A review of catastrophic drainage of moraine-dammed lakes in British Columbia

John J. Clague*, Stephen G. Evans

*Department of Earth Sciences and Institute for Quaternary Research, Simon Fraser University, 8888 University Drive, Burnaby, BC Canada V5A 1S6
Geological Survey of Canada, 101 – 605 Robson St., Vancouver, BC Canada V6B 5J3
Terrain Sciences Division, Geological Survey of Canada, 601 Booth Street, Ottawa, Ont., Canada K1A 0E8

Abstract

Moraine-dammed lakes are common in the high mountains of British Columbia. Most of these lakes formed when valley and cirque glaciers retreated from advanced positions achieved during the Little Ice Age. Many moraine dams in British Columbia are susceptible to failure because they are steep-sided, have relatively low width-to-height ratios, comprise loose, poorly sorted sediment, and may contain ice cores or interstitial ice. In addition, the lakes commonly are bordered by steep slopes that are prone to snow and ice avalanches and rockfalls. Moraine dams generally fail by overtopping and incision. The triggering event may be a heavy rainstorm, or an avalanche or rockfall that generates waves that overtop the dam. The dam can also be overtopped by an influx of water caused by sudden drainage of an upstream ice-dammed lake (jökulhlaup). Melting of moraine ice cores and piping are other possible failure mechanisms. Failures of moraine dams in British Columbia produce destructive floods orders of magnitude larger than normal streamflows. Most outburst floods are characterized by an exponential increase in discharge, followed by an abrupt drop to background levels when the water supply is exhausted. Peak discharges are controlled by dam characteristics, the volume of water in the reservoir, failure mechanisms, and downstream topography and sediment availability. For the same potential energy at the dam site, floods from moraine-dammed lakes have higher peak discharges than floods from glacier-dammed lakes. The floodwaters may mobilize large amounts of sediment as they travel down steep valleys, producing highly mobile debris flows. Such flows have larger discharges and greater destructive impact than the floods from which they form. Moraine dam failures in British Columbia and elsewhere are most frequent following extended periods of cool climate when large lateral and end moraines are built. A period of protracted warming is required to trap lakes behind moraines and create conditions that lead to dam failure. This sequence of events occurred only a few times during the Holocene Epoch, most notably during the last several centuries. Glaciers built large moraines during the Little Ice Age, mainly during the 1700s and 1800s, and lakes formed behind these moraines when climate warmed in the 1900s. Twentieth-century climate warming is also responsible for recent moraine dam failures in mountains throughout the world. Warming from the late 1800s until about 1940 and again from 1965 to today destabilized moraine dams with interstitial or core ice. The warming also forced glaciers to retreat, prompting ice avalanches, landslides, and jökulhlaups that have destroyed some moraine dams. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Many lakes impounded by moraines are a threat to people and property in mountain regions throughout the world. The dams may fail suddenly, producing destructive floods with peak discharges far in excess of normal flows. Notable failures include four large moraine dam failures in the Cordillera Blanca of Peru between 1938 and 1950 (Heim, 1948; Lliboutry et al., 1977). The most devastating of the four events was the 1941 emptying of moraine-dammed Lake Cohup which destroyed one-third of the city of Huaraz, killing more than 6000 people. Recent large outbursts from moraine-dammed lakes have also been reported in other parts of the Andes (Reynolds, 1992; Hauser, 1993), the Himalayas (Gansser, 1983; Vuichard and Zimmerman, 1987; Ding and Liu, 1992; Reynolds, 1995, 1998; Watanabe and Rothacher, 1996; Cenderelli and Wohl, 1997), the mountains of central Asia (Niyazov and Degovets, 1975; Yesenov and Degovets, 1979; Popov, 1990), and North America (Evans, 1987; O’Connor and Costa, 1993; Clague and Evans, 1994; Evans and Clague, 1994; O’Connor et al., 1994) (Fig. 1; Table 1). The draining of Laguna del Cerro Largo in Chile in 1989 involved the release of $229 \times 10^6$ m$^3$ of
water (Hauser, 1993), the largest moraine dam failure documented in the literature.

Moraine-dammed lakes are common in the Cordillera of western Canada, and many of them have drained suddenly in recent years, producing floods and debris flows (Fig. 2). The phenomenon, however, is not well understood in Canada, partly because moraine dam failures have occurred in remote mountain valleys where they have gone largely unnoticed. Recently, development associated with forestry and mining, hydro-electric power generation, and recreational activities has extended into these remote valleys, and there is now more of a need to understand potential hazards associated with outburst floods.

In this paper, we review and discuss moraine dam failures in British Columbia. Our main objectives are to document how moraine dams form and fail, and to provide insights on failure processes and hazards.

### Table 1

**Examples of moraine dam failures**

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Date of failure</th>
<th>Outburst volume (\text{m}^3 \times 10^6)</th>
<th>Failure mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madatschferner</td>
<td>Austria</td>
<td>August 7, 1890</td>
<td></td>
<td>Ice avalanche</td>
<td>Eisbacher and Clague (1984)</td>
</tr>
<tr>
<td>Galrittferner</td>
<td>Austria</td>
<td>December 13, 1941</td>
<td></td>
<td>Ice avalanche</td>
<td>Eisbacher and Clague (1984)</td>
</tr>
<tr>
<td>Cohup</td>
<td>Peru</td>
<td>July 1942</td>
<td></td>
<td>Excess meltwater</td>
<td>Hopson (1960)</td>
</tr>
<tr>
<td>White Branch</td>
<td>Oregon, USA</td>
<td>1942-1953</td>
<td>6-10</td>
<td>Collapse of undercut glacier</td>
<td>Rabassa et al. (1979)</td>
</tr>
<tr>
<td>Tempanos</td>
<td>Argentina</td>
<td>1950</td>
<td></td>
<td></td>
<td>Lliboutry et al. (1977)</td>
</tr>
<tr>
<td>Jancaruish</td>
<td>Peru</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artesoncoda</td>
<td>Peru</td>
<td>July 16-17, 1951</td>
<td>0.19</td>
<td>Ice avalanche</td>
<td>Lliboutry et al. (1977)</td>
</tr>
<tr>
<td>Broken Top</td>
<td>Oregon, USA</td>
<td>October 7, 1966</td>
<td>0.33</td>
<td>Ice avalanche</td>
<td>Nolf (1966)</td>
</tr>
<tr>
<td>Squaw Creek</td>
<td>Oregon, USA</td>
<td>September 7, 1970</td>
<td>4.9*</td>
<td>Earthquake-induced piping</td>
<td>Laenen et al. (1992)</td>
</tr>
<tr>
<td>Safuna Alta</td>
<td>Peru</td>
<td>1970</td>
<td></td>
<td></td>
<td>Lliboutry et al. (1977)</td>
</tr>
<tr>
<td>Moraine no. 13</td>
<td>Soviet Union</td>
<td>August 3, 1977</td>
<td>0.08</td>
<td>Melt of frozen soil</td>
<td>Yesenov and Degovets (1979)</td>
</tr>
<tr>
<td>Dig Tsho</td>
<td>Nepal</td>
<td>August 4, 1985</td>
<td>8</td>
<td>Excess runoff?</td>
<td>Fushimi et al. (1985)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ice avalanche</td>
<td>Galay (1985); Vuichard and Zimmerman (1987)</td>
</tr>
</tbody>
</table>

