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The drainage of the Lake Ha!Ha! reservoir and downstream geomorphic impacts along Ha!Ha! River, Saguenay area, Quebec, Canada

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Abstract

On July 18–21, 1996, a severe rainstorm caused widespread flooding along the north shore of the St. Lawrence River, southern Quebec, Canada, particularly along rivers that drain the area just south of the Saguenay–Lake St. Jean region. At the Lake Ha!Ha! reservoir, inadequate available capacity to spill during the storm at the outlet dam resulted in the overtopping and erosion of a nearby earthfill saddle dyke. A new outlet formed at the site of the dyke and drained the reservoir over a period of many hours decreasing its area from 8.1 to 4.7 km^2. Estimates of discharge range from 910 to 1380 m^3 s^{-1} at the site of the eroded dyke to 1080 to 1260 m^3 s^{-1} at a location 27 km downstream (about 8 km above the mouth of the river). The uncontrolled drainage of the Lake Ha!Ha! reservoir increased flooding along the lower 35 km of Ha!Ha! River where flooding was already in progress because of the rainstorm runoff. The flooding caused extensive geomorphic impacts along the river. Long sections of the river (totalling 25 km) experienced significant widening (locally up to 280 m) and channel incision (locally up to 20 m) while two reaches (6 and 4.5 km long) experienced up to several metres of aggradation. In general, the slope of the valley was the most important variable affecting whether or not the energy of the flow was above or below the erosive threshold of the valley bottom. Locally, a permanent channel diversion now exists where the drainage divide between the main river course and a small ravine was overtopped and extensively eroded. Communities, infrastructure, and industry located along the river were extensively damaged by the flood waters. The effects of flooding along Ha!Ha! River demonstrate that rivers on the Canadian Shield can undergo severe geomorphic changes caused by very high-magnitude flooding.

Keywords: flooding; dam breach; Canadian Shield; Quebec; Canada

1. Introduction

The uncontrolled drainage of a reservoir by the failure of a dam [2] can produce a flash flood of magnitude well beyond the ‘natural’ flow regime of a river or stream. Such floods can have catastrophic effects on the geomorphology downstream in the valley bottom and on communities and infrastructure situated within the flood path. Numerous floods

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[2] The term ‘dam’ is used here in a broad sense, and includes all types of dams, embankments and dykes.

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caused by dam failures have been documented worldwide with the flood magnitude in part being proportional to the impoundment size (see Costa, 1988). Breaches in dams can occur for a variety of reasons, including foundation failure, the effects of piping, inadequate capacity for spilling (due to a deficiency in either the spillway design or the operation of the spillway gates), differential settlement, and poor construction and maintenance (Jansen, 1983).

Flooding from a dam failure has not caused a major disaster in Canada. Nonetheless, some significant floods have occurred from dam failures, although these are poorly documented. As examples, on April 7, 1912, a dam owned by the Erindale Power on the Credit River, near Toronto, Ontario,

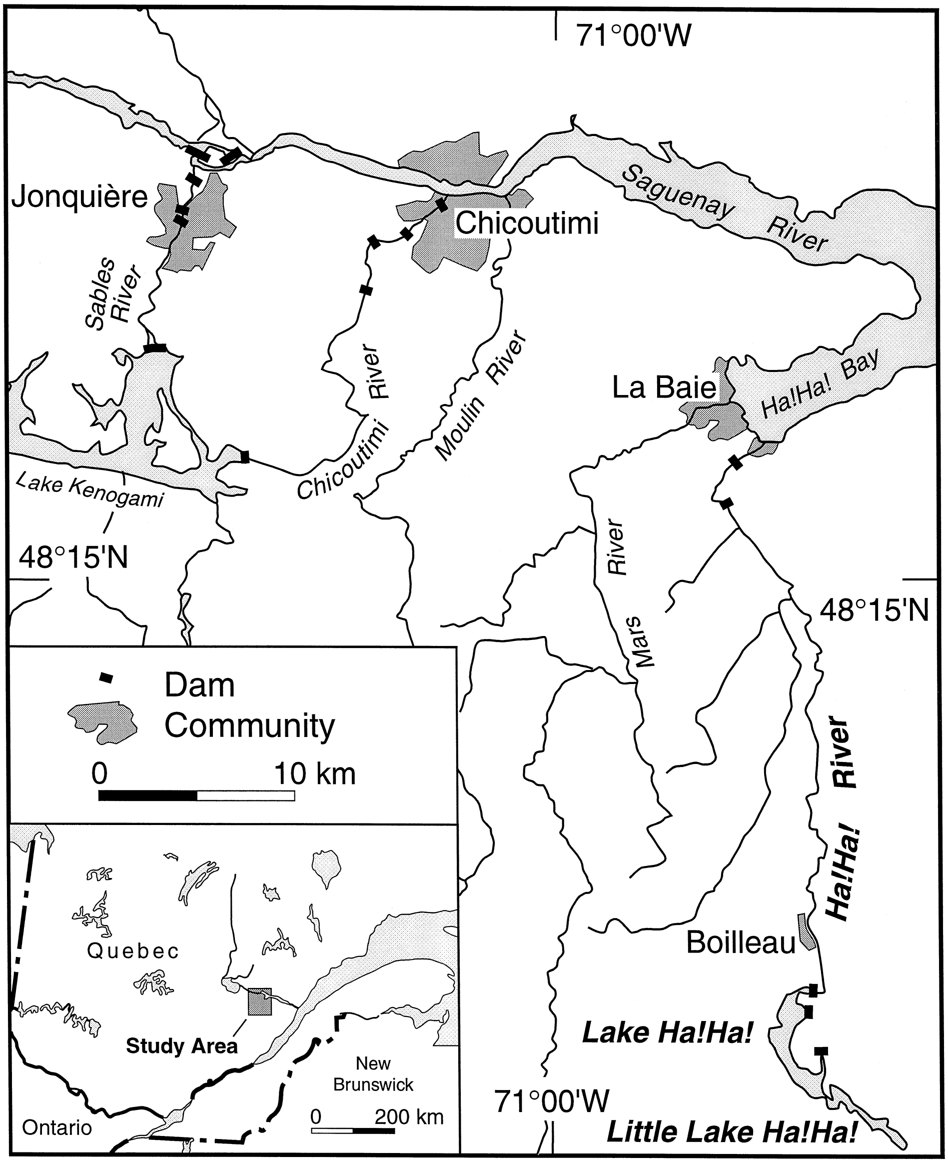

Fig. 1. Map of the Saguenay area showing Ha!Ha! River and the Lake Ha!Ha! reservoir, consisting of Lake Ha!Ha! and Little Lake Ha!Ha!.

breached during spring flooding as overtopping water eroded the leeside of the dam causing failure of a section of the concrete core, 40 m wide and 4.6 m high (Longley, 1912). This breach was caused by the inadequate capacity of the spillway and undoubtedly compounded the flooding already underway, although this is not mentioned in the description of the failure. Piping lead to the breaching of the Scott Experimental Farm Dam No. 2 in Saskatchewan, on April 21, 1948 and resulted in flooding downstream without 'significant' damage (Lukey and Noonan, 1986). Lapointe (1986) mentions that a dam 'burst' in 1966 killed three people at Saint-Joseph River, near Quebec City, Quebec. Seepage problems led to the September 18, 1985 failure of the Beloeil dam, located in a sparsely populated area 120 km north of Quebec City, Quebec. The failure drained Lake Beloeil and led to severe flooding and channel erosion along a 7-km long reach of Little Pikauba River (Robitaille and Dubois, 1989; Robert and Paré, 1992). Notably, all of these failures involved small dams less than 15 m high.

In July 1996, eight dams along Chicoutimi, Sables and Ha!Ha! rivers in the Saguenay area, Quebec, were overtopped and breached by the floodwaters from a severe rainstorm (described below; see Brooks et al., 1997; CSTGB, 1997; INRS-Eau, 1997; Brooks and Lawrence, 1998; Fig. 1). At all eight sites, the impoundments were at least partially drained, however, seven of the reservoirs were relatively small, essentially shallow, back-flooded reaches of river channel. The breaches were small or occurred slowly, over many hours. The draining of these reservoirs did not contribute significantly to the downstream flooding already in progress. The exception, however, occurred with the draining of the Lake Ha!Ha! reservoir (Fig. 1) which greatly accentuated the rainfall runoff along Ha!Ha! River.

The drainage of the Lake Ha!Ha! reservoir is the most significant Canadian dam breach documented in terms of downstream geomorphic and human impacts. The flood also represents an important geomorphic event because it triggered an extreme flood event along a Canadian Shield river system where the effects of such flooding are poorly documented. The purpose of this paper is to review events leading to the draining of Lake Ha!Ha!, provide estimates of the resulting flood discharge, and summarize the downstream geomorphic impacts of the flood along Ha!Ha! River.

2. The storm

Between July 18–21, 1996, a severe rainstorm stalled over the Gulf of St. Lawrence and record amounts of rain fell on southern Quebec (see Milton and Bourque, 1997). The greatest accumulation of rain (greater than 200 mm) fell in an area south of the Lake St. Jean–Saguenay River area, Quebec (Fig. 2). Orographic processes and the counter-clockwise rotation of the storm system were responsible for the concentration of rain in this area. Individual locations within this zone reported receiving accumulations of, for example, 210.9 mm (Portages-des-Roches station 061001), 271.9 mm (Pikauba station 061022), and 279.4 mm (Rivière-aux-Ecorces station 061020) (Milton and Bourque, 1997). Although these totals are for a 4 day period, most of the rain in this area fell within a 36 h period beginning at about 0800 h on July 19 and continuing until about 2000 h July 20.

This rainfall, in combination with the near-saturated ground from antecedent July rainfall (Environment Canada, 1996) and the generally thin and discontinuous overburden blanketing the bedrock of the Laurentian Highlands, produced widespread flooding throughout the north shore area of the St. Lawrence River in southern Quebec. The most severe flooding occurred along rivers flowing northwards into the Saguenay Valley whose headwater areas are located within the zone of greater than 200 mm accumulation (Fig. 2; see CSTGB, 1997). The flooding damaged or destroyed homes, cottages, farms, businesses and infrastructure, and impaired local industry (CSTGB, 1997).

3. Lake Ha!Ha!

The Lake Ha!Ha! reservoir, 12 km long and with a surface area of 8.1 km^2, is located about 34 km above the mouth of Ha!Ha! River (Fig. 3). It consists of Lake Ha!Ha! and Little Lake Ha!Ha! which occupy separate, but connected lake basins (Fig. 3).

