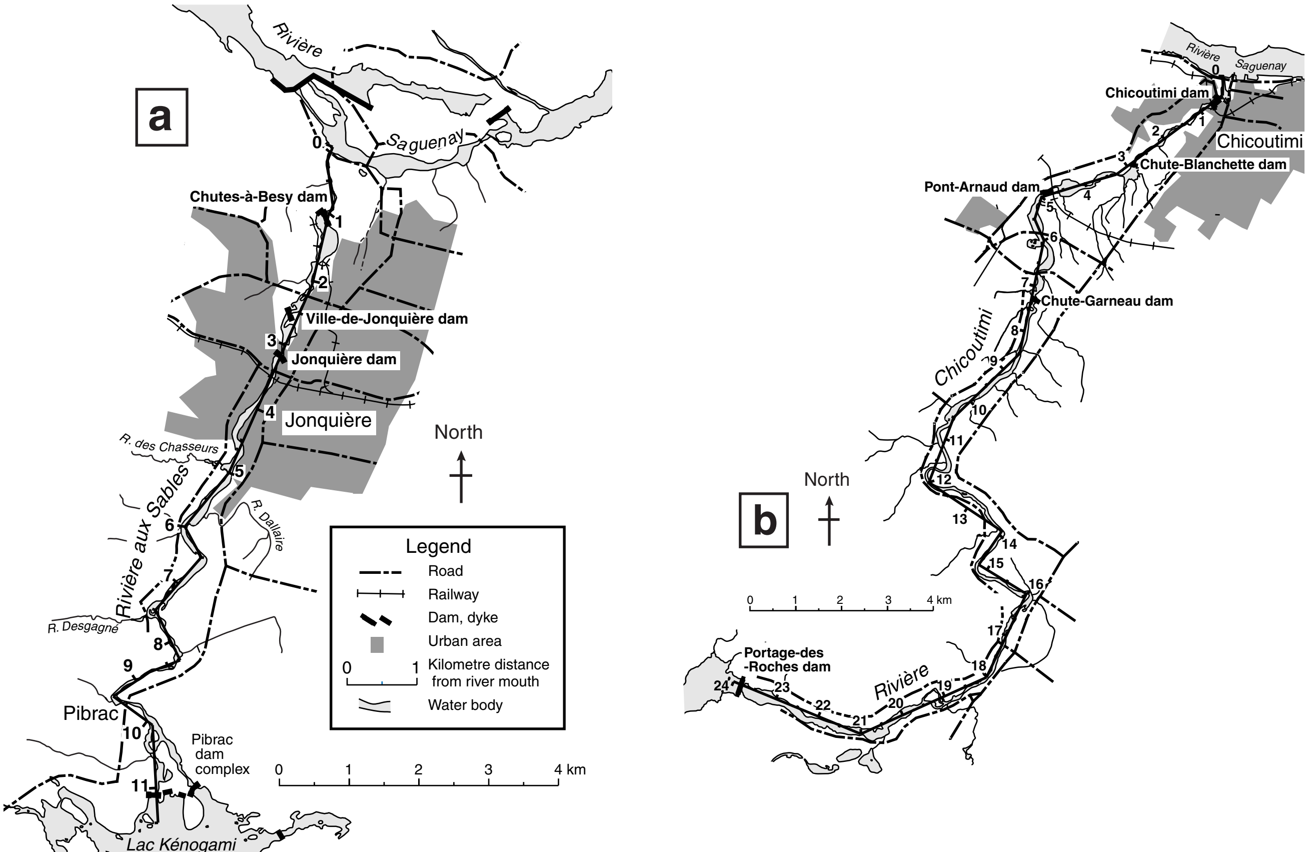


FIGURE 1. Map showing the watersheds of the Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin, and Rivière à Mars, and the locations of the study reaches.

Carte montrant les bassins versants des rivières aux Sables, Chicoutimi, du Moulin et à Mars, ainsi que les tronçons d’étude.

The study reaches are located within populated portions of the watersheds where local communities were severely impacted by the flooding. Although the focus is on the fluvial geomorphic effects, the lack of “notable” effects along a given section of river is not intended to diminish or discount the substantial social impacts and material costs of the flooding. This paper supplements an expanding literature that addresses various aspects of the Saguenay floods. From a fluvial geomorphic perspective, this includes Brooks *et al.* (1997), a technical reports that overviews the geomorphic effects and impacts of the flooding, CSTGB (1997), the report of the official inquiry into the flood disaster, INRS-Eau (1997), a technical report that models the floods along the Rivière Chicoutimi and Rivière des Ha! Ha! and includes geomorphic information, and Lapointe *et al.* (1998) and Brooks and Lawrence (1999), both of which examine aspects of the combined dam breach–rainstorm flood along the Rivière des Ha! Ha!. More popular accounts of the flood disaster are Germain (1997), Grescoe (1997), and Brooks and Lawrence (1998).



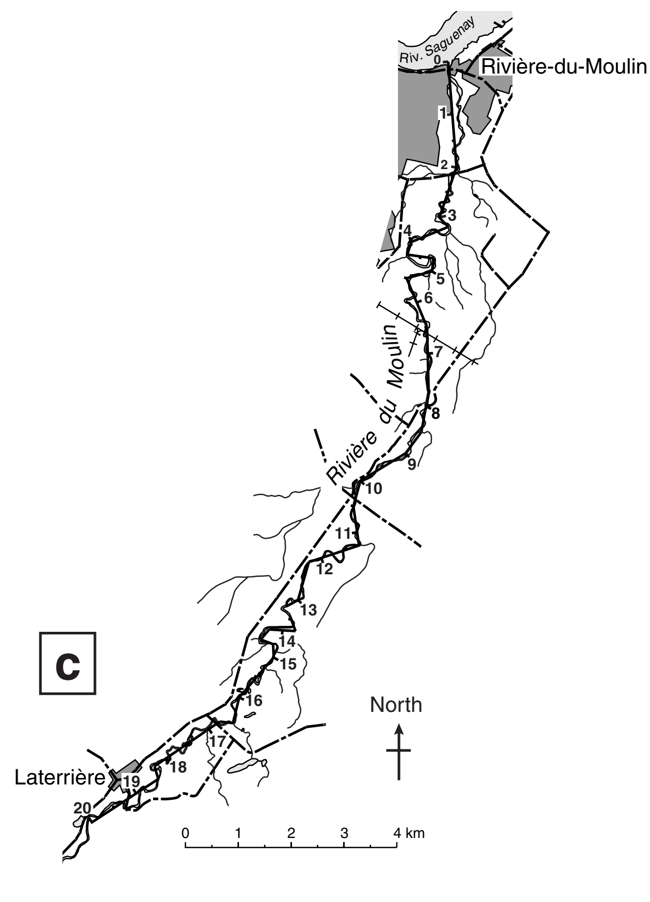
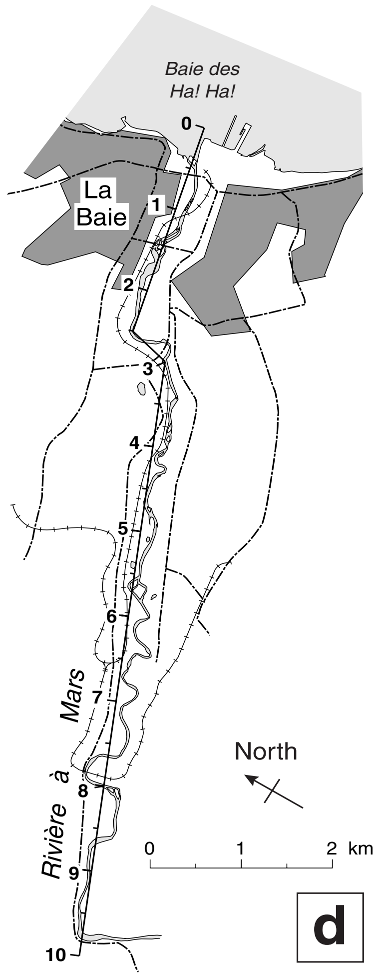


FIGURE 2. Pre-flood maps depicting the four study reaches along the a) Rivière aux Sables, b) Rivière Chicoutimi, c) Rivière du Moulin and d) Rivière à Mars. A kilometre distance scale is superimposed along each river to facilitate locating sites referred to in the text. Note the location of the run-of-the-river dams on the Rivière aux Sables and Rivière Chicoutimi.

Cartes montrant les quatre tronçons d'étude sur les rivières a) aux Sables, b) Chicoutimi, c) du Moulin et d) à Mars, avant la crue. L'échelle des distances (km) est présentée le long de chaque rivière pour faciliter la localisation des sites mentionnés dans le texte. Noter l'emplacement des barrages au fil de l'eau sur les rivières aux Sables et Chicoutimi.

STUDY REACH DESCRIPTIONS

The Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin, and Rivière à Mars are tributaries of the Rivière Saguenay (88 100 km^2; Fisheries and Environment Canada, 1978). All four rivers are situated southeast of Lac Saint-Jean and occupy an adjacent series of watersheds that flow northwards into the Saguenay Valley to join the Rivière Saguenay (Figs. 1 and 2). The watersheds lie mostly within the Laurentian Highlands, a rugged, heavily dissected region of the Canadian Shield. Elevations in the headwater areas reach up to 1 100 m. The vegetated, hummocky bedrock surfaces of the highlands generally outcrop or are covered with a thin, discontinuous veneer of drift (Fulton, 1995). The drift cover thickens and becomes more continuous in the valley bottoms and towards the Saguenay Valley (Fulton, 1995). Numerous small lakes and wetlands are present



within bedrock basins that form low-lying, poorly drained areas within the highlands.

The study reaches are situated along the lower 11.1, 23.8, 20 and 9.8 km of the Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin and Rivière à Mars, respectively (Figs. 1 and 2). These are located within the Saguenay Valley, a broad, raised lowland of relatively moderate relief. Here, large areas of bedrock are covered with a thick layer of Quaternary deposits; predominately fine-grained marine sediments (silt, silty clay, clay) deposited in the Laflamme Sea during the late Pleistocene and early Holocene (LaSalle and Tremblay, 1978). Extensive glaciofluvial and fluvial sand and gravel deposits form several raised deltas that are present along the southern margin of the lowland and overlie the marine sediments (LaSalle and Tremblay, 1978). Following recession of the Laflamme Sea prior to 8000 yrs BP (Parent *et al*., 1985), the rivers developed across and gradually incised into the deltaic and marine sediments that cap the lowland bedrock.

The channels along the aux Sables, Chicoutimi and du Moulin study reaches are generally similar in profile and morphology. All three have relatively gentle gradients (ranging from 0.001 to 0.008) across the lowland surface of the Saguenay Valley, but steepen markedly along the lower 3 km where the channels descend several bedrock steps (Fig. 3a, b and c). On the lowland, the rivers occupy shallow stream-cut valleys that are entrenched roughly 10 to 20 m into the surficial materials and, in places, down to bedrock. Coinciding with the steepening of gradient along the lower 3 km, the valleys are up to 70 m deep and incised into marine sediments, commonly to bedrock. Although occurring well above the influence of the rivers, the sides of the lower aux Sables and du Moulin valleys are subject to instability and several large landslides scars are present (Dion, 1986); the most recent large landslide happened in 1924 (Brzezinski, 1971).