\*Adapted from Costa and Schuster (1988, Table 5).

\*Volume stored in lake.

2. Setting

Lateral and end moraines are common in glacier forelands outside present ice margins in most high mountain ranges, including those in western Canada (Fig. 3). The moraines were constructed during a recent period of cool
climate that ended in the late nineteenth century (the “Little Ice Age” (Matthes, 1939; Grove, 1988), which is the last part of the Neoglacial period (Porter and Denton, 1967)). Researchers working in British Columbia and Alberta have shown that these moraines date mainly to the eighteenth and nineteenth centuries (e.g., Ryder and Thomson, 1986; Luckman, 2000; Fig. 4). Little Ice Age advances also occurred in other parts of the world during this period (Grove, 1988).

In many areas, glaciers began to retreat from their Little Ice Age moraines at the end of the nineteenth century (Fig. 5). Retreat was rapid and substantial during the warmer decades of the twentieth century, especially in the 1920s and 1930s, and from about 1980 until today. Lakes formed in closed basins between Little Ice Age moraines and retreating glaciers (Fig. 5). In some instances, lakes drained slowly soon after they formed as the moraine dams were slowly eroded. In other cases, overflow channels on the moraines became naturally armored and the lakes persisted.

Most moraine-dammed lakes occur in cirques or the upper reaches of steep-walled valleys behind end moraines (Fig. 6). Other, less common settings include trunk valleys behind lateral moraines deposited by ice flowing out of tributary valleys, and tributary valleys behind...
lateral moraines deposited by ice flowing in trunk valleys. Most, although not all, moraine-dammed lakes lie near or above treeline and may be close to steep rock slopes susceptible to landslides and snow and ice avalanches.

3. Characteristics of dams

Moraine dams may consist of a single moraine or two or more moraines deposited during several Neoglacial advances and separated by swales. Most moraines are steep-sided (up to ca. 40°) and have width-to-height ratios of 0.1–0.2. Width-to-height ratios are generally smaller than those of landslide dams and comparable to those of constructed dams (Fig. 7; Costa and Schuster, 1988). Heights of a few tens of metres are common, and some moraine dams are more than 100 m high.

Moraine dams comprise loose, poorly sorted, stratified to massive sediment deposited directly from glacier ice (Fig. 8). The sediment was transported both within and at the surface of the glacier and released on a growing ridge at the glacier snout. Some moraines consist largely of coarse, blocky and bouldery material with a matrix of sand and gravel. Blocks and boulders up to several metres across may constitute up to 80% of the moraine. These materials resemble rockslide deposits and, in fact, are accumulations of supraglacially transported landslde debris. Other moraines consist of silty and sandy diamicton and sandy gravel (Fig. 8). These deposits contain 25–50% gravel-size material and are generally finer than the blocky and bouldery deposits described above. The sediment is crudely stratified; strata dip either irregularly or away from the former ice-contact face towards the distal edge of the moraine (Fig. 8). Some moraines are ice-cored and may have only a thin cover of sediment (Ostrem and Arnold, 1970). Others lack ice cores but contain interstitial ice in pores within the sediment.

4. Historical failures in British Columbia

At least nine moraine dams failed in British Columbia during the historical period – five in the Coast Mountains, one in the Saint Elias Mountains, and three in the Columbia Mountains (Fig. 2; Table 2; Evans, 1987; Ryder, 1991; Clague and Evans, 1992, 1994; Clague and Mathews, 1992; Evans and Clague, 1993, 1994). Five of the nine events are described briefly below to illustrate the scope of the phenomenon. None of the failures was directly witnessed.

4.1. Nostetuko Lake

Nostetuko Lake (ca. 1600 m asl), located at the head of Nostetuko River 230 km north of Vancouver, is dammed by a Little Ice Age end moraine that probably dates to the 1800s (Fig. 3). The moraine was built by Cumberland Glacier, which has since receded and now terminates on a steep rock face above the lake.
Fig. 8. Poorly sorted, bouldery sediments exposed in the breached, Little Ice Age moraine at Nostetuko Lake, British Columbia. Most moraine dams in the Canadian Cordillera are composed of such materials. The height of the exposure is about 40 m.

