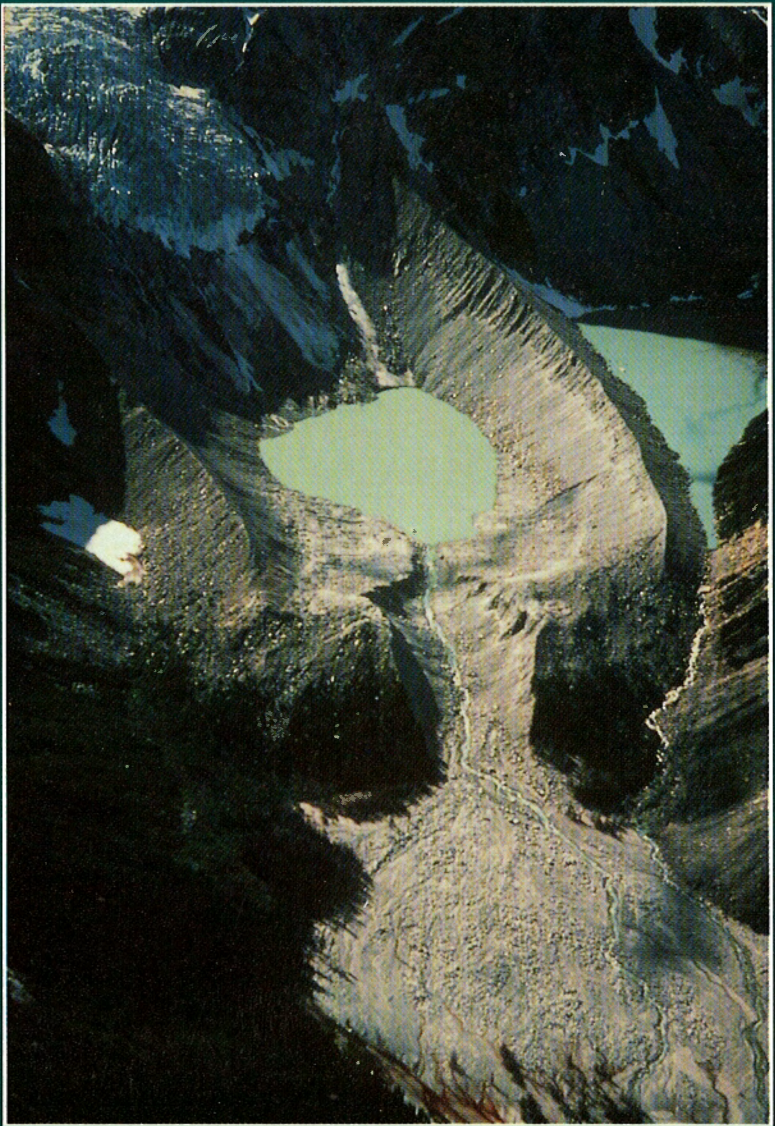
GEOLOGICAL SURVEY OF CANADA
BULLETIN 464

FORMATION AND FAILURE OF NATURAL DAMS IN THE CANADIAN CORDILLERA

John J. Clague and Stephen G. Evans



1994

Natural Resources Canada Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
BULLETIN 464

FORMATION AND FAILURE OF NATURAL DAMS IN THE CANADIAN CORDILLERA

John J. Clague and Stephen G. Evans

1994

Available in Canada through authorized
bookstore agents and other bookstores

or by mail from

Canada Communication Group — Publishing
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.,
Calgary, Alberta T2L 2A7

100 West Pender Street
Vancouver, B.C. V6B 1R8

A deposit copy of this publication is also available for
reference in public libraries across Canada

Cat. No. M42-464E
ISBN 0-660-15496-X

Price subject to change without notice

Cover description

The breached moraine of Cumberland Glacier and Nostetuko Lake after the outburst flood of July 1983. A large fan of bouldery debris was deposited in the meadow below the moraine by floodwaters escaping from the lake. Photo taken in August 1984.

Original manuscript received: 1992 – 12
Final version approved for publication: 1991 – 09

CONTENTS

Tables

Figures

Preface

Lakes dammed by landslides, moraines, and glaciers are common in mountain ranges around the world. Some of these lakes have drained suddenly, causing destructive floods and debris flows in the valleys below. Geologists can infer much about the processes responsible for the formation and failure of natural dams by examining historical examples. Such studies are essential for government officials and planners to properly assess natural hazards in mountainous areas and to minimize future property damage and loss of life from outburst floods and debris flows.

This report describes historical natural-dam failures in the Cordillera of western Canada. Many damaging floods in this region have resulted from the sudden failure of landslide, moraine, and glacier dams. The authors point out that potentially hazardous natural dams can be identified through airphoto interpretation and that the likelihood of any particular dam failing can be determined through ground inspection. They show how the size and downstream effects of a flood can be assessed from the material properties and morphology of the dam and from reservoir size. They also show that, under certain conditions, a flood can transform into a highly destructive debris flow as it moves downvalley.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

Préface

Dans les chaînes de montagne du monde entier, il arrive souvent que des lacs soient créés par des glissements de terrain, des moraines et des glaciers. Certains de ces lacs se sont vidés de façon soudaine, causant des inondations dévastatrices et des coulées de débris dans les vallées situées en aval. En étudiant des phénomènes passés, les géologues peuvent tirer de nombreuses conclusions sur les mécanismes de formation et de rupture des barrages naturels. Ces études sont essentielles aux fonctionnaires et aux planificateurs chargés d'évaluer précisément les risques naturels présents dans les régions montagneuses et de réduire au minimum les pertes de vies et les dommages matériels que pourraient occasionner les inondations soudaines et les coulées de débris.

Le présent rapport décrit des ruptures de barrages naturels qui se sont produites dans la Cordillère de l'ouest du Canada. De nombreuses inondations ayant causé des dégâts dans cette région ont été provoquées par la rupture soudaine de barrages glaciaires et de barrages produits par des glissements de terrain et des moraines. Les auteurs signalent qu'il est possible de reconnaître les barrages naturels éventuellement dangereux par une interprétation de photographies aériennes et d'évaluer les probabilités de rupture de barrages par une inspection du sol. Ils exposent comment on évalue l'ampleur et les effets en aval d'une inondation en examinant les propriétés physiques et la morphologie du barrage ainsi que la taille du bassin. Ils montrent également que, dans certaines conditions, une inondation peut se transformer en une coulée de débris très destructrice au fur et à mesure qu'elle descend la vallée.

Elkanah A. Babcock
Sous-ministre adjoint
Commission géologique du Canada

FORMATION AND FAILURE OF NATURAL DAMS IN THE CANADIAN CORDILLERA

Abstract

In western Canada, existing and former lakes dammed by landslides, moraines, and glaciers have drained suddenly to produce floods orders of magnitude larger than normal streamflows. Landslide dams consisting of failed bedrock generally are stable, whereas those comprising Quaternary sediments or volcanic debris fail soon after they form, typically by overtopping and incision. Moraine dams are susceptible to failure because they are steep-sided and consist of loose, poorly sorted sediment. Irreversible rapid incision of a moraine dam may result from a large overflow associated with a severe rainstorm, avalanche, or rockfall. Some glacier-dammed lakes drain suddenly through englacial and subglacial tunnels to produce large floods.

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 lake volume, dam characteristics, failure mechanisms, and downstream topography and sediment availability.

An appraisal of the likelihood that a natural dam will fail can be made by studying the dam, the reservoir, and the surrounding terrain. A moraine dam may be hazardous if it contains ice or has a low width-to-height ratio, or if the reservoir is bordered by steep, rockfall- or avalanche-prone slopes. All glacier-dammed lakes with a recent history of outburst floods should be considered hazardous, but even stable lakes may drain suddenly after a long period of glacier retreat. Many landslides dams fail soon after they form, consequently hazard appraisal may be concerned more with the location and size of potential dams than with the stability of existing dams.

Résumé

Dans l'Ouest canadien, des lacs de glissement de terrain, de moraines et de barrage glaciaire, existants et disparus, se sont vidés soudainement, produisant des inondations beaucoup plus importantes que les écoulements fluviatiles normaux. Les barrages de substratum rocheux effondré, formés par glissement de terrain, sont en général stables, tandis que ceux constitués de débris volcaniques ou de sédiments du Quaternaire s'effondrent peu après leur formation, le plus souvent par débordement ou excavation. Les barrages morainiques sont susceptibles à la rupture parce qu'ils sont à pente très forte et sont constitués de sédiments meubles et mal triés. L'excavation rapide et irréversible d'un barrage morainique peut produire un fort débordement lors d'une chute de pluie, d'une avalanche ou d'un éboulis important. Certains lacs glaciaires se vident soudainement par des tunnels intraglaciaires et sous-glaciaires, produisant de fortes inondations.

La plupart des ces débâcles se caractérisent par une montée exponentielle du débit, suivie d'un retour soudain à la normale lorsque l'eau est épuisée. Le débit de pointe varie en fonction du volume du lac, des caractéristiques du barrage, des mécanismes de rupture, ainsi que de la disponibilité de sédiments et du relief en aval.

Il est possible d'évaluer la vraisemblance d'une rupture d'un barrage naturel en étudiant le barrage, le réservoir et le terrain environnant. Un barrage morainique peut être dangereux s'il renferme de la glace ou s'il présente un faible rapport largeur/hauteur, ou encore si le réservoir est bordé par des pentes abruptes, sujettes à des éboulis ou à des avalanches. Tous les lacs de barrage glaciaire où il s'est produit de récentes débâcles devraient être considérés comme dangereux, mais même les lacs stables peuvent se vider soudainement après une longue période de retrait des glaciers. Nombre de barrages de glissement de terrain s'effondrent peu après leur formation, de sorte que l'évaluation des dangers pourrait porter davantage sur l'emplacement et la taille des barrages éventuels que sur la stabilité des barrages existants.

SUMMARY

Lakes dammed by landslides, moraines, and glaciers pose significant hazards to people and property in western Canada. Large landslide dams commonly form in steep, rock-walled mountain valleys and in intermontane valleys cut into thick Quaternary sediment fills. Most dams located in small- to medium-size watersheds and consisting of bedrock debris (excluding mine rock waste and tailings) are stable. In contrast, dams formed of displaced Quaternary sediments and volcanic rocks are extremely unstable and generally fail soon after they form. The most common, although smallest and most ephemeral, dams form during rainstorms when slides and slumps in till and colluvium block streams in steep mountain watersheds.

Most moraine-dammed lakes in the Canadian Cordillera have formed during the last 200 years as glaciers have retreated from Little Ice Age maximum positions. The moraines typically are steep-sided and consist of coarse, poorly sorted sediment. Failure of both moraine and landslide dams is generally the result of overtopping and rapid incision. Many landslide dams fail by normal overflow immediately after the reservoir fills. In contrast, moraines commonly are breached long after they form by unusually large outflows of water from the lake. Such anomalous flows may result from heavy rainfall or snowmelt, or from waves triggered by rockfalls or ice avalanches.

Lakes trapped at the margins of and beneath glaciers may drain suddenly through englacial and subglacial tunnels to produce large floods, referred to as jökulhlaups. Many glacier-dammed lakes in the Cordillera have experienced a phase of jökulhlaup activity in the twentieth century, preceded by an extended period of stability during which there were no outbursts. In many cases, former unstable lakes have disappeared due to retreat of the glaciers that impounded them.

Outburst floods from moraine- and glacier-dammed lakes typically are many times larger than snowmelt and rainfall floods in the same drainage basins. In most cases, discharges increase exponentially to a peak and then drop off rapidly to background levels. Peak discharges are controlled by many factors, the most important of which are lake volume, dam height and width, the internal properties of the dam, the mechanism of failure, and downstream topography and sediment availability. For lakes of similar size, failures of glacier dams produce smaller floods than failures of landslide and moraine dams. This is because the enlargement of tunnels within ice is a slower process than overtopping and incision of sediment dams. Floods from landslide-dammed lakes generally have smaller peak discharges than floods from moraine-dammed lakes of comparable size. This appears to be a consequence of the different morphologies (e.g. width-to-depth ratios) of the two types of dams.

SOMMAIRE

Les lacs de glissement de terrain, de moraines et de barrage glaciaire présentent de grands dangers pour la population et le bien-fonds dans l'Ouest canadien. Les grands barrages formés par glissement de terrain se trouvent dans des vallées de montagne, fortement encaissées dans la roche, et dans des vallées intermontagneuses découpées dans d'épais sédiments de remplissage du Quaternaire. La plupart des barrages situés dans des bassins versants de petite à moyenne taille et constitués de débris de substratum rocheux (autres que des stériles et des résidus de mine) sont stables. En revanche, les barrages constitués de roches volcaniques et de sédiments déplacés du Quaternaire sont très instables et s'effondrent en général peu après leur formation. Les barrages les plus communs, qui sont par ailleurs les plus petits et les plus éphémères, se forment pendant les chutes de pluie lorsque des glissements et des éboulements de till et de colluvions se produisent dans des bassins versants montagneux abruptes.

La plupart des lacs morainiques de la Cordillère canadienne se sont formés au cours des 200 dernières années lorsque les glaciers se sont retirés de leurs positions d'avancée maximale du petit âge glaciaire. Les moraines sont en général pentues et renferment des sédiments grossiers mal triés. La rupture des barrages morainiques et des barrages de glissement de terrain se produit généralement par débordement et excavation rapide. De nombreux barrages de glissement de terrain s'effondrent par débordement normal immédiatement après le remplissage du réservoir. Par opposition, les moraines se fissurent habituellement longtemps après leur formation, sous l'effet d'écoulements anormalement forts provenant du lac. Ces écoulements anormaux peuvent provenir d'une importante chute de pluie ou fonte de neige, ou encore de vagues engendrées par des chutes de roche ou des avalanches de glace.

Les lacs piégés en bordure ou en-dessous de glaciers peuvent se vider soudainement par des tunnels intraglaciaires et sous-glaciaires, produisant de fortes inondations, appelées «*jökulhlaups*». Nombre de lacs glaciaires de la Cordillère ont produit des *jökulhlaups* au XX^{e} siècle, après une longue période de stabilité ne comportant aucune débâcle. Il est souvent arrivé que d'anciens lacs instables ont disparu lorsque les glaciers qui les retenaient se sont retirés.

Les débâcles de lac morainique ou glaciaire sont en général beaucoup plus importantes que les inondations qui suivent une fonte de neige ou une chute de pluie dans le même bassin hydrographique. Le plus souvent, les débits croissent exponentiellement jusqu'à un maximum, puis reviennent rapidement à la normale. Les débits de pointe dépendent de plusieurs facteurs, les plus importants étant le volume du lac, la hauteur et la largeur du barrage, et la disponibilité de sédiments et le relief en aval. Dans le cas de lacs de même taille, les ruptures de barrages de lac glaciaire produisent de plus petites inondations que les ruptures de barrages de glissement de terrain et de moraine. Dans les inondations de lacs formés par glissement de terrain, les débits de pointe sont en général plus faibles que dans les inondations de lacs morainiques de taille comparable. Cela semble tenir à des morphologies (p. ex. rapports largeur/hauteur) différentes des deux types de barrages.

Floods triggered by natural dam failures may transform into debris flows as they travel down steep valleys. Historical data from the Canadian Cordillera indicate that such flows can only form and be sustained on slopes greater than 10-15° and only where there is an abundant supply of sediment in the valley below the dam. Entrainment of sediment and plant debris by floodwaters may cause peak discharge to increase downvalley, which has important implications for hazard appraisal.

An appraisal of the likelihood that a natural dam will fail can be made by studying the dam, its reservoir, and the surrounding terrain. A moraine 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 rockfalls and ice avalanches. Glacier-dammed lakes with a recent history of jökulhlaups should be considered hazardous, although a glacier may recede sufficiently that it no longer impounds water and thus is not an immediate threat. On the other hand, some formerly stable lakes have drained suddenly and unexpectedly after a long period of glacier retreat during which the dam gradually weakened. Similar new outbursts may occur in the future if glaciers continue to retreat under a warming climate. Climatic warming also may cause some moraine dams to fail, both by melting ice cores and by increasing the amount of water flowing over the moraines. Many landslide dams fail soon after they form, consequently hazard appraisal often is concerned more with the location and size of potential dams than with the stability of existing dams. Unfortunately, it is almost impossible, with our present level of knowledge, to forecast where in western Canada landslide-dammed lakes will form in the future.