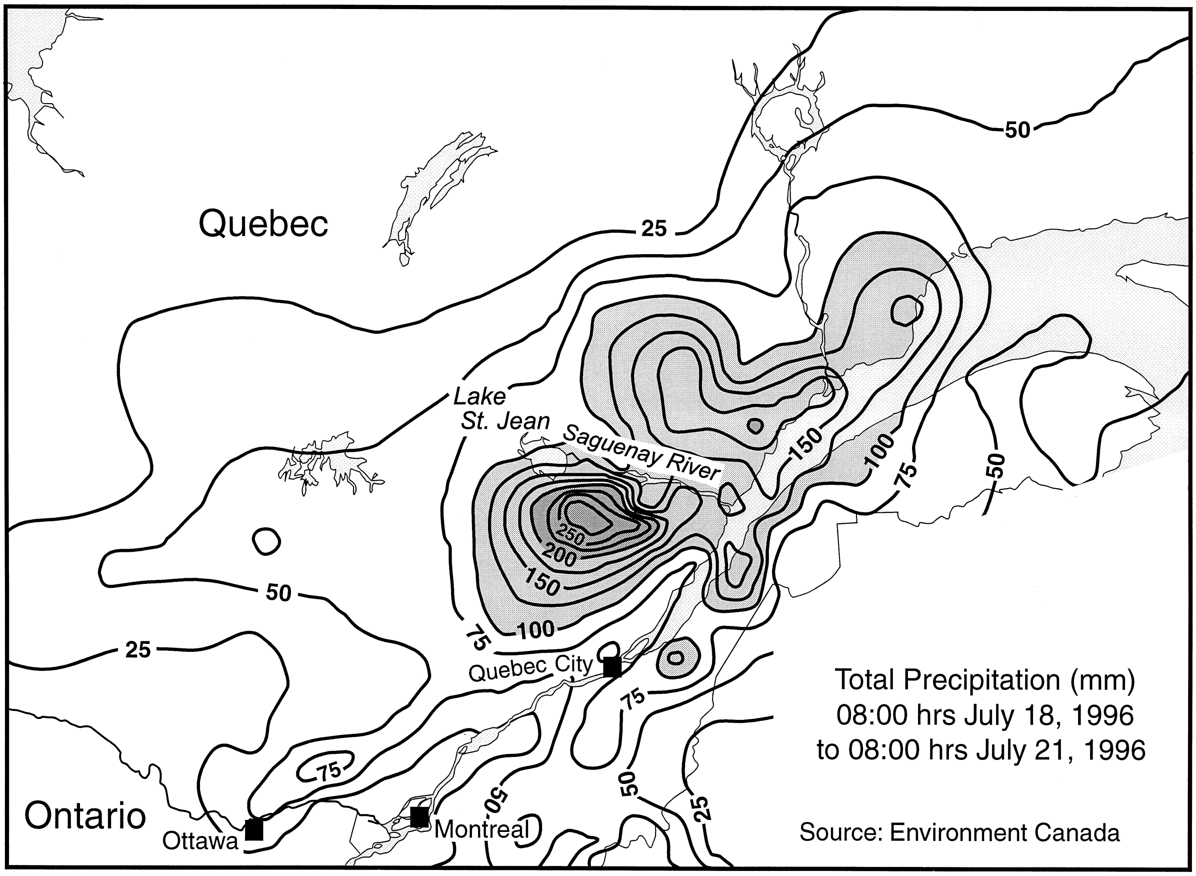

Fig. 2. Map showing rainfall accumulation in southern Quebec between 0800 h July 18 and 0800 h July 21, 1996 (after Milton and Bourque, 1997, reproduced with permission).

The contributing area of the reservoir represents 37.5% of the Ha!Ha! River drainage basin (608 km^2; CSTGB, 1997). Before the water level was raised by the construction of a dam and two dykes (see below), the Lake Ha!Ha! and Little Lake Ha!Ha! basins contained separate lakes.

Prior to the July 1996 rainstorm, the level of Lake Ha!Ha! reservoir was controlled by a concrete gravity dam located at the north end of Lake Ha!Ha! (Figs. 3–5). Two earthfill saddle dykes (known as the ‘Cut-away’ and ‘Rive-gauche’ dykes), located across the head of separate bays just to the south of the dam, also retain lake water (Figs. 3 and 4). Attributes of the dam and two dykes are summarized in Table 1. Most significantly, the elevation of the crest of the dam (control structure) is higher than the two earthfill dykes; the dam, Cut-away and Rive-gauche dykes have crests at 381.06, 380.65, 381.0 m a.s.l., respectively (Table 1).

The purpose of the reservoir was to maintain the level of discharge of Ha!Ha! River for use by two small ‘run of the river’ power dams along the lower part of the river and a paper mill located in the town of La Baie at the river mouth. The dam was built in 1950 at the site of an older dam originally constructed in the early 1920s (Le Quotidien, 1996). Owned by Consolidated-Stone (now Abitibi Consolidated), the spillway of the dam consists of four stoplog sluices, each 4.56 m high and 3.66 m wide, the levels of which are controlled by inserting and removing 0.3 m square logs. The elevation of the sill of the sluice gates (i.e., the base with all of the

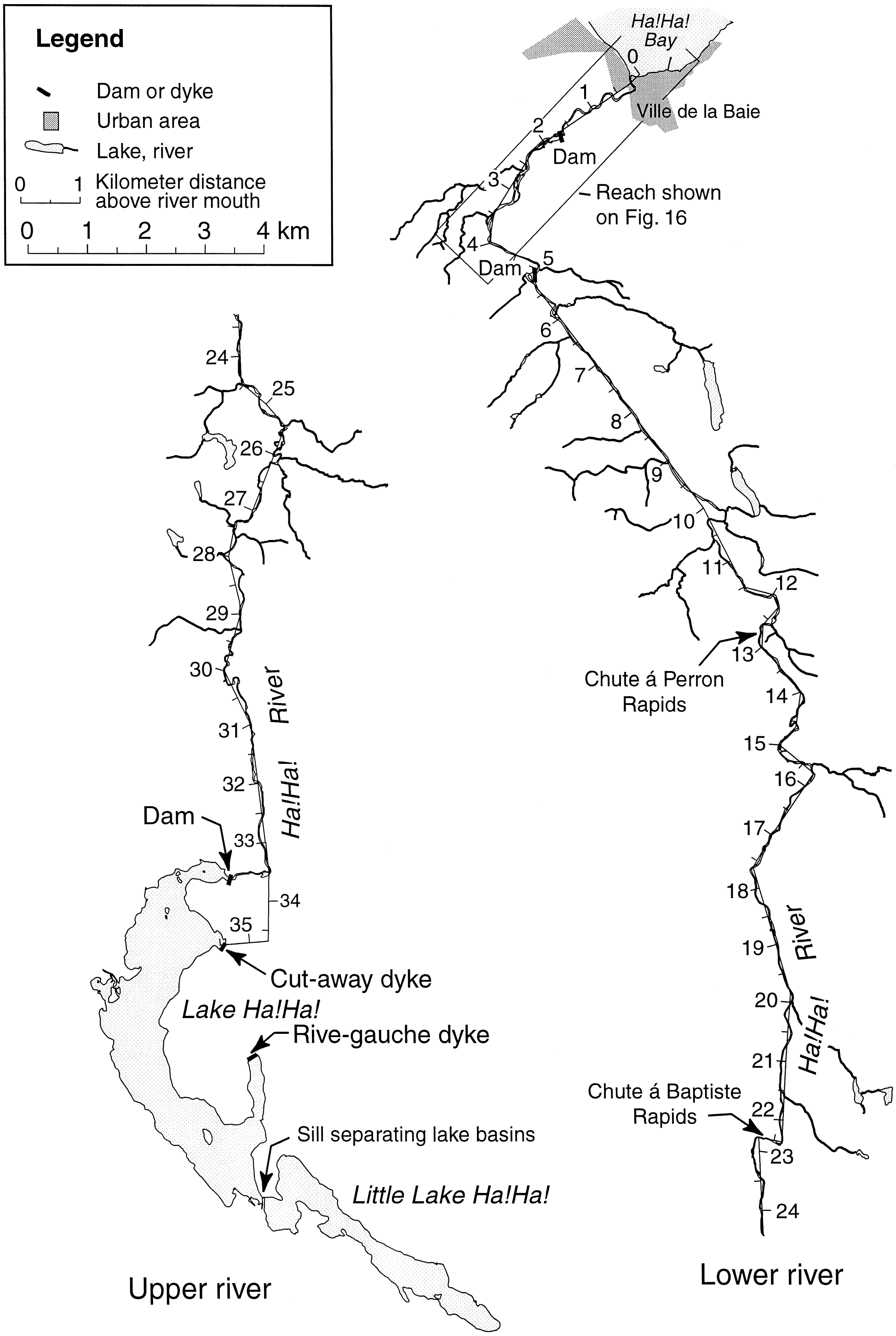

Fig. 3. Map of the pre-flood course of Ha!Ha! River from the river mouth to Lake Ha!Ha!, showing the kilometre distances referred to in the text. Also shown are the location of the dam and two dykes at Lake Ha!Ha!.