Table 2
Moraine dam failures in western Canada

<table>
<thead>
<tr>
<th>Site</th>
<th>Date of failure</th>
<th>Outburst volume (m³ × 10⁶)</th>
<th>Peak discharge (m³/s)</th>
<th>Effect</th>
<th>Failure mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide Lake</td>
<td>1927–1930</td>
<td></td>
<td></td>
<td>Flood</td>
<td></td>
<td>Clague and Mathews (1992)</td>
</tr>
<tr>
<td>Bridge Glacier</td>
<td>1964–1970¹</td>
<td>1–2</td>
<td>&lt; 1000</td>
<td>Flood</td>
<td></td>
<td>Ryder (1991)</td>
</tr>
<tr>
<td>Klattasine Lake</td>
<td>1971–1973</td>
<td>1.7</td>
<td>&gt; 1000</td>
<td>Flood/debris flow</td>
<td></td>
<td>Clague et al. (1985)</td>
</tr>
<tr>
<td>Nostetuko Lake</td>
<td>July 19, 1983</td>
<td>6.5</td>
<td>ca 10 000</td>
<td>Flood</td>
<td>Ice avalanche</td>
<td>Blown and Church (1985)</td>
</tr>
<tr>
<td>North Macoun Lake</td>
<td>July 1983</td>
<td></td>
<td></td>
<td>Flood</td>
<td></td>
<td>Evans (1987)</td>
</tr>
<tr>
<td>South Macoun Lake</td>
<td>Before 1949</td>
<td>0.4</td>
<td>&lt; 1000</td>
<td>Flood/debris flow</td>
<td>Ice avalanche²</td>
<td>Evans (1987)</td>
</tr>
<tr>
<td>Patience Mountain</td>
<td>1951–1966</td>
<td>0.3</td>
<td>&lt; 1000</td>
<td>Flood/debris flow</td>
<td>Ice avalanche²</td>
<td>Evans (1987)</td>
</tr>
<tr>
<td>Tats</td>
<td>June 28, 1990</td>
<td>0.004</td>
<td>&lt; 1000</td>
<td>Flood/debris flow</td>
<td>Ice avalanche²</td>
<td>Clague and Evans (1992)</td>
</tr>
<tr>
<td>Queen Bess Lake</td>
<td>August 12, 1997</td>
<td>8</td>
<td>&gt; 1000</td>
<td>Flood</td>
<td>Ice avalanche</td>
<td>Unpublished</td>
</tr>
</tbody>
</table>

¹Other partial breachings, accompanied by floods, may have occurred between 1935 and 1947.

On July 19, 1983, part of the toe of Cumberland Glacier broke away and cascaded into the lake. A wave generated by the impact of the ice avalanche moved across the lake and overtopped the moraine dam. The wave eroded the inner face of the moraine near the outlet to a height of 4 m above the shoreline (Blown and Church, 1985). The outflow channel on the moraine was naturally armoured with a boulder lag, but the overtopping wave breached the armour and initiated catastrophic incision. Within four hours, the moraine had been incised to a depth of almost 40 m and about 6.5 × 10⁶ m³ of water had been released (Fig. 9; Blown and Church, 1985). The resulting flood swept down Nostetuko and Homathko valleys to the sea (Fig. 10).

Over 1 × 10⁶ m³ of sediment were eroded from the moraine; most of this sediment was deposited as a large fan on top of a former meadow directly downstream from the dam (Fig. 9). Farther downstream, floodwaters extensively eroded unconsolidated deposits in Nostetuko valley, damaged large tracts of forest, and left piles of trees, other woody debris, and coarse sediment on bars and channel margins. Erosion was particularly severe at bends along the river where colluvial fans extended out onto the valley floor. Much of the sediment eroded from
channels and valley sides was transported short distances and then redeposited, contributing to local aggradation of the valley floor. However, along steeper reaches of the river, the valley floor was stripped clean of sediment by the floodwaters (Fig. 11). Fine material (sand, silt) was carried a long distance downstream and deposited in overbank areas. Forest was flattened where the flood and floating debris overflowed channel banks.

The flood attenuated as it moved downvalley. The two Water Survey of Canada gauging stations closest to Nostetuko Lake were damaged and ceased functioning, but two other gauging stations remained operational. A hydrograph at a site 67 km downstream from dam showed an increase in discharge from the background level of 330 m$^3$/s$^{-1}$ to over 900 m$^3$/s$^{-1}$ in one hour (Fig. 12). At a site a further 45 km downvalley, the increase in discharge was less and slower (Fig. 12). Nevertheless, the flood was still large enough at the mouth of Homathko River, 115 km downstream from the dam, to briefly inundate part of a logging camp. The average velocity of the flood wave between the two operational gauging stations was about 10 km h$^{-1}$.

In the 18 yr since the event, Nostetuko River has incised its flood deposits, but it has not yet recovered its pre-flood channel planform and morphology. This observation suggests that such rare flood events may affect streams for decades.

4.2. Queen Bess Lake

Queen Bess Lake (1692 m asl) is located near the head of a major tributary of Nostetuko River, 9 km northwest of Nostetuko Lake. The lake is dammed by Little Ice Age moraines built in the nineteenth and possibly eighteenth centuries.

Fig. 10. Cross-sections showing the maximum depth of the 1983 Nostetuko outburst flood in Nostetuko River valley. Distances from Nostetuko Lake are indicated at the upper left of the cross-sections.

Fig. 9. Digital image of Nostetuko Lake and the breached, Little Ice Age moraine of Cumberland Glacier (view southeast). The snout of Cumberland Glacier fell into the lake in July 1983 and generated a wave that overtopped and incised the moraine. The digital image consists of an orthophoto, based on July 1994 aerial photographs, draped on a digital elevation model obtained from the same photos. Changes in surface elevation between July 1981 and July 1994 are shown in colour tones. Dramatic surface lowering is seen at the snout of Cumberland Glacier (the blue and purple area behind Nostetuko Lake). This lowering is the result of the 1983 glacier avalanche and climate-related glacier retreat. Surface lowering at Nostetuko Lake records the fall in lake level due to failure of the moraine dam. Note deposition of debris on the large fan in the foreground. Compare this figure with Fig. 3, which is a pre-outburst photograph.
Queen Bess Lake drained suddenly on August 12–13, 1997, when its moraine dam was overtopped and incised by a displacement wave triggered by a large ice avalanche from Diadem glacier (informal name) (Fig. 13). The wave overrode a 600 m length of the moraine crest to depths of 15–25 m (Fig. 14). The avalanche occurred during a warm rainy period when large amounts of water were discharging from the base of Diadem glacier. About $8 \times 10^6$ m$^3$ of water escaped from the lake, producing a flood that stripped vegetation from the valley floor below the dam (Fig. 14).

The level of Queen Bess Lake dropped 8 m, and a steep-walled ravine up to 15 m deep, 60–75 m wide, and 360 m long was carved into the end moraines at the site of the former outflow channel (Fig. 15). Sediment eroded from the ravine was carried downstream by floodwaters and deposited on a fan 200 m from the moraine. Incision of the moraine was limited by bedrock cropping out on the floor of the ravine at its north end. Were it not for this sill, outflow from the lake probably would have more deeply incised the moraine, and a much larger volume of water would have been released.