Les inondations déclenchées par la rupture de barrages naturels peuvent se transformer en coulées de débris lorsqu'elles dévalent les vallées pentues. Selon des données historiques de la Cordillère canadienne, de telles coulées ne peuvent se former et se maintenir que sur des pentes de plus de 10 à 15 et que dans les endroits où il y a abondance de sédiments dans la vallée en aval du barrage. Les sédiments et les débris de plantes entraînés par les eaux peuvent grossir le débit de pointe en aval, ce qui influe considérablement sur l'évaluation des dangers.

Il est possible d'évaluer la vraisemblance d'une rupture de barrage naturel en étudiant le barrage, son réservoir et le terrain environnant. Un barrage de moraine peut être dangereux s'il renferme une masse de glace ou de la glace interstitielle, si son rapport largeur/hauteur est faible et qu'il ne comporte pas de déversoir armé, si la surface du réservoir arrive à la hauteur de la crête du barrage ou juste en dessous, ou si le réservoir est proche de pentes sujettes à des éboulis et à des avalanches de glace. Les lacs de barrage glaciaire qui ont donné lieu à de récents jökulhlaups devraient être considérés comme dangereux, même si un glacier peut se retirer au point de ne plus retenir d'eau, cessant ainsi d'être une menace immédiate. Par ailleurs, certains anciens lacs stables se sont vidés soudainement et sans avertissement après une longue période de retrait des glaciers, le barrage s'étant progressivement affaibli. De telles débâcles peuvent se reproduire dans l'avenir si les glaciers continuent de se retirer pendant un épisode de réchauffement climatique. Le réchauffement du climat peut aussi entraîner la rupture de barrages de moraine, en faisant fondre les noyaux de glace et en augmentant l'écoulement de l'eau sur les moraines. De nombreux barrages de glissement de terrain se rompent peu après leur formation, de sorte que l'évaluation des dangers doit souvent porter davantage sur l'emplacement et la taille des barrages éventuels que sur la stabilité des barrages existants. Malheureusement, il est presque impossible, dans l'état actuel de nos connaissances, de prévoir les futurs emplacements des lacs de glissement de terrain dans l'Ouest canadien.

INTRODUCTION

Many lakes impounded by natural dams pose a threat to people and property in parts of the Cordillera of western Canada. Some have formed suddenly, inundating valley bottoms upstream from the dams; many have drained even more rapidly, producing floods with peak discharges far in excess of normal flows.

There are many types of natural dams (Davis, 1882; Hutchinson, 1957; Costa and Schuster, 1988), but those formed by landslides, glacier ice, and Neoglacial moraines are the most unstable and thus the most likely to fail suddenly, with devastating consequences for downvalley settlement and other development. Although such failures are common in mountain regions throughout the world and have caused widespread destruction and loss of life in many areas that have been settled for hundreds or thousands of years (e.g. Alps, Andes, Himalayas; Costa and Schuster, 1988), they are poorly understood and appreciated in Canada. This is partly due to the fact that many natural dam failures have occurred in remote mountain valleys and thus have escaped attention. In addition, European settlement in the Cordillera of western Canada commenced less than 200 years ago. In recent decades, however, development associated with the forestry and mining industries, hydroelectric power generation, and recreational activities has extended into these formerly remote valleys, and potential hazards associated with outburst floods from lakes must be understood.

This bulletin provides an overview of the most dangerous types of natural dams in the Canadian Cordillera (Fig. 1). Our objectives are to: 1) document how these dams form and fail; 2) catalogue historical natural dam failures in the region; and 3) discuss the nature and effects of outburst floods, and the hazards that they pose.

ACKNOWLEDGMENTS

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 and Robert Schuster whose 1988 paper entitled "The formation and failure of natural dams" (Geological Society of America Bulletin, v. 100, p. 1054-1068) stimulated us to prepare this report. Many of their ideas have been incorporated into our paper. Reviews by Jim O'Connor and Robert Fulton improved the manuscript. Tonia Oliveric drafted many of the figures.

LANDSLIDE DAMS

Setting

Landslide dams form most frequently in narrow valleys bordered by steep slopes. Such settings are common in the Canadian Cordillera, both within mountain ranges and in deeply incised intermontane valleys. The presence of steep slopes and unstable source materials, such as highly fractured and hydrothermally altered bedrock and thick Quaternary sediments, increases the likelihood of slope failure and associated dam formation. The most common triggers are earthquakes, rainfall, and snowmelt. In many instances, however, the fabric of rock or sediments slowly deteriorates to the point where an insignificant event causes failure.

Types of dams

Four general groups of landslide dams can be distinguished in the Canadian Cordillera: 1) dams formed by failures of bedrock slopes; 2) dams produced by failures of dissected Quaternary valley fills; 3) dams produced by failures of relatively thin Quaternary sediments mantling rock slopes; and 4) dams resulting from failures of mine waste rock dumps and tailings piles (Fig. 2, Table 1). The first group can be further subdivided into dams consisting of competent bedrock

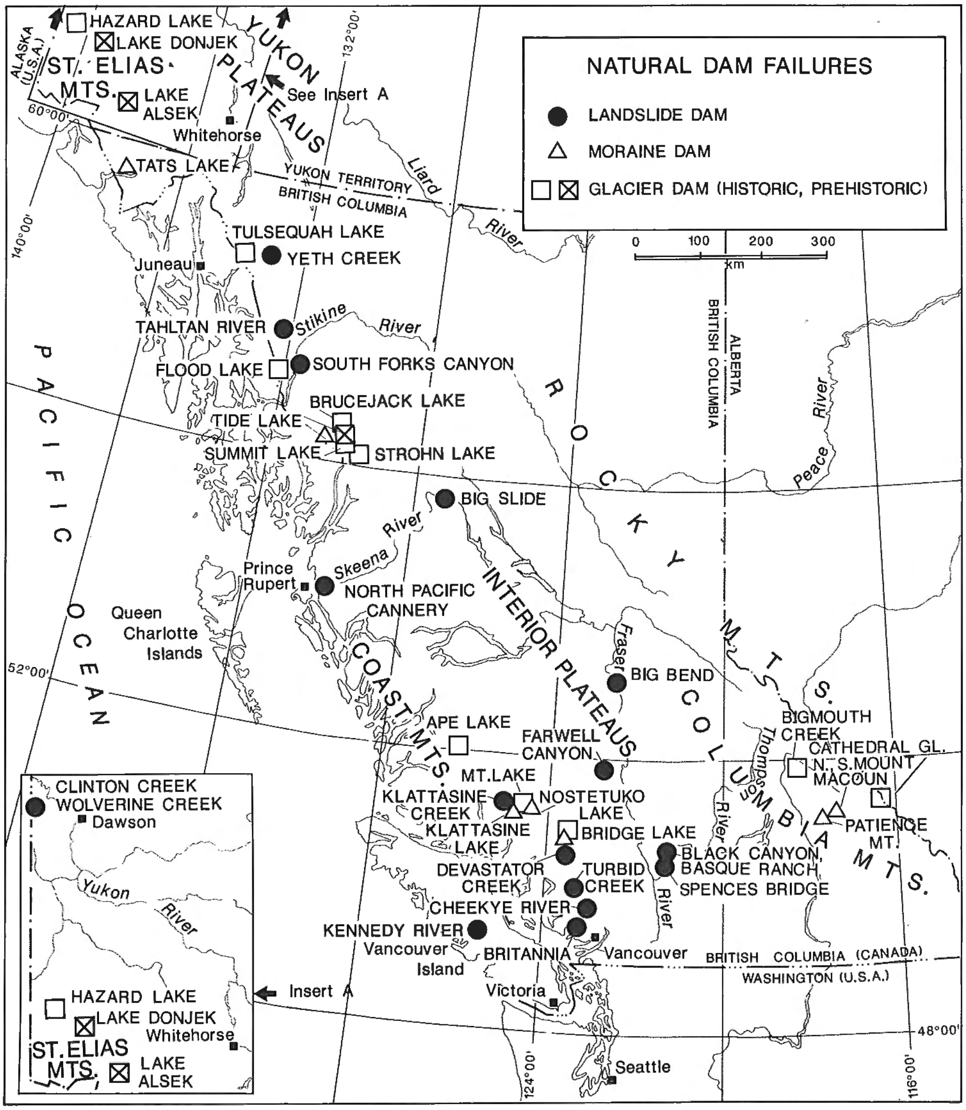


Figure 1. Locations of natural dam failures mentioned in the text (see also Tables 2, 3, and 4).

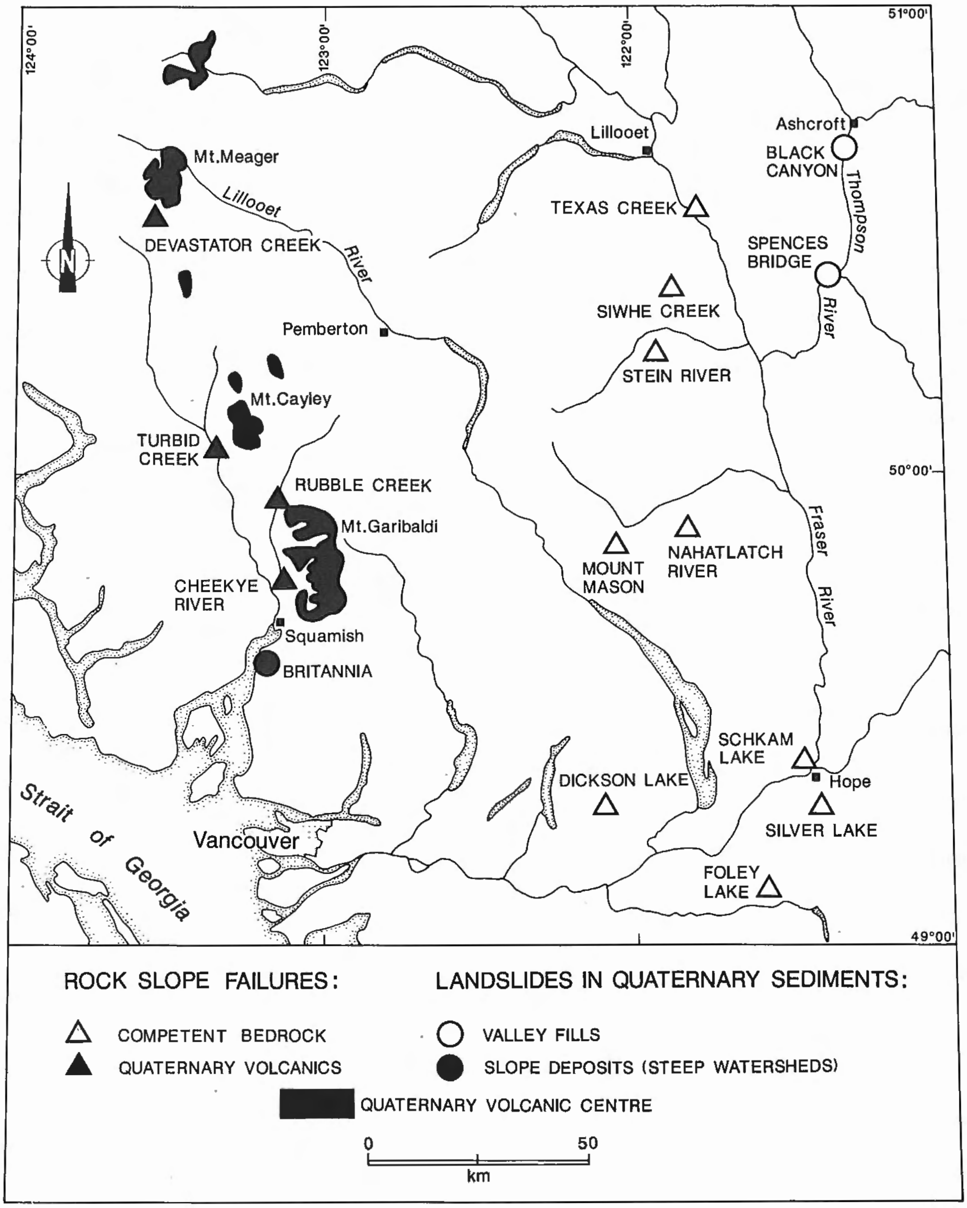


Figure 2. *Documented landslide dams in southwestern British Columbia. (Modified from Fig. 3 of Evans, 1986a).*

Table 1. Aspects of landslide dams

Source material	Landslide type	Size of dam[a]	Stability of dam	Frequency and hazard
Bedrock				
Pre-Quaternary	Slump, rock avalanche	Large	Stable[b]	Low
Quaternary volcanics	Flow	Medium	Drains soon after formation	Moderate[c]
Unconsolidated sediments				
Valley fill	Slump, flow	Medium-large	Drains soon after formation	Moderate[d]
Slope mantle	Slump, flow	Small	Drains soon after formation	High[e]
Mine rock waste, tailings	Slump, flow	Small-medium	Unstable	Moderate

[a] Large = commonly >10 x 10^6 m^3; medium = 1-10 x 10^6 m^3; small = <1 x 10^6 m^3.
[b] Dams that impound large rivers may be unstable.
[c] Loss of life at Devastator Creek, 1975.
[d] Loss of life at Spences Bridge, 1905; property damage during four historic events.
[e] Loss of life at North Pacific Cannery, 1891, and Britannia, 1921.

debris and those consisting of debris derived from poorly indurated, semiconsolidated "bedrock", mainly Quaternary volcanic and pyroclastic rocks.

Dams produced by failures of bedrock slopes

The largest and most stable dams are produced by failures of competent bedrock (rock avalanches, rockslides, rock slumps, sags) (Fig. 3). These dams commonly exceed 5×10^6 m^3 in volume and consist of either blocky debris (in the case of rock avalanches and rockslides) or relatively coherent, nonfragmented masses of displaced bedrock (rock slumps, sags). Dams along small streams are unlikely to fail suddenly, and thus pose little hazard to downvalley development. Those blocking large rivers, on the other hand, are more susceptible to failure due to overtopping and incision; if failure is rapid enough, a destructive flood will sweep the valley below the dam. Although no bedrock failures have blocked major rivers in the Cordillera during the historical period, this has happened earlier during the Holocene. For example, rock avalanches at Texas Creek in southern British Columbia impounded large lakes in Fraser River valley during middle and late Holocene time (Ryder et al., 1990). These dams may have failed catastrophically, producing large downstream floods. Inundation of inhabited or developed valley bottom upstream of a newly formed landslide dam represents an additional hazard. In some instances, the damage from such inundation may be greater than that caused by downstream flooding. These hazards, however, should be viewed in a historical perspective: there have been at least 20 large rockslides and rock avalanches in the Canadian Cordillera in the last 150 years, yet only one has formed a lake of any consequence.

With two exceptions, all present-day landslide-dammed lakes in the Cordillera are products of competent bedrock failures that are hundreds to thousands of years old. The exceptions are an unnamed lake in Kennedy River valley on Vancouver Island, dammed by a rockslide ca. 1970, and Hudgeon Lake northwest of Dawson, Yukon Territory, which

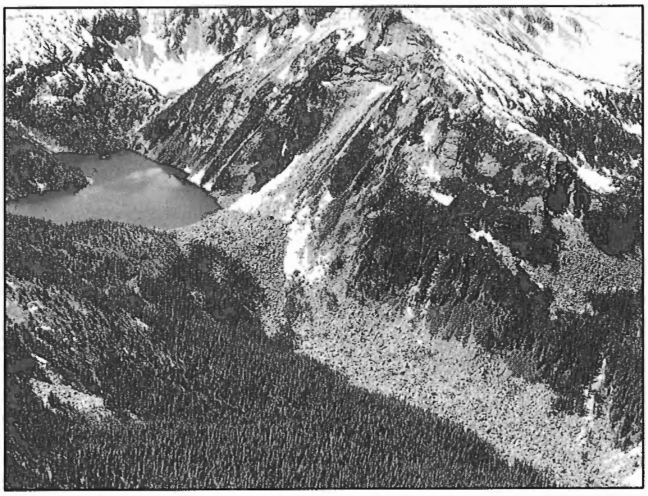


Figure 3. Landslide-dammed lake near Mount Mason in the southern Coast Mountains, British Columbia. The landslide dam comprises blocky rock debris and is stable.