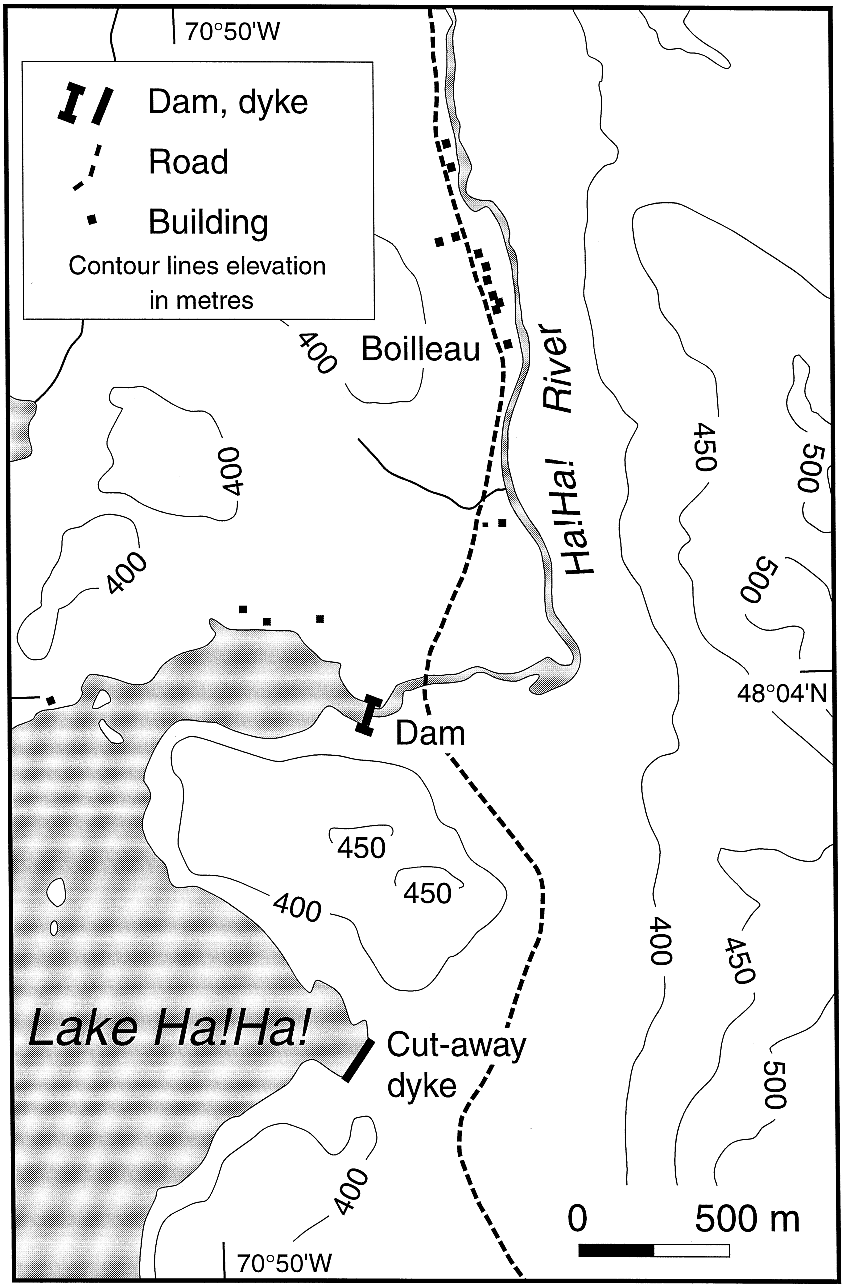

Fig. 4. Map of the northern portion of Lake Ha!Ha! reservoir prior to the flood event showing the location of the dam which controlled the lake level, and the Cut-away dyke.

stoplogs removed) is 376.5 m a.s.l. (4.56 m below the 381.06 m a.s.l. crest of the dam). The reservoir level was normally maintained between about 379 and 380 m a.s.l. (Le Quotidien, 1996).

4. The drainage of Lake Ha!Ha!

At the Lake Ha!Ha! meteorological station (706347), located near the head of Lake Ha!Ha!,

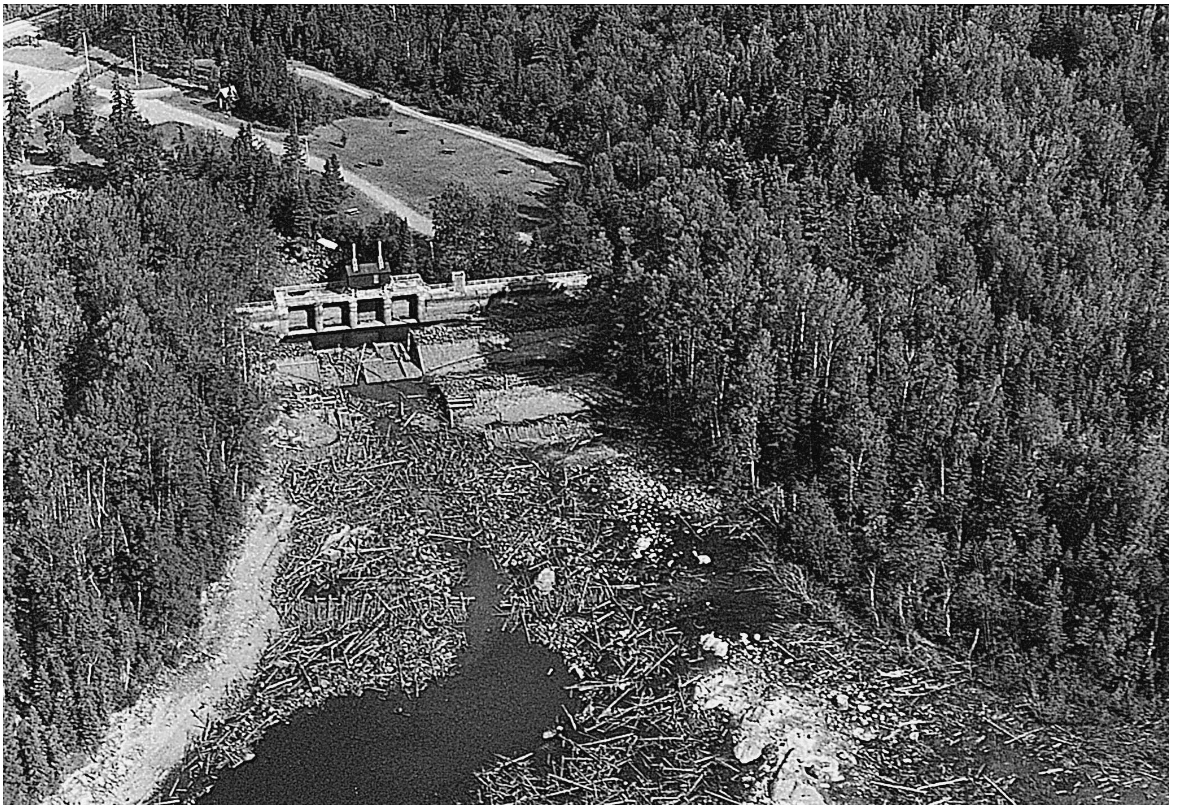

Fig. 5. Post-flood view of the concrete gravity dam that controlled the level of Lake Ha!Ha!. Lake basin is in the foreground. For scale, the four stoplog sluices within the dam are 4.56 m high.

251.4 mm of rainfall were recorded between 0300 and 0400 h July 19, 1996 and 1000 h July 21, 1996 (Milton and Bourque, 1997). At 1100 h July 19, the lake level was 380.08 m a.s.l., having fallen slightly over the previous 2 h (CSTGB, 1997). (All reported water levels and stoplog sluice heights were made originally in feet relative to a scale extending above the spillway sill. These have been converted to elevations by adding the converted height in S.I. units to the elevation of the spillway sill (see Table 1). All should be regarded as approximate elevations.) At some time shortly after this, the influx of runoff into the reservoir caused the lake level to rise gradually (CSTGB, 1997). The water level eventually rose to an elevation of 380.91 m a.s.l. or 0.15 m below the crest of the dam, as indicated by a water line formed by organic matter on the side of the dam and debris lines on the ground at the outer margins of the structure. CSTGB (1997) reports a maximum water level of 380.77 m; our level may be slightly higher because of wave actions.

When the lake reached its maximum level, the Cut-away dyke was being overtopped by up to 0.26 m of water, an estimate based on the maximum difference in elevation between the water level on the dam and the crest of the saddle dyke (Table 1). Water spilling from the lake incised into the dyke and subsequently into the Quaternary deposits of the saddle underlying the dyke (Fig. 6). A new outlet channel, about 130 m wide and 14 m deep, was formed at the site of the dyke. This new channel extends 2 km downvalley and joins the pre-flood Ha!Ha! River channel (Figs. 7–9). The erosion of the new outlet reduced the level of Lake Ha!Ha! by about 13 m, although the level of Little Lake Ha!Ha! was reduced by only about 2 m because of a sill located at the narrows between the two basins (Fig. 3). Lake Ha!Ha! decreased from a pre-flood surface

Table 1
Summary of dam and dyke attributes at the Lake Ha!Ha! reservoir (after CSTGB, 1997)

Structure	Year in service	Type	Maximum height (m)	Length (m)	Number, type and dimensions (m) of sluices	Maximum outlet capacity ($m^3 s^{-1}$)	Elevation of crest (m a.s.l.)	Elevation of the spillway sill (m a.s.l.)	Critical maximum level (m a.s.l.)
Dam	1950[a]	concrete gravity	8.2	106.3	4 stoplog 4.56×3.66	250	381.06	376.5[c]	380.45
Cut-away dyke	1926[b]	earthfill	2–3	162	na	na	380.65	na	380.45
Rive-gauche dyke	1926	earthfill	2.8	38	na	na	381	na	380.45

[a] This apparently is a new structure built at the site of an older one which was constructed in conjunction with the two dykes.
[b] There is a disagreement about the age of the Cut-away dyke, INRS-Eau (1997) reports that it was built in 1917.
[c] Estimated by subtracting the 4.56 m (15′) depth of the sluice gates from the top of the dam.

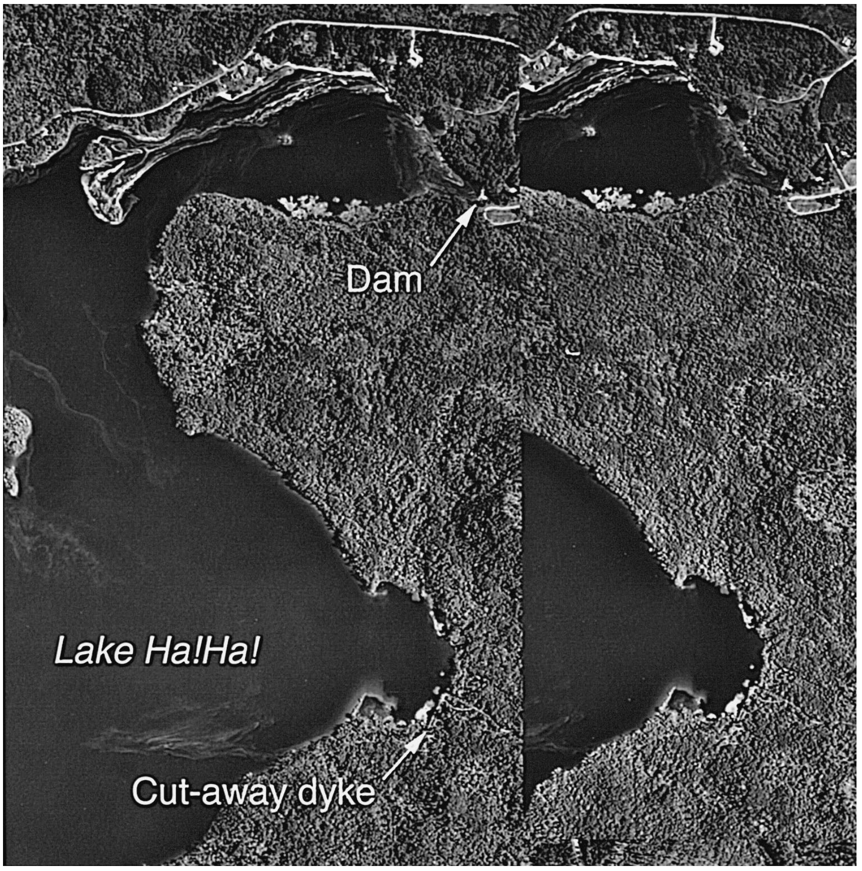

Fig. 6. Photostereogram of the pre-flood morphology of the dyke and saddle where the new channel was eroded causing the drainage of the Lake Ha!Ha! reservoir (aerial photographs 22D3-92; -93, June 15, 1994; reproduced with permission Photocartothèque Québécoise, Ministère des ressources naturalles, Québec).