The flood wave surged 9 km down the west fork of Nostetuko River to the main Nostetuko valley (Fig. 14). It travelled another 12 km in Nostetuko valley to Homathko River, and thence west down Homathko valley. Although the flood attenuated as it moved downvalley, it still was noticed by forestry personnel at the mouth of Homathko River, 100 km from the source.

The floodwaters extensively eroded Quaternary deposits in the west fork of Nostetuko valley, damaged tracts of forest, and left wood debris and coarse sediment on bars and channel margins (Fig. 15). Margins of many colluvial fans impinging on the valley floor were eroded back tens of metres, leaving steep unstable scarps (Fig. 15). Most of the sediment eroded from channels and valley sides was transported short distances and then redeposited, contributing to aggradation of the valley floor. Steeper, rock-controlled reaches of the river were stripped clean of sediment by the floodwaters. Boulders up to 10 m across were transported in traction through these reaches and deposited on more gently sloping sections of the valley floor. Fine sediments were deposited upstream of channel constrictions where water was hydraulically ponded during the flood. In the two years since the outburst, Nostetuko River has incised its flood deposits, but it has not yet recovered its pre-flood channel morphology and is unlikely to do so for decades.

4.3. Klattasine Lake

Klattasine Lake (1640 m asl) is situated at the head of the west fork of Klattasine Creek, 35 km west of Nostetuko Lake. The moraine impounding Klattasine Lake dates to the nineteenth century. It failed sometime between June 1971 and September 1973, causing the sudden release of $1.7 \times 10^6$ m$^3$ of water from the lake (Clague et al., 1985). Escaping waters trench ed the moraine down to a bedrock sill, which now forms the stable outlet of the remnant lake (Fig. 16). The cause of the failure is unknown.
The Klattasine event is instructive because it was a debris flow rather than a flood. The escaping waters eroded sediment from the moraine dam and, more importantly, mobilized large quantities of sediment along the channel and margins of the steep valley below the lake. In this manner, the flood rapidly evolved into a debris flow as it travels downstream from a breached moraine dam (vertical and horizontal scales are dimensionless). (1) Site near the moraine; (2) mid-valley site; (3) site distant from moraine. The total volume of the flood is the same at each of the three sites, but flood height decreases and flood period increases downstream. Base flows also increase downstream due to normal inputs from tributary streams.

The Klattasine event is instructive because it was a debris flow rather than a flood. The escaping waters eroded sediment from the moraine dam and, more importantly, mobilized large quantities of sediment along the channel and margins of the steep valley below the lake. In this manner, the flood rapidly evolved into a debris flow as it travels downstream from a breached moraine dam (vertical and horizontal scales are dimensionless). (1) Site near the moraine; (2) mid-valley site; (3) site distant from moraine. The total volume of the flood is the same at each of the three sites, but flood height decreases and flood period increases downstream. Base flows also increase downstream due to normal inputs from tributary streams.

The Klattasine event is instructive because it was a debris flow rather than a flood. The escaping waters eroded sediment from the moraine dam and, more importantly, mobilized large quantities of sediment along the channel and margins of the steep valley below the lake. In this manner, the flood rapidly evolved into a debris flow as it travels downstream from a breached moraine dam (vertical and horizontal scales are dimensionless). (1) Site near the moraine; (2) mid-valley site; (3) site distant from moraine. The total volume of the flood is the same at each of the three sites, but flood height decreases and flood period increases downstream. Base flows also increase downstream due to normal inputs from tributary streams.

The Klattasine event is instructive because it was a debris flow rather than a flood. The escaping waters eroded sediment from the moraine dam and, more importantly, mobilized large quantities of sediment along the channel and margins of the steep valley below the lake. In this manner, the flood rapidly evolved into a debris flow as it travels downstream from a breached moraine dam (vertical and horizontal scales are dimensionless). (1) Site near the moraine; (2) mid-valley site; (3) site distant from moraine. The total volume of the flood is the same at each of the three sites, but flood height decreases and flood period increases downstream. Base flows also increase downstream due to normal inputs from tributary streams.

4.4. Tide Lake

Tide Lake (ca. 680–790 m asl) is a small (1 ha), moraine-dammed lake located in the Saint Elias Mountains of northwestern British Columbia. The lake is bordered on three sides by a single, sharp-crested moraine built during the Little Ice Age. As this morainal complex grew in size, it created a growing barrier to drainage beneath the glacier. In the late 1800s or early 1900s, Frank Mackie Glacier retreated from the end moraine and no longer directly blocked the Bowser River drainage. Tide Lake, however, continued to be dammed by the moraine. The moraine dam persisted until sometime between 1927 and 1930 (Hanson, 1932), when it was breached by overflow from Tide Lake, perhaps during a period of rapid snowmelt or heavy rainfall. Only a remnant of the moraine dam remains today. Tide Lake can only re-form if Frank Mackie Glacier were to readvance far enough to block Bowser River.

4.5. Tats Lake

Tats Lake (1500 m asl) is a small (1 ha), moraine-dammed lake located in the Saint Elias Mountains of northwestern British Columbia. The lake is bordered on three sides by a single, sharp-crested moraine built during the Little Ice Age. Along its eastern side, the lake is in contact with the steep snout of a cirque glacier. On June 28, 1990, about 4000 m$^3$ of water escaped from Tats Lake, lowering its level about 0.4 m (Clague and Evans, 1992). The escaping waters eroded a steep-walled trench up to 10 m deep and 25 m wide over a distance of 500 m from near the crest of the moraine to its toe (Fig. 19); 5000–15,000 m$^3$ of sediment were removed from the moraine dam.
The outburst produced a slurry of sediment and water that moved downvalley either as a sediment-laden water flood or a debris flow, locally entraining additional sediment from the valley floor. The first 2.7 km of the flow path below the moraine has an average gradient of 11°, whereas the final 1.3 km to Tats Creek is much steeper (20° on average; 40° maximum). It is not known if a flood or a debris flow traversed the relatively low-gradient section of the valley below the moraine, but it is clear that a debris flow passed down the steep, dominantly rocky reach above Tats Creek. A considerable amount of sediment may have been incorporated into the flow as it moved down this final steep reach.