Figure 4. Drowned trees in Foley Lake, southwestern British Columbia. This lake formed and the trees were drowned when the local drainage was blocked by a rock avalanche, sometime between 150 and 310 years ago (Clague and Shilts, 1993).

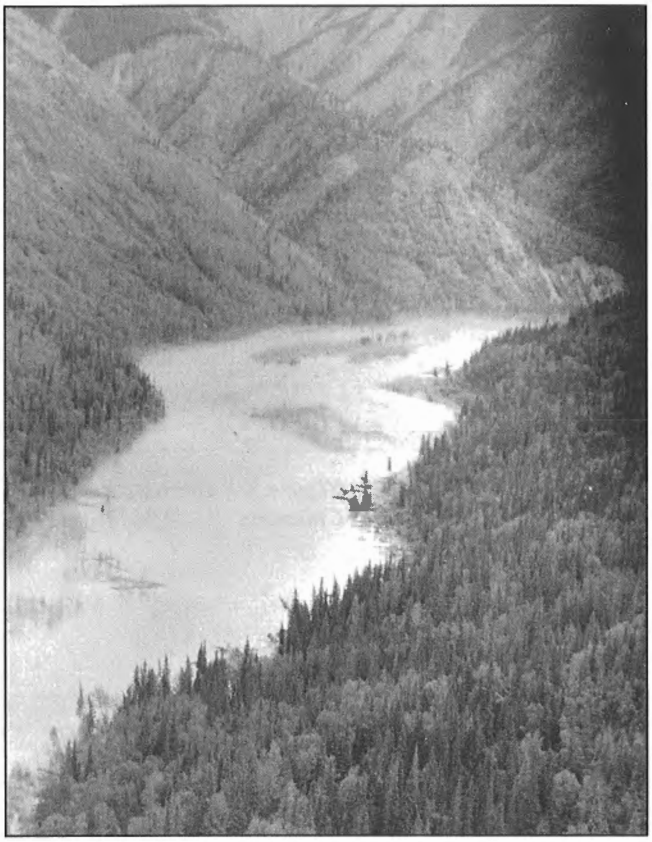


Figure 5. Aerial view of a lake dammed by a landslide in May 1979 in Inklin River valley upstream of Yeth Creek (Fig. 1), northern British Columbia. The landslide occurred in thick Quaternary sediments which form a dissected fill in the valley. (Photograph courtesy of Sandy Johnston, Fisheries Canada).

formed in the early 1970s when a mine rock waste dump failed, blocking a nearby stream (Stepanek and McAlpine, 1992). Only two other existing landslide-dammed lakes have been accurately dated. Foley and Silver lakes in the Cascade Mountains of southwestern British Columbia contain trees that were drowned when the lakes formed (Fig. 4). Radiocarbon ages on the trees, and other evidence, indicate that Foley Lake is 150-310 years old, and Silver Lake formed, or grew greatly in size, 800-1000 years ago (Clague and Shilts, 1993).

In striking contrast to these stable, long-lived dams are those emplaced by landslides in Quaternary volcanic and pyroclastic rocks. Such dams are made up of highly fragmented, weathered, and commonly water-rich debris deposited by high velocity flows. Dams produced by historical failures were highly unstable and failed soon after they formed. Some dams emplaced by prehistoric landslides, on the other hand, were much larger than any of the historical period and may have persisted for months or years (Brooks and Hickin, 1991; Evans and Brooks, 1991; Evans, 1992). Quaternary volcanoes constitute a very small part (<1%) of the western Canada landscape, but large landslides are much more likely to occur in these rocks than in any other. In the future, landslides from volcanoes such as Mount Cayley and Mount Meager in British Columbia can be expected to impound lakes.

Dams produced by failures of dissected Quaternary valley fills

Large lakes have formed historically when rivers were blocked by landslides from nearby bluffs of Quaternary sediments (Fig. 5). Many valleys in the Canadian Cordillera contain remnants of complex fills deposited during alternating

Figure 6. Dissected Quaternary fill in Fraser River valley north of Lillooet, British Columbia. Landslides from the steep bluffs bordering this and other rivers in western Canada have, on occasion, failed and impounded short-lived lakes. (Province of British Columbia airphoto BC1087-46).

Table 2. Historical landslide dams

Site	Date	Dammed stream	Source material	Dam failed?	Reference
Spences Bridge	August 1, 1880	Thompson River	Quaternary sediments	Yes	Evans, 1984
Black Canyon[b]	October 14, 1880	Thompson River	Quaternary sediments	Yes, after 2 days	Stanton, 1898; Evans, 1984, 1986a
North Pacific Cannery	July 6, 1891	Unnamed	Quaternary sediments	Yes, after 7 hours[c]	Evans, 1986a
Spences Bridge	December 31, 1899	Thompson River	Quaternary sediments	Yes	Stanton, 1898; Evans, 1984, 1986a
Spences Bridge	August 13, 1905	Thompson River	Quaternary sediments	Yes, after 5 hours	Stanton, 1898; Drysdale, 1914
Basque Ranch	August 13, 1921	Thompson River	Quaternary sediments	Yes, after several hours	Evans, 1986a
"Big Bend" (Quesnel)	1921	Fraser River	Quaternary sediments	Yes	Evans, 1986a
Britannia	October 28, 1921	Britannia Creek	?[d]	Yes[e]	Evans, 1986a
Devastator Creek	October 1931	Tributary of Meager Ck.	Quaternary volcanic rocks	Yes[f]	Carter, 1932
South Forks Canyon	November 1947	Mess Creek	Quaternary sediments	Yes	Evans, 1986a
"Big Slide"	1951	Babine River	Quaternary sediments	Dam removed	Evans, 1986a
"Big Slide"	February 1953	Babine River	Quaternary sediments	Dam removed	Evans, 1986a
Cheekye River[g]	August 1958	Cheakamus River	Quaternary volcanic rocks	Yes	Jones, 1959
Farwell Canyon[h]	August 19, 1964	Chilcotin River	Quaternary sediments	Yes, after 1 week	Evans, 1986a
Tahltan River	1964	Tahltan River	?	Yes	Evans, 1986a
Kennedy River	ca. 1970	Kennedy River	Pre-Quaternary rocks	No	
Klattasine Creek[i]	1971-1973	Homathko River	Quaternary sediments	Yes	Blown and Church, 1985; Clague et al., 1985
Clinton Creek[j]	1970s	Clinton Creek	Mine rock waste	No	Stepanek and McAlpine, 1992
Wolverine Creek	1974	Wolverine Creek	Mine tailings	Yes[k]	Stepanek and McAlpine, 1992
Devastator Creek	July 22, 1975	Meager Creek	Quaternary volcanic rocks	Yes	Mokievsky-Zubok, 1977; Smith and Patton, 1984
Yeth Creek[l]	April 1979	Inklin River	Quaternary sediments	Yes	Evans, 1986a
Turbid Creek	June 1984	Squamish River	Quaternary volcanic rocks	Yes	Evans, 1986a

[a] Table assembled from archival sources which are available, on request, from the authors.

[b] The lake was 18 km long and had a maximum volume of 42-145 x 10^6 m^3. The volume of the landslide was 15 x 10^6 m^3.

[c] Failure of the dam triggered a debris torrent that buried a village, causing 13-40 deaths.

[d] The dam was either landslide debris or a railway embankment.

[e] The resulting flood destroyed part of the mining community of Britannia and claimed 37 lives.

[f] The resulting flood devastated Meager Creek.

[g] A 5 m high dam diverted Cheakamus River over the Cheekye fan.

[h] Rising lake waters floated a highway bridge off its foundation.

[i] Homathko River was blocked by a debris flow caused by the failure of a moraine-dammed lake.

[j] The dam impounds Hudgeon Lake, which has a surface area of 73 ha and a maximum depth of 26 m.

[k] The lake drained soon after it formed, but continued flow of tailings into the valley impounded another small lake in 1985.

[l] The lake was 12 km long.

glacial and nonglacial periods (Ryder and Clague, 1989). These fills were deeply incised during the Holocene, and many streams today flow in trench-like inner valleys tens or hundreds of metres below late-glacial valley floors (Fig. 6). Silty and sandy glacial lake sediments are an important component of these dissected fills in many areas, and may become unstable and slump or flow when pore pressures are elevated. This may occur during a prolonged period of heavy rainfall, due to irrigation, or as a result of natural or artificial changes in the pattern of groundwater flow. Some of the large landslides that dammed Thompson River in the late nineteenth and early twentieth centuries, for example, may have been triggered by irrigation on nearby benches (Stanton, 1898; Evans, 1984). Lakes impounded by Quaternary sediments generally drain within days of formation when the dam is overtopped and incised.

Dams produced by failures of thin Quaternary sediments mantling rock slopes

Very small lakes form when slumps and slides in till and colluvium block steep stream courses in mountain watersheds during rainstorms. Such dams commonly collapse or are overtopped minutes or hours after they form; the resulting floods and debris flows can be very destructive if they cross inhabited fans (Fig. 7). This type of dam is the most common in the wetter parts of the Cordillera, but is also the smallest ($<1 \times 10^4$) and shortest lived.

Dams produced by failures of mine waste rock dumps and tailings piles

Steep mine waste rock dumps and tailings piles are unstable and may slump or flow in a dry or wet state. In a few cases, landslides in these materials have blocked stream courses and impounded lakes. The dams generally are unstable and short-lived. In permafrost areas, however, rock waste and tailings may continue to flow slowly downslope long after the initial failure, augmenting the original dam or producing repeated blockages (Stepanek and McAlpine, 1992).

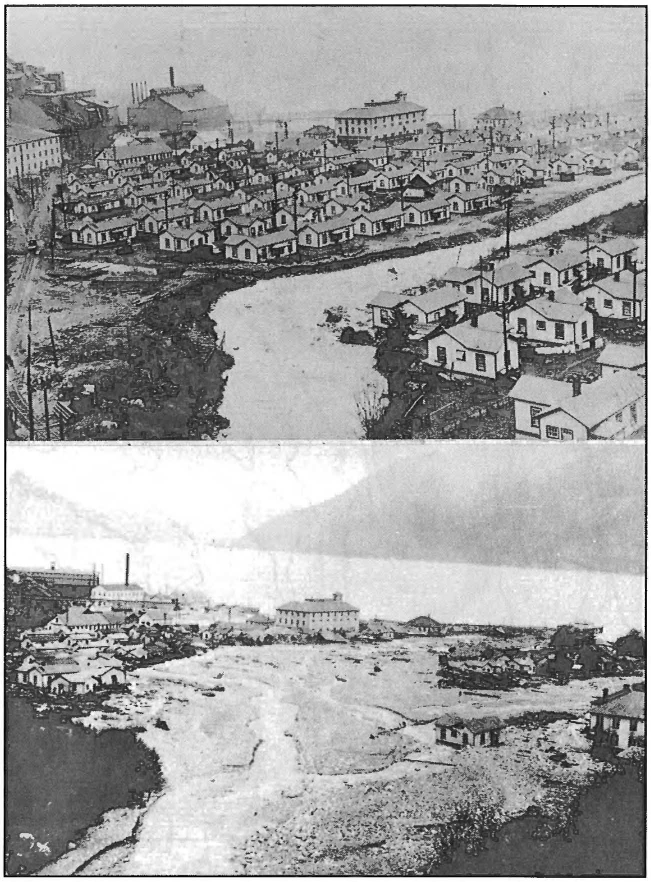


Figure 7. The mining town of Britannia before and immediately after the catastrophic outburst flood of October 28, 1921. The flood, which occurred after several days of heavy rain, resulted from the failure of a landslide dam or an earthfill embankment carrying a mine railway (Eisbacher, 1983; Jackson et al., 1985; Evans, 1986a). Thirty-seven people were killed and about half of the 170 houses in the town destroyed. (Photographs courtesy of Britannia Mining Museum, Browning family collection).

Historical damming events

Documentation exists for 21 historical landslide-damming events in the Canadian Cordillera (Table 2). There undoubtedly have been many other similar damming events that have gone unnoticed because of their small size or remote location. The list in Table 2, therefore, is incomplete.

All but two of the known events have involved failures of Quaternary sediments and volcanic rocks (the exceptions are mine waste failures, described below). The largest dams and lakes have been in the Thompson, Chilcotin, and Inklin river valleys in British Columbia and have resulted from slumps, flows, and complex landslides in thick Quaternary sediments exposed in steep valley walls. The best documented is the Black Canyon landslide which occurred just south of Ashcroft in Thompson River valley on October 14, 1880 (Fig. 8; Evans, 1984). Approximately 15×10^6 m^3 of Pleistocene glacial lake sediments on the east wall of the valley suddenly failed and flowed across Thompson River, stemming its flow. A lake formed upstream of the blockage and attained a maximum depth of 18 m and a length of 14 km before it began to empty through a channel cut by workmen. The escaping waters enlarged the spillway until, two days after the landslide, the lake was empty.

In this century, several large landslides have occurred on the flanks of Quaternary volcanoes at Mount Garibaldi, Mount Cayley, and Mount Meager; some of these dammed nearby streams. An example is the Devastation Glacier landslide near Mount Meager (Fig. 9). On July 22, 1975, about 12×10^6 m^3 of ice and hydrothermally altered volcanic rock broke away from the flank of Pylon Peak, slid across the stagnant toe of Devastation Glacier, and flowed at high velocity down Devastator Creek to its mouth (Mokievsky-Zubok, 1977; Smith and Patton, 1984). There, the debris buried four men who were awaiting the arrival of a helicopter and blocked

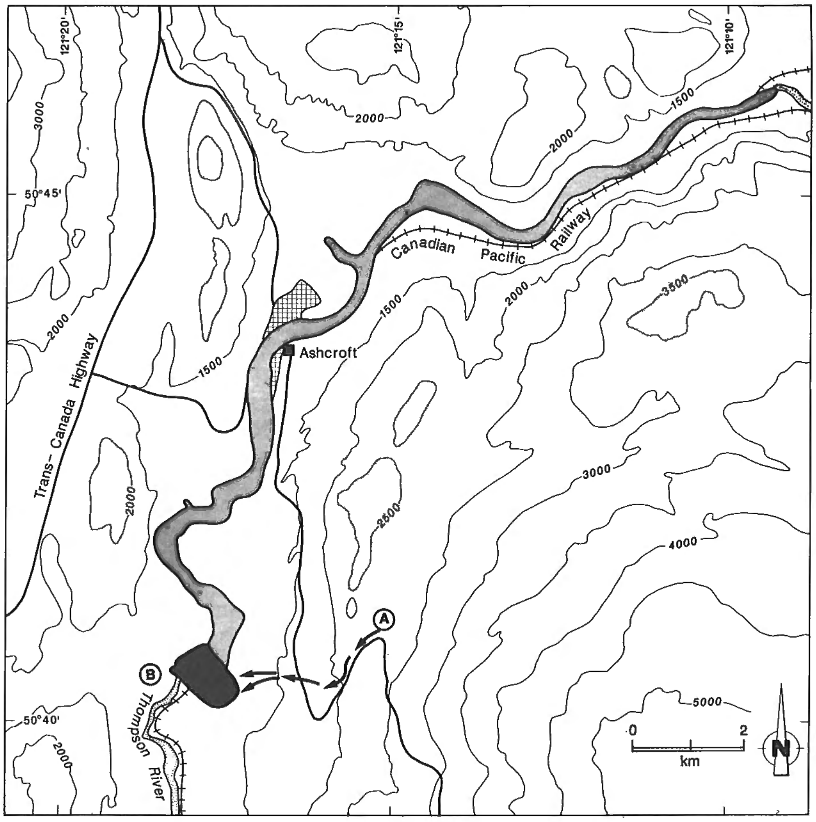


Figure 8.

Location of the 1880 landslide dam (B) in Thompson River valley, south of Ashcroft, British Columbia, and the maximum extent of the reservoir impounded behind the dam. The lake drained about two days after it formed. A is the probable location of an irrigation dam failure, suggested by Stanton (1898) as being a possible cause of the landslide; arrows mark the path of the water to the head of the landslide. Topographic contour interval = 500 feet (152 m). (Modified from Fig. 1 of Evans, 1984).