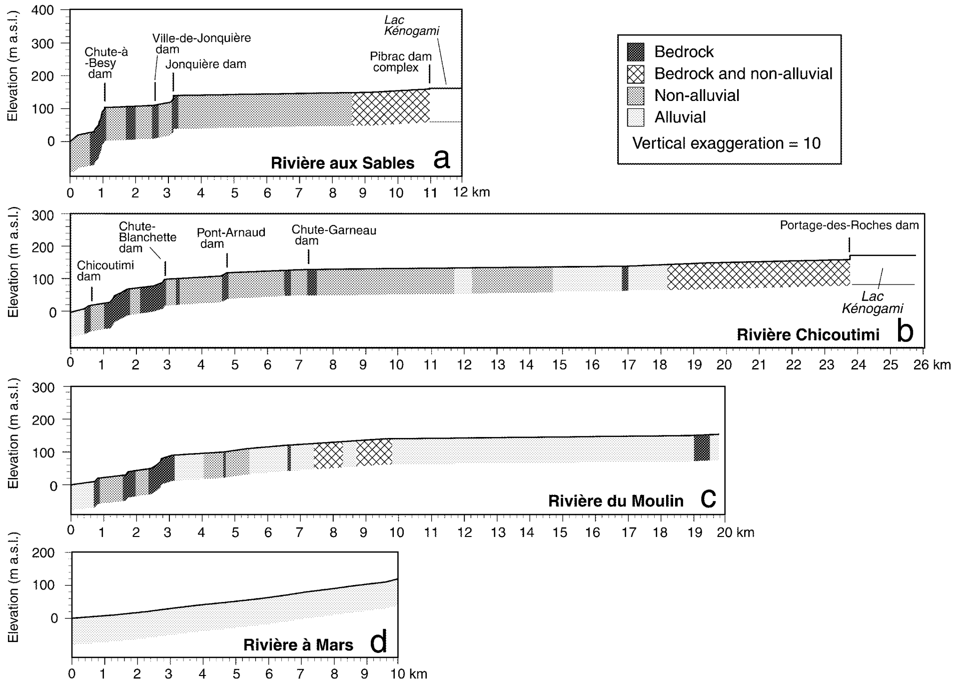
The pre-flood channel morphologies along the aux Sables, Chicoutimi and du Moulin study reaches vary between alluvial, non-alluvial and bedrock (Fig. 3a, b and c). The distinction between alluvial and non-alluvial is based qualitatively on the presence or absence of a floodplain surface along at least one side of the channel. Significantly, there is no obvious evidence of active lateral channel migration along any of the alluvial reaches in pre-flood aerial photographs (*e.g.*, active cutbanks, fresh point bar accretion, a succession of progressively older vegetation with increasing distance from the inner bank of a given meander). The outer banks of the bends regularly are confined against a valley side inhibiting lateral channel migration. The only “classic” example of an alluvial valley bottom was between km 18.9 and 15.2 along the Rivière du Moulin (Fig. 2c), where the channel was partially confined (less than 30 %) against the valley sides and numerous oxbow lakes and channel scars are present on the floodplain[1]. Rapids are present along the bedrock sections of rivers (Figs. 3a, b and c). A total of three and four run-of-the-river dams are situated on the aux Sables and Chicoutimi study reaches, respectively (Figs. 2a and b; Table I), while none are present on the du Moulin study reach.

Along the Rivière à Mars study reach, the gravel-bed channel is significantly different from those along the other three study reaches. The pre-flood alluvial channel exhibited an irregular meandering course (sinuosity 1.2) and was predominately single channeled from km 9.8 to 5.8, then alternating between single and split channels from km 5.8 to the river mouth (Fig. 2d). Where split, the channel was divided by partially vegetated bars and forested islands. Small side channels that branched from the main channel formed some split-channeled sections. At km 5.6, the river was divided very locally into multiple channels (Fig. 2d). Active point bars were present along the convex banks of many meanders. Indicative of past lateral channel instability, numerous inactive (containing stagnant water) and abandoned (dry) channels, and channel scars (vegetated) were present along the river.

1. Features referred to in the text are keyed to the maps in Fig. 2 by a kilometre distance scale that is superimposed along the respective river.

FIGURE 3. Longitudinal profiles and channel morphologies along the a) aux Sables, b) Chicoutimi, c) du Moulin and d) à Mars study reaches.

Profils longitudinaux et morphologies du lit des tronçons d'étude sur les rivières a) aux Sables, b) Chicoutimi, c) du Moulin et d) à Mars.



The morphology of the Rivière à Mars varies from the other study reaches due to a markedly different geomorphic setting. At the head of the study reach, the river emerges from a narrow bedrock canyon and enters a deep stream-cut valley, 300 to 1 200 m wide and incised up to about 70 m into deltaic sand and fine grained marine sediment, that it follows to the river mouth. The floodplain or terrace surfaces (up to about 15 m above the river channel) extend continuously along the valley bottom, except between km 7.6 to 7.3 where the channel impinges against the right valley side. The valley slope averages a relatively uniform 0.012 along the study reach (Fig. 3d). About 1 km upstream of the study reach within the aforementioned bedrock canyon, an abandoned concrete run-of-the-river dam still impounds river waters and traps bed material.

STORM

The rain that caused the flooding was generated by a low pressure system of greater than normal intensity for the summer period (Milton and Bourque, 1997). The storm system deepened and intensified during the afternoon of July 19 and the morning of July 20 as it moved eastward from the Montréal area, Québec, to northern New Brunswick, producing heavy rainfall along the north shore of the St. Lawrence River (Milton and Bourque, 1997). The zone of greatest accumulation was centred just south of the Lac Saint-Jean–Saguenay Valley area, where in excess of 200 mm of rain fell (Fig. 4). In the Saguenay area, most of the rain fell within a 36 hour period beginning at about 08:00 on July 19 and continuing until approximately 20:00 July 20 (Milton and Bourque, 1997). One-day, two-day and three-day accumulations exceeded the 100-year return period at a number of area meteorological stations that have precipitation records in excess of 20 years (Milton and Bourque, 1997).

The most extreme flooding occurred along rivers flowing northwards into the Saguenay Valley whose watersheds drained the greater than 200 mm rainfall accumulation zone. Relevant to this paper, these are the Rivière aux Écorces, Rivière Pikauba, and Rivière Cyriac, which flow into Lac Kénogami (and therefore are tributaries of the Rivière aux Sables and Rivière Chicoutimi; Fig. 1 and see below), and the Rivière du Moulin and Rivière à Mars. Factors contributing to the flooding were near-saturated ground conditions produced by rain that fell earlier in July (Environment Canada, 1996) and the generally thin, discontinuous overburden cover blanketing the bedrock of the Laurentian Highlands.

DISCHARGE

The rainstorm of July 18 to 21, 1996, produced the flood of record along many rivers in the Saguenay area (some with discharge records extending back to the 1910s). Of the four study reaches, storm hydrographs exist for only the Rivière aux Sables and Rivière Chicoutimi (Fig. 5). These two hydrographs are linked closely because both river reaches drain the Lake Kénogami reservoir and thus share a common source area of 3 390 km^2. The discharge regimes are regulated by control dams at the reservoir; the Portage-des-Roches dam and the Pibrac dam complex (two control dams and two dikes) at the heads of the Rivière Chicoutimi and Rivière aux Sables, respectively (Fig. 2a and b). Of note, the Rivière Chicoutimi has a larger channel than the Rivière aux Sables, despite the common watershed, as reflected by the differences in mean flows (Table II).

TABLE I

Attributes of run-of-the-river dams along the Rivières aux Sables et Chicoutimi and summary of impacts from flooding (modified after CSTGB, 1997)

River	Dam (owner)	Year completed	Type (founding material)	Dam height (m)	Dam length (m)	Maximum spilling capacity (m^3s^{-1})[a]	Impacts of flooding
Riv. aux Sables							
	Jonquière dam (Abitibi Price, now Abitibi Consolidated)	1943	Concrete gravity (bedrock with soil abutments)	8	95	530	- abutment breached, lateral valley side erosion, reservoir drained, river flow diverted away from dam
	Ville-de-Jonquière dam (Ville de Jonquière)	1996	Concrete gravity (bedrock)	< 15	~ 105[b]	455	- concrete wing-wall breached, partial drawdown of reservoir
	Chute-à-Besy (a.k.a. Kénogami) dam (Abitibi Price, now Abitibi Consolidated)	1911	Concrete gravity (bedrock) and earthen dike (soil)	< 15	~ 220[b]	770	- dike breached, incision and lateral erosion of valley side, reservoir drained, river flow diverted away from dam
Chicoutimi							
	Chute-Garneau dam (Hydro Québec)	1925	Concrete gravity (bedrock with soil abutments)	8	146	541	- abutment breached, lateral valley side erosion, reservoir drained, river flow diverted away from dam
	Pont-Arnaud dam (Hydro Québec)	1912	Concrete gravity (bedrock with soil abutments)	8	168	710	- breach eroded beside penstocks and powerhouse, reservoir drained, river flow diverted away from dam, knickpoint incision into reservoir bed
	Chute-Blanchette dam (Elkem Metal)	1958	Concrete, gravity and earthen dike (bedrock and soil)	15	137	1 076	- scour of vegetation from bedrock at left abutment
	Chicoutimi dam (Abitibi Price, now Abitibi Consolidated)	1923	Concrete gravity and buttress (bedrock)	30	295	630	- overburden and road beds scoured in places to bedrock, and buildings damaged and destroyed within an urban subdivision by flood waters overtopping dam

[a]spilling capacity at maximum working level of reservoir
[b]estimated from aerial photographs

During the flood, the maximum instantaneous flows for the two rivers were 653 m^3s^{-1} (Rivière aux Sables) and 1 100 m^3s^{-1} (Rivière Chicoutimi; Fig. 5; Table II; CSTGB, 1997). The maximum average daily flows are not reported, but were about 600 and 1 080 m^3s^{-1} for the Rivière aux Sables and Rivière Chicoutimi, respectively, as estimated from the curves in Figure 5 (Table II). For comparison, the historic maximum daily flows for each river are listed in Table II (the historic maximum instantaneous flows are not reported). These historic maximum flows were exceeded during the July 1996 flood, by a factor of about 2.1 for the Rivière Chicoutimi and about 2.4 for the Rivière aux Sables. The hydrographs also indicate that flows in excess of the previous records persisted for at least three days along the two rivers (Fig. 5). This persistence relates in part to the dampening of the flood peak by storage within Lac Kénogami, and the release of water from the drawdown of this reservoir.