The debris flow stopped as it entered Tats Creek. It left a fan-shaped mass of debris about 100 m wide and 100 m long, which temporarily stemmed the flow of the stream. Soon, however, the stream overflowed the debris dam and established a new course through forest along the south side of the valley.

The cause of the Tats Lake outburst is uncertain, but the two most likely possibilities are (1) a sudden influx of water into the lake owing to drainage of a pond within or beneath the glacier to the east, or (2) avalanche or calving of ice from the glacier snout. The former explanation is hypothetical because no evidence was found for the presence of a pond within or beneath the glacier. A few blocks of ice were present in the lake in the summer of 1991 when we visited the site, but it is not clear if these could have produced waves large enough to overtop and incise the outlet.

The Tats Lake outburst, although small, is notable for two reasons: (1) the moraine was not completely breached during the event; and (2) a relatively small release of water initiated a significant debris flood or
Fig. 14. Map of the path of the 1997 Queen Bess outburst flood. Inset map shows the Queen Bess moraine dam, the upper limit of the displacement wave, and the terminus of Diadem glacier at various times between 1949 and 1998.

debris flow that travelled over 4 km from the source. The escaping waters did not completely cut down through the moraine, which is unusual in British Columbia, although there are many examples of this behavior in other regions (e.g., Cascade Range in Oregon; Laenen et al., 1992; Cordillera Blanca in Peru; Lliboutry et al., 1977). Commonly, when water begins to erode a moraine dam, outflow increases exponentially until either the lake is empty or further downcutting becomes impossible due to exposure of a bedrock sill. At Tats Lake, on the other hand, the overflow channel became naturally armoured as downcutting proceeded.

5. Failure mechanisms

The cause of only two of the nine, documented, moraine dam failures in the Canadian Cordillera is known with certainty. The Nostetuko and Queen Bess moraine dams failed because they were overtopped by waves generated by ice avalanches. The overflowing waters eroded the crest and outer flank of the moraines, initiating catastrophic incision. Incision probably propagated from the steepest part of the moraines back towards the crest. Avalanche-induced wave overtopping is probably responsible for some other moraine dam failures in British Columbia (Table 2), and this may be the most
Fig. 15. Flood-devastated west fork of Nostetuko valley about 5 km below Queen Bess Lake (view south). Photograph taken in 1998, one year after the August 1997 flood.

Fig. 16. Breached moraine at Klattasine Lake. View north through the breach from the shore of Klattasine Lake; person (circled) near outlet provides scale. Photograph taken in 1987 by Isabelle McMartin.
Fig. 17. Diagrammatic sketch showing stages in the evolution of the Klattasine Creek debris flow (modified from Evans and Clague, 1994, Fig. 15). (1) The moraine damming Klattasine Lake begins to fail; (2) escaping waters mobilize large quantities of sediment, initiating a debris flow; (3) the debris flow rapidly moves downvalley and entrains additional sediment; (4) the front of the debris flow reaches Homathko River and temporarily blocks it; secondary landslides occur in Klattasine valley. Stippled area = moving debris; black area = wake of debris flow.

Fig. 18. Fan at the mouth of Klattasine Creek. Bouldery debris deposited by the Klattasine Creek debris flow temporarily blocked Homathko River.
common cause of failure in other mountain ranges (Lliboutry et al., 1977; Ding and Liu, 1992). The very low cohesion of morainal sediments accounts for the ease with which they are incised by overflow, unless the surface is armoured by coarse material.

Ice avalanching is a common trigger for moraine dam failures because many glaciers have retreated up steep rock slopes since they abandoned their Little Ice Age moraines (Figs. 3 and 9). Toes of glaciers clinging to steep slopes are heavily crevassed and wet, and thus prone to failure.

The Queen Bess and Nostetuko events are end members of a group of moraine dam failures attributable to wave overtopping triggered by landslides and ice avalanches. One end member, represented by the Queen Bess event, includes failures in which large displacements of waves are the primary source of the flood waters. Much of the water that escaped from Queen Bess Lake was propelled over the moraine by one or more waves. At the other end of the spectrum of overtopping failures is the 1983 Nostetuko Lake event, described above, which involved a much smaller wave, produced by a smaller ice avalanche. In this case, the wave initiated catastrophic incision of the moraine dam but did not itself displace much water from the lake. Nearly all of the water that escaped from Nostetuko Lake did so through a breach in the moraine that rapidly grew as the outburst progressed.

Other trigger mechanisms, which are either external or internal to the moraines, are also important (Fig. 20; Eisbacher and Clague, 1984; Costa and Schuster, 1988). Overtopping and breaching of moraine dams can result
from unusual meteorological conditions – increased streamflow during periods of rapid glacier retreat, heavy rainfall, or rapid snowmelt. Such conditions must be exceptional, however, as most moraines have been stable since they formed more than 100 yr ago, a period during which high overflows must have occurred.

Piping and settlement may gradually weaken a dam to the point that a less exceptional event initiates failure. Moraines consisting of silty and sandy diamicton and sandy gravel may be susceptible to piping. Particle-size analysis of a sample from the Nostetuko moraine, for example, shows that the sediment internal erosion factor \((D_{15}/D_{85})\) (Sherard, 1979) ranges from about 3 to 10 (Blown and Church, 1985). A value of 5 or more indicates a potential for piping. Groundwater derived from the lake may entrain silt and sand and carry them out of the moraine. Piping may be facilitated where strata dip down the outer flank of the moraine, focussing groundwater flow.

Moraine dams containing ice cores or interstitial ice are also vulnerable to failure (Reynolds, 1998). The ice may melt if climate warms, causing the moraines to subside and eventually fail. In addition, thaw flows and slumps may further weaken the moraines. Climate warming from the late 1800s until about 1940 and from about 1965 to the present (Hansen and Lebeácape, 1987; Folland et al., 1990) may have melted ice within some moraines and contributed to their failure. Collapse of the dam during an earthquake is another possible cause of failure. An earthquake may also trigger an ice avalanche or rockfall that generates waves that overtop the moraine.