Meager Creek to form a small lake (Fig. 10). This lake later drained slowly by overtopping and incision of the dam. There also is geological evidence for much larger, prehistoric landslide dams in the Mount Meager and Mount Cayley areas (Brooks and Hickin, 1991; Evans and Brooks, 1991; Evans, 1992).

In the early 1970s, the rock waste dump at the Clinton Creek asbestos mine, which is 80 km northwest of Dawson in Yukon Territory, failed, probably due to degradation of permafrost in underlying fluvial sediments (Stepanek and McAlpine, 1992). The rock waste flowed across Clinton Creek and up the opposing slope. The blockage impounded a lake (Hudgeon Lake), which has an area of 73 ha and a maximum depth of 26 m (Fig. 11). An overflow channel developed soon after the failure and was subsequently armoured with rip-rap to prevent uncontrolled erosion and breaching of the dam. In 1974, the tailings pile of the Clinton Creek mine, which is located near the rock waste dump, also failed and formed a small lake in the valley of Wolverine Creek (Stepanek and McAlpine, 1992). The dam was almost immediately breached, and tailings were dispersed about

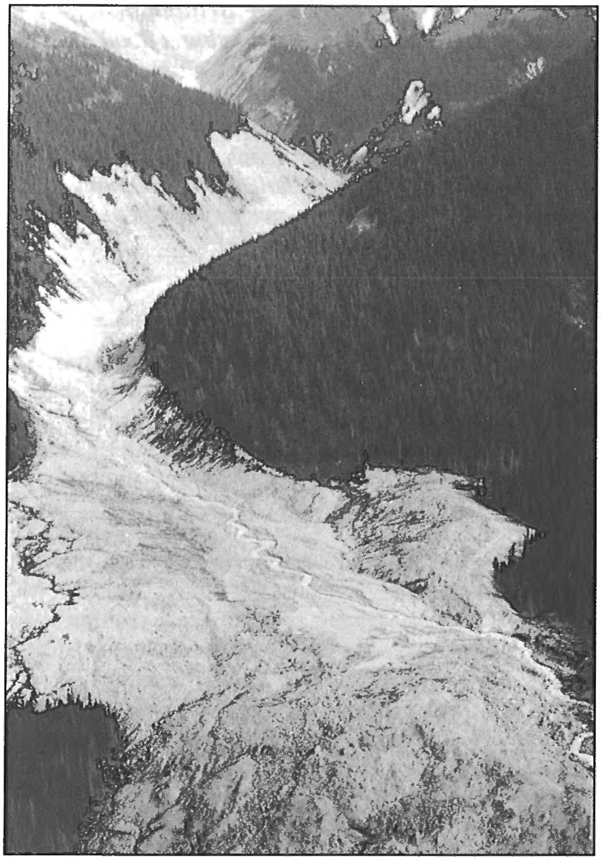


Figure 9. *Aerial view of the valley of Devastator Creek, showing the track of the Devastation Glacier landslide which occurred on July 22, 1975. This landslide is one of many historical failures on the flanks of Quaternary volcanoes in southwestern British Columbia. It dammed a small lake in Meager Creek valley at the mouth of Devastator Creek (see Fig. 10). (GSC 204165-J)*

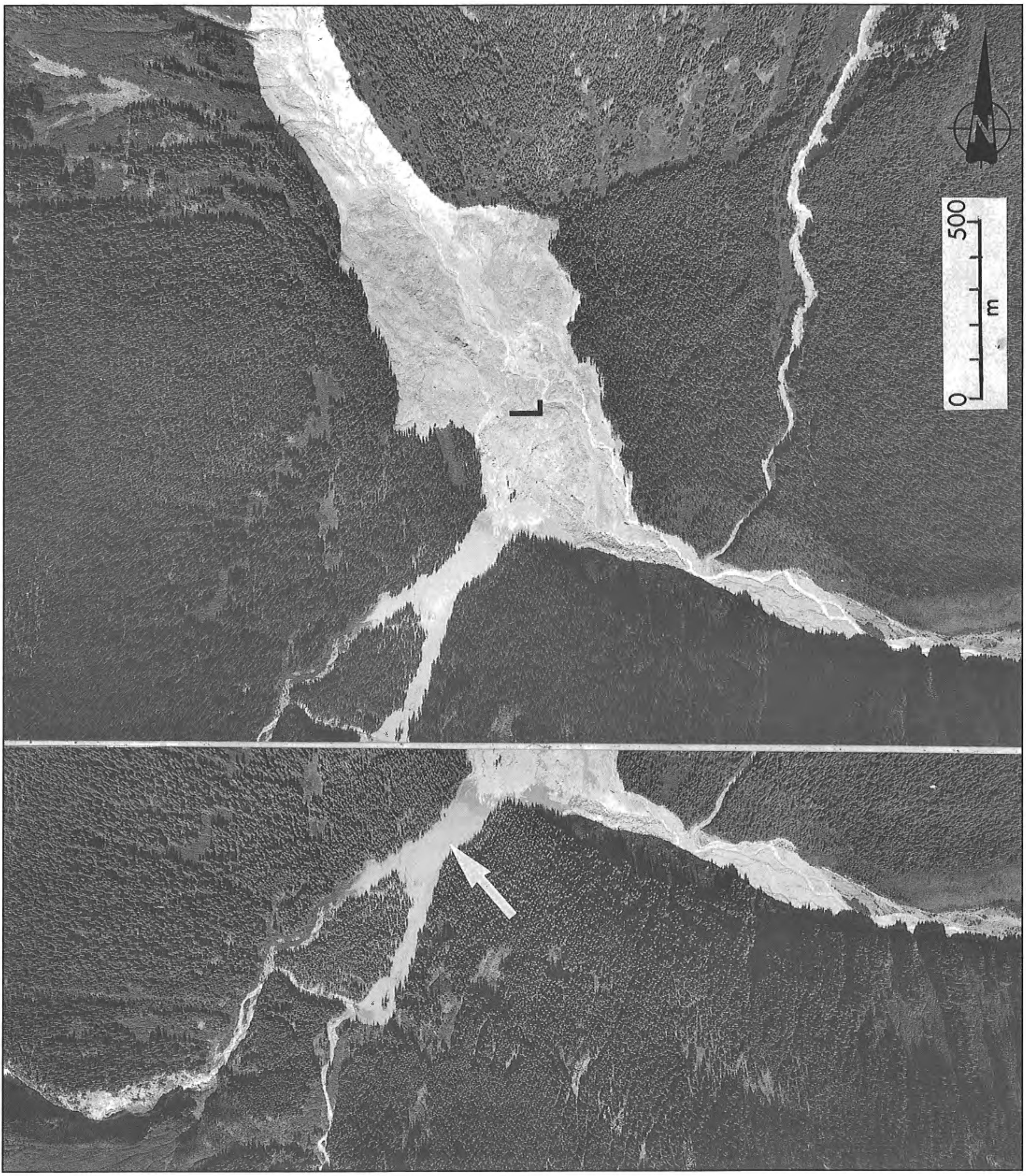


Figure 10. *Photostereogram showing the lake (arrow) in Meager Creek valley impounded by the 1975 Devastation Glacier landslide (L). (Province of British Columbia airphotos BC5685-86, -87).*

2 km downvalley. Since then, however, the continued flow of tailings into the valley created two additional small lakes (Fig. 11). The dominantly silty and sandy tailings are highly erodible, thus there is a high likelihood of future catastrophic breachings at Wolverine Creek.

Finally, floods or debris flows resulting from dam failures near Vancouver (Britannia) and Prince Rupert (North Pacific Cannery) have caused considerable destruction and loss of life (Fig. 7). These are examples of small events that would not be notable were it not for their impact on human activity.

Failure of landslide dams

Most historical landslide dams in the Canadian Cordillera have failed within hours or days of their formation by overtopping, followed by incision. Commonly, the escaping waters first erode the toe of the dam and then progressively cut headward toward the lake. Other, less common modes of failure that may apply in some instances, but have not yet been documented in western Canada, include: 1) internal erosion of the dam by seepage waters (piping); and 2) collapse of part of the dam. Failure may occur rapidly enough to produce severe floods, although the high width-to-height ratio of many landslide dams provides a measure of protection against this.

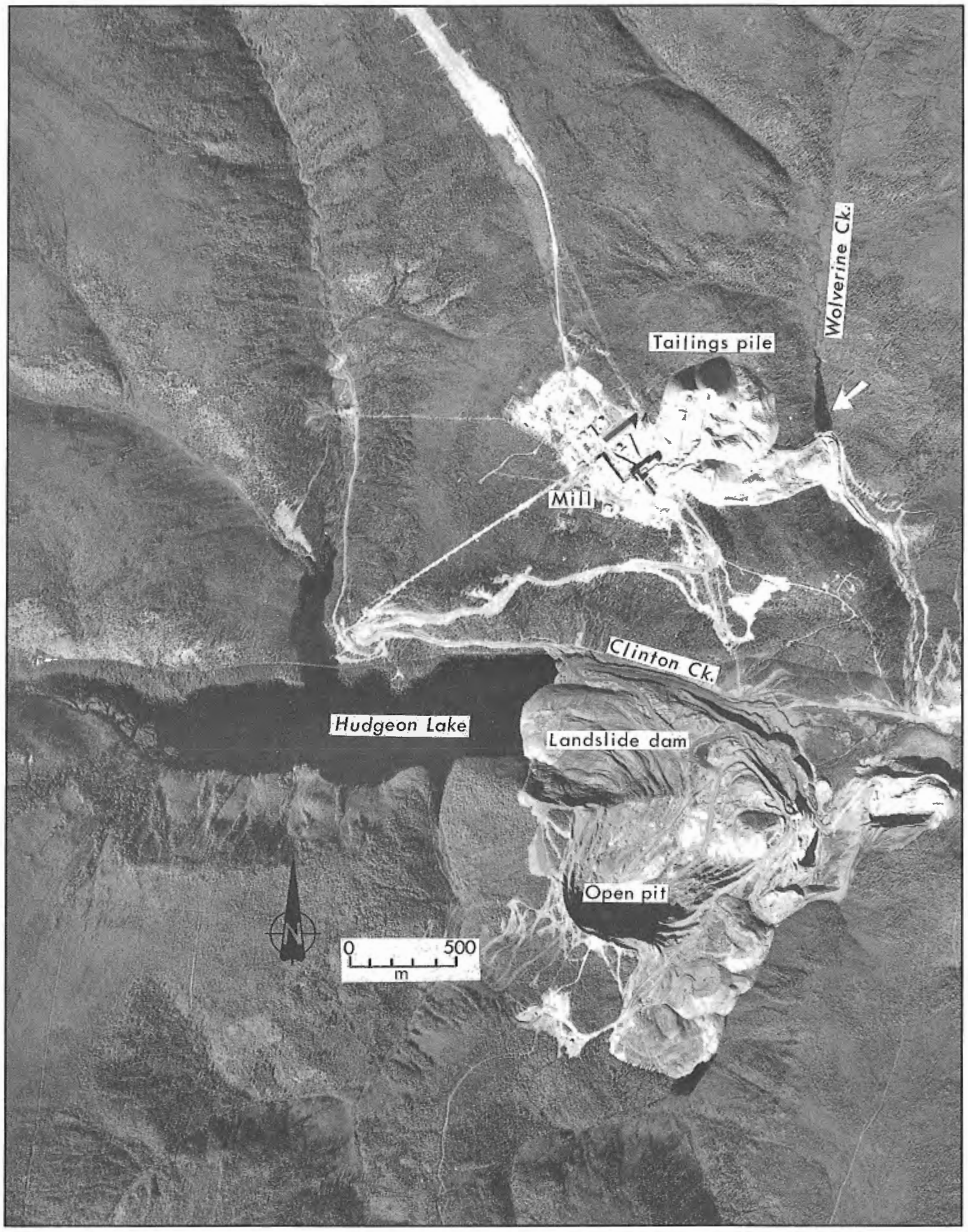


Figure 11. *Aerial view of the Clinton Creek mine area in 1976, showing Hudgeon Lake and its dam of failed mine rock waste. A smaller lake, dammed by failed mine tailings, is visible in the upper right (arrow). (Photo courtesy of M. Stepanek, Geo-Engineering (M.S.T.) Ltd.).*

The short lifespan of historical landslide dams in the Canadian Cordillera (Fig. 12) is a consequence of the rapid filling of the reservoirs and the material properties of the dams. Most of the dams consist of loose porous sediments, which commonly are water-rich and predominantly fine grained (i.e. they have a high proportion of clay, silt, and sand). The shear strength of such materials is low, and consequently the dams are susceptible to slope failure or to erosion when overtopped. In contrast, dams consisting of blocks of competent bedrock tend to be stable because any overflowing water is incapable of eroding the coarse materials and because the dam slopes are unlikely to fail. In any case, these latter dams are so porous and permeable that there commonly is little or no overflow.

MORAINE DAMS

Setting and character

Lateral and end moraines beyond present-day glacier margins are common in the high mountains of western Canada (Fig. 13). Most were constructed during a recent period of cooler climate that ended in the late nineteenth century (the "Little Ice Age" (Matthes, 1939), which is the last part of the Neoglacial period). Glaciers have retreated from climax positions attained during the Little Ice Age, leaving behind many lakes dammed by these moraines.

Moraine-dammed lakes typically occur in cirques and steep-walled valleys behind end moraines (Fig. 13) or at the mouths of tributary valleys blocked by lateral moraines. Most, although not all, are near or above treeline and may be close to steep rock slopes that are prone to frequent rockfalls and snow and ice avalanches.

Moraine dams may consist of a single moraine or nested moraines deposited during several Neoglacial advances. Most are steep-sided (up to ca. 40°) and have relatively low width-to-height ratios (generally much lower than those of landslide dams; Costa and Schuster, 1988). Heights of a few tens of metres are common, and some moraine dams are more than 100 m high.

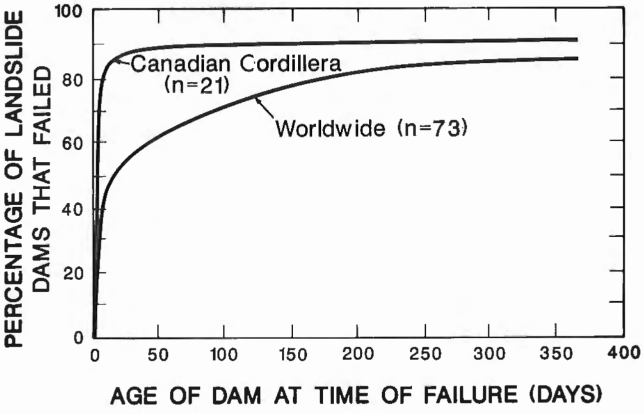


Figure 12. *Length of time before failure of historical landslide dams in the Canadian Cordillera (this bulletin) and worldwide (Costa and Schuster, 1988).*

The dams comprise poorly sorted, stratified to massive sediment, including: 1) blocky and bouldery deposits with a matrix of sand and gravel; and 2) silty and sandy diamicton (Fig. 14). Stratification, where present, commonly dips away from the former ice-contact face toward the distal edge of the moraine. Much of the sediment was deposited at the glacier snout by the dumping of debris carried on and in ice. Some moraines are cored by ice and may have only a thin cover of sediment.

Historical failures

There have been at least eight historical failures of moraine dams in the Canadian Cordillera, four in the Coast Mountains, one in the St. Elias Mountains, and three in the Columbia Mountains (Table 3; Fig. 1; Evans, 1987; Ryder, 1991; Clague and Evans, 1992; Clague and Mathews, 1992).