An indication of the magnitude of the flood flows (as well as the degree of encroachment of settlement) along the two study reaches is the critical discharges beyond which houses begin to be flooded. These discharges are 170 m^3s^{-1} and 310 m^3s^{-1} along the aux Sables and Chicoutimi study

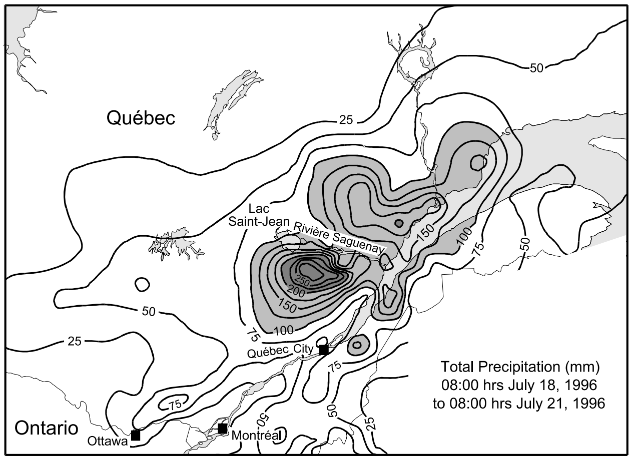


FIGURE 4. Map showing rainfall accumulation in southern Québec between 08:00 hrs July 19 and 08:00 hrs July 21, 1996 (after Milton and Bourque, 1997, reproduced with permission).

Carte montrant les accumulations de pluie dans le sud du Québec, de 8 h le 19 juillet 1996, à 8 h le 21 juillet 1996 (selon Milton et Bourque, 1997 ; droit de reproduction accordé).

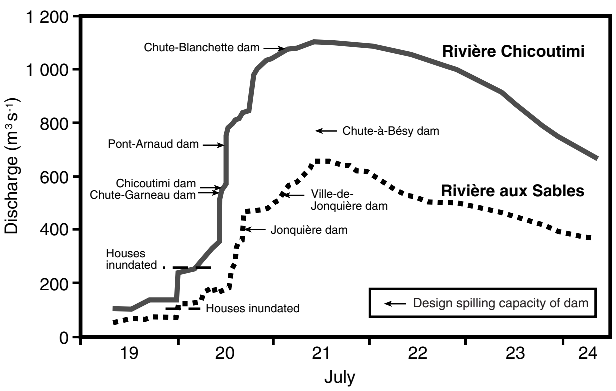


FIGURE 5. Storm hydrographs for the Rivière Chicoutimi and Rivière aux Sables for the period July 19 to mid-day July 24, 1996 (CSTGB, 1997; reproduced with permission). Both rivers drain the Lac Kénogami reservoir and have regulated discharge regimes. Maximum spilling capacities of small run-of-the-river dams and the critical discharge levels beyond which houses begin to be flooded are shown on each hydrograph.

Hydrogrammes des rivières Chicoutimi et aux Sables pour la période du 19 juillet à la mi-journée du 24 juillet (CSTGB, 1997 ; droit de reprtoduction accordé). Les deux rivières sont des exutoires du réservoir du lac Kénogami et ont un débit régularisé. Les capacités maximales de déversement des petits barrages au fil de l'eau et les débits critiques au-delà desquels la crue atteint les maisons sont présentés.

reaches, respectively (CSTGB, 1997), both of which were exceeded by a significant margin during the flood (Fig. 5). Expressing the magnitudes of the peak flows as recurrence intervals is complicated by the regulated flow regimes. For Lac Kénogami, however, the source of flow along both study reaches, the maximum average daily inflow of runoff from all sources into the reservoir during the flood was 2 364 m^3s^{-1} on July 21 (CSTGB, 1997). This inflow exceeded an estimate for the 10 000-year inflow (1 437 m^3s^{-1}) in CSTGB (1997) that is based on an extrapolation of inflow for the period 1912 to 1995. The inflow during the July 1996 storm thus clearly represents a high magnitude, low frequency event. Since the reservoir basin has an area of about 57 km^2 that forms about 2 % of the contributing watershed, the outflow from Lake Kénogami is also considered to represent a high magnitude, low frequency event.

The Rivière du Moulin and Rivière à Mars both have natural flow regimes. At the river mouths, estimates of instantaneous peak discharges during the flood are 393 m^3s^{-1} for the Rivière du Moulin and 445 m^3s^{-1} for Rivière à Mars, based on hydrologic modeling of the storm runoff (Table II; CSTGB, 1997). Since neither river is gauged, there are no pre-flood discharge data to compare with these flows. As was the case with the watersheds contributing to the extreme level of inflow into Lac Kénogami, much of the Rivière du Moulin and Rivière à Mars watersheds encompass the accumulation zone receiving greater than 200 mm of rain.

METHODS

The geomorphic effects described in this paper are based primarily on a post-flood aerial assessment of flood damage conducted between July 26 and 30, 1996, and the interpretation of post-flood oblique aerial photographs, pre- and post-flood vertical aerial photographs and post-flood, high resolution (1 m pixel size), low level, multi-spectral video (MSV) imagery. Information contained in published reports on the flood damage is utilized as cited in the text. The summaries of the geomorphic effects emphasize lateral erosion since this is readily measurable on aerial photographs and the MSV. The accounts of the four study reaches highlight areas of severe or "notable" erosion and are not intended to be comprehensive inventories of erosion. The descriptive terminology of the river characteristics generally follows Kellerhals *et al.* (1976). Longitudinal profiles of the rivers (Fig. 3) were constructed from 1: 20 000 scale topographic maps that have a 10 m contour line interval. While providing a reasonable depiction of the river profiles, there are local variations in the river gradients (*e.g.*, at rapids) along the du Moulin and the Chicoutimi study reaches that correspond to relatively short occurrences of specific channel morphologies, but which fall between the contour lines (Fig. 3). The profiles, thus, are averaged across these morphologies with the locally more gently sloped gradients being overestimated by the contour lines and the steeper gradients being underestimated. Pre-flood river channel widths were also measured on the 1: 20 000 scale topographic maps unless otherwise mentioned.

GEOMORPHIC EFFECTS

ALLUVIAL REACHES

The most widespread geomorphic effects at any of the four study reaches occurred along the Rivière à Mars which experienced large-scale erosion. Most obviously, channel width increased locally from 20-50 m wide to up to about

TABLE II

Summary stream flow data for the four rivers

River	Drainage basin area (km^2)	July 1996 maximum instantaneous flow (m^3s^{-1})	July 1996 maximum daily flow (m^3s^{-1})	Historic maximum daily flow with date of flow (m^3s^{-1})	Mean annual discharge (m^3s^{-1})
Chicoutimi	~ 3 500	1 100[a]	~ 1 080[b]	532[c,d] (June 16, 1942)	49[c]
Riv. aux Sables	~ 3 500	653[a]	~ 600[b]	259[e] (May 1912)	24[e]
Riv. du Moulin[f]	373	393[g]	-	-	-
Riv. à Mars[f]	660	445[g]	-	-	-

[a]CSTGB (1997).
[b]estimated from the hydrograph depicted in Fig. 5.
[c]based on 1910 to 1994 discharge record (provided by R. Couture, Milieu Hydrique, Environnement et Faune Québec, written comm., 1997).
[d]Water Survey of Canada (1992) also reports a maximum daily flow of 532 m^3s^{-1} for this day, but Environnement et Faune Québec (1997) reports a maximum daily flow of 631 m^3s^{-1}.
[e]based on 1912 to 1994 discharge record (provided by R. Couture, Milieu Hydrique, Environnement et Faune Québec, written comm., 1997).
[f]this river is not gauged.
[g]estimate based on hydrologic modeling of the storm runoff (after CSTGB, 1997).

400 m wide, and the sinuosity was reduced from 1.2 to about 1.0 (Figs. 6 and 7). The post-flood river flow was divided into multiple branches within a broad flood channel, and exhibited a braided planform (Fig. 8). The greatest amount of channel widening occurred between km 8.75 and 8.25, km 7 and 3.75, and at km 1.75 (Fig. 7). Between km 3.9 and 3.4, a broad channel along the right side of the valley bottom was re-activated, causing partially stripping of and localized deposition on the floodplain. This re-activated channel did not fully develop and remained perched on the floodplain above the level of the main channel after the flood waned. Below km 0.5, channel widening was hindered by the presence of rip-rap armouring of the river banks. Sediments eroded from the study reach and upstream areas were carried into the Baie des Ha! Ha!, aggrading the tidal flats off the river mouth.

The large-scale widening of the Rivière à Mars channel was the product of reworking of the floodplain and the lateral erosion of terraces along the valley bottom. Although complicated by the large-scale erosion and re-organization of the river, close inspection of the pre- and post-flood imagery reveals that the channel widening was the product of several common riverine processes (Fig. 6b). These include: concave bank erosion that caused the expansion and downstream migration of pre-flood meanders; lateral erosion along the margins of the channel; avulsions that created new channels between successive river meanders causing meander cut-offs; and bank erosion along re-activated, abandoned and inactive channels. At some locations, the widening was the product of a combination of these processes, which operated either concurrently or successively. Along the right valleyside at km 7.5, concave bank erosion caused the collapse of an overlying slope over a distance of about 270 m, exposing a thick sequence of deltaic sand and gravel underlain by fine-grained, marine sediment.

In marked contrast to the à Mars study reach, there was negligible channel widening along the alluvial sections of the Rivière du Moulin (Fig. 3c). Where present, erosion was generally confined within the pre-flood channel margins and, commonly, stranded flood debris and sediment coloration of vegetation on the floodplain were the only obvious evidence of the flood. Between km 9.7 and 3.2, there was scouring and/or cutbank erosion at the lower slopes along the outer banks of a number of sharp bends along short alluvial (as well as non-alluvial and bedrock) sections of the river, but negligible bank retreat. Similarly, along the Rivière Chicoutimi study reach, there was negligible widening along the alluvial sections of the channel. Although it did not affect the channel margins, notable erosion occurred at a sharp bend located at km 14 where an elongated scour hole, about 95 m long, was eroded into the floodplain surface along the left side of the valley (Brooks and Lawrence, Fig. 6, 1998). The scour hole was eroded by macroturbulence (*e.g.*, Miller and Parkinson, 1993) during the flood and represents an intermediate stage in the development of a chute channel across the meander.

NON-ALLUVIAL AND BEDROCK REACHES

Non-alluvial, bedrock, and combined bedrock/non-alluvial sections form the dominant morphologies along the Rivière aux Sables and Rivière Chicoutimi and significant morphologies along the Rivière du Moulin (Fig. 3a, b, and c). Significant geomorphic change occurred at only isolated locations along these sections of the rivers. Much more typically, the outer margins of the river channels were unchanged or along the steeper reaches (Fig. 3) floodwaters scoured the channel perimeter exposing bedrock and marine sediments along and immediately adjacent to the pre-flood channel margin. A prominent trimline in the vegetation adjacent to the channel commonly marked the limit of scouring, as occurred along the Rivière du Moulin (including the alluvial reaches) between km 6.5 and 5.5, km 5.2 and 4.8, km 4.7 and 4.2, and km 3.2 and 0.7, and the Rivière Chicoutimi between km 2.9 to 0.7.