As noted above, an outburst commonly continues until the moraine is completely breached or the lake is emptied. Of course, any bedrock below the moraine, but above the floor of the lake, will arrest the process, and, in such cases, no further outbursts are possible. In some cases, as at Tats Lake, an outburst may abort before the moraine is completely breached due to armouring of the overflow channel. The recognition of such partial breach failures is significant because it raises the possibility that multiple outbursts can occur from a single moraine-dammed lake.

6. Longevity of dams

Little Ice Age moraine dams have relatively low width-to-height ratios and are composed of loose permeable sediment. These characteristics limit the stability of the dams and suggest that they are likely to be short-lived. There are, of course, exceptions. Dams composed of coarse blocky and rubbly debris may be stable irrespective of their morphology. Moraines that are low and wide and have armoured overflow channels may persist for centuries or millenia, although such dams can be breached if overtopped by sufficiently large waves (e.g., the 1997 Queen Bess event). Ice-cored moraines may thaw for decades or centuries until a critical threshold is reached, whereupon failure may occur under normal overflow conditions. The anticipated warming of climate during the next century should accelerate this process. A warmer climate may also increase the amount of water that flows into moraine-dammed lakes, further destabilizing many dams. Finally, unusual external events, such as a strong earthquake, may cause an otherwise stable moraine dam to fail.

We propose a simple temporal model to explain the occurrence of moraine dam failures following a formative event such as the Little Ice Age (Fig. 21). A new population of moraine dams is created during an extended period of cooler climate (i.e., the eighteenth and nineteenth centuries in the case of the Little Ice Age). Lakes form behind these dams during the first retreat of glaciers at the end of the cool period (the late 1800s or early 1900s, immediately after the Little Ice Age). The least stable dams (e.g., those that are high and narrow, or that have large amounts of water flowing over or through them) fail soon after they form. If climate continues to warm, as it did during much of the twentieth century, dams that were formerly stable fail due to (1) overtopping by waves triggered by ice avalanches and landslides, (2) high overflow during storms; (3) high overflow caused by sudden influxes of water from upstream glacial lakes, and (3) melt of interstitial and massive ice. In the process, the population of unstable moraine dams is reduced. If glaciers continue to retreat, this population is not regenerated, and the incidence of moraine dam failures decreases.

Moraine dams in British Columbia persist longer than landslide dams, except those consisting of coarse blocky debris (Clague and Evans, 1994). The difference in longevity is due partly to differences in the sizes of upstream drainage areas. Landslides generally dam streams with large drainage areas, relative to the size of the dams, and thus are overtopped by large flows. In contrast, moraine dams have much smaller drainage areas, and overflow discharges are relatively small under normal conditions.

7. Outburst floods

7.1. Natural dam failure

A dam failure is a complex phenomenon that is controlled primarily by the form and material properties of the dam and by the failure mechanism (Costa and Schuster, 1988). Most moraine dams have low width-to-height ratios and consist of noncohesive granular materials, thus the lakes impounded by them drain very rapidly. Generally, however, an unusual event, such as an ice avalanche, is required to initiate failure.
Fig. 21. Hypothesized relation between climate (A) and the formation and failure of moraine dams (B). Moraines are built during a lengthy period of cool climate such as the Little Ice Age. Lakes form behind the moraines when climate warms and glaciers retreat, as happened in the late 1800s and early 1900s. Moraine dams begin to fail as climate continues to warm. The regional frequency of failures may increase to a peak decades later.

In contrast, width-to-height ratios of landslide dams are typically high, thus when they are overtopped, much more material must be eroded before a full breach is developed than is the case for moraine dams. Peak flood discharges of outburst floods from landslide-dammed lakes, however, are not necessarily smaller than peak discharges of floods from moraine-dammed lakes (Costa, 1985, 1988; Evans, 1986; Costa and Schuster, 1988).

The form, material characteristics, and failure mechanisms of moraine dams are fundamentally different from those of glacier dams. Most glacier dams are much larger than the lakes they impound, and floodwaters must travel long distances beneath or over ice. Failure of glacier dams generally involves erosion of the dam by a meltwater stream flowing at the ice margin or enlargement of a subglacial tunnel, sometimes with the collapse of the tunnel roof (Walder and Costa, 1996). Wholesale mechanical collapse of the dam and overflow via a spillway are less common failure mechanisms (see Clague (1987) and Mayo (1989) however, for an example of a collapse failure). Enlargement of subglacial tunnels by heat transfer and other processes is a slower process than overtopping and incision of sediment dams, thus glacier-dammed lakes that drain through tunnels generally empty more slowly than do moraine-dammed lakes.

7.2. Flood discharges

Study of moraine dam failures in British Columbia and elsewhere indicates that flood size is controlled by many factors, including the volume of water released from the reservoir, lake hypsometry, the height, width, structure and texture of the dam, the failure mechanism, and downstream topography and sediment availability (Costa and Schuster, 1988; Clague and Evans, 1994). In general, flood size is proportional to the volume of water released and, therefore, reservoir volume. Failures of narrow high dams commonly produce higher peak flood discharges than failures of wide low dams. Dams containing large amounts of sand and gravel tend to fail more rapidly, and produce floods with higher peak discharges, than dams of coarser, rubbly and blocky material. Failure mechanism also influences flood size. For example, large displacement waves (viz. Queen Bess Lake, 1997) produce spiky, large-amplitude, low-duration floods, whereas some incision failures generate floods with much smaller peak discharges. Finally, the character of the downstream flood path is also important. Floods in steep narrow-floored valleys attenuate more slowly than floods in more gentle broader valleys. Hydraulic ponding may occur above constrictions in the flood path and thus strongly influence the peak discharge and downstream attenuation of the flood.
A variety of empirical equations have been proposed, based on documented outburst floods from moraine-dammed lakes, to estimate peak discharges \( Q_p \). The most common variables in these equations are the volume of water released from the lake \( V \) and potential energy of the impounded lake water \( PE \) — e.g. \( Q_p \approx 0.045V^{0.66} \) (Walder and O’Connor, 1997); \( Q_p \approx 0.0013PE^{0.60} \) (Costa and Schuster, 1988). Potential energy is calculated as the product of dam height, reservoir volume, and the specific weight of water.