Figure 13. *Unnamed moraine-dammed lake in the southern Coast Mountains, British Columbia. The large moraine impounding the lake was constructed during the Little Ice Age.*

Figure 14. *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 made of similar materials. The height of the exposure is about 40 m.*

The most spectacular of these is the Nostetuko Lake outburst of July 1983 (Blown and Church, 1985). Nostetuko Lake, located at the head of Nostetuko River, 230 km north of Vancouver, is dammed by a Little Ice Age end moraine (Fig. 15). This moraine was deposited by Cumberland Glacier which has since receded and now terminates on a cliff above Nostetuko Lake. On July 19, 1983, part of the toe of Cumberland Glacier broke away and cascaded into the lake. Waves generated by the impact of the icefall moved down the lake, and overtopped and rapidly incised the moraine at the opposite end. Within four hours, the moraine had been breached to a depth of almost 40 m and about 6 x 10^6 m^3 of water had been released (Fig. 16). This produced a destructive flood that swept 115 km down Nostetuko and Homathko valleys to the sea (Fig. 17). Over 1 x 10^6 m^3 of sediment was eroded from the moraine; most of this was deposited as a large fan on top of a former meadow directly downstream from the dam (Fig. 16). Farther downstream, floodwaters extensively eroded unconsolidated deposits in Nostetuko River valley (Fig. 18), damaged large tracts of forest, and left substantial piles of wood debris and coarse sediment on bars and channel margins. Rare floods such as this may affect floodplain geomorphology for decades.

Four other historical moraine dam failures produced debris flows rather than water floods. The largest, in the valley of Klattasine Creek 35 km west of Nostetuko Lake, occurred sometime between June 1971 and September 1973 (Clague et al., 1985). It was triggered by the sudden release of about 1.7 x 10^6 m^3 of water from moraine-dammed Klattasine Lake. The escaping waters breached the moraine (Fig. 19), mobilized large quantities of sediment in the valley below the lake, and generated a debris flow that travelled in one or more surges 8 km to the mouth of Klattasine Creek (Fig. 20, 21). Here, the flow deposited a sheet of coarse bouldery debris up to 20 m thick that temporarily stemmed the flow of Homathko River (Fig. 22).

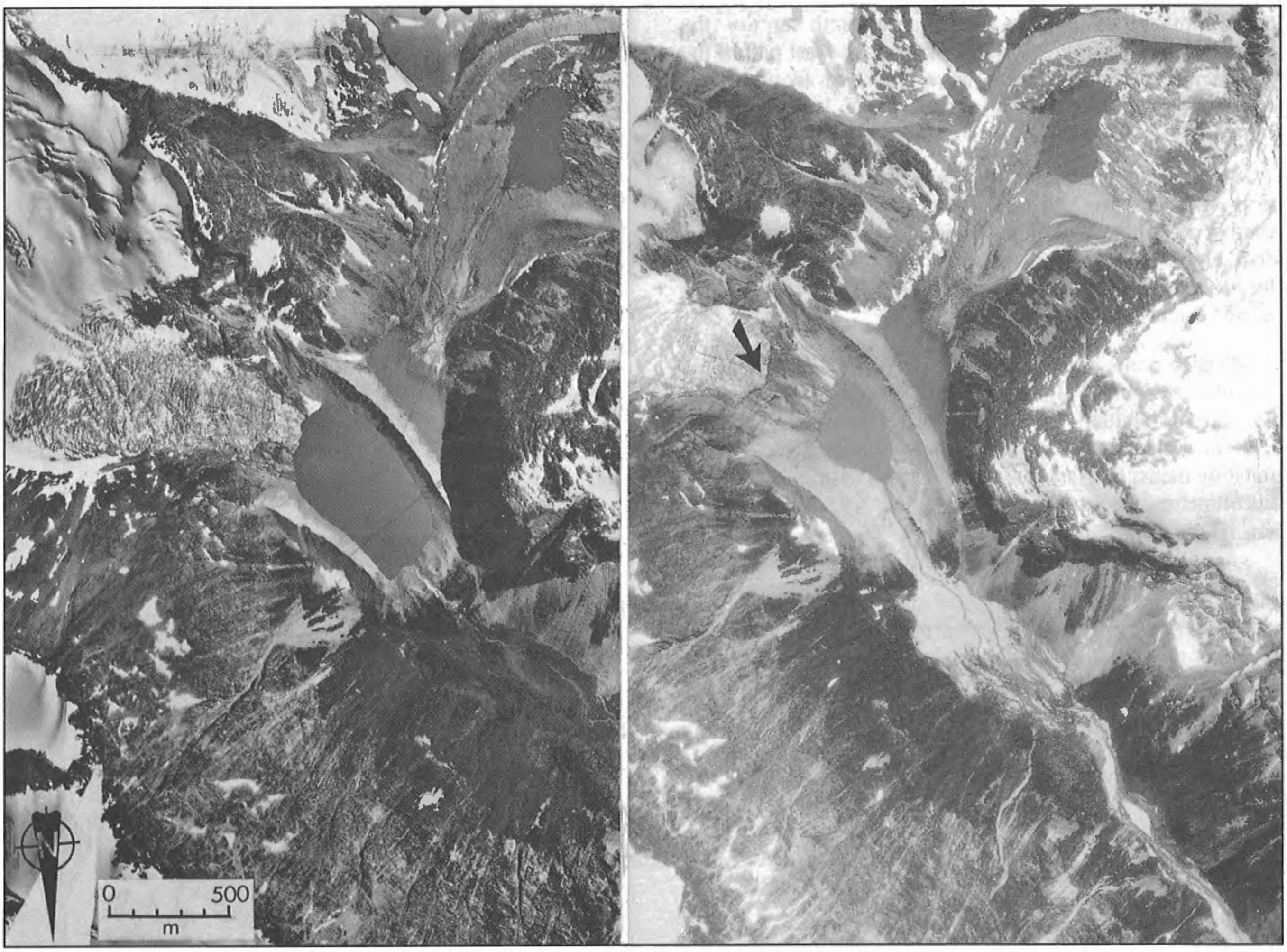


Figure 15. Aerial photographs of Nostetuko Lake before (left) and after (right) the outburst flood of July 19, 1983. Failure occurred when part of the toe of Cumberland Glacier (arrow) collapsed into the lake and generated waves that overtopped the moraine. (Province of British Columbia airphotos BC79069-190, left, and BC86048-147, right).

Table 3. Moraine dam failures

Lake	Date	Outburst volume ($m^3 \times 10^6$)	Peak discharge (m^3/s)	Effect	Failure mechanism	Reference
Tide	1927-1930			Flood		Clague and Mathews, 1992
Bridge	1964-1970[a]	1-2	<1000	Flood		Ryder, 1991
Klattasine	1971-1973	1.7	>1000	Flood/debris flow		Clague et al., 1985
Nostetuko	July 19, 1983	6.5-7.5	ca. 10 000	Flood	Wave overtopping	Blown and Church, 1985
North Mount Macoun	July 1983			Flood	Piping?	Evans, 1987
South Mount Macoun	Before 1949	0.4	<<1000	Flood/debris flow	Wave overtopping?	Evans, 1987
Patience Mountain	1951-1966	0.3	<<1000	Flood/debris flow	Wave overtopping?	Evans, 1987
Tats	June 28, 1990	0.004	<<1000	Flood/debris flow		Clague and Evans, 1992

[a] Other partial breachings, accompanied by floods, may have occurred between 1935 and 1947.

Causes of failure

The cause of only one of the eight documented moraine dam failures in the Canadian Cordillera is known. As mentioned previously, the Nostetuko moraine failed because it was overtopped by waves generated by an icefall. The overflowing waters eroded the crest and outer flank of the moraine, initiating catastrophic incision.

This is a common cause of moraine dam failure in other mountain ranges, for example the Himalayas and Andes, but other mechanisms also have been suggested (Eisbacher and Clague, 1984; Costa and Schuster, 1988). Overtopping and breaching of moraine dams can result from increased streamflow during periods of rapid glacier retreat, intense rainfall, or snowmelt. Piping and settlement or collapse during earthquakes are two other possible causes of failure. Moraine dams with ice cores or interstitial ice are particularly vulnerable to failure during a period of climatic warming.

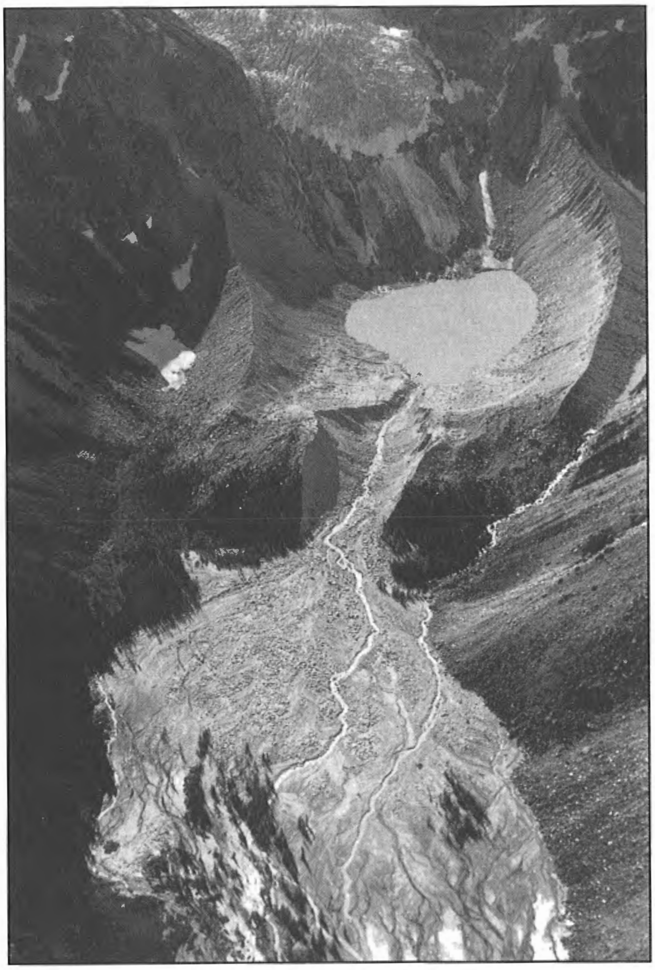


Figure 16. *The breached, Little Ice Age moraine of Cumberland Glacier and Nostetuko Lake after the 1983 outburst flood. Note the large fan of bouldery debris in the foreground.*

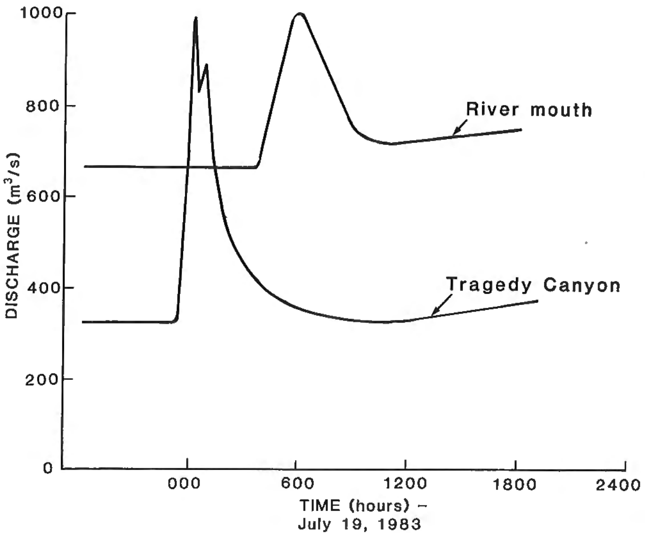


Figure 17. *Hydrographs showing the flood that resulted from the failure of the moraine dam at Nostetuko Lake in July 1983. The lower hydrograph is from a site 67 km downstream from the dam and shows an increase in discharge from 330 m/s to over 900 m/s in one hour; the upper hydrograph, from a site a further 45 km downvalley, shows a somewhat attenuated flood wave. (Modified from Fig. 4 of British Columbia Hydro and Power Authority, 1983).*

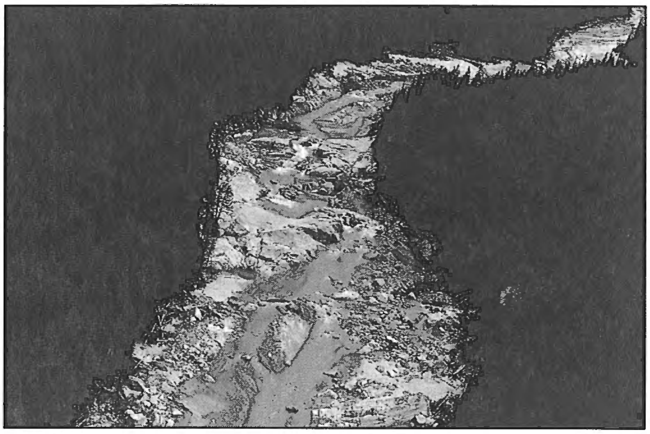


Figure 18. *Lower Nostetuko River valley in August 1984, approximately one year after the Nostetuko flood. All sediments and trees were stripped from the valley floor by the floodwaters, which were about 5 m deep here.*

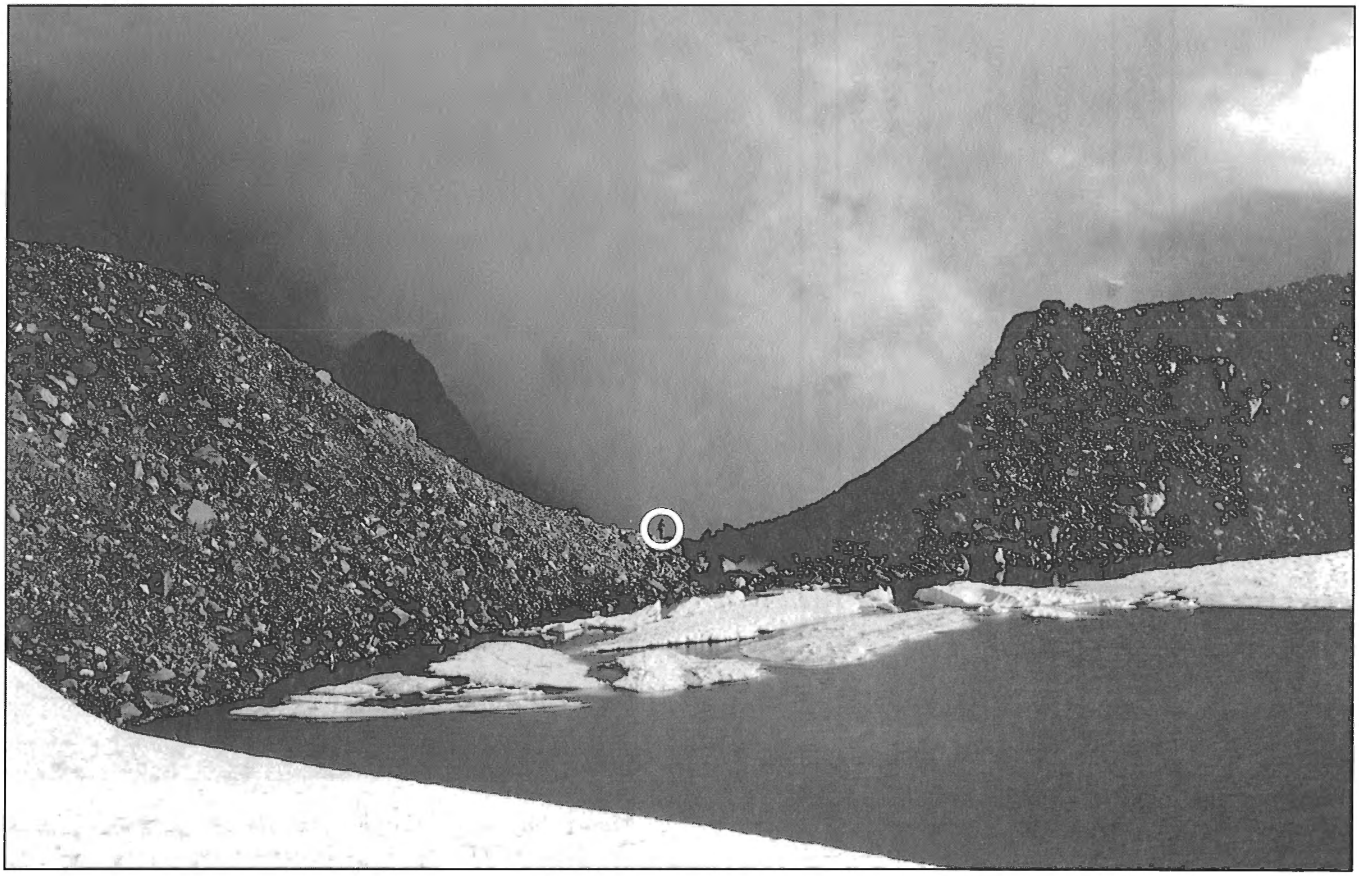


Figure 19. *Breached moraine at Klattasine Lake. View to the north through the breach from the shore of Klattasine Lake; person (circled) near outlet provides scale.*