As examples of locations that experienced more notable geomorphic change, along the Rivière du Moulin study

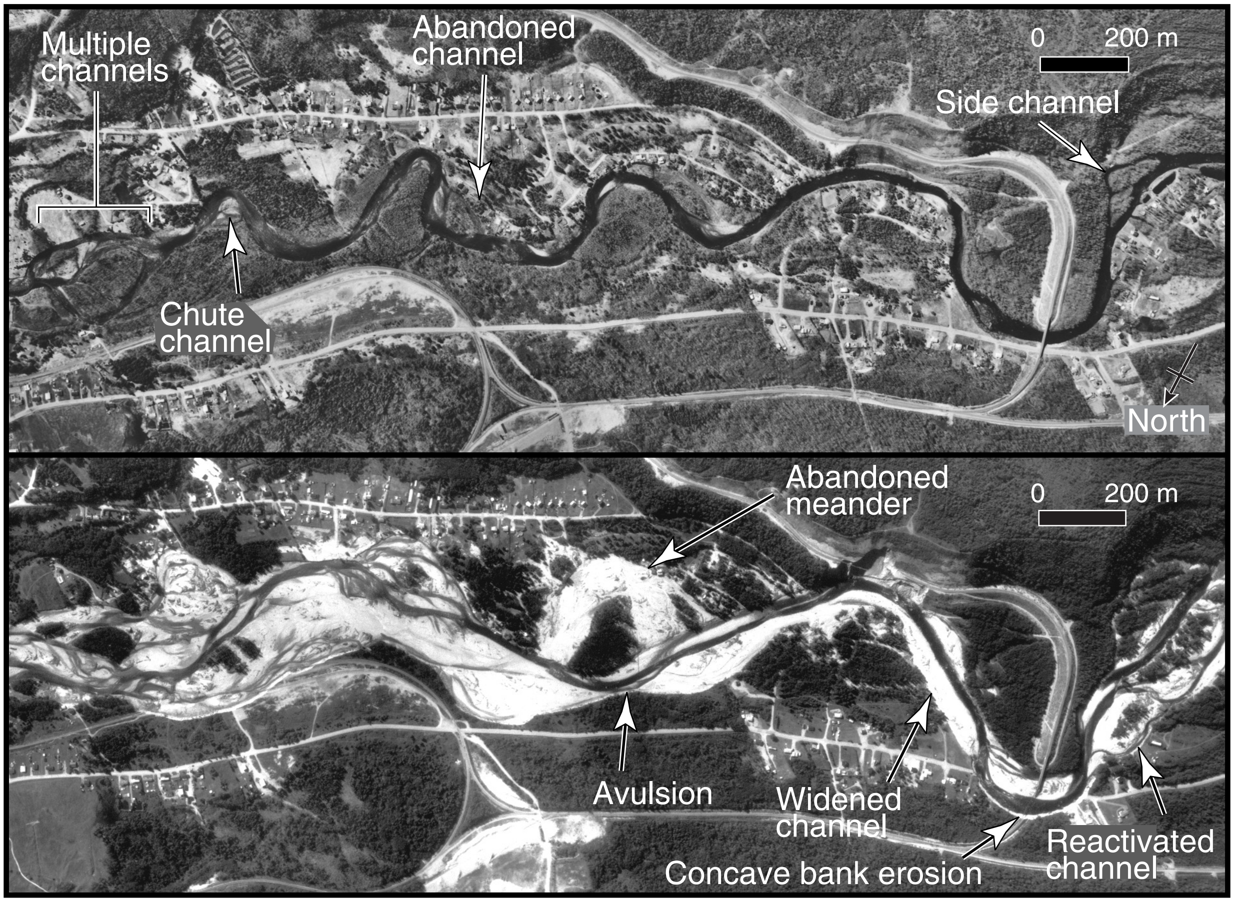


FIGURE 6. Pre-flood (above) and post-flood (below) aerial photographs of the Rivière à Mars between km 8.2 and 5.5; the river flows from right to left (aerial photographs HMQ94-119-231, taken May 24, 1994; Q96304-48, taken July 30, 1996; reproduced with permission of Hauts-Monts Inc., and Photocartothèque québécoise, Ministère des Ressources naturelles, Québec, respectively). Note, the substantial change in the width of the channel between the pre- and post-flood photographs. Examples of fluvial features common to a transitional meandering–braided channel morphology are shown on the pre-flood aerial photograph. Examples of locations along the post-flood channel where specific fluvial processes can be attributed to the channel widening are labeled on the post-flood aerial photograph.

Photographies aériennes montrant le tronçon de la rivière à Mars situé entre les kilomètres 8,2 and 5,5, avant (en haut) et après (en bas) la crue (photographies aériennes HMQ94-119-231, prise le 24 mai 1994, et Q96304-48, prise le 30 juillet 1996 ; reproduites avec la permission de Hauts-Monts Inc. et de la Photocartothèque québécoise, ministère des Ressources naturelles du Québec, respectivement). Noter la grande différence de la largeur du lit dans les deux photographies. La photographie prise avant la crue donne des exemples de formes fluviatiles caractéristiques de la morphologie de transition entre rivière à méandres et rivière réticulée. La photographie prise après l'inondation montre les lieux où certains processus fluviatiles peuvent être attribués à l'élargissement du lit.

reach, up to about 40 m of lateral bank erosion occurred adjacent to and immediately downstream of a short bedrock rapids located within Laterrière between km 19.1 and 18.8 (Fig. 2c). At km 4.9, the development of a cut-off channel caused the abandonment of a sharp meander along a section of river that is entrenched into marine sediments (Fig. 9a). The cut-off occurred when floodwaters overtopped and incised a narrow (about 14 m wide) land bridge or gooseneck. Near the river mouth at km 0.8, a channel avulsion caused the abandonment of about 200 m of bedrock channel when floodwaters overtopped and incised surficial sediments along the outer bank of an artificial(?) pool at a sharp bend in the river (Fig. 9b). Derived of material from the avulsion as well as channel scouring upstream, a compound gravel bar, about 300 m long and up to 90 m wide, was deposited at the mouth of the new channel, beginning at km 0.7, where there is a marked decrease in gradient (Fig. 3c). Also, immediately at the mouth of the avulsed channel, there was up to about 60 m of lateral erosion of a terrace along the right bank of the river.

Along the Rivière Chicoutimi study reach between km 19.6 and 19.4, floodwaters spilled across a low-lying bedrock surface, scouring a thin layer of overburden along the right channel where the river is divided by a bedrock island. Along the Rivière aux Sables, up to about 20 m of lateral bank erosion occurred along the left bank of a non-alluvial channel between km 8.6 to 8.4. This bank erosion was caused by a high velocity current that extended downstream from a rapids located immediately upstream, between

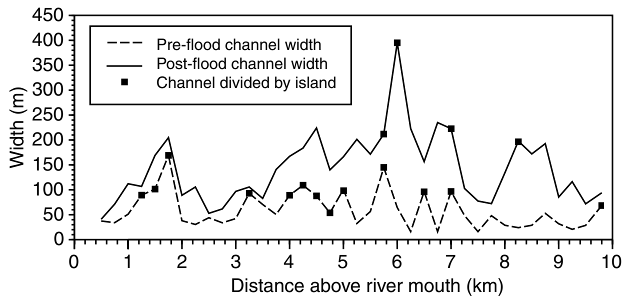


FIGURE 7. Pre- and post-flood channel widths along the Rivière à Mars study reach at 0.25 km intervals. The total width of channel is depicted where it is divided by vegetated islands. The common points of measurement between the pre- and post-flood widths are approximate along the sections of the river where there was large-scale erosion. In all cases, width was measured perpendicular to the channel axis.

Largeurs du lit avant et après la crue à intervalles de 0,25 km dans le tronçon d'étude de la rivière à Mars. La largeur totale du lit est donnée là où il est divisé par des îles portant une végétation. Dans les tronçons où la rivière est très érodée, les repères de mesure avant et après la crue sont approximatifs. Dans tous les cas, la largeur a été mesurée perpendiculairement à l'axe du lit.

FIGURE 8. Oblique photograph of the post-flood channel of the Rivière à Mars looking upstream of km 8. Note, the multi-channeled character of the river and the broad width of the "flood" channel relative to that of the post-flood flow. Photograph taken July 29, 1996.

Photographie oblique du lit de la rivière à Mars présentant une vue en aval du kilomètre 8. Noter les multiples chenaux ainsi que la grande largeur du lit de « crue » par rapport au lit d'après crue. Photographie prise le 29 juillet 1996.

km 9.3 and 8.6. A series of sand and gravel mid-channel, side, and point bars were aggraded between km 8.3 and 7.2. This deposition is attributed to sediments derived from the aforementioned bank erosion that occurred upstream as well as from bed scouring. Near the river mouth, a short non-alluvial section of channel located between km 0.6 and the river mouth (km 0), was widened from 20-30 m to 60-130 m.

DAMS

The most severe geomorphic effects along the Rivière aux Sables and Rivière Chicoutimi occurred locally at run-of-the river dams. At four of the seven run-of-the river dams, the Jonquière (km 3.2) and Chute-à-Besy (km 1.1) dams on the Rivière aux Sables (Fig. 2a) and the Chute-Garneau (km 7.3) and Pont-Arnaud (km 4.9) dams on the Rivière Chicoutimi (Fig. 2b), floodwaters overtopped and incised an area immediately adjacent to each dam, breaching the impoundment, and diverting the entire river flow into a newly-eroded channel course. The new channels rejoined the river downstream of the dams over distances ranging from several 10s of metres (Chute-Garneau dam) to about 500 m (Chute-à-Besy dam). Following the flood, all four dams were intact, but non-functional, as the level of the diverted flow was below the base of the dams. Exemplifying the severe erosion at these dams, pre- and post-flood photo-stereograms of the Pont-Arnaud dam are depicted in Figure 10, and an oblique photograph of the Chute-à-Besy dam is shown in Figure 11. Oblique photographs of the other two dams can be found in Brooks and Lawrence (1998).

The incision at the breaches occurred into cohesive, fine-grained marine sediments, although at the Chute-à-Besy dam, floodwaters initially overtopped and incised an earthen dike (up to 6 m high and 180 m wide). At each location, the incision was arrested by bedrock, except at the Pont-Arnaud dam where it was arrested by a combination of bedrock and marine sediments. The breachings occurred progressively over a period of hours at at least three of the dams (CSTGB, 1997) and did not produce outburst floods downstream. At the Chute-à-Besy dam, the initial stages of incision occurred into an earthen dike (as mentioned above) that conceivably could have eroded much more rapidly relative to the other sites. However, we are not aware that the incision of the dike generated a flood wave downstream that significantly exceeded the overall peak flood discharge along the Rivière aux Sables.

The formation of the new channels adjacent to the dams resulted in maximum lateral erosion of a valleyside that ranged from 55 m (Jonquière and Chute-Garneau dams) to 110 m (Chute-à-Besy dam), and extended over distances along the river varying between 325 m (Jonquière dam) to 550 m (Chute-à-Besy dam). The maximum depths of incision ranged from 15 to 25 m (CSTGB, 1997). The valleyside erosion caused the loss of property at all four dams, and it undermined several apartment buildings adjacent to the Jonquière dam and an industrial building at the Chute-à-Besy dam, causing the buildings to partially or totally collapse into the river. Immediately below the breach at the Chute-à-Besy dam, the diverted river flow scoured a bedrock surface over a distance of 300 m before re-entering the pre-flood river channel.