Plots of \( Q_p \) vs. \( V \) and \( Q_p \) vs. \( PE \) show considerable scatter (Fig. 22), reflecting the diverse characteristics of moraine dams, basin geometry, and flood paths, as well as downstream changes in peak discharge and errors in estimating discharge. Direct measurements of flood discharge are virtually impossible, thus a variety of indirect methods are commonly used to estimate peak discharges, including drawdown rates and measurements based on hydraulic formulae or post-flood channel surveys, all of which are subject to error. Many published estimates of peak discharge come from hydrographs that are considerable distances below the dam. Such estimates are generally smaller than the peaks at the breach because floods attenuate as they move downstream (Fig. 12; Cenderelli and Wohl, 1997). Downvalley attenuation of outburst floods results from interactions of the flood wave with the channel, including flow retention outside the channel, frictional resistance to flow, acceleration and deceleration, flow losses, backwater effects, deposition, and channel constrictions and expansions (Manville et al., 1999).

Notwithstanding these problems, the data in Fig. 22 show that peak discharges of floods from moraine-dammed lakes differ from those of other types of natural dam failures. For the same potential energy, moraine dams produce larger flood peaks than most glacier dams because, as mentioned earlier, the failure mechanisms of the two types of dam are different.

Another technique for estimating peak discharges of floods resulting from failures of morainal and other dams is to formulate the problem as critical flow through an enlarging outlet (Walder and O’Connor, 1997; Manville et al., 1999). This approach establishes the relative importance of breach growth rates and lake volume and shape on the peak discharge of a dam breach flood. A dimensionless measure of peak discharge \( Q_p^* \) is defined relative to the dimensional discharge \( Q_p \):

\[
Q_p^* = Q_p^{0.5d^{2.5}} - 1,
\]

where \( g \) is gravitational acceleration and \( d \) is the amount of lake lowering or breach depth. \( Q_p^* \) is primarily controlled by the dimensionless parameter \( \eta \), where

\[
\eta = k^*V_o^* = kV_o(g^{0.5d^{3.5}})^{-1},
\]

in which \( k^* \) is the dimensionless rate of breach growth, \( k \) is the rate of breach growth, \( V_o^* \) is the dimensionless volume of water discharged, and \( V_o \) is the volume of water discharged. Dimensionless measures of breach erosion rate, breach geometry, and lake shape are derived from the dimensional estimates of (1) the volume of the lake and the amount of water discharged during the outburst, (2) the hypsometry of the lake, (3) the breach erosion rate, and (4) the breach geometry. Peak discharges obtained using this approach may be more accurate than those determined from empirical relationships derived from historical dam failures. Dimensionless analysis, however, requires knowledge of the rate of breach growth, which is often unknown and must be estimated. This approach has not been widely applied to failures of lake water versus peak discharge for selected failures of landslide, moraine, and glacier dams (modified from Costa and Schuster (1988, Fig. 12); data from Costa (1985). Least-squares regression lines for the three types of dams and the envelope curve encompassing all plotted data are also shown.
8. Hazard assessment and mitigation

8.1. General considerations

Peak discharges of floods from moraine-dammed lakes generally are many times larger than the peak flows of rainfall and snowmelt floods in the same basin. The large discharges and long travel distances of outburst floods must be taken into account when developing valleys below natural dams.

Estimates of peak discharges of outburst floods may be obtained by dimensionless analysis or from empirical relationships such as those shown in Fig. 22. Costa and Schuster (1988) have argued for the use of conservative peak-discharge estimates for planning purposes where there is a potential loss of life or property damage. These can be obtained from the envelope curve encompassing data points for all natural dam failures for which there are reasonable estimates of peak discharge (e.g., $Q = 0.063PE^{0.42}$, Fig. 22).

A more detailed assessment of the magnitude and possible impact of a particular outburst flood can be made by taking into account the morphology and internal characteristics of the dam, the character of the flood path below the dam, and the availability of sediment and vegetation for entrainment by floodwaters. Discharges may increase substantially through addition of easily eroded sediment and woody debris. If sufficient sediment is added, the flood may transform into a debris flow. This occurred, for example, when Klattasine Lake drained in the early 1970s. Historical examples indicate that, following failure of a moraine dam, a debris flow can only form and be sustained on gradients steeper than 10–15° (Fig. 23), and only if there is an abundant supply of sediment downvalley of the dam (Clague and Evans, 1994; O'Connor et al., 1994). Moraine dams contain large volumes of sediment, but additional material generally must be picked up in the valley below the dam to generate a true debris flow. Bulking of flood flows with sediment and plant debris, by as much as a factor of four, has important consequences for the assessment of outburst flood hazards (Laenen et al., 1992; O'Connor et al., 1993), but the phenomenon remains poorly understood.

Most historical floods from moraine-dammed lakes in the Canadian Cordillera have occurred in remote mountain valleys. Recently, however, many of these valleys have been opened to forestry, mining, and recreational activities. Such development will continue in coming years, increasing the likelihood that outburst floods and related debris flows will damage human works.

8.2. Hazard assessment

An assessment of hazards associated with moraine dams commonly begins with an airphoto search. At this stage in the investigation, all moraine dams should be considered potentially unstable, although subsequent field study may indicate that many of the dams are unlikely to fail.
The likelihood that a particular dam will fail can be assessed, at least qualitatively, by studying (1) its morphology and internal characteristics, (2) the size, hypsometry, and hydrology of the reservoir, and (3) the proximity of the reservoir to slopes that are susceptible to landslides or avalanches.

One or a combination of the following factors may indicate that a moraine dam has a high probability of failure: (1) the width-to-height ratio of the dam is small; (2) the dam lacks an armoured overflow channel; (3) outflow occurs mainly by seepage through the dam; (4) the reservoir surface is normally at or just below the crest of the dam; (5) one or more highly crevassed glaciers cling to steep slopes directly above the reservoir; and (6) slopes above the reservoir are subject to rockfalls.