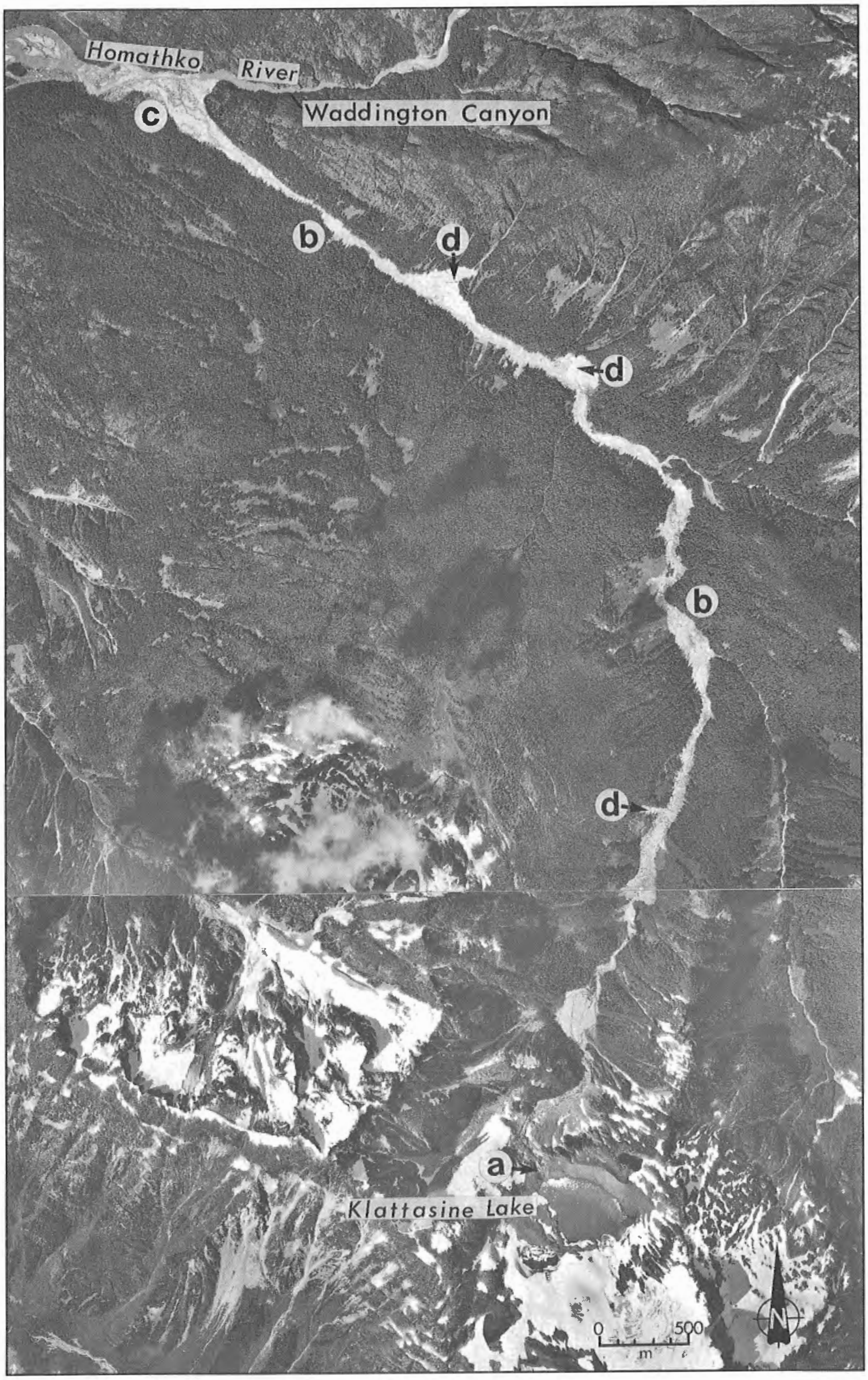


Figure 20. Photomosaic of the Klattasine Creek debris flow. ***a****, breached moraine at Klattasine Lake;* ***b****, unvegetated strip delineating the path of the flow;* ***c****, main depositional area at the mouth of the stream; and* ***d****, secondary slope failures. (Province of British Columbia airphotos BC79069-235, BC79074-041; Fig. 2 of Clague et al., 1985).*

An outburst generally continues until the moraine is completely breached or the lake empties. 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. However, there is at least one instance in the Cordillera of an outburst that was arrested before the moraine was completely breached and the lake emptied (Tats Lake, B.C.; Clague and Evans, 1992). In this case, the escaping waters produced a bouldery lag in the overflow channel, armouring it from further erosion. 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.

Longevity

Moraine dams in the Canadian Cordillera tend to exist longer than all landslide dams, except those consisting of competent rock debris. This is due partly to differences in the materials that constitute these dams, but also reflects differences in the size 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.

The stability of moraine dams is controlled by so many factors that it is difficult to draw general conclusions about their longevity. However, dams that are low and wide and have armoured overflow channels may persist for centuries, whereas high narrow dams impounding lakes below steep rock slopes that are prone to rockfalls and avalanches have a high potential for failure. Ice-cored moraines may thaw for decades or centuries until a critical threshold is reached, whereupon failure may result from normal overflow. The anticipated global climatic warming of the next century should accelerate this process. A warmer climate may also increase the amount of water that flows into the lakes and over the crest of the moraines, further destabilizing many dams. Finally, unusual external events, such as an earthquake, may cause an otherwise stable moraine dam to fail.

GLACIER DAMS

Setting

Glacier-dammed lakes (Fig. 23, 24) are present in the high mountain ranges of western Canada. Most occur at the margins of glaciers, but some are present beneath the ice. The most common locations are main valleys adjacent to the

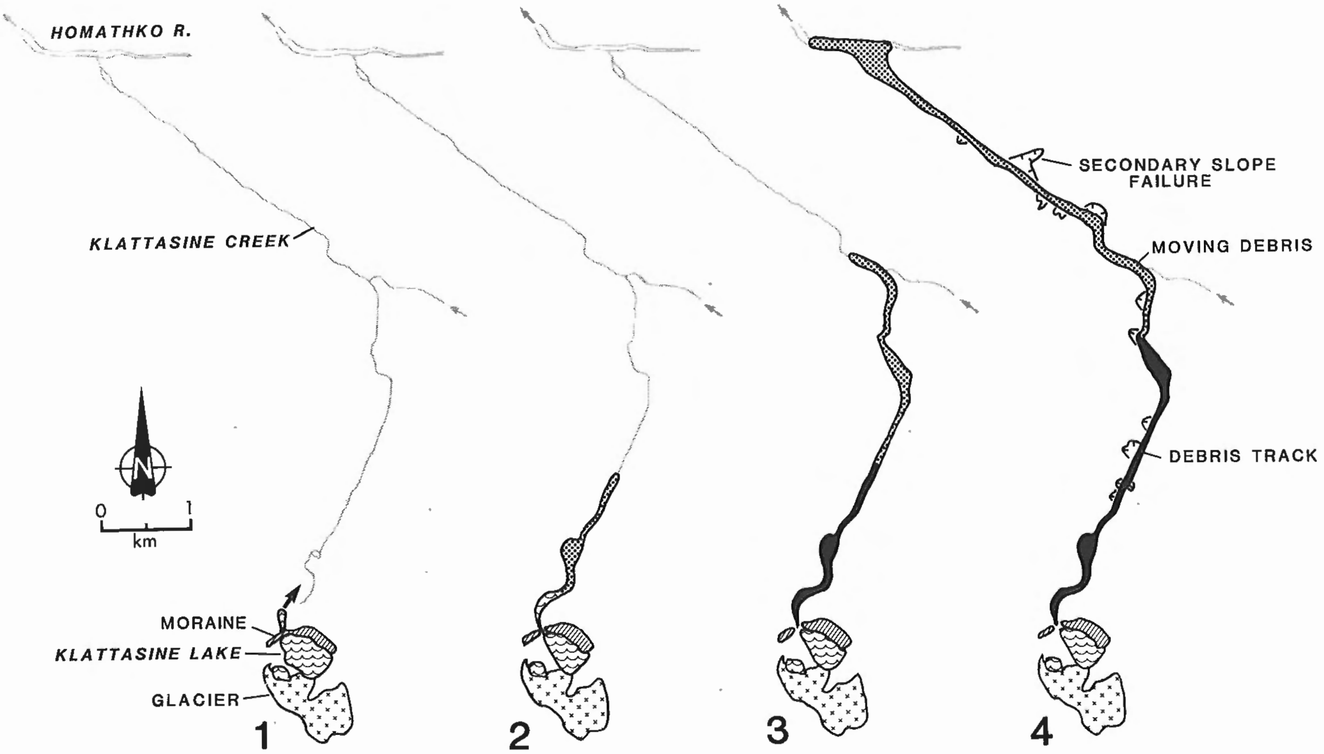


Figure 21. *Stages in the evolution of the Klattasine Creek debris flow.* ***1****, the moraine damming Klattasine Lake begins to fail;* ***2****, escaping waters mobilize large quantities of sediment, initiating a debris flow;* ***3****, the debris flow rapidly moves downvalley and entrains additional sediment;* ***4****, the front of the debris flow reaches Homathko River and temporarily blocks it; secondary landslides occur in Klattasine Creek valley. Stippled area = moving debris; black area = wake of debris flow.*

snouts of tributary glaciers, mouths of tributary valleys blocked by trunk glaciers, and low-lying glacier-marginal areas (Fig. 25; Blachut and Ballantyne, 1976).

Many glacier-dammed lakes are unstable and, on occasion, drain suddenly to produce large floods, termed jökulhlaups (an Iceland term meaning "glacier burst") (Fig. 26). Such floods have caused loss of life and severe property damage in many parts of the world, including Alaska, Austria, France, Iceland, India, Italy, Norway, Pakistan, Peru, and Switzerland (see Eisbacher and Clague, 1984, and Costa and Schuster, 1988, for references).

Mode of failure

Glacier dams most commonly fail through the formation and enlargement of subglacial and englacial tunnels (Gilbert, 1969, 1971, 1972; Mathews, 1973). Crevasses and cavities within and at the base of the glacier become interconnected, perhaps due to cracking caused by glacier flow or hydrostatic pressure. When this happens, water begins to flow from the lake. The escaping waters melt ice and thus enlarge the tunnel system. This process continues until the dam collapses or, more commonly, until the level of the lake drops below the tunnel inlet. When the outflow ceases, the tunnel closes by plastic flow, and the lake begins to reform.

Another possible failure mechanism is hydrostatic flotation (Thorarinsson, 1953). In theory, an ice dam may become detached from its bed and float when the hydrostatic pressure of water in the lake exceeds the ice overburden pressure in the dam. This occurs when the depth of water in the lake reaches 0.9 times the height of the dam. There is, however, some question as to whether this mechanism occurs in nature. Many glacier-dammed lakes begin to empty before filling to 0.9 times the dam height, whereas others fill to higher levels.

Figure 22. *Fan at the mouth of Klattasine Creek. Bouldery debris deposited by the Klattasine Creek debris flow temporarily blocked Homathko River to form a lake. (Fig. 5 of Clague et al., 1985).*

Figure 23. *Photostereogram showing Tulsequah Lake, a large glacier-dammed lake in the northern Coast Mountains, British Columbia. Note the potentially unstable, moraine-dammed lake (arrow) just west of Tulsequah Lake. (Province of British Columbia airphotos BC82009-86, -87)*

Figure 24. *Summit Lake, August 1989. The lake is dammed by Salmon Glacier (visible in the distance), and empties and fills annually.*

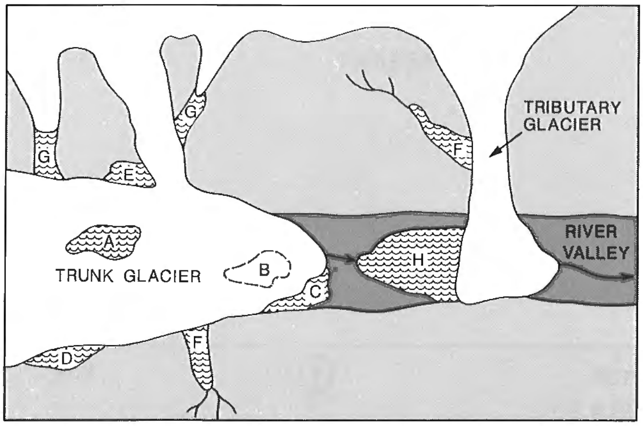


Figure 25. *Schematic diagram showing locations of glacier-dammed lakes.* ***A****, supraglacial;* ***B****, subglacial;* ***C****, proglacial;* ***D****, embayment in slope at glacier margin;* ***E****, area of coalescence of two glaciers;* ***F****, tributary valley adjacent to a trunk or tributary glacier;* ***G****, same as F except glaciers dam both ends of the lake;* ***H****, main valley adjacent to a tributary glacier. Toned area is land; unpatterned area is ice. (Modified from Fig. 9 of Costa and Schuster, 1988).*

Figure 26. *Jökulhlaup from Summit Lake, at Ninemile, Alaska, September 17, 1967. The discharge is almost 3000* m^3/s*, which is 100 times larger than the mean discharge of the stream at this site. The steel bridge was washed away a few hours after this photograph was taken. (Photo by J.J. Plummer).*

Furthermore, lakes generally continue to drain after the lake falls below this critical level. Most glacier-dammed lakes are small relative to the ice masses that impound them, thus flotation is unlikely to occur at any water depth. In those rare cases where flotation does occur, it probably is a short-lived phenomenon and may only trigger other processes that allow continued draining of the lake, for example erosion of subglacial channels by escaping water, formation of cracks due to flotation, or uneven settling of the ice dam after flotation, creating openings at the base of the glacier.

Other failure mechanisms, which are relatively unimportant in the Canadian Cordillera but which are mentioned for the sake of completeness, include overflow and incision of the ice dam, subglacial melting by volcanism or geothermal heat, and weakening of the dam by earthquakes (Post and Mayo, 1971).