area of 5.9 km^2 to a residual lake of 2.6 km^2 (the pre-flood area is based on the 1:50,000 scale NTS map Ferland whereas the post-flood area is from a July 29, 1996 multispectral SPOT satellite image (20 m pixel resolution)). Little Lake Ha!Ha! was reduced in area only slightly from 2.2 to 2.0 km^2 because of the lower drop in water level. Overall, 59×10^6 m^3 of water is estimated roughly to have drained from the reservoir (55×10^6 and 4×10^6 m^3 from the Lake Ha!Ha! and Little Lake Ha!Ha! basins, respectively, based upon the mean of the pre- and post-lake surface areas and the change in water levels). The dam, which formerly controlled the level of the Lake Ha!Ha! reservoir, remained completely intact after the drainage, but no longer impounding any water.

The drainage of the Lake Ha!Ha! reservoir began during the afternoon of Saturday, July 20, 1996. CSTGB (1997) estimates that the reservoir level began to overtop the Cut-away dyke at about 0200 h Saturday. At 0600 h, Ha!Ha! River was in flood because of runoff from the severe rainstorm; the contribution from the overflow of the Cut-away dyke was likely minimal (see below). By this time, a bridge located about 10 km above the river mouth had been washed out (Le Quotidien, 1996). By mid-morning, the residents of the village of Boilleau, located along the valley bottom 1 to 6 km downstream of the dam (Fig. 4), were evacuated from their homes because of flooding downstream. At 1400 h, the Cut-away dyke is alleged to have 'burst' because of the overtopping, and by 1430 h, the reservoir level is reported to have fallen to 380.06 m a.s.l. (Le Quotidien, 1996), from the maximum level of 380.92 m a.s.l. 'Massive' erosion of the dyke occurred between 1600 and 1700 h; by 1800 h the water level had dropped to 379.55 m a.s.l., and to 379.09 m a.s.l. by 1845 h (Le Quotidien, 1996).

Based upon the drawdown rate between 1800 and 1845 h, the water level in Lake Ha!Ha! probably dropped below the level of the sluice gates late Saturday night, eventually falling another 8 m to about 368 m a.s.l. sometime Sunday morning when the rapid erosion of the new outlet terminated. CSTGB (1997) estimates that the lake emptied in 18 h, a time interval that is generally consistent with our interpretation. The drainage of Lake Ha!Ha!, thus, occurred over a period of many hours, but not catastrophically as in a period of many tens of minutes or within few hours. The duration of drainage probably reflects that roughly three quarters of the 14 m incision at the site of the Cut-away dyke eroded into surficial material of the saddle (compact, massive, matrix-supported (silty-sand), glacigenic diamicton) rather than entirely of earthfill dyke material. Also significant is the high ratio of pre-flood height to width of the topography across the saddle into which the escaping waters incised (see Fig. 7a).

With the stoplog sluices completely open, the maximum spilling capacity of the dam impounding the Lake Ha!Ha! reservoir is 250 $m^3\ s^{-1}$, well above the maximum inflow into the lake during the July rainstorm, estimated to be 160 $m^3\ s^{-1}$ (CSTGB, 1997). As observed on July 28, 1996, after the drainage of the reservoir, three of the stoplog sluices were set at levels of 380.16 m a.s.l., the fourth 378.94 m a.s.l.; which represents the outlet state during the rainstorm. Initially during the storm, outflow occurred through only one of the four stoplog

Fig. 7. The new outlet at the Lake Ha!Ha! reservoir that was eroded through the Cut-away dyke, (a) looking downstream from above the lake basin and (b) looking upstream into the drained lake basin. The outlet is about 130 m wide at the site of the dyke. In both pictures, visible locations of the remnant dyke are marked with arrows.

Fig. 7 (continued).

sluices (the lake level was 380.08 m a.s.l. at 1100 h July 19; see above) until the reservoir level later rose to 380.16 m a.s.l. and began to overtop the other three sluices. (The crest of the Cut-away dyke was only 0.49 m above the level of the three highest sluices, based upon elevations of the stoplogs and dyke crest (Table 1).) Because the sluices had a maximum capacity above the influx of runoff into

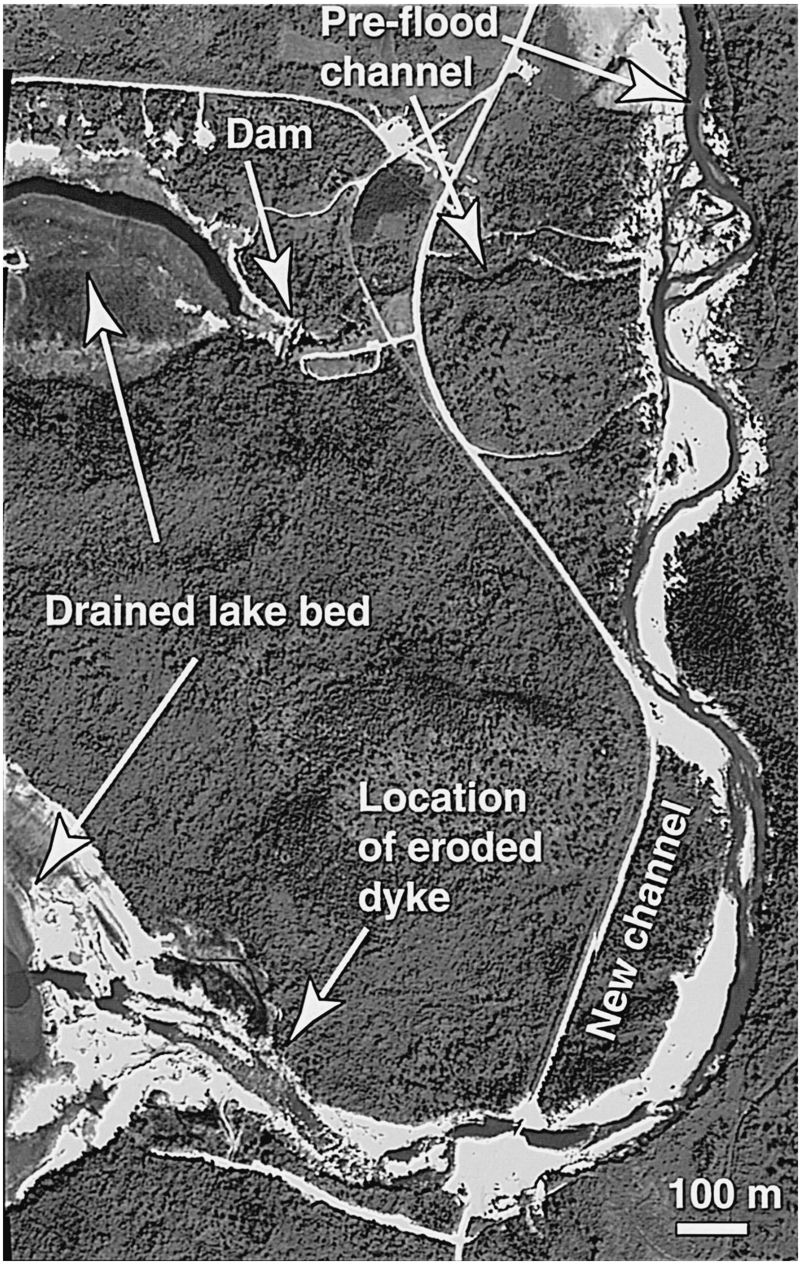

Fig. 8. Vertical multi-spectral video image of the northern portion of the Lake Ha!Ha! reservoir showing the new outlet and a portion of the drained lake bed, taken August 6, 1996 (courtesy of Canada Centre of Remote Sensing).

the reservoir, but were only partially opened, the overtopping of the Cut-away dyke is the result of inadequate available spilling capacity rather than insufficient maximum spilling capacity at the control dam (CSTGB, 1997).