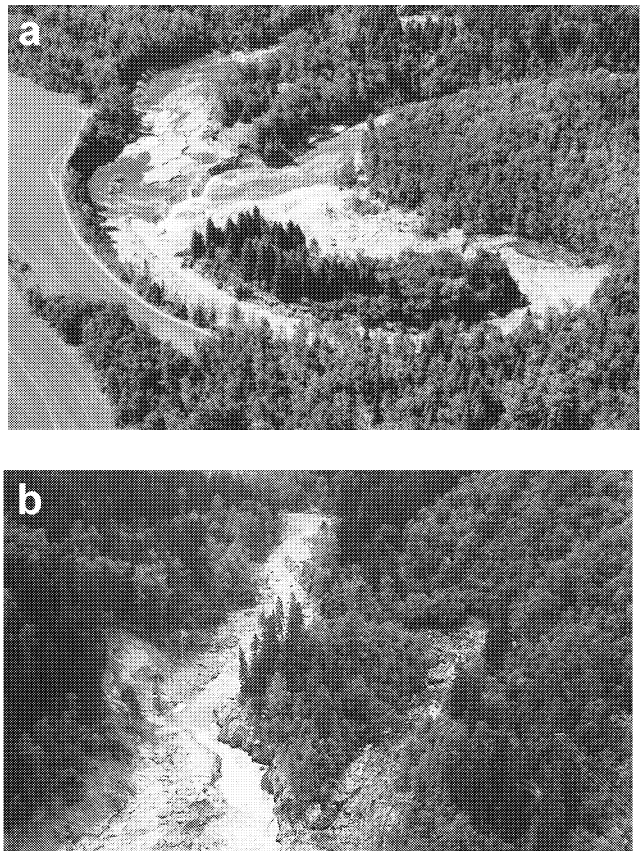


FIGURE 9. a) Meander on the Rivière du Moulin (km 4.9) that was cut-off and abandoned during the flood. The overtopping and erosion of a narrow section of land about 14 m wide caused the cut-off. Note, the knickpoint, about 2 m high, present at the head of the cut-off channel that is developed in marine sediments. Photograph taken July 27, 1996. b) Avulsion near the mouth (between km 0.8 and 0.7) of the Rivière du Moulin that resulted in the abandonment of a bedrock section of channel. Photograph taken July 27, 1996.

a) Méandre de la rivière du Moulin (kilomètre 4,9) abandonné pendant la crue en raison de la submersion et de l'érosion d'une étroite bande de terre d'environ 14 m de largeur. Noter, à la tête du méandre abandonné, le dénivelé d'environ 2 m de haut qui s'est formé dans des sédiments marins. Photographie prise le 27 juillet 1996. b) Coupure de méandre près de l'embouchure de la rivière du Moulin (entre les kilomètres 0,8 et 0,7) qui a entraîné l'abandon d'une partie du chenal creusée dans le substratum. Photographie prise le 27 juillet 1996.

The incision of the channels beside the dams lowered local base level and steepened the water surface of the rivers upstream over distances ranging from about 1.1 (Chute-à-Besy dam) to 2.8 km (Jonquière and Chute-Garneau dams). The most conspicuous effects of the drop in base level occurred at the Pont-Arnaud dam where a knickpoint developed at the breach within cohesive marine sediments, and migrated upstream a distance of about 1.2 km. This migration excavated a "gorge", several metres deep and 25 to 120 m wide, into the bed of the drained reservoir, forming a striking post-flood erosional feature (Fig. 10b). The erosion of this gorge was confined primarily to the reservoir bed except along the left bank between km 5.4 and 5.0 where there was up to 15 m of lateral bank retreat. The combination of knickpoint incision, which oversteepened the river banks, and drawdown of the reservoir, triggered several landslides along the valleyside; the largest was about 2 100 m^2 (Fig. 10b).

Far less striking in comparison, upstream of the Jonquière dam, the reservoir bed was scoured as water levels fell. As a direct result, the left abutment of a railway bridge located about 400 m upstream of the dam, was eroded and a support pier was undermined and tilted (Brooks and Lawrence, Fig. 11, 1998). Also, bank erosion adjacent to the left bank immediately upstream of the bridge triggered a shallow retrogressive landslide about 75 m wide.

The erosion of the channels adjacent to the four dams also introduced a significant quantity of sediment into the river channels. Estimates of the volume of materials eroded are available for the Chute-Garneau and Pont-Arnaud dams, and are 147 000 and 750 000 m^3, respectively (CSTGB, 1997). The geomorphic effects, however, were limited to only the immediate downstream section of the river. Bed materials formed compound side bars immediately downstream of these two dams covering areas of about 5 000 (Pont-Arnaud dam; Fig. 10b) and 10 000 m^2 (Chute-Garneau dam). This aggradation occurred within broad, irregularly-shaped, non-alluvial sections of the river, and the development of the bars did not precipitate erosion of a valleyside by significantly deflecting the river current. Below the Jonquière dam, the eroded sediment aggraded the bed of the reservoir basin of the Ville de Jonquière dam (2.6 km) located immediately downstream. Below the Chute-à-Besy dam, coarse bed materials derived from the erosion of the breach, scoured from the reservoir bed, and eroded from a short non-alluvial channel below the dam, formed an alluvial fan at the river mouth that splayed about 150 m into the Rivière Saguenay channel.

Severe erosion also occurred adjacent to the Chicoutimi dam, Rivière Chicoutimi (km 0.6; Fig. 2b), but there was no breach of the impoundment. During the flood, water overtopped the buttressed concrete wing-wall that extends to the right of the control structure, and spilled into a residential-commercial area of downtown Chicoutimi (Fig. 12). The water cascaded downvalley along the steep local slope stripping overburden from the bedrock, scouring road beds, and damaging and destroying buildings prior to rejoining the river channel. This erosion created an "overflow" channel, about 290 m long, through the subdivision (Fig. 12). At the mouth of the overflow channel, debris and coarse sediment formed a bar that prograded about 90 m into a broad, non-alluvial section of channel. Just downstream of the bar, flow from the overflow channel was directed towards the right valleyside causing up to about 60 m of bank erosion over a distance of about 250 m.

BRIDGES

As commonly occurs during major floods, numerous bridges were damaged to varying degrees by floodwaters along all four study reaches. In extreme cases, large-scale bank erosion was underway in the general area independent

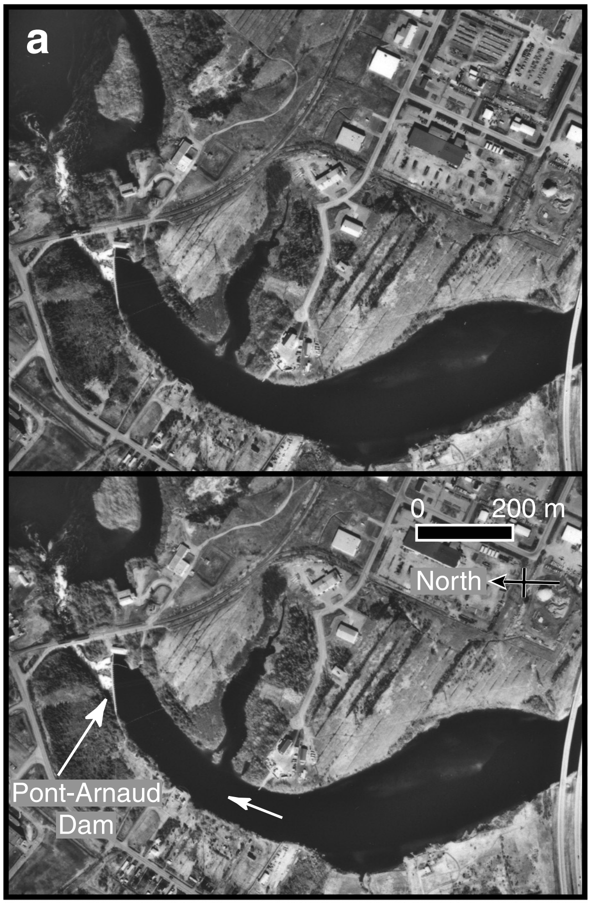


FIGURE 10. a) Pre- and b) post-flood photostereograms of the Pont-Arnaud dam (aerial photographs HMQ94-116-214, -215, taken May 23, 1994; Q96304-23, -24, -25, taken July 30, 1996; reproduced with permission of Hauts-Monts Inc., and Photocartothèque Québécoise, Ministère des Ressources naturelles, Québec, respectively). In the post-flooded images (b), the river flows within the breach channel and by-passes the dam. Note the "gorge" incised into the bed of the drained reservoir, the active knickpoint at the head of the gorge and two dry knickpoint near the head of the gorge. Arrows mark the Pont-Arnaud dam and a landslide that developed along an oversteepened river bank.

Stéréogrammes du barrage du Pont-Arnaud a) avant et b) après la crue (photographies aériennes HMQ94-116-214 et -215, prises le 23 mai 1994, ainsi que Q96304-23, -24 et -25, prises le 30 juillet 1996; reproduits avec la permission de Hauts-Monts Inc. et de la Photocartothèque québécoise, ministère des Ressources naturelles du Québec, respectivement). Dans les images prises après la crue (b), la rivière emprunte le chenal de contournement du barrage. Remarquer la « gorge » encaissée dans le lit du réservoir asséché, la rupture de pente active à la tête de la gorge et deux ruptures de pente à sec près de la tête de la gorge. Noter les flèches qui identifient le barrage du Pont-Arnaud et un glissement de terrain qui s'est produit le long d'une berge très escarpée de la rivière.