Some formerly stable, glacier-dammed lakes in the Cordillera have gone through a cycle of jökulhlaup activity during the twentieth century as glaciers have retreated from maximum positions achieved during the Little Ice Age climax (Fig. 27). As a glacier dam weakens due to downwasting and

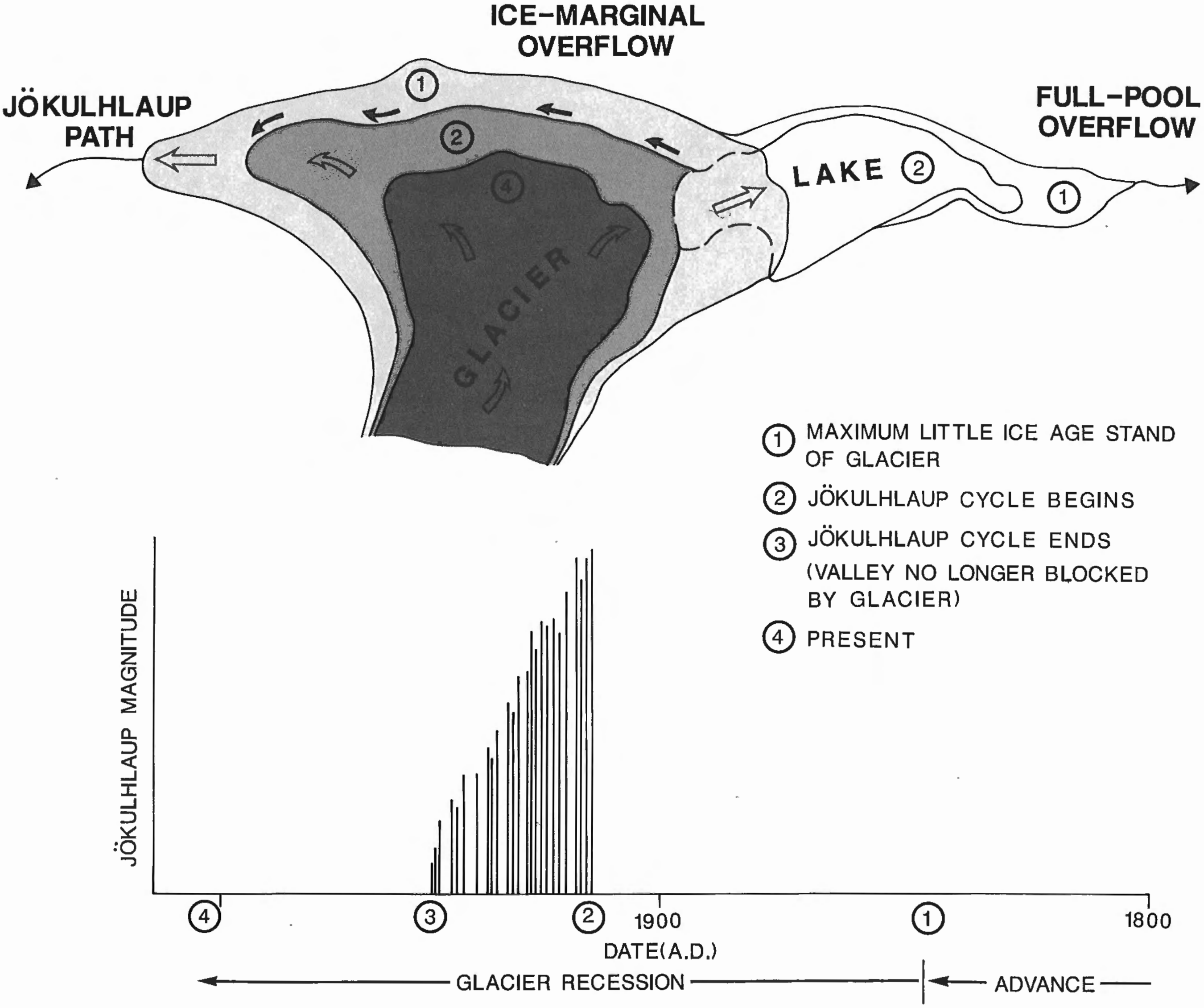


Figure 27. *Pattern of jökulhlaup activity accompanying glacier retreat during the twentieth century. The top diagram is a plan view of the toe of a hypothetical glacier at three times (1, 2, 4; ice-flow directions are shown by open arrows). The bottom diagram is a plot of jökulhlaup magnitude (relative scale) versus time. At time 1, the lake impounded by the glacier is stable and drains via a stable overflow channel. Between times 1 and 2, the lake overflows along the margin of the glacier (solid arrows). The first jökulhlaup occurs at time 2, and sporadic or cyclic outburst floods continue until time 3 when the glacier has retreated to the point that it can no longer impound a lake. The glacier then continues to retreat to the present (time 4).*

retreat, a critical threshold is reached when the dam can no longer continuously support the water behind it (e.g. Summit Lake, British Columbia, in December 1961; Mathews, 1965; Mathews and Clague, 1993). Thereafter, the lake drains and refills on either a regular (one or more times a year) or irregular basis. In the words of W.H. Mathews (1965), the lake becomes "self-dumping". This continues until either the glacier readvances and forms a stronger dam or, more typically, at least in this century, until it retreats to the point where it no longer impounds water (e.g. Ape and Strohn lakes, British Columbia; Mathews, 1965; Desloges et al., 1989). The frequency of dam failure is also likely to change with time. As a glacier recedes, failures may increase in frequency but decrease in magnitude, ending with the establishment of a permanent outlet (Thorarinsson, 1939; Marcus, 1960).

Prehistoric and historical failures

Documented jökulhlaups in the Canadian Cordillera are listed in Table 4. The largest of these are prehistoric and include the floods from former Lake Alsek, Lake Donjek, and Tide Lake.

An extremely large, self-dumping lake formed many times during the Little Ice Age when Lowell Glacier advanced or surged across Alsek River in the St. Elias Mountains (Fig. 28, 29; Clague and Rampton, 1982). Giant dunes on the floor of Alsek valley (Fig. 30; Clague and Rampton, 1982; Schmok and Clarke, 1989) provide evidence of large jökulhlaups from Lake Alsek during recent centuries. Calculations using a paleohydrological simulation model (Clarke, 1982; Clarke et al., 1984) indicate that the peak discharges of floods from Lake Alsek during the mid-nineteenth century were roughly 3×10^4 m^3/s (Clarke, 1989), which is about one third of the mean flow of Amazon River at its mouth. A jökulhlaup associated with an earlier phase of the lake discharged approximately 30 km^3 of water and had a peak discharge of about 4.7×10^5 m^3/s (Clarke, 1989); this is perhaps the largest flood of the last 10 000 years on Earth. Although Lake Alsek no longer exists, it would re-form if Lowell Glacier were to surge about 1 km (Fig. 29). A major blockage of Alsek River might inundate the town of Haines Junction and sections of Haines Road and Alaska Highway (Fig. 28).

Table 4. Glacier dam failures

Lake	Year failed	D[a] (m)	H[b] (m)	V[c] ($m^3 \times 10^6$)	Q_{max}[d] (m^3/s)	References
Ape	1984[e]	58	74	84[f]	1600[g]	Jones et al., 1985; Desloges et al., 1989
Alsek	ca. 1850	101	110	4700	30 000[g]	Clarke, 1989
Bigmouth						
Bridge	1935-1947[h]					Ryder, 1991
Brucejack	1989					
Cathedral[i]	1984[j]			0.03	210[k]	Jackson et al., 1989
Donjek	ca. 1810	60	150	234	3970-5970[l]	Clarke and Mathews, 1981
Flood	1979[m]	70	200	150	2160[g]	Clarke and Waldron, 1984
Hazard	1978[m]	100	530	20	511[n]	Clarke, 1982
MT	1982	25	150	0.5	47[g]	Blown and Church, 1985
Strohn						Mathews, 1965
Summit	1967[m]	200	620	251	2560[n]	Mathews, 1973
Tide	1800s[o]	180	240	1100	5000-10 000[p]	Clague and Mathews, 1992
Tulsequah	1958[m]	73	210	229	1556	Marcus, 1960

[a] D = depth of lake at glacier dam.
[b] H = height of lake surface above toe of glacier dam.
[c] V = lake volume.
[d] Q_{max} = peak discharge.
[e] The lake also drained in 1986.
[f] 46×10^6 m^3 of water drained during the jökulhlaup.
[g] Discharge estimated from empirical relationship (independent variable = lake volume or potential energy) or numerical model.
[h] There probably were several jökulhlaups during this period.
[i] Englacial and supraglacial water bodies in Cathedral Glacier.
[j] Debris flows were produced by jökulhlaups in 1925, 1946, 1962, 1978, and 1984.
[k] Peak discharge of debris flow. Volume of debris flow = 9×10^4 m^3 (note: the largest debris flow, in 1978, had an estimated volume of 1.4×10^5 m^3).
[l] Most probable range.
[m] Frequent jökulhlaups (commonly one per year in recent decades).
[n] Largest measured discharge.
[o] There were several large jökulhlaups during the nineteenth and early twentieth centuries. The last flood(s) from Tide Lake, which occurred between 1927 and 1930, resulted from the breaching of a moraine dam.
[p] The total amount of water discharged during the largest jökulhlaup from Tide Lake is unknown, although it was considerably less than 1100×10^6 m^3 (= V). Accordingly, only broad limits can be placed on estimates of Q_{max}.

Similar, although smaller, jökulhlaups occurred in the 1800s in Donjek River valley, 100 km north of Lowell Glacier, after Donjek Glacier advanced to impound a lake (Fig. 31; Clarke and Mathews, 1981). Likewise, Tide Lake in the northern Coast Mountains produced several large jökulhlaups in the nineteenth and early twentieth centuries (Clague and Mathews, 1992). Neither Lake Donjek nor Tide Lake exists today, but they, like Lake Alsek, would form again if the glaciers that formerly dammed them readvanced. Jökulhlaups from a renewed Lake Donjek would threaten the Alaska Highway (Fig. 31).

There have been many jökulhlaups in the Canadian Cordillera during the historical period. Studies of some of these have laid the foundation for much of our present understanding of the physics of outburst floods. Jökulhlaups from Summit Lake (Fig. 24) in the northern Coast Mountains of British Columbia menaced the transportation corridor between the Granduc mine site and Hyder, Alaska, and motivated the research of W.H. Mathews (1959, 1964, 1965, 1973) and his student R. Gilbert (1969, 1971, 1972). Mathews (1973) reconstructed the 1965 and 1967 Summit Lake jökulhlaups from observations of falling lake levels, lake areas, and surface outflow, plus estimates of inflow. He showed that outflow discharge increased in proportion to a power (1.5) of the volume of water previously lost from the lake (Fig. 32). From this and from calculations of effective tunnel diameter following the jökulhlaups, Mathews concluded that the tunnels developed by melting due to heat transfer from water, rather than mechanical

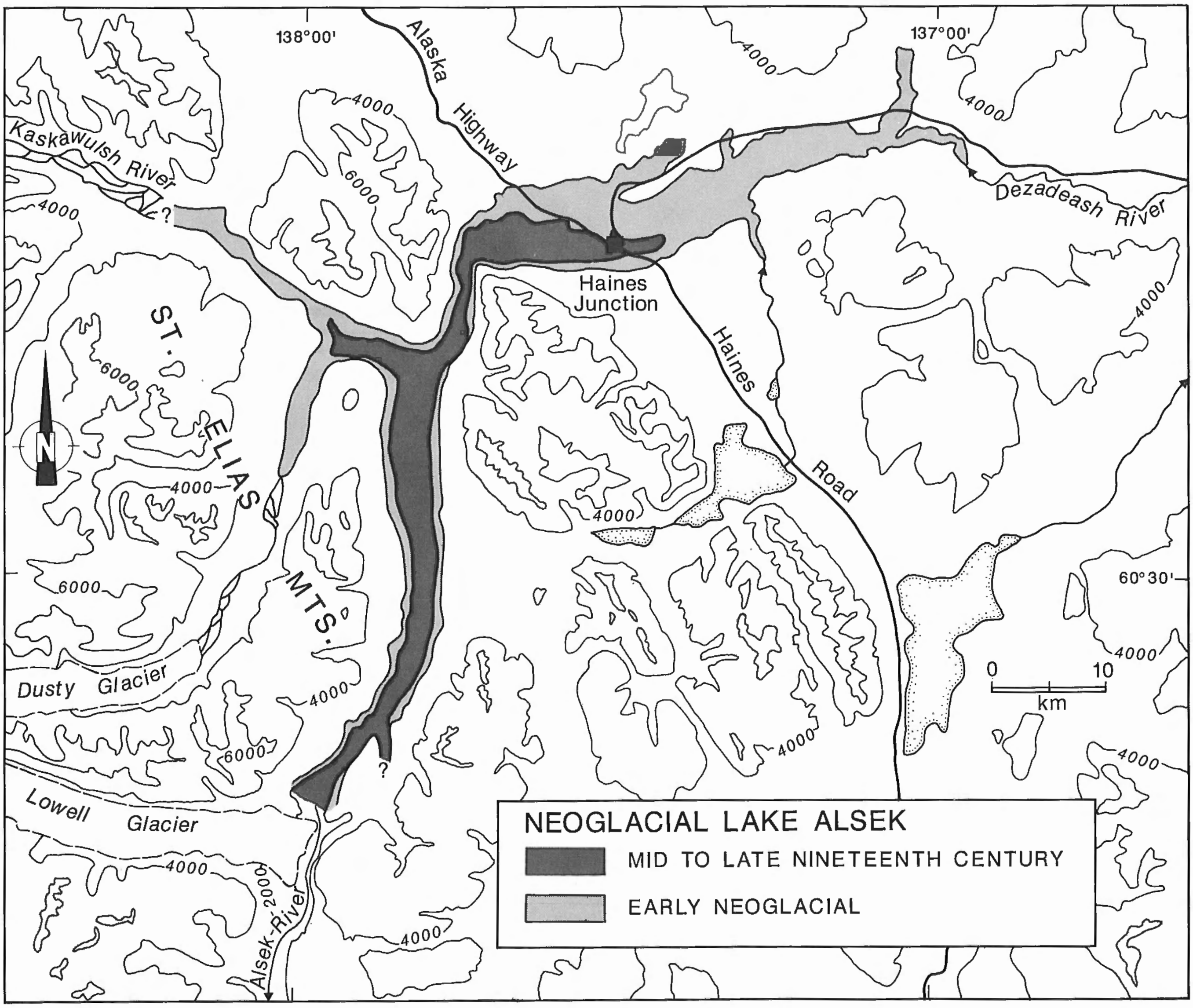


Figure 28. Maximum extent of Lake Alsek during the middle nineteenth century and earlier during the Neoglacial period (perhaps 2000-3000 years BP). The lake formed when Lowell Glacier advanced across Alsek River valley. Topographic contour interval = 2000 feet (610 m). (Modified from Fig. 3 of Clague and Rampton, 1982).

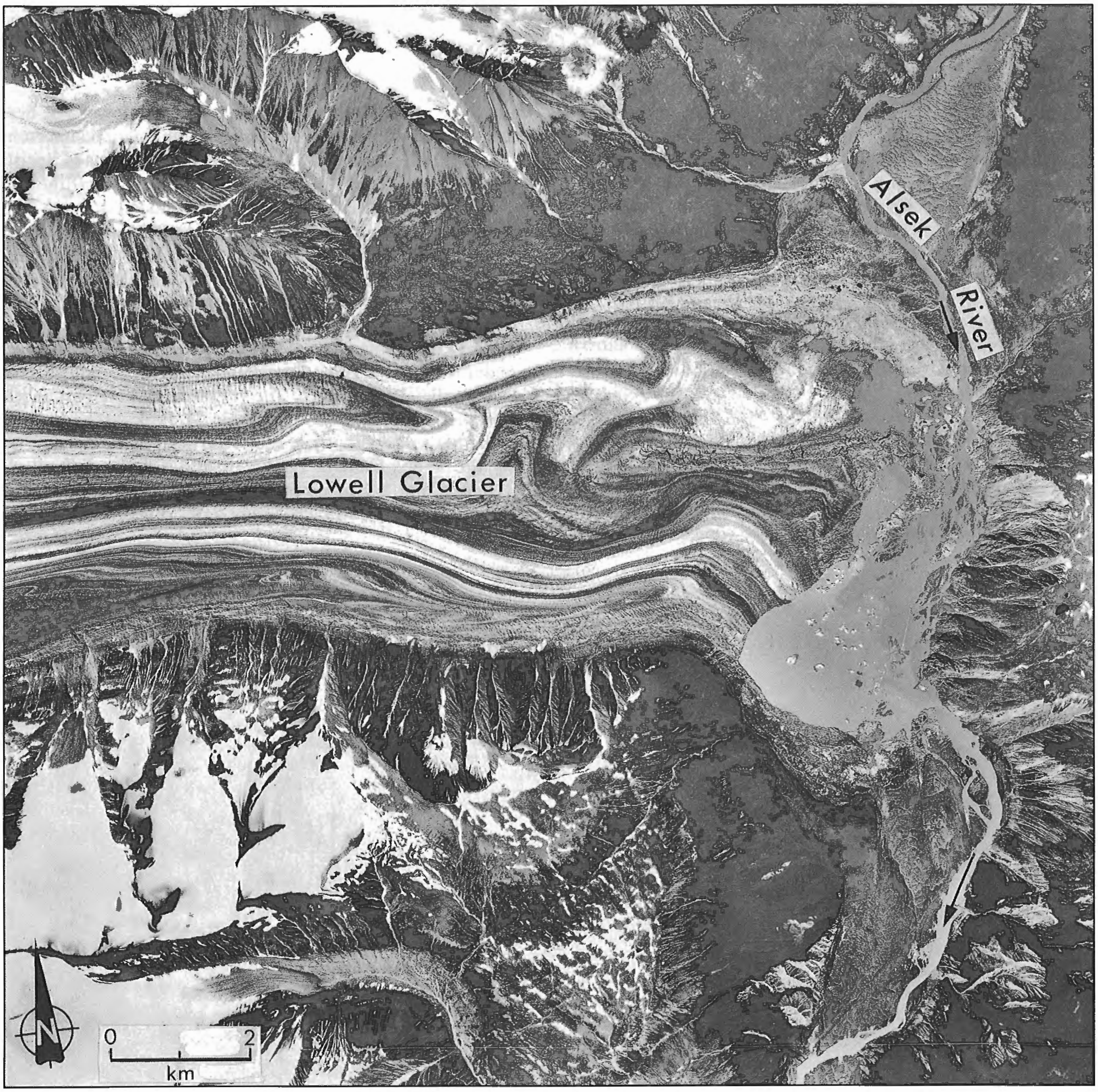


Figure 29. Aerial photograph of the lower part of Lowell Glacier and adjacent Alsek River valley, July 1976. Lake Alsek was impounded many times at this site when Lowell Glacier advanced across Alsek River valley. The lake extended north of the glacier snout (Fig. 28). (Canada Department of Energy, Mines and Resources airphoto A24515-148)

erosion. The exponential increase in discharge with time indicates a positive feedback loop in outflow from the lake: progressively larger discharges cause more heat production and melting of ice, leading to a larger tunnel, further increases in discharge, more heat, and so on until the water supply is exhausted.