5. Estimates of discharge

Streamflow records for Ha!Ha! River during and immediately after the July 18–21 rainstorm are not available because the gauging station located about 8

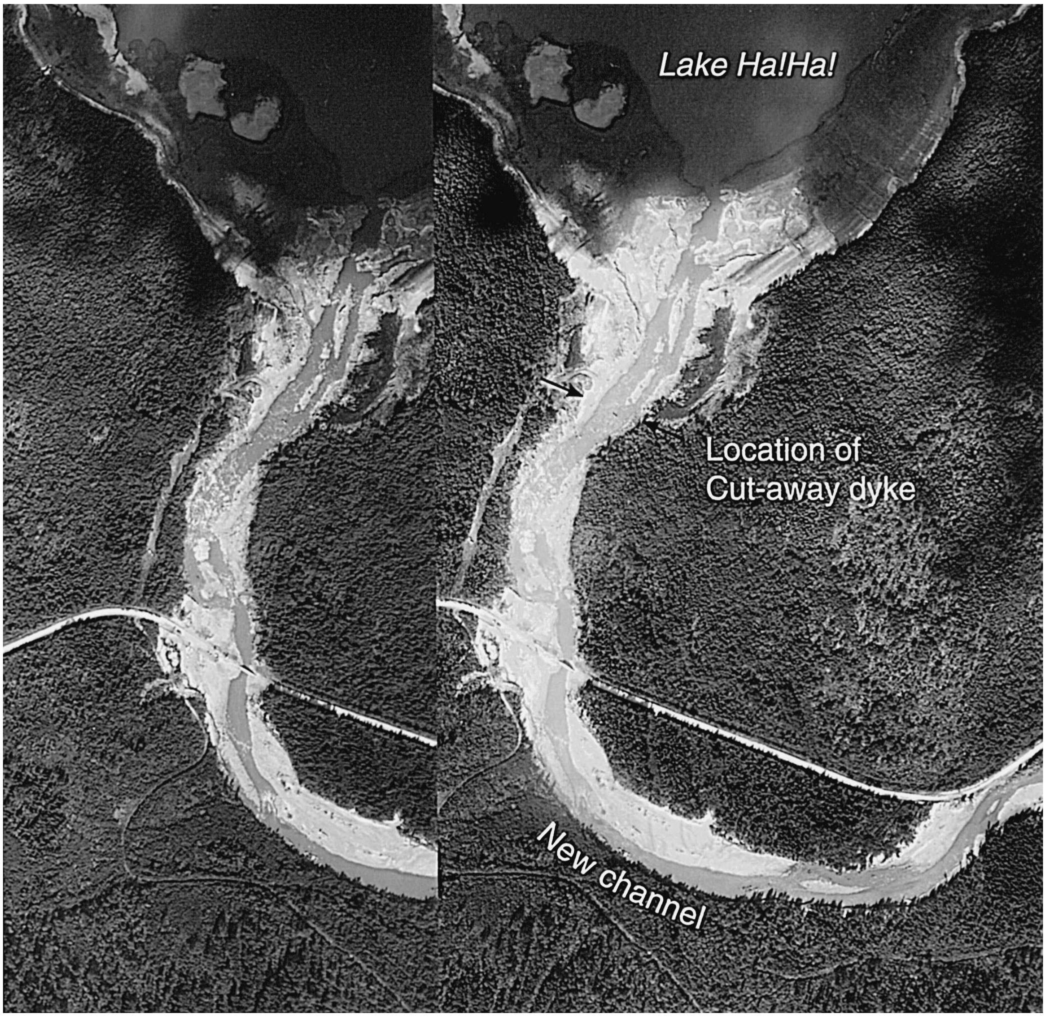

Fig. 9. Photostereogram of the post-flood outlet of the Lake Ha!Ha! reservoir eroded through the Cut-away dyke (aerial photographs Q96304-90, -91; reproduced with permission Photocartothèque Québécoise, Ministère des ressources naturalles, Québec). The outlet channel extending downvalley was created by the escaping water. Note the dry knickpoints branching from the channel incised into the subaerial lake bed.

km above the river mouth was destroyed by the flood. Quantitative estimates of the discharge of the flood, calculated by three independent methods with a fourth from CSTGB (1997), are listed in Table 2.

The estimates of discharge in Table 2 range from 910 to 7650 m^3 s^{-1}. Of these, the estimate based upon the empirical relationship between lake volume and peak flow produced the largest discharge (7650 m^3 s^{-1}; Table 2). This estimate is 5.5 to 8.5 times larger than the other three estimates, and thus is interpreted to be unreasonably high.

The estimates of discharge based upon lake drawdown (1380 m^3 s^{-1}), runoff modelling/drawdown (910 m^3 s^{-1}), and slope-area method (1080 to 1260 m^3 s^{-1}) are reasonably close (Table 2). These estimates, however, are only generally comparable because: the estimate of drawdown is based upon an early stage of lake drainage and does not necessarily represent the peak discharge (see Table 2); the esti-

Table 2
Estimates of the flood discharge along Ha!Ha! River

Method	Discharge estimate (m^3 s^{-1})	Ratio to historic maximum instantaneous flow (114 m^3 s^{-1})[a]	Comments
Empirical relationship between lake volume and peak flow[b]	7650	67	Calculated using a volume of 22.1×10^6 m^3 which is based on the 5.9 km^2 pre-flood surface area of Lake Ha!Ha! and a 3-m drop in lake level reflecting the maximum height of the dyke, in combination with a 2-m drop in the 2.2 km^2 pre-flood surface area of Little Lake Ha!Ha! (a sill between the basins limited a further decrease in level). Since a large portion of the incision occurred into surficial material underlying the dyke, to estimate the peak discharge based on the total drained volume is deemed beyond the applicability of the empirical equation.
Drawdown of reservoir[c]	1380	12	This estimate may be smaller than peak discharge since this represents an early stage of the incision.
Slope-area method (continuity and Manning equations)[d]	1080–1260[e]	9.5–11.1	Discharge represents a combination of rainfall runoff and drainage from Lake Ha!Ha!.
Runoff modelling/drawdown[f]	910	8	Based upon the combination of hydrologic modelling of runoff into Lake Ha!Ha! and the reconstruction of the reservoir drawdown.

[a] From the 1976–1995 discharge record (R. Couture, Milieu Hydrique, Environnement et Faune Quebec, pers. comm., July 1997).
[b] Based on the equation $Q_{max} = 1730\ V^{0.48}$ modified from Costa (1988) following Desloges et al. (1989).
[c] Based on a reported drop in the water surface of 0.46 m which is reported to have occurred between 1800 and 1845 h, July 20, 1996 (Le Quotidien, 1996).
[d] Based on a surveyed cross-section of the flood channel located 27 km downstream of Lake Ha!Ha! (8.4 km above the river mouth) and which was not significantly modified by the flood.
[e] The data used for this calculation is as follows: hydraulic radius and mean depth, 4.6 m; width, 131 m; Manning's n, 0.036 and 0.043; slope of the high water surface, 0.0007 (this slope is lower than that on Fig. 10 and is believed to reflect a backwater effect from bridge located 1.5 km downstream that was later washed out).
[f] This estimate is from CSTGB (1997).

mate from runoff modelling/drawdown represents the peak discharge at the new outlet of Lake Ha!Ha!; and the slope-area estimate relates to peak discharge 27 km downstream (8 km above the river mouth) and thus incorporates rainfall runoff from other portions of the drainage basin. That the discharge near the river mouth could have been similar to or lower than that at the lake outlet might reflect downstream attenuation of the flood wave (Richards, 1982; Costa, 1988), if the rainfall runoff forms a small component of the peak flow at the slope-area cross-section. Overall, the available data indicate that the discharge was in the 910 to 1380 m^3 s^{-1} range at the new outlet of Lake Ha!Ha! and 1080 to 1260 m^3 s^{-1} along the lower part of the river.

Significantly, all four estimates of discharge are nearly an order-of-magnitude or more larger than the previously recorded maximum instantaneous discharge for Ha!Ha! River (114 m^3 s^{-1} occurring at 1500 h, May 9, 1983; see Table 2). This large difference clearly indicates that the drainage of the Lake Ha!Ha! reservoir, in combination with the runoff from the rainstorm, created an exceptionally high-magnitude flood along the river.

5.1. Discussion

Based upon a simulation model of runoff, the peak discharge at the mouth of Ha!Ha! River, resulting exclusively from the rainstorm, is estimated to be 384 m^3 s^{-1} (CSTGB, 1997; INRS-Eau, 1997). Although over 3 times larger than the previous maximum instantaneous discharge of 114 m^3 s^{-1} (Table 2), this discharge is roughly one-half to one-third less than the 910 to 1380 m^3 s^{-1} range of the estimates of discharge arising from the lake drainage contained in Table 2. The drainage of the Lake Ha!Ha! reservoir from the erosion of the dyke and saddle, obviously severely compounded the flooding problem downstream to the river mouth. The flooding along Ha!Ha! River below the reservoir, therefore, represents a combination of a dam-break flood superimposed on a severe ‘natural’ hydrological event caused by the rainstorm in progress at the same time the reservoir was draining. The accentuation of a severe rainstorm-generated flood already in progress by a dam failure is not unique to Lake Ha!Ha!, having also occurred, for example, at the South Fork dam, PA (1889), the Lower Otay dam, CA (1916), and the Canyon Lake dam, SD (1972) (see Jansen, 1983).

6. Downstream impacts of the flood

The flooding downstream of the Cut-away dyke had severe, but variable, geomorphic impacts along Ha!Ha! River. These effects, outlined for seven successive reaches (reference to the river mouth; Fig. 3), are discussed in terms of change in the width and incision/aggradation of the channel. The pre- and post-flood widths of the channel were measured at 250 m intervals, respectively, from Quebec Ministère de L’Energie et des Ressources 1:20,000 scale maps (‘La Baie’, 22D02-200-0101; ‘Ferland’, 22D02-200-0201; and ‘Boilleau’, 22D07-200-0101) and post-flood aerial photographs taken on July 30, 1996 (Table 3). Cartographic error present in the pre-flood channel boundaries on these maps was determined to be low compared to pre-flood aerial photographs and was deemed acceptable for our purposes. Depths of incision or aggradation reported are based upon field observations, the interpretation of oblique 35 mm aerial photographs, and/or figures within INRS-Eau (1997).

6.1. km 35.5 to 33.5—erosion of a new channel

Immediately below the overtopped dyke, a completely new channel, 2 km long, was eroded into the saddle and valley bottom and joined the pre-flood channel at km 33.5 (Fig. 8). The new channel ranges

Table 3
List of post-flood aerial photographs along Ha!Ha! River used in this study

Source	Flight line	Aerial photograph numbers	Date of photography	Range of scale
Photocartothèque Quebecoise	Q96304	53–91	July 30, 1996	1:12,000–14,100