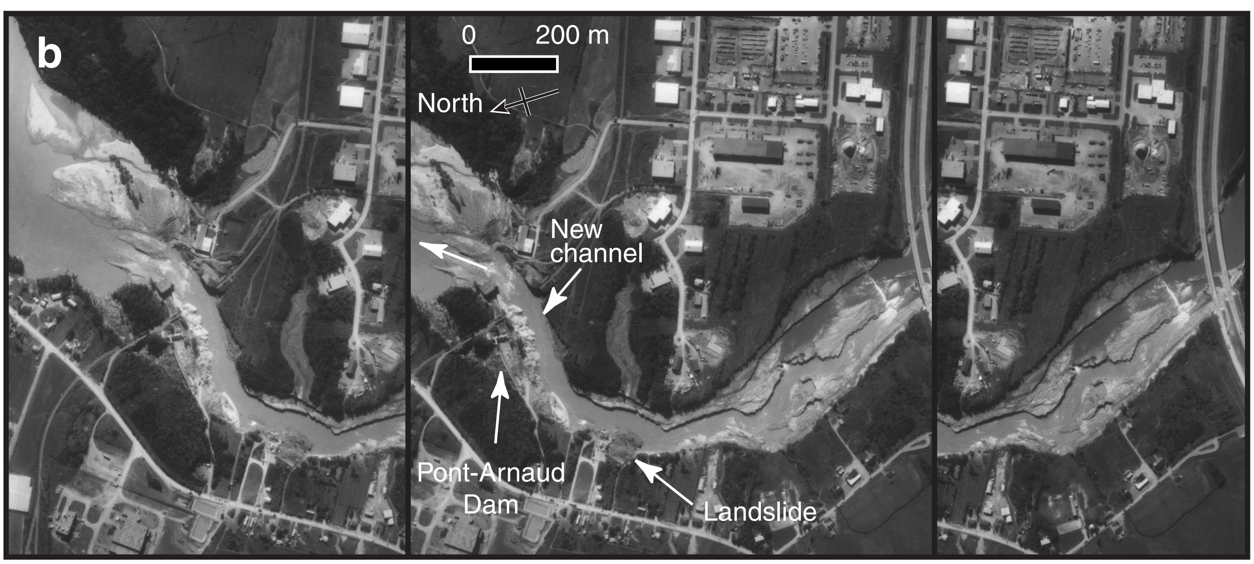


FIGURE 11. Post-flood view of the Chute-à-Besy dam, taken on July 26, 1996. The entire flow of the river has been diverted through the breach, as discussed in the text. The intact, but non-functional dam is marked by an arrow.

Photographie (prise le 26 juillet 1996) du barrage de la Chute-à-Besy après la crue. Le cours entier de la rivière a été dérivé vers la brèche, comme le décrit le texte. Le barrage intact mais non fonctionnel est identifié par la flèche.

FIGURE 12. Post-flood view of the Chicoutimi dam located in downtown Chicoutimi, taken on July 26, 1996. During the flood, floodwaters overtopped the buttressed concrete wing-wall of the dam that extends to the left of the control structure in the photograph, and flowed rapidly through the residential-commerical area situated immediately down slope. Along the flow path, overburden and road beds were scoured in places to bedrock, and buildings were washed away or damaged. A bar composed of bed materials extends into the pre-flood channel (bottom centre right of photograph), where the flood flow re-entered the river .

Photographie (prise après la crue, le 26 juillet 1996) du barrage de Chicoutimi, situé au centre-ville de Chicoutimi. Ayant submergé l'aile de béton à pilastres qui s'étend à gauche du barrage, les eaux de crue se sont rapidement écoulées dans le secteur résidentiel et commercial situé immédiatement en contrebas. Le long de leur trajet, les eaux de crues ont affouillé les matériaux non consolidés, érodé les assises de routes, parfois jusqu'au soubassement rocheux et ont emporté ou endommagé des bâtiments. Un banc composé de matériaux du lit s'étend jusqu'au chenal d'avant crue (en bas, au centre droit de la photographie), là où l'écoulement érosif réintégrait la rivière.

of the presence of a bridge, and resulted in the washing out of an abutment or pier, causing a bridge span to partially collapse into the river. Examples of this occurred at bridges on the Rivière à Mars at km 7.9 and 2.9, and on the Rivière aux Sables at km 0.1. There were a number of locations, however, where the interaction between the bridge and the flood flow resulted in localized erosion. For example, adjacent to a bridge at km 19.3 on the Rivière du Moulin (Fig. 2c), there was up to about 9 and 13 m of bank erosion along the left and right banks, respectively. At Chute-à-Martel falls (km 8, Rivière du Moulin; Fig. 2c), a bridge was overtopped when the flood waters were partially obstructed by the bridge structure. The overtopping flow washed out the road approaches and severely damaged two residential buildings located beside the river, where the channel is contained within a narrow bedrock gorge (Brooks and Lawrence, Fig. 13, 1998). On the Rivière Chicoutimi, scouring occurred laterally along the left bank both upstream (up to about 40 m) and downstream (up to about 15 m) of a bridge located at km 6.7 (Fig. 2b). Below the bridge, the erosion probably arose because of the marked constriction of flow by the bridge abutments combined with a local steepening of channel gradient over bedrock.

DISCUSSION

The geomorphic effects of flooding varied significantly among the four study reaches. The large-scale lateral bank erosion and floodplain stripping along the Rivière à Mars study reach represents "catastrophic" change since the pre-existing alluvial channel morphology was altered completely, except below km 0.5 due to bank armouring. Qualitatively, this indicates that the erosive threshold of the valley bottom was exceeded during the flood. Conversely, the negligible or limited erosion along the alluvial sections of the Rivière du Moulin and Rivière Chicoutimi attests that the erosive threshold was not exceeded at these locations.

Investigations of alluvial streams eroded extensively during extreme floods suggest a minimal erosive threshold of about 300 Wm^{-2}, expressed as unit stream power (ω), for large-scale bank erosion and floodplain stripping to ensue (Miller, 1990; Magilligan, 1992; Lapointe *et al.*, 1998). That this minimal threshold was obtained or exceeded along the à Mars study reach can be assessed quantitatively using the following equation, after Baker and Costa (1987):

(1) $$\omega = \gamma QS/w$$

where, "γ" is specific weight of water (assumed to be 9 800 Nm^{-3}, the value for clear water), "Q" is discharge (m^3s^{-1}), "S" is energy slope (assumed to be reasonably similar to the pre-flood valley slope; see Magilligan, 1988), and "w" is width of the flood flow (m). Of these variables, for the Rivière à Mars study reach, "Q" is defined in Table II, "S" derived from the longitudinal profile in Figure 3d, and "w", represented by the width of the alluvial valley bottom (*i.e.*, the floodplain), as measured from pre-flood aerial photographs. Use of valley bottom width does produce a conservative estimate of "ω" since the flood flow may not have inundated the entire valley bottom along all sections of the study reach. However, since the minimal erosive threshold for alluvial channels ("ω_{thres}") has been estimated to be 300 Wm^{-2} (see references above), equation 1

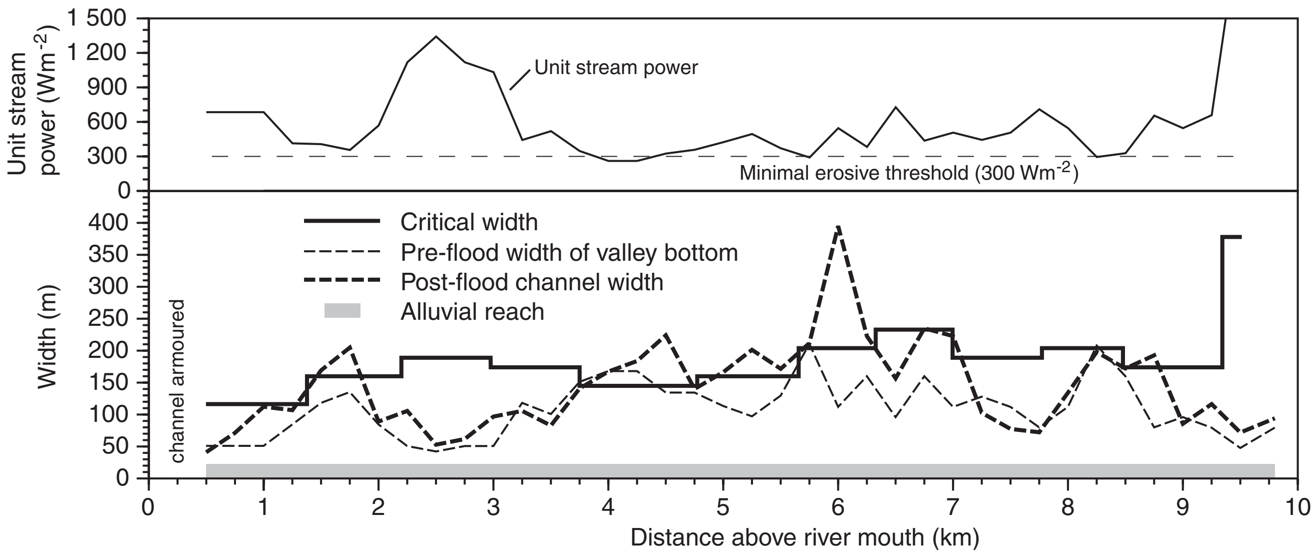


FIGURE 13. Plots depicting unit stream power, critical width (defined in the text), pre-flood width of the valley bottom, and post-flood channel width along the Rivière à Mars study reach. Note that unit stream power exceeds the minimal erosive threshold of 300 Wm^{-2}, as defined in the literature, over most of the study reach, as discussed in the text. Despite there having been substantial widening of the river channel, flow remained above the erosive threshold along those sections of the river where the post-flood channel width plots below the critical width.

Diagrammes de la puissance unitaire du cours d'eau, de la largeur critique (définie dans le texte), de la largeur du fond de vallée d'avant crue et de la largeur du lit d'après crue, le long du tronçon d'étude de la rivière à Mars. Noter que la puissance unitaire du cours d'eau dépasse le seuil minimal d'érosion de 300 Wm^2, tel que défini dans la littérature, sur la plus grande partie du tronçon (voir le texte). Même si la rivière s'est considérablement élargie, l'écoulement dépasse toujours le seuil d'érosion dans les tronçons où la largeur du lit après crue est inférieure à la largeur critique.

can be re-arranged to define a critical width (w_{crit}), at or below which flow is sufficiently concentrated to have a unit stream power that equals or exceeds the minimal erosive threshold. Equation 1, therefore, becomes:

$$w_{crit} = \gamma QS/\omega_{thres} \quad (2)$$

Expressing the minimal erosive threshold as "w_{crit}" produces a quantity that can be readily compared to the pre- and post-flood morphologies of the valley bottom and channel, respectively. This allows a comparison of the channel widening and flow energy from which factors affecting the degree of lateral erosion can be identified.

The estimated "ω" and "w_{crit}" along the Rivière à Mars study reach are depicted in Figure 13. "ω" ranges from a minimum of 260 Wm^{-2} to greater than 1 500 Wm^{-2}. However, the minimal erosive threshold of 300 Wm^{-2} was exceeded or approximately equaled along most of the study reach, as is consistent with the occurrence of large-scale erosion during the flood. An exception occurs along a short section between km 4.3 and 3.9, where "ω" fell to 260 Wm^{-2}, but which also experienced large-scale widening consistent with that immediately upstream and downstream. With "w_{crit}" the stepped character of the plot reflects the variation in averaged valley slope along segments of the study reach as defined by contour lines on the topographic map. Depicted with "w_{crit}" is the pre-flood width of the valley bottom and the post-flood channel width as measured at 0.25 km intervals from pre- and post-flood aerial photographs, respectively.

Channel widening during a flood represents the adjustment of the channel cross-section to accommodate the flood flow as well as dissipating flow energy by creating a broader, shallower flow (*i.e.*, higher channel width/depth ratio). Along the à Mars study reach, channel widening occurred to varying degrees. In Figure 13, the post-flood channel width exceeds or approaches "w_{crit}" between about km 8.75 to 8.25, km 7 to 3.75 and km 2 to 1, indicating that channel widening resulted in the dissipation of "ω" to or below the minimal erosive threshold. Of note, at km 6, where the post-flood channel far exceeded "w_{crit}" (about 400 versus 200 m, respectively), the "excessive" width reflects an avulsion and the abandonment of a meander as well as the presence of a large island of remnant floodplain that divides the post-flood channel.