Once the likelihood of dam failure is known, the down-valley effects of an outburst flood can be assessed. Peak flood discharges can be estimated using the empirical equations mentioned earlier, although such estimates assume complete emptying of the lake. Discharge attenuation and bulking must be taken into account when predicting the height of the flood wave at various points downstream from the dam (Laenen et al., 1992). The possibility that the flood could transform into a debris flow must also be considered. As pointed out by O’Connor and Costa (1993), these complexities make it difficult to formulate reliable deterministic models for assessing hazards from moraine-dammed lakes. A hazard assessment may have to be based on empirical data from case studies (e.g., Costa, 1988).

8.3. Hazard mitigation

No efforts have been made in western Canada to prevent or reduce the impact of outburst floods from moraine-dammed lakes because, until recently, valleys at risk from such floods were unsettled and undeveloped. In contrast, in other parts of the world where people and property are at much greater risk from outburst floods, countermeasures have been taken (Lliboutry et al., 1977; Yesenov and Degovets, 1979; Eisbacher, 1982; Eisbacher and Clague, 1984). Control measures that have been applied to moraine-dammed lakes include excavation of trenches and tunnels to lower or empty reservoirs, construction of paved revetments and low earthen dams to stabilize outlets and increase freeboard, the use of siphons to drain water from lakes, and construction of downvalley retention basins to trap floodwater and debris (Lliboutry et al., 1977; Reynolds, 1992, 1993, 1995, 1998; Grabs and Hanisch, 1993; Reynolds et al., 1998). The following two examples, taken from Lliboutry et al. (1977), illustrate common types of control measures and potential dangers of constructing such works.

Laguna Jancarurish was impounded by a large, Little Ice Age end moraine at the head of an inhabited valley in the northern Cordillera Blanca of Peru. The lake drained by seepage through the moraine, but the freeboard between the lake surface and the lowest point on the moraine was only 10 m. Numerous small ice avalanches fell into the lake from a nearby glacier in the 1940s, and concern mounted that the moraine might be overtopped and incised by a displacement wave from a large avalanche, triggering a catastrophic flood or debris flow (termed “aluvion” locally). In 1949, the Comisión de control de la Lagunas de la Cordillera Blanca (CCLCB) began to lower the lake by digging a trench across the moraine. The digging proceeded in steps—the trench was lowered while a gate blocked outflow from the lake; the gate was then opened and the lake lowered to the level of the trench; and so forth. By 1950, the lake had been lowered 15 m in this manner. In October 1950, the trench was deepened an additional two metres and a stone revetment was being constructed under the precarious protection of the gate. On October 20, the toe a partly submerged apron consisting of avalanched snow and ice broke away at the opposite end of the lake and generated large waves that overflowed the moraine, destroying the gate. The escaping waters began to erode the distal flank of the moraine, which was formed almost entirely of sand and pebbles. The erosion advanced upslope towards the crest of the moraine, and a waterfall formed that swept the revetment away and caused the moraine to fail. The level of the lake fell 21 m in a short period of time, and $6 \times 10^6$ m$^3$ of water were released. The resulting aluvion may have killed as many as 500 people in the valley below the dam.

One of the most dangerous moraine-dammed lakes in the Cordillera Blanca in the late 1960s was Laguna de Safuna Alta. The lake began to form in 1950, and by 1969, about $5 \times 10^6$ m$^3$ of water were impounded between a steep end moraine and the retreating glacier. The surface of the lake in 1969 was 18 m below the lowest point of the moraine. Water escaped by seepage through the moraine. In 1968 and 1969, a tunnel was dug through the moraine, 80 cm above the lake surface and lined with sections of iron pipe encased in concrete. Plans were made to completely drain the lake with powerful pumps, but in May 1970 before the project could be implemented, a powerful earthquake caused the moraine to move and settle. The tunnel cracked in numerous places and settled at its upstream end below the level of the lake. Water escaped through the tunnel and through natural pipes within the moraine. Discharge grew exponentially but fortunately ceased after the lake had fallen 38 m. A new 150 m long tunnel was later dug, rendering Laguna de Safuna Alta safe.

9. Conclusions

Most moraine-dammed lakes have formed during the last 200 yr as glaciers retreated from their Little Ice Age
maximum positions. The moraines are commonly steep-sided and consist of coarse, poorly sorted, cohesionless sediment. Most moraine dams fail when they are overtopped and incised by unusually large overflows. Anomalous overflows result from heavy rainfall or snowmelt, from sudden influxes of water from upstream glacial lakes, or from waves triggered by snow and ice avalanches or rockfalls.

Outburst floods from moraine-dammed lakes typically are many times larger than snowmelt and rainfall floods in the same basins. In many cases, discharges increase rapidly to a peak and then drop off to background levels. Peak discharges are controlled by many factors, the most important of which are lake volume, dam height and width, internal properties of the dam, failure mechanism, and downstream topography and sediment availability. Moraine dam failures generally produce larger floods than do glacier dam failures, in part because enlargement of tunnels within ice is a slower process than overtopping and incision of sediment dams.

Floods triggered by moraine dam failures may transform into debris flows as they travel down steep valleys. Historical data from British Columbia indicate that such flows can only form and be sustained in channels steeper than 10–15° and only where there is an abundant supply of sediment in the valley below the dam. Although most outburst floods attenuate as they move downvalley, entrainment of sediment and plant debris by floodwaters may, in some instances, increase discharge. Such flow bulking has important implications for hazard appraisal.

A hazard assessment of a moraine dam is made by studying the dam, its reservoir, and the surrounding terrain. A dam may be hazardous if it has an ice core or contains interstitial ice, if it has a low width-to-height ratio and lacks an armoured overflow channel, if the reservoir surface is at or just below the crest of the dam, or if the reservoir is close to slopes subject to ice avalanches or rockfalls. Climatic warming may cause some moraine dams to fail, both by melting ice cores and by increasing the amount of water flowing over the moraines.

Acknowledgements

This study draws on many data sources and personal communications from a large number of researchers—too numerous to list individually. We are particularly indebted to John Costa, Jim O’Connor, and Joseph Walden, whose work on natural dam failure helped us focus our thoughts. Tonia Williams drafted some of the figures. Fig. 9 was produced by Tim Albert of Geosolutions Consulting Inc., Nepean, Ontario. Jim O’Connor, Lionel Jackson, Jr., and Willie Scott provided thoughtful critiques of a draft of the paper.

References