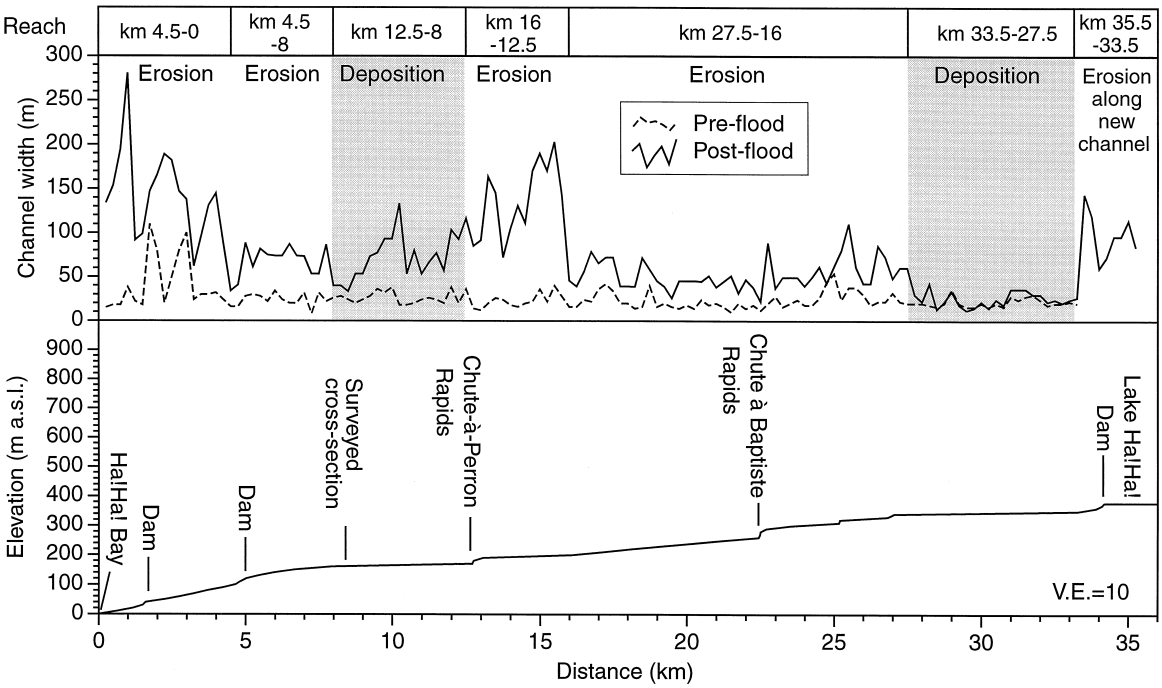

Fig. 10. Graphs depicting the pre-flood and post-flood downstream changes in channel width along Ha!Ha! River and the pre-flood longitudinal gradient of the valley. The erosion and deposition designations (the latter zones are also shaded) across the top of the channel width graph refer to the dominant geomorphic process along the valley bottom within a given reach.

from 60 to 144 m wide, with a mean width of 98 m (Fig. 10). Reflecting the high-magnitude of the outflow from Lake Ha!Ha!, the post-flood mean width is approximately 4.5 times greater than the pre-flood channel of the river downstream between km 33.5 and 27.5. Incision along the new channel decreases downstream from a maximum of about 14 m in the area of the eroded dyke to a negligible change at the junction of new and pre-flood channels (INRS-Eau, 1997).

6.2. km 33.5 to 27.5—aggradation in the valley bottom

From km 33.5 to 27.5, the flood waters swept along the relatively gently-sloped (0.0016) valley bottom and caused minor to negligible widening of the channel; the pre-flood meandering planform of the river essentially was preserved. The pre-flood and post-flood widths ranged from 16 to 36 m (mean 22 m) and 12 to 42 m (mean 26 m; Fig. 10), respectively, with some of this difference probably partially reflecting minor error in measurement, on the map, or minor aggradation of the channel.

The most significant erosion along the entire reach occurred at km 33.5 to 33 where the floodplain was partially dissected, and at km 28 where an elongated scour hole, 35 m wide and 150 m long, was eroded into the floodplain (Fig. 11a). Large tracts of mature coniferous trees were knocked over between km 30.5 to 29.5. At km 28 (Fig. 11a), where the forest encroaches upon the channel, flood waters cut across several well-defined meander loops (Fig. 3).

In contrast, extensive deposition occurred along the valley bottom adjacent to the river, particularly

Fig. 11. Geomorphic effects along Ha!Ha! River between km 33.5 and 27.5: (a) trees on the floodplain knocked over by flood water and an elongated scour hole, view looking upvalley from about km 29.5 (GSC photograph 1997-42HH), and (b) overbank deposition on the valley bottom (light-shaded areas), looking upvalley of km 32.5 (GSC photograph 1997-42II). Photographs taken on July 28, 1996.


(a)
(b)

between km 33.5 to 32.5 and 31 to 29.5 where up to 2 m of sediment was deposited (Fig. 11b). The sediments, derived from erosion of the new channel immediately upstream, form broad fine sand sheets that aggraded wide, low-lying areas of the valley bottom. Deposition also occurred along the narrower parts of the valley bottom and within the forested areas of the floodplain where the vegetation trapped the sediment.

6.3. km 27.5 to 16—moderate channel widening

Moderate widening of the channel occurred along this reach where the pre-flood morphology consisted of predominately non-alluvial sections of river confined within a narrow valley bottom (short bedrock and alluvial (meandering planform) sections are also present). The post-flood channel ranges from 22 to 111 m wide (mean 54 m) compared to the 10 to 54 m wide (mean 24 m) pre-flood channel. Channel widening, in general, was limited by the confined morphology of the valley bottom. Negligible to up to several metres of incision occurred along this reach of the river (INRS-Eau, 1997).

6.4. km 16 to 12.5—erosion of a new channel

Extensive alteration of the channel occurred between km 16 and 12.5. Prior to the flood, the river profile from km 13 to 16 was controlled by a bedrock outcrop which formed the Chute-à-Perron rapids (Figs. 3 and 12). During the flood, water overtopped a low divide along the right side of the river, situated at about km 13, and flowed into a ravine that provided a shorter route downvalley (Fig. 12). Subsequently, along this new course, deep incision and extensive lateral erosion into late Pleistocene sand and clay–silt deposits ensued and propagated upstream to about km 16. The section of channel leading to the rapids was left hanging on the valley-

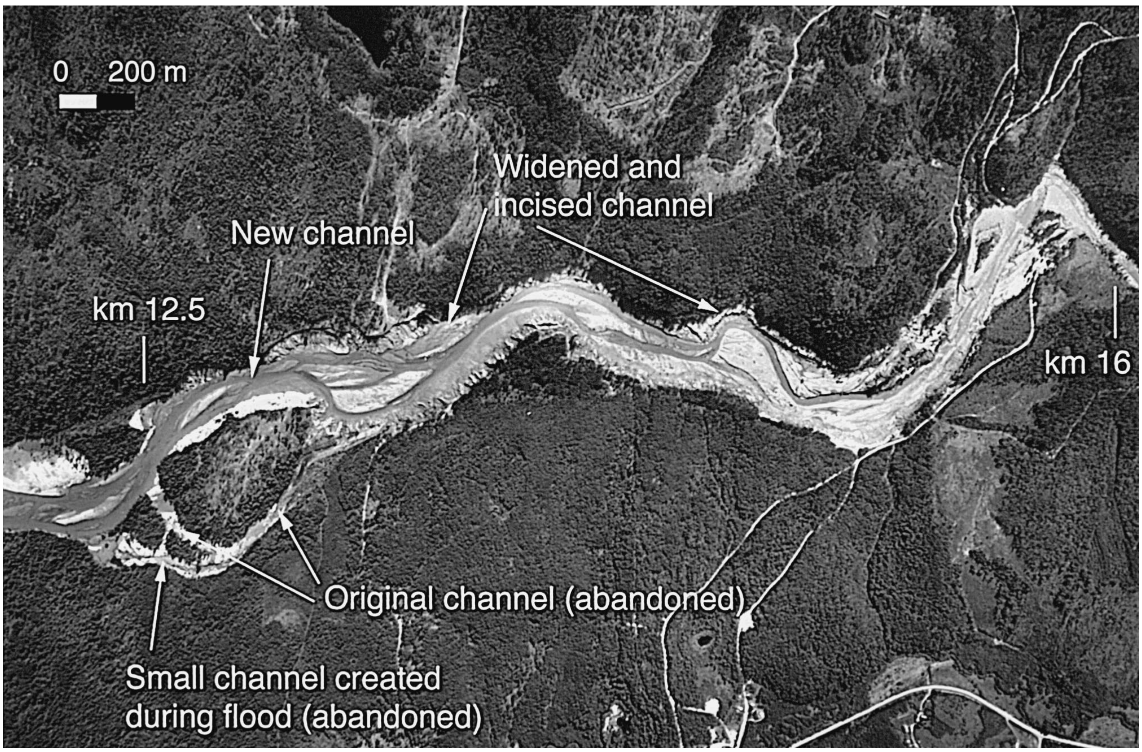

Fig. 12. Post-flood aerial photograph of the reach from km 16 to 12.5 reach which was severely altered by the flood, as mentioned in the text (aerial photograph Q96304-74, taken July 30, 1996; reproduced with permission Photocartothèque Québécoise, Ministère des Ressources naturalles, Québec). Flow of the river is from right to left.

side (Fig. 13). The entire flow of the river is now carried down the new channel and re-joins the pre-flood channel at km 12.5 (Figs. 3 and 12).

Along this reach, the depth of incision decreases upstream gradually from a maximum of about 20 m at km 13 to several metres at km 16 (INRS-Eau, 1997). The post-flood channel is considerably wider (72 to 190 m, mean 136 m) than the pre-flood channel (12 to 40 m, mean 24 m) along the entire reach (Fig. 10). A section of the pre-flood channel at

Fig. 13. View looking downstream from about km 13 along the new channel course that follows the route of a pre-flood ravine. The original channel (marked by a white arrow) which leads to the now-abandoned Chute-à-Perron rapids, ‘hangs’ about 20 m above the valley bottom. Up to 20 m of incision occurred locally along this portion of the river. Photograph taken on July 28, 1996.

the Chute-à-Perron rapids is preserved, albeit somewhat widened and with a new branch extending downstream from it (Fig. 12). The combination of major incision and widening of the channel along this reach resulted in the reworking of a considerable volume of unconsolidated sand, silt and clay, estimated by INRS-Eau (1997, Table 2) to be 6.3×10^6 m^3.

6.5. km 12.5 to 8—aggradation in the valley bottom

The geomorphic effects of the flood between km 12.5 and 8 were primarily depositional. The large volume of sediment derived from the km 16 to 12.5 reach, in combination with the relatively low slope of the valley (0.002) between km 12.5 and 8 (Fig. 3), resulted in extensive aggradation of the valley bottom and buried the pre-flood channel. The sand deposited along the valley bottom thins gradually downstream from a maximum of about 6 m (INRS-Eau, 1997) at km 12.5 to its limit at about km 8.5 where the pre-flood channel margins again become recognizable.

Between km 12.5 to 8.5, the width of the post-flood (33 to 133 m, mean 77 m) is considerably wider than the pre-flood channel (18 to 36 m, mean 26 m, Fig. 10). This reflects the development of a new channel on the aggraded valley bottom rather than the erosion of the pre-existing margins of the channel. At km 10.5 to 10, a large sheet of sand, up to several metres thick, was deposited in a broad, low-lying area of the valley bottom and buried the pre-flood channel and a large area along the right side of the valley bottom (including the foundations of several homes; Fig. 14). From km 8.5 to 8, the subaerial margins of the channel essentially are preserved, but the post-flood width is greater than the pre-flood (33 to 40 m vs. 24 to 28 m, respectively; Fig. 10). This apparent widening probably reflects minor aggradation of the river bed. Beginning at km 8 and extending downstream, the river bed is eroded into the pre-flood bottom of the channel.