In contrast, the post-flood channel width is significantly below "w_{crit}" between km 9.8 and 8.75, km 8.25 and 7, km 3.75 and 2, and at km 0.5, revealing "limited" channel widening even though "ω" remained above the minimal erosive threshold. These sections correspond to where the channel margins are armoured (specifically at km 0.5), the valley bottom is constricted by relatively high terraces (5-15 m), and/or the outer bank of a bend is confined directly against a valley side. In the latter two instances, lateral bank erosion was impeded by higher banks and, in places, more resistant bank material where fine-grained marine sediments became exposed at the base of a bank. Bank height is a factor controlling the rate of lateral bank erosion because a greater amount of material must be removed by the flow for each unit of lateral bank retreat (*e.g.*, Hickin and Nanson, 1984). Although a function of the flow energy, the amount of channel widening that occurred at any given location ultimately reflected the pre-flood morphology of the valley bottom

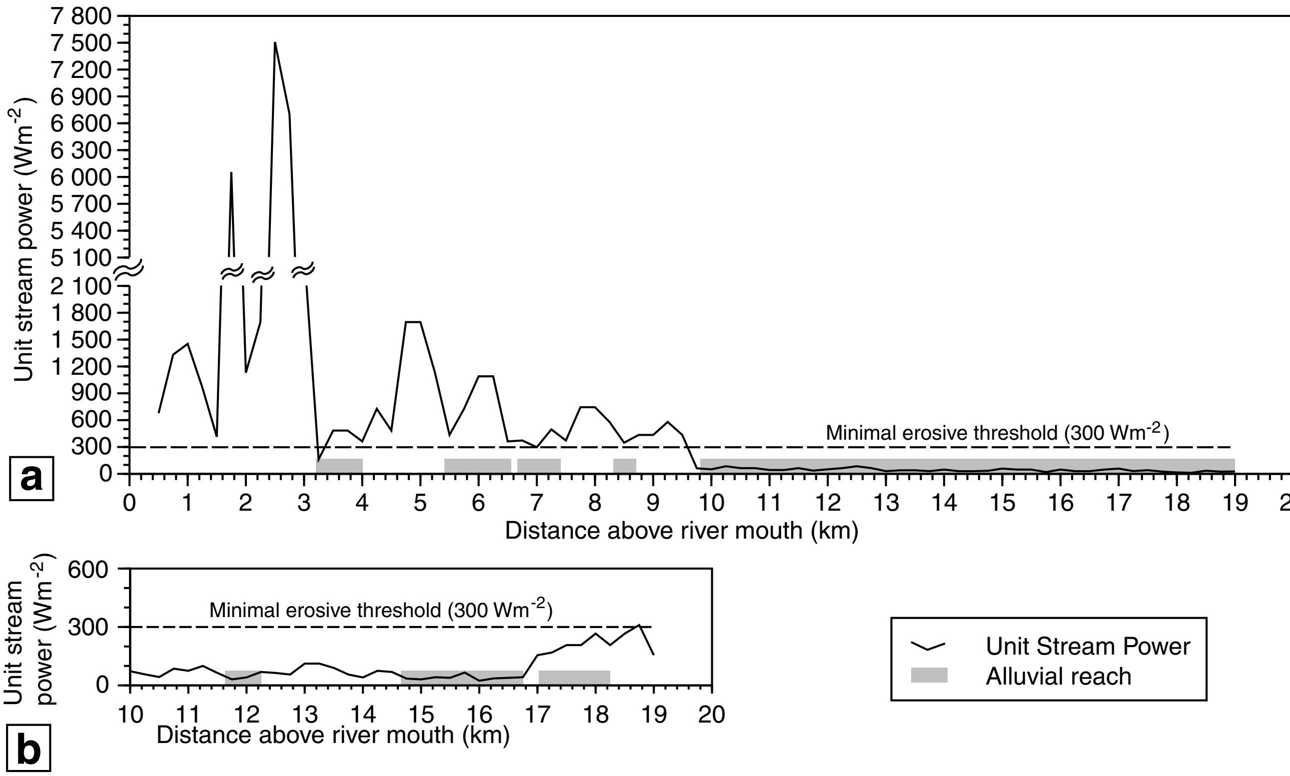


FIGURE 14. Plots depicting unit stream power along alluvial sections of the a) the du Moulin and b) Chicoutimi study reaches. The calculated unit stream power for the alluvial sections along the Rivière Chicoutimi and the Rivière du Moulin between km 19 and 9.8, fall below the minimal erosive threshold (300 Wm^{-2}) as is consistent with the observed lack of large-scale erosion. Below km 9.8 along the Rivière du Moulin, the minimal erosive threshold was generally exceeded across the relatively short alluvial sections. Reasons for the lack of large-scale erosion are discussed in the text.

Diagrammes de la puissance unitaire du cours d'eau le long des parties alluviales des tronçons d'étude des rivières a) du Moulin et b) Chicoutimi. La puissance unitaire du cours d'eau calculée pour les tronçons alluviaux de la rivière Chicoutimi et de la rivière du Moulin, entre les kilomètres 19 et 9,8, est inférieure au seuil d'érosion (300 Wm^2), conformément en cela à nos observations quant à l'absence d'érosion à grande échelle dans ces tronçons. En aval du kilomètre 9,8 le long de la rivière du Moulin, le seuil minimal d'érosion a généralement été dépassé le long des tronçons alluviaux relativement courts. Le texte explique pourquoi il n'y a pas eu d'érosion à grande échelle.

with the greatest widening occurring along the broad, low-lying sections. Since there was limited dissipation of flow energy through channel widening, these four sections may have experienced incision during the flood, but this is not readily apparent from our observations, and can only be assessed from a detailed analysis of the pre- and post-flood topographies of the valley bottom.

For comparative purposes, "ω" along the alluvial sections of the Rivière du Moulin and Rivière Chicoutimi is depicted in Figure 14. For the Rivière Chicoutimi, it should be noted that the actual width of the flood was used to determine "ω" rather than valley bottom width, using maps of the flood extent in INRS-Eau (1997). With the Rivière du Moulin, flow along the gently-sloped section of the river between km 19 and 9.8 is well below the minimal erosive threshold (300 Wm^{-2}), ranging from 12 to 85 Wm^{-2} (Fig. 14a), as is consistent with the lack of large-scale erosion along this portion of the river. Downstream of km 9.8, "ω" is consistently above the minimal erosive threshold, however, there was no large-scale erosion along the relatively short alluvial sections. The lack of large-scale erosion may reflect an actual erosive threshold along the alluvial sections that is higher than 300 Wm^{-2} (*i.e.*, the minimal erosive threshold defined in the literature), but it is also possible that "ω" across these sections is overestimated and falls below 300 Wm^{-2}. Below km 9.8, the river morphology alternates between relatively short sections of alluvial, non-alluvial, bedrock, and combined non-alluvial/bedrock (Fig. 3c), all of which have variable gradients with the alluvial sections having the lowest gradient (as is apparent stereoscopically on aerial photographs). As mentioned in the Methodology section, the gradients along the relatively short, more gently-sloped sections of the river will be overestimated in the profile defined by the 10 m contour lines. This in turn produces an exaggeration of "ω" in Figure 14 across these same sections. Regardless of the specific reason, the lack of large-scale erosion along the alluvial reaches downstream of km 9.8 clearly indicates that the actual erosive thresholds were not exceeded during the flood.

Along the Rivière Chicoutimi study reach, "ω" was below the minimal erosive threshold (300 Wm^{-2}) across the three alluvial sections of channel (Figs. 3b and 14b). Between km 16.75 and 14.75, and km 12.25 and 11.75, “ω” ranged from 24 to 69 Wm^{-2}, but was higher between km 18.25 and 17 (155 to 266 Wm^{-2}). Along all three sections, the limited geomorphic effects of the flood were consistent with “ω” being below the minimal erosive threshold.

The large-scale widening along the Rivière à Mars study reach transformed the channel morphology into a braided planform. Such planform transformations commonly are attributed to river morphologies that are transitional between meandering and braided (*e.g.*, Ferguson, 1987) whereby a major flood imposes a change in regime on the channel (Desloges and Church, 1992). Following the flood, the channel will recover and revert to its pre-flood morphology, assuming there is a sufficient period before the recurrence of another extreme flood (Wolman and Gerson, 1978; Nanson, 1986). A river reach can be identified as transitional qualitatively by the presence of channel features suggestive of a transitional morphology (Mollard, 1973; Ferguson, 1987), and quantitatively using empirical planform discriminate equations based on slope-discharge relationships (Thorne, 1997).

Close inspection of pre-flood aerial photographs reveals features along the Rivière à Mars study reach that are consistent with a transitional reach. These include split and multiple-channeled sections, small side channels, partially vegetated bars, and chute channels across some meanders (some of these are shown in Fig. 6a), none of which are attributable to an archetypal meandering planform. Thus, morphologically, the pre-flood channel of the Rivière à Mars seems to exhibit a transitional planform.

Supporting this qualitative interpretation using empirical discriminate equations is hindered by the absence of data on the size of pre-flood bed material along the à Mars study reach and, more significantly, by the lack of a slope-discharge discriminate equation based on regional eastern Canadian rivers. However, two equations that should be adequate to use are:

(3) $S \approx 0.065\, Q_{2f}^{-0.5}$ (after Desloges and Church, 1992)

(4) $S \approx 0.033\, Q_{2f}^{-0.44}$ (after Bray, 1982)

Both equations are derived from data sets consisting of western Canadian gravel-bed rivers and thus incorporate aspects of bed material size. Also, the equations discriminate between transitional and braided morphologies rather than between archetypal meandering and “braided” channels. Specifically, equation 3 differentiates braided and “wandering” gravel-bed channels (Desloges and Church, 1989) while equation 4 distinguishes braided channels from those divided intermittently by islands (Bray, 1982). For both equations, discharge (Q_{2f}) is represented by the 2-year flood while the products of the equations represent the threshold valley slope (S) above which a braided planform is expected to be present along an alluvial channel. Although there are no stream flow data for the Rivière à Mars, the 2-year flood of the Rivière des Ha! Ha!, which occupies a slightly smaller watershed immediately to the south of the Rivière à Mars (660 km^2 versus 572 km^2, at the location of the Rivière des Ha! Ha! gauging station), is 47 m^3s^{-1} (based on the 1977 to 1994 discharge record; R. Couture, Milieu Hydrique, written communication, 1996). Proportional to the difference in watershed area, the 2-year flood along the lower Rivière à Mars is estimated as 54 m^3s^{-1}. The predicted threshold slopes for braiding using this discharge are summarized in Table III.

The valley slope of the Rivière à Mars study reach is twice that predicted by equation 4 and slightly above that of equation 3 (Table III); both suggesting a braided morphology should be present along the study reach. That a braided morphology is predicted implies that the pre-flood à Mars channel was “near” the braided zone in the continuum of planform types. This supports the qualitative interpretation based on the pre-flood channel morphology, that the pre-flood channel was transitional between archetypal meandering and braided.