Fig. 14. Extensive sand aggradation along the right side of the valley at km 10.5 to 10. The post-flood channel flows on fresh alluvium that covers the valley bottom. Photograph taken on July 28, 1996 (GSC photograph 1997-42KK).

6.6. km 8 to 4.5 — moderate channel widening

From about km 9.5 and extending downstream to the top of a canyon at km 5, Ha!Ha! River is confined within a narrow, relatively straight valley bottom. Beginning at km 8 and extending to km 5, the flood caused extensive erosion into late Pleistocene sediments (alluvium underlain by diamicton) and widened and deepened the channel, completely destroying the pre-flood channel. The mean width of the post-flood channel (34 to 88 m wide, mean 68 m) is about 3 times greater than the pre-flood channel (8 to 34 wide m, mean 24 m; Fig. 10); the widening was restricted by the narrow morphology of the valley bottom which confines the river, the material strength of the deposits now exposed along the river, and, locally, by exposed bedrock. The depth of incision increases downstream gradually from km 8 to a maximum of about 15 m at km 6 (Fig. 15), and then declines, eventually grading to the top of the canyon. Downstream along the canyon (km 5 to 4.5), the bedrock was extensively scoured of vegetation (grasses, mosses, small shrubs) and small, thin pockets of overburden by the flood.

Notably, a small concrete dam located at km 5 was breached and the reservoir drained and partially aggraded with sediment (Fig. 3). The powerhouse, situated at the base of the canyon (km 4.5), was destroyed.

6.7. km 4.5 to 0 — major channel widening

The flood caused major geomorphic change along the lower 4.5 km of the river. Previously, this portion of the river followed an irregular meandering course (sinuosity 1.2) that alternated between single channelled and divided reaches (the latter flowing around small islands representing stabilized mid-channel bars; Fig. 16). Between km 4.5 and 3.25,

Fig. 15. The incised and widened channel, about 15 m deep, looking upstream from km 6. Exposed alluvium, diamicton and bedrock, and bouldery lag form the perimeter of the channel. Note the homes damaged by undermining along the right bank. Photograph taken on July 28, 1996 (GSC photograph 1997-42NN).

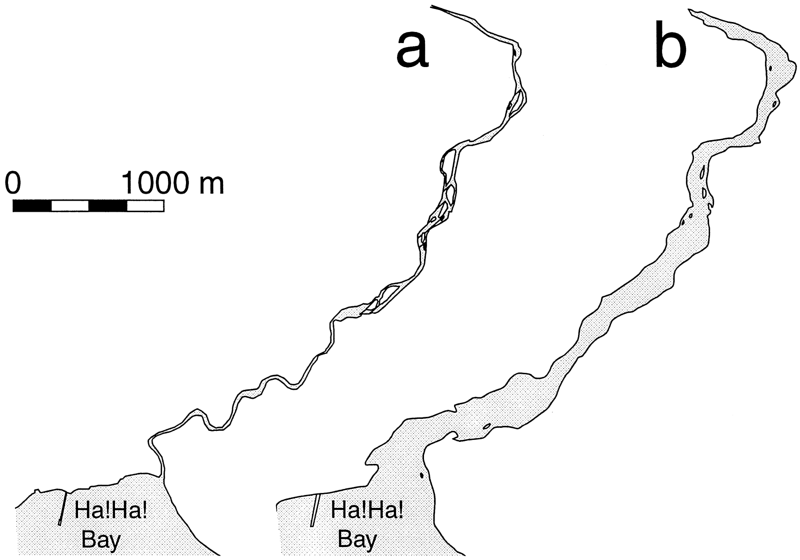

Fig. 16. Maps showing (a) the pre-flood and (b) post-flood channel width along the lower 4 km of Ha!Ha! River (see Fig. 3). The pre-flood map is based on Quebec Ministère de L'Energie et des Ressources map 'La Baie' (22D02-200-0101), 1:20,000 scale while the post-flood map was obtained from a rectified mosaic of multi-spectral video images acquired on August 6, 1996 (courtesy of Canada Centre for Remote Sensing).

widening and deepening of the river destroyed the pre-flood channel, similar to conditions that occurred upstream between km 8 and 5. In places, the alluvium was completely stripped and the post-flood river flowed on exposed marine sediments. The post-flood channel ranges from 62 to 145 m wide (mean 105 m) compared to 24 to 32 m wide (mean 28 m) for the pre-flood channel (Fig. 10); up to about 6 m of incision occurred locally (INRS-Eau, 1997). The largest amount of widening occurred at a sharp bend within a wider section of valley bottom (Fig. 16).

Below km 3.25, the valley bottom broadens markedly. Here, extensive widening of the channel occurred through lateral erosion of the floodplain and low terraces (Figs. 16 and 17a). The post-flood channel ranges from 92 to 281 m wide (mean 160 m) compared to 15 to 110 m (mean 47 m) for the pre-flood channel (Figs. 3 and 16), but of note, the wider sections of the pre-flood channel reflect either the subdivision of the channel by vegetated islands (measured as total width) or a small reservoir impounded by a dam at km 1.8. The post-flood morphology of the channel, in places, is multi-channelled and resembles a braided planform. Major widening occurred adjacent to the small dam (km 1.8) where overflow of the left abutment resulted in major lateral erosion and incision of the floodplain formed a new channel adjacent to, and lower than, the dam (Fig. 17a). This erosion drained the small reservoir, damaged the dam, severed the penstocks, and destroyed the powerhouse.

At the river mouth, 9.3×10^6 m^3 of sediment, derived from erosion upstream (INRS-Eau, 1997; Table 2), was deposited within Baie des Ha!Ha! as a broad sheet on the tidal flat and considerably increased its subaerial extent at low tide (Fig. 17b). Debris, from buildings undermined and washed away by flood waters, was also carried out and deposited on the tidal flat (Fig. 17b).

6.8. Discussion

Significant widening of the channel (Fig. 10) along much of Ha!Ha! River (specifically, from km 35.5 to 33.5, 27.5 to 12.5 and 8 to 0) is evidence that the flow energy of the flood exceeded the erosive threshold of the pre-flood perimeter of the channel and associated valley bottom (floodplain, terraces). In the recent flood literature (following Baker and

Costa, 1987), flow energy of a flood is expressed quantitatively in terms of unit stream power (ω):

$$\omega = \gamma QS/w \tag{1}$$

where, ω is unit stream power (W m^{-2}), γ is specific weight of water (assumed to be 9800 N m^{-3}, the value for clear water), Q is discharge (m^3 s^{-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).

Along Ha!Ha! River the downstream variation of the slope, discharge and width in Eq. (1) differ significantly. Valley slope changes downstream by two orders-of-magnitude (0.2 to 0.0016) and reflects the irregular profile of the river as the channel traverses bedrock, non-alluvial, and bedrock-controlled alluvial and non-alluvial reaches (Fig. 3). The discharge estimates at the outlet of Lake Ha!Ha! are reasonably similar to that made 27 km downstream (km 8.4; see Table 2) and suggest that no pronounced downstream change occurred in the peak discharge. The downstream variation in the width of flow is more complicated to assess because: (i) along many sections of the valley bottom the maximum width of flow is difficult to measure accurately in the post-flood aerial photographs because vegetation obscures the flood margins; (ii) low-energy backwater areas can exist adjacent to the general flow in reaches of the valley bottom that significantly widen and narrow abruptly; and (iii) along reaches that experienced major erosion the hydraulic geometry of the flood flow was altered by lateral bank erosion and/or incision. However, a comparison of the pre-flood width (Fig. 10) to either the width of the post-flood channel or to the approximate maximum width of flooding, whichever was more appropriate, indicates that the width of flow changes downstream along the river by no more than an order-of-magnitude. The difference ranges from several 10 s to several 100 s of metres. Overall, along Ha!Ha! River, the change in valley gradient is the most important variable that controls the downstream variation in unit stream power. The importance of gradient affecting geomorphic response to flooding is well recognized in the literature (e.g., Kochel, 1988).

The importance of the change in valley gradient along Ha!Ha! River can be demonstrated along a reach between km 10 and 5 where a marked transition at about km 8 occurs from major aggradation and non-erosion, to major erosion. This occurs along a narrow, very uniform section of valley. If it can be assumed that the discharge (no major tributary(s) join), flow width and, composition and roughness of the valley bottom are reasonably constant, then the downstream increase in valley slope is isolated as the critical variable that raises the unit stream power beyond the erosive threshold of the valley bottom. Downstream along this 5 km long section of valley bottom, the gradient of the pre-flood valley increases gradually by about 11 times (0.002 to 0.023; Fig. 10). The unit stream power of the successive reaches immediately above and below km 8 (approximately where the gradient of the valley begins to steepen) is 163 to 190 and 651 to 760 N m^{-2} (using slopes of 0.002 and 0.008 (Fig. 9), the discharge data of 1080 to 1260 m^3 s^{-1} (Table 2), and a flow width of 130 m from the cross-section surveyed at km 8.5). These ranges of unit stream power fall on either side of the 300 N m^{-2} threshold for major erosion of the channel suggested by Miller (1990) and Magilligan (1992), and correspond to the observed zones of aggradation/non-erosion and erosion along the river.

Widening of the channel during the flood represents an adjustment in the morphology of the river that most readily dissipates the local unit stream power (see Eq. (1)). The most extensive widening of the channel occurred below km 3.25, where the valley bottom broadens markedly and a floodplain was present along the river. This degree of widening could not occur to the same extent along the eroded reaches elsewhere along the river because the channel generally is confined within a narrow valley bottom. The pre-existing width of a valley bottom is thus a limiting control on the magnitude of widening that can occur along reaches where the erosive threshold is exceeded. However, along reaches where the valley bottom margins are composed of Quaternary deposits, additional factors also control the degree of widening. These relate to the material strength of the sediments (e.g., material size distribution, cohesiveness, compaction, internal stratigraphic relations and vegetative binding) and the height of the eroding bank. The difference in material strength of the banks is undoubtedly a significant factor in the major widening that occurred between km 16 and 12.5 relative to, for example, between km 8 and 5. In the latter case, the river was eroding into a compact diamicton overlain by a gravel alluvium deposit (Fig. 15) vs. initially into sand and then a clay–silt unit at the former reach (Fig. 13).