The lack of either a well developed braided or wandering morphology along the study reach probably reflects a much lower contemporary sediment supply than the western Canadian rivers on which equations (3) and (4) are based. The transitional channel morphology indicates that, with the advantage of hindsight, the à Mars study reach was vulnerable to a planform transformation during an extreme flood. Given a sufficient period of recovery to revert back to a similar pre-flood morphology, it must be expected that the river will again be vulnerable to severe widening and transformation into a braided planform during a subsequent flood of comparable magnitude. Major post-flood restoration of the valley bottom, including channel training, bank armouring, and back-filling and seeding of reworked floodplain areas (Ministère du Conseil exécutif Québec, 1997), has greatly accelerated the recovery process, but also altered the geomorphic setting to some degree, complicating the response of the river channel to a future extreme flood. Nevertheless, the response of the Rivière à Mars study reach to the July 1996 flood clearly demonstrates that there are reaches of Canadian Shield rivers systems that have transitional meandering-braided planforms and thus are vulnerable to large-scale channel widening and floodplain reworking during extreme flood events.

The July 1996 flood had an extraordinary impact at run-of-the-river dams on the Rivière aux Sables and Rivière Chicoutimi, where severe erosion occurred at five of the seven dams, far exceeding the severity of erosion elsewhere along these two study reaches. The occurrence of this erosion relates directly to the presence of the dams and was caused by floodwaters spilling across unconsolidated deposits or, in one case, an earthen dike, that were never intended to be overtopped by flow. It is not unreasonable to conclude that the resulting erosion far exceeded that which would have occurred at these sites had there been no dams. Yet surprisingly, two channel avulsions did occur at sharp bends on the lower Rivière du Moulin. This river may represent a less-developed example of the aux Sables and Chicoutimi study reaches because it has a similar longitudinal profile, but lacks the run-of-the-river dams.

The erosion at the run-of-the-river dams also provides conspicuous examples of the consequences of uncontrolled

TABLE III

Threshold slopes of braiding for the Rivière à Mars as defined by empirical equations

Equation	Discharge (m^3s^{-1})	Predicted valley slope at threshold of braiding	Average valley slope along the Rivière à Mars study reach
$S \approx 0.065\ Q_{2f}^{\ -0.5}$	54[a]	0.011	0.012
	445[b]	0.004	0.012
$S \approx 0.033\ Q_{2f}^{\ -0.44}$	54[a]	0.006	0.012
	445[b]	0.002	0.012

[a]2-year flood derived from the rivière des Ha! Ha! stream flow data (1977-1994; Milieu Hydrique, written communication 1996) and adjusted by the proportional difference in the watershed areas.
[b]estimate based on hydrologic modeling of the storm runoff (after CSTGB, 1997).

overtopping of dams and abutments during a major flood, as summarized in Table I. Of note, the Chute-Blanchette dam on the Rivière Chicoutimi (Fig. 2b) abuts bedrock, and consequently there was no major erosion problems when overtopped during the flood (Table I). At the four sites where the impoundments were fully breached, the dams were founded on bedrock and did not fail structurally. Coincidentally, the depth to bedrock was lower at the locations of the breaches than immediately under the dams. Incision into the unconsolidated deposits adjacent to the dams, thus could erode to a level deeper than the dam bases, causing the complete drainage of the reservoirs. At the Jonquière dam (Figs. 2a and 6), the new course of the river seems to have re-excavated a old pre-glacial(?) bedrock channel.

Jansen (1983) outlines that dam breaches can occur from one of a variety of reasons. Particularly relevant to dams on the aux Sables and Chicoutimi study reaches is the predicament of inadequate capacity for spilling due to a deficiency in either the spillway design or the operation of the spillway gates, and the blockage of gates by debris. The peak discharges of the Rivière aux Sables and Rivière Chicoutimi exceeded the maximum spilling capacities of six of the seven dams (Fig. 5). However, at many dams, the maximum spilling capacity was not available because all of the sluice gates had not been opened or could not be opened because of inoperative machinery, which, in some cases, had been damaged by flood waters (CSTGB, 1997). Also, the available spilling capacity became impaired by floating debris clogging the sluice gates (CSTGB, 1997). Thus, the flood discharges exceeded the available, but impaired, spilling capacity at all seven dams. The problem of insufficient spilling capacity (be it designed, available or impaired) at the Rivière aux Sables and Rivière Chicoutimi run-of-the-river dams clearly reveals that small dams are vulnerable to uncontrolled overtopping during an extreme flood and that severe localized erosion may be a consequence.

The general lack of severe erosion along the steeper non-alluvial, bedrock, and combined non-alluvial/bedrock sections of channel along the lower Rivière aux Sables, Rivière Chicoutimi and Rivière du Moulin is not related to low unit stream power. As exemplified in Figure 14a, it is clear that very high magnitudes of unit stream power were generated along the non-alluvial and bedrock section that far exceeded the minimal erosive threshold of 300 Wm^{-2} for alluvial channels, particularly below km 3. The lack of large-scale erosion is attributed to the presence of fine-grained marine sediments and bedrock that form a narrow conduit of resistant substrate along the valley bottom. Where the notable erosion did occur along the Rivière aux Sables, Rivière Chicoutimi and Rivière du Moulin, it was caused by the re-routing of floodwaters along low-lying bedrock areas, natural avulsions, and the interaction of flow with dams and bridges.

The two channel avulsions on the du Moulin study reach are noteworthy. These represent a significant geomorphic effect along a study reach similar to those along the Rivière aux Sables and Rivière Chicoutimi, yet lacking the run-of-the-river dams. The avulsions occurred on relatively steep sections of the river where it is entrenched into marine sediments, which form at least part of the channel perimeter. At the site of the meander cut-off (km 4.9) in pre-flood aerial photographs, there is a crescent-shaped indentation in the bank on the leeside of the narrow land bridge that separates the entrance and exit channels of the meander. This feature is interpreted to be a dry knickpoint (*i.e.*, dry water falls) eroded into marine sediments by waters overtopping the land bridge during previous floods. The cut-off that occurred in July 1996 thus represents the most recent erosion at this knickpoint although it did ultimately cut-off the meander. Immediately after the flood, knickpoint erosion in marine sediments was still active within the new channel (Fig. 9a). In the case of the avulsion at km 0.8, the flow followed a route that pre-flood aerial photographs reveal was cleared of trees, but we are uncertain if this represents an older overflow channel. Both of these avulsions demonstrate that significant alterations of a channel course can occur along entrenched non-alluvial or bedrock reaches of a Canadian Shield river system where flow is able to overtop a minor internal drainage divide. The avulsion at km 0.8 is a smaller-scale example of a similar avulsion that occurred from flooding also during the July 1996 rainstorm at Chute-à-Perron Falls along the nearby Rivière des Ha! Ha! (Lapointe *et al.*, 1998; Brooks and Lawrence, 1999).

Although overshadowed by the large-scale widening along the Rivière à Mars and the problems at the run-of-the-river dams, there were isolated, albeit much less severe, erosional problems at bridges. These examples are significant geomorphically because the erosion is directly attributable to the interaction of the flood flow and the bridge structure, and contrasts markedly with the otherwise negligible or limited erosion in the immediate area. Several specific problems can be identified and all are well recognized as arising at bridges during floods (*e.g.*, Shen, 1971; Wohl, 2000). At some sites, the hydraulic damming of flow caused elevated water levels upstream, contributing to the overtopping and washing out of road approaches (*e.g.*, bridges at km 16.9 and km 8, Rivière du Moulin). At other locations, the presence of the bridge abutments formed a local constriction of the channel causing an acceleration of flow that lead to erosion of the banks underneath (*e.g.*, bridges at km 19.3, Rivière du Moulin, and km 9.6, Rivière aux Sables) and immediately downstream of a bridge (*e.g.*, bridge at km 6.7, Rivière Chicoutimi). A clear example of a location where the acceleration of flow around a bridge pier locally scoured the river bed leading to foundation settlement and pier toppling occurred at a railway bridge (km 3.5) on the Rivière aux Sables.

CONCLUSIONS

The geomorphic effects along the Rivière aux Sables, Rivière Chicoutimi, Rivière du Moulin and Rivière à Mars varied from negligible to catastrophic channel widening and floodplain reworking, reflecting differing channel morphologies and valley bottom substrates, variations in flow energy, and, at some locations, the presence of small run-of-the-river dams and, to a lesser extent, bridges. This wide range in geomorphic effects likely is typical of Canadian Shield river systems of comparable size. Such rivers have developed on a recently deglaciated landscape and may follow, in part, geomorphically very young courses. Consequently, they commonly have irregular longitudinal profiles and variable channel morphologies and valley bottom substrate, all strongly influenced by bedrock and/or late Quaternary surficial deposits.

The catastrophic channel widening along the Rivière à Mars study reach resulted from flow energy exceeding the erosive threshold of the valley bottom. Along the majority of the study reach, unit stream power approximately equaled or exceeded 300 Wm^{-2}, which previous studies have indicated represents the minimal erosive threshold for large-scale erosion of an alluvial valley bottom. The magnitude of channel widening produced a post-flood channel width that dissipated unit stream power to a magnitude equaled to or below the minimal erosive threshold, except at locations where the river was confined by terraces or the valley sides. Morphological and empirical evidence indicate that the pre-flood channel planform was transitional meandering-braided, and thus was vulnerable to a planform transformation during an extreme flood. The catastrophic erosion along the Rivière à Mars study reach demonstrates that alluvial reaches of some Canadian Shield river systems have transitional channel morphologies that are vulnerable to large-scale erosion and planform transformations during extreme floods. The existence of such reaches should be considered when floodplain mapping is undertaken since catastrophic channel widening represents an obvious hazard to development situated along or immediately adjacent to valley bottoms, in addition to problems from inundation.

The severe erosion at the run-of-the-river dams on the Rivière aux Sables and Rivière Chicoutimi occurred due to flood levels exceeding the design or available spilling capacity (which became further reduced by debris clogging the sluice gates) of the dams. Deep breach channels that completely captured the river flow were eroded at four of the seven dams when they were overtopped and floodwaters spilled over unconsolidated sediments, and in one case an earthen dike, that were vulnerable to incision. At a fifth site, floodwaters overtopped a concrete wingwall of a dam and spilled into an urban subdivision stripping overburden and damaging numerous buildings, property and roads. Overall, the problems at these dams reveal the consequences of the uncontrolled overtopping of small dams and illustrate that the design spilling capacity of small dams can be exceeded during an extreme flood.

While providing a useful context for assessing the geomorphic effects of extreme flooding, the notion of a geomorphic threshold does not explain all of the geomorphic effects along a given river. As this paper demonstrates, severe erosion, albeit far more localized, can also result from the interaction of floodwaters and infrastructure, particularly dams, when an overtopping flow is diverted along a course that is vulnerable to incision. This can lead to channel avulsions at locations along a river that otherwise likely would have experienced minimal erosion from flooding.

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