The two major sections of the river that experienced negligible erosion and/or major aggradation (reaches km 33 to 27 and 12.5 to 8), not surprisingly, had the lowest pre-flood gradient (0.0016 and 0.002)

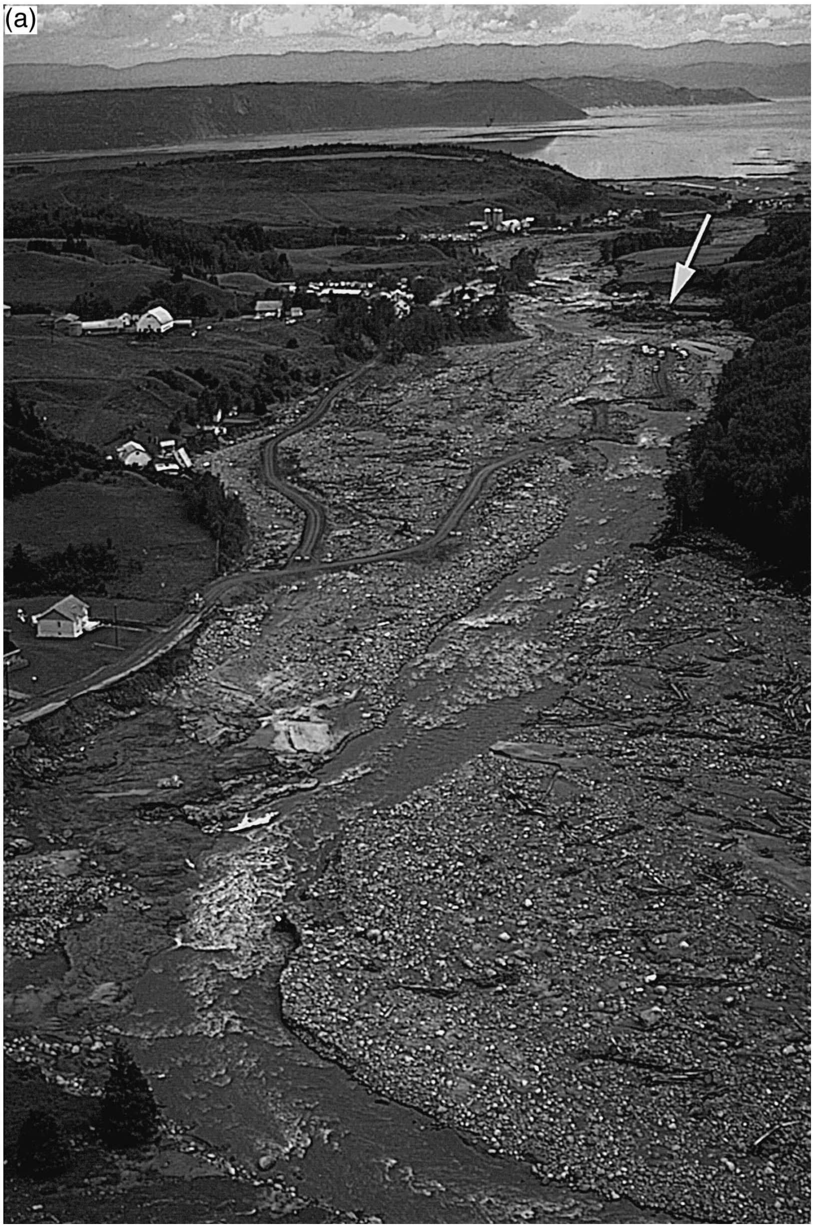

Fig. 17. The broad post-flood channel of Ha!Ha! River (picture 'a'), viewed downstream from km 3 (GSC photograph 1997-42RR). The pre-flood valley bottom (floodplain and terraces) has been extensively reworked; an arrow marks the remains of a dam severely damaged during the flood. Tidal flat at the river mouth looking upstream into the Ha!Ha! River valley (picture 'b'; GSC photograph 1997-42TT). Note the debris from destroyed buildings on the tidal flats and the considerable damage to residential and commercial areas within the City of La Baie at the river mouth. Photographs taken on July 28, 1996.

Fig. 17 (continued).

of any reach along the river. Unit stream power at these reaches (Table 4) ranged locally from 65 to 289 N m^{-2} (km 33 to 27) and 64 to 260 N m^{-2} (km 12.5 to 8) which are both below the 300 N m^{-2} erosive threshold, mentioned previously. Major erosion did not occur along either reach which indicates that the 'real' erosive threshold (be it 300 N m^{-2} or marginally(?) higher) was not crossed, being a function of the local valley bottom roughness, vegetative cover, and surficial material.

Major aggradation along the reaches of river between km 33 to 27 and 16 to 12.5 occur immediately downstream of reaches that experienced major erosion; specifically, the formation of the new channel into the saddle at Lake Ha!Ha! (reach km 35 to 33) and the diverted and deeply incised channel in the

Table 4
Estimate of unit stream power along the km 33–27 and 16–12.5 reaches

Reach	Valley slope	Specific weight of water (N m^{-3})[a]	Discharge (m^3 s^{-1})[b]	Width range (m)[c]	Unit stream power[d] (W m^{-2})
km 33–27	0.0016	9800	910–1380	75–220[e]	65–289
km 16.5–12	0.002	9800	1080–1260	95–330[e]	64–260

[a]Value for clear water.
[b]See Table 2.
[c]Estimated from post-flood aerial photographs.
[d]See Eq. (1) in text.
[e]Maximum width of flow is conservative. Irregularly shaped, low-lying areas of the valley bottom that were obviously back-flooded were not included in measurement.

area of the Chute-à-Perron rapids (km 16 to 12.5). The relatively low unit stream power is a significant factor influencing the aggradation, but equally important is the presence of abundant sand-sized sediment being carried by the river and is thus available for deposition where the energy of flow decreases.

Not all of the erosion and deposition along Ha!Ha! River can be explained in terms of variation in unit stream power. At km 16 to 13, the gradient of the pre-flood valley averages 0.003, just slightly greater than that of reaches km 33 to 27 and km 12.5 to 8, yet this reach experienced major lateral erosion and incision during the flood. In this instance, the effects of the flood relate specifically to events along the reach immediately downstream. As described above, a major diversion of the river occurred at km 13 and the river cut a new route across the drainage divide between the main channel course and a ravine; previously, the river had been flowing over a bedrock surface that controlled the baselevel of the reach immediately upstream. Incision and lateral erosion, thus, ensued along the new course and extended several kilometres upstream severely altering a previously gently-sloped reach. This geomorphic change is the product of a decrease in local baselevel, the effects of which propagated upstream.

7. Implications for other rivers on the Canadian Shield

The events along Ha!Ha! River demonstrate that rivers on the Canadian Shield draining less than 1000 km^2 can experience significant geomorphic change from exceptionally high-magnitude floods. These changes include major widening and aggradation/incision of the channel along alluvial and non-alluvial reaches. Widening in places will be restricted by narrow valley bottoms formed of bedrock or Quaternary deposits. In the latter cases, variations in widening will also reflect changes in the material strength and height of the eroding valleyside deposits. The erosive threshold of the valley bottom will be exceeded locally rather than uniformly along the river course because of local variations in slope as the river passes over bedrock, alluvial and non-alluvial surfaces. Small lake basins, however, are very common along many rivers on the Canadian Shield and these will dampen the downstream progression of a flood wave. For example, the flood arising from the 1985 failure of Beloeil dam (see Section 1) was significantly dampened by Lake Talbot located only 7 km downstream.

The occurrence of the channel diversion at km 13 may not be a phenomenon unique to Ha!Ha! River. Drainage on the Canadian Shield follows the regional slope of the land surface, but the stream courses generally are controlled by bedrock structure, faulting and joint patterns, and are diverted in places by the presence of glacial deposits (Bostock, 1970). The lack of a well-developed valley along some reaches suggests that channel diversions could occur during extreme floods along other Shield rivers from the overtopping and incision of low within-basin drainage divides formed of glacial sediments. Such diversions could have severe and irreversible local geomorphic impacts.

A number of homes were damaged or destroyed along Ha!Ha! River by undermining of the river banks despite, in many instances, the homes being located above the level of inundation. At some river settings, extensive bank erosion during very high-magnitude floods can be a severe hazard to communities and the infrastructure located in valley bottoms in addition to the obvious inundation problems.

8. Conclusions

The overtopping and erosion of the Cut-away dyke caused the draining of the Lake Ha!Ha! reservoir, and significantly accentuated flooding along Ha!Ha! River already in progress from a severe rainstorm. The drainage of the reservoir occurred over a period of many hours. The overtopping of the dyke was caused by insufficient available capacity of the spillway at the time of the rainstorm and because the elevation of the dyke crest was below that of the concrete dam controlling the reservoir level.

The flood discharge along Ha!Ha! River is estimated to be 910 to 1380 m^3 s^{-1} at the new lake outlet and 1080 to 1260 m^3 s^{-1} at a point 27 km downstream. This is about an order-of-magnitude or more larger than the previously recorded maximum instantaneous flow.

The flooding produced morphologic changes downstream of the reservoir. Long sections of the Ha!Ha! River experienced significant widening and incision of the channel because the energy in the flood surpassed the erosive threshold of the valley bottom. Major aggradation occurred along two reaches where the flood energy was below threshold and where extensive erosion happened immediately upstream. Valley gradient was the most important variable controlling whether energy of flow exceeded the erosive threshold of the valley bottom. One reach underwent major incision and widening as a result of the flood overtopping and eroding across the drainage divide between the main course of the channel and a small ravine. This resulted in a short diversion of the channel where deep incision ensued and propagated upstream. The morphologic changes along Ha!Ha! River demonstrate that rivers on the Canadian Shield can experience significant impacts from high magnitude floods.

9. Postscript

Preliminary work to reconstruct a replacement earthfill dyke across the new outlet channel of Lake Ha!Ha! began within days of the waning of the flood. Work on the dyke was underway in mid-November, 1996 and scheduled to be completed by the end of December, 1996 (Emile Soucie, pers. comm., November 13, 1996). The new dyke is located several hundred metres west of the remnants of the Cut-away dyke, on ground that was originally part of the reservoir bed. The dam that again controls the reservoir level has been rebuilt and now incorporates a wide concrete overflow spillway.

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