Mathews and Clague (1993) summarized the record of jökulhlaups from Summit Lake and noted the tendency toward smaller floods and floods that occur earlier in the calendar year in recent years (Fig. 33). This suggests a progressive development with time of tunnels within or beneath Salmon Glacier and a corresponding thinning and weakening of the dam (Fisher, 1973). A critical threshold in the thinning of the glacier was reached in 1961 when the seasonal enlargement of a small tunnel exceeded the rate of closure due to flow and the overburden of the ice; this resulted in the first jökulhlaup.

Other examples of recent jökulhlaups that have been extensively studied are those from Ape Lake in the southern Coast Mountains of British Columbia (Jones et al., 1985; Desloges et al., 1989) (Fig. 34). The first historical outburst flood from this lake occurred in October 1984 when a subglacial tunnel opened in the snout of Fyles Glacier. Following tunnel closure, the lake refilled in 150 days, but it drained again in August 1986. High discharges during these floods (up to about 1600 m^3/s) damaged forestry roads, bridges, a logging camp, and an airstrip, and caused widespread channel and floodplain erosion. Retreat of Fyles Glacier after 1986 allowed drainage around the north edge of the ice dam and prevented the lake from refilling. No additional jökulhlaups are expected from this basin unless there is a significant readvance of Fyles Glacier. The presence of undamaged trees as old as 300 years on the floodplain below Fyles Glacier before the first flood indicates that the two recent outburst events are unique in the Little Ice Age history of the basin.

Some jökulhlaups have triggered debris flows. The best documented and most destructive are the jökulhlaups from Cathedral Glacier in the southern Rocky Mountains of British Columbia (Jackson, 1979; Jackson et al., 1989) (Fig. 35). These have resulted from the repeated sudden draining of a small ephemeral lake on the south side of Cathedral Glacier. Several times during this century, water from this lake, augmented perhaps by water stored within the glacier, emptied into a steep ravine and mobilized large volumes of glacial and colluvial sediments. This produced debris flows that travelled up to 3 km and blocked the Canadian Pacific Railroad (CPR) mainline and the Trans-Canada Highway in Kicking Horse River valley (Fig. 35, 36). The volumes of the largest debris flows are about 100 000 m^3 (Table 5). Peak discharges and velocities of the flows just above the head of the fan crossed by the Trans-Canada Highway and CPR mainline are 210 m^3/s and 5.5 m/s, respectively. Historical debris flow activity began in 1925 when retreat of Cathedral Glacier left

Figure 30. *Photostereogram of Alsek River valley immediately upstream of the terminus of Lowell Glacier, showing large gravel dunes formed by currents during the rapid draining of Lake Alsek (the dunes are also visible in Fig. 29). The maximum dune height is about 4 m. (Canada Department of Energy, Mines and Resources airphotos A23819-49, -51)*

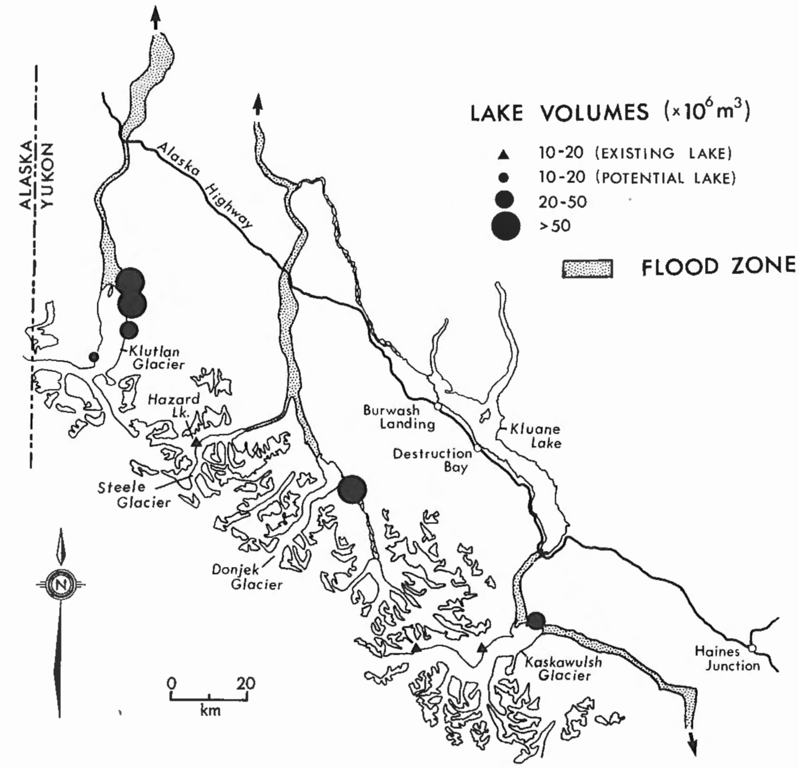


Figure 31.

Jökulhlaup zones and existing and potential glacier-dammed lakes larger than 10 x 10^6 m^3 in the White, Donjek, and Slims-Kaskawulsh basins, St. Elias Mountains, Yukon Territory. Potential lakes are basins in which water would be ponded in the event of a glacier advance. Basins near the termini of Klutlan and Kaskawulsh glaciers have not held water for several centuries and are unlikely to do so in the foreseeable future. (Fig. 9 of Clague, 1982).

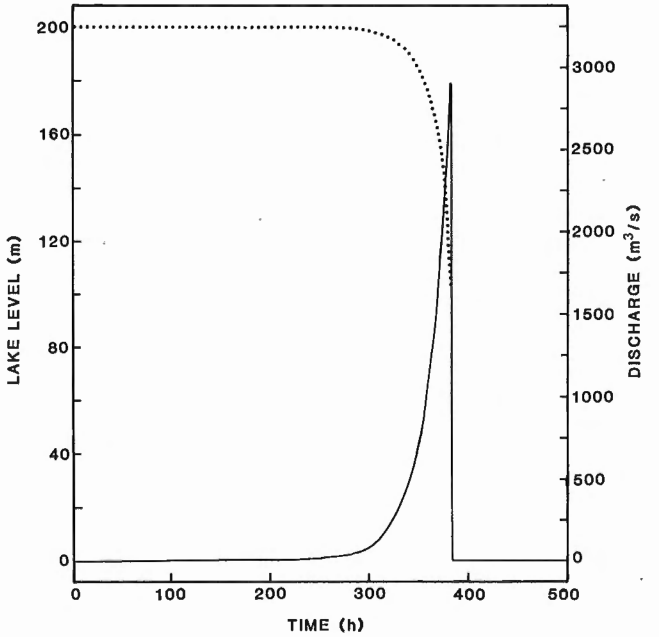


Figure 32. *Variations in lake level (dotted line) and discharge (solid line) for a jökulhlaup from Summit Lake (September 1967), illustrating the characteristics of a typical outburst, namely an exponential increase in discharge followed by an abrupt termination. (Fig. 4 of Mathews and Clague, 1993).*

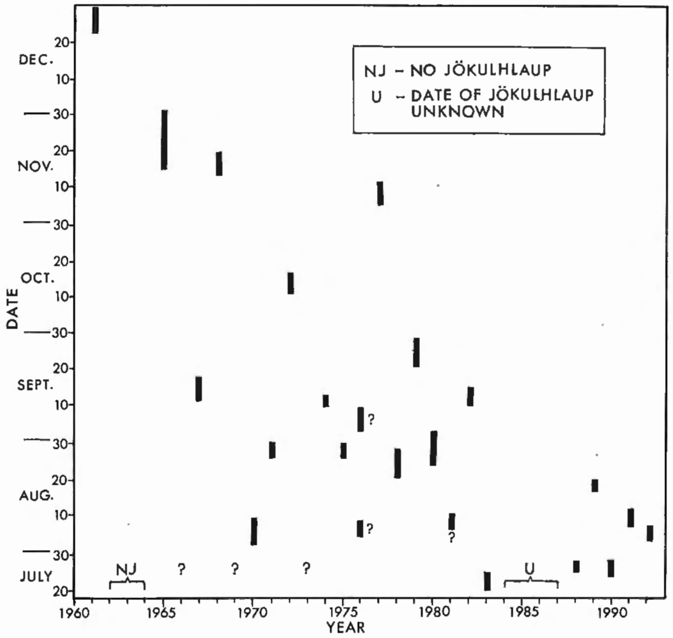


Figure 33. *Dates of Summit Lake jökulhlaups, 1961-1992. There has been a tendency for the floods to occur earlier in the year with time, probably related to progressive thinning and weakening of the glacier dam. Question marks indicate uncertain jökulhlaup dates (1976, 1981) and years of small or no jökulhlaups (Fig. 8 of Mathews and Clague, 1993).*

unstable accumulations of sediment supported by melting and collapsing stagnant ice. This probably was accompanied by changes in the morphology and internal hydrology of the glacier, which led to the periodic storage and catastrophic release of water. Debris flows increased in frequency from 1925 to 1985, when CPR began pumping water from Cathedral Glacier. Since then, no jökulhlaups or significant debris flows have occurred in this area.

COMPARISON OF FLOODS CAUSED BY DIFFERENT TYPES OF NATURAL DAM FAILURES

A dam failure is a complex phenomenon controlled primarily by the form and material properties of the dam and by the failure mechanism (Costa and Schuster, 1988).

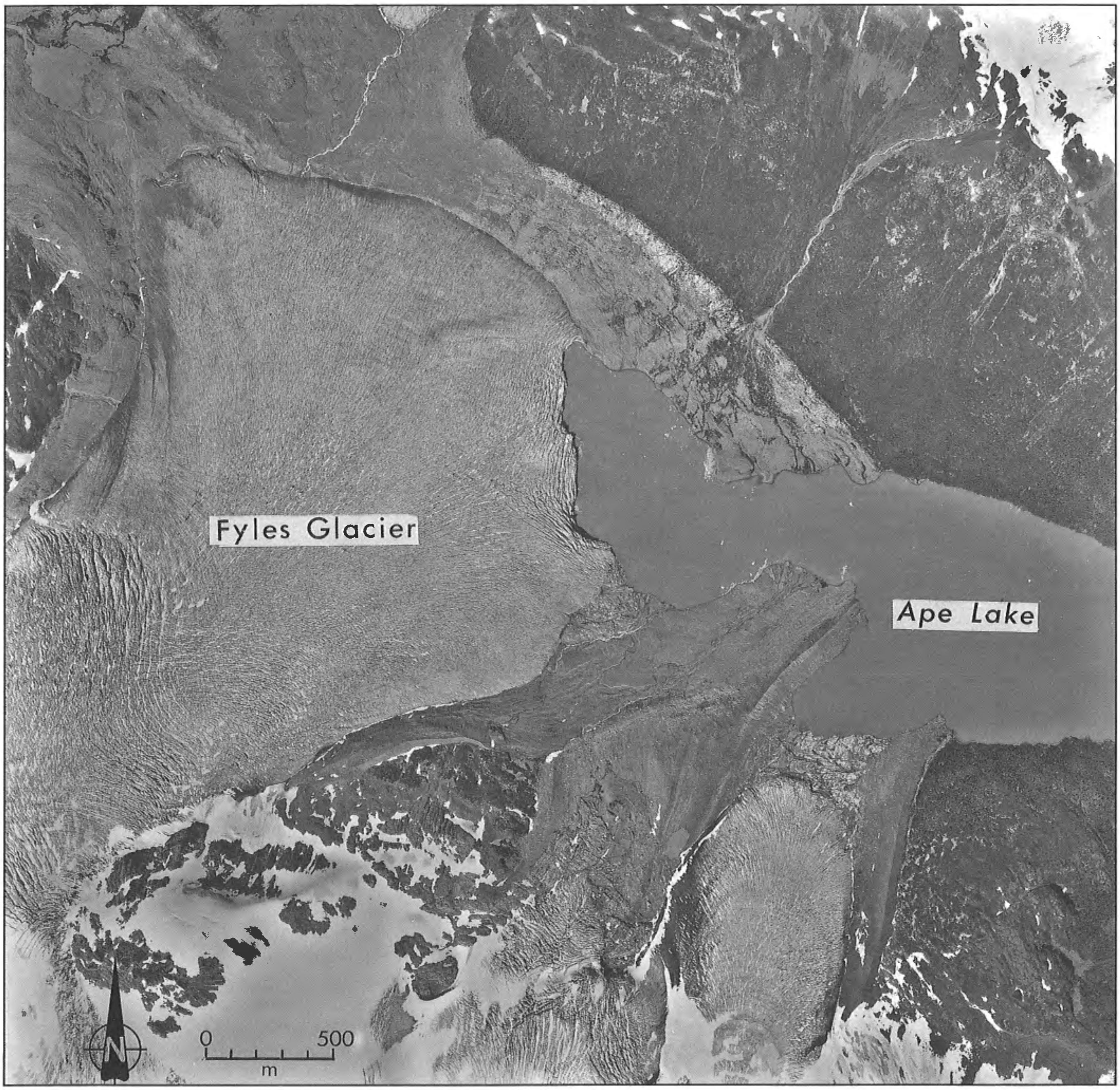
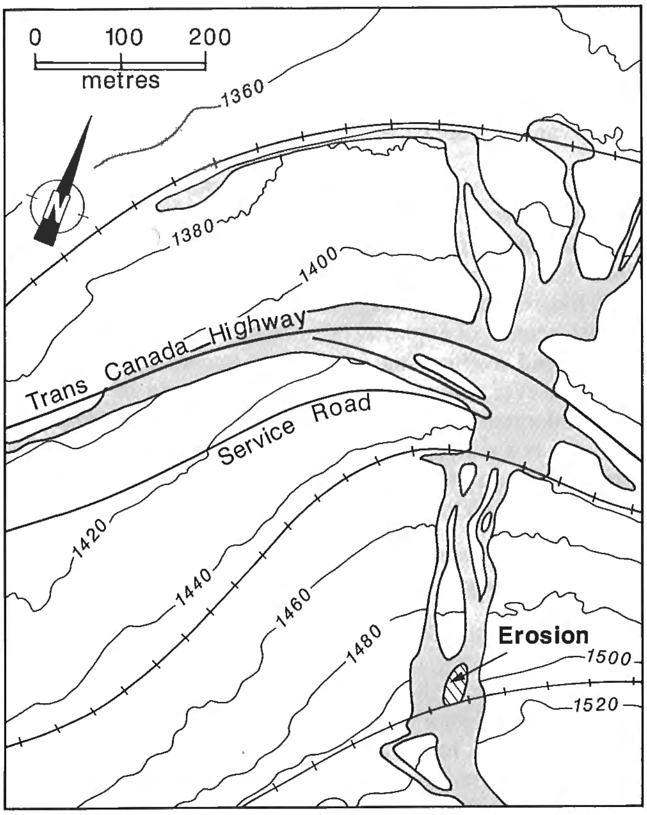


Figure 34. *Aerial photograph of Ape Lake taken in 1978 prior to the first jökulhlaup (October 1984). The conspicuous trimline beyond the snout of Fyles Glacier delineates the maximum Little Ice Age extent of the glacier. (Province of British Columbia airphoto BC78125-019).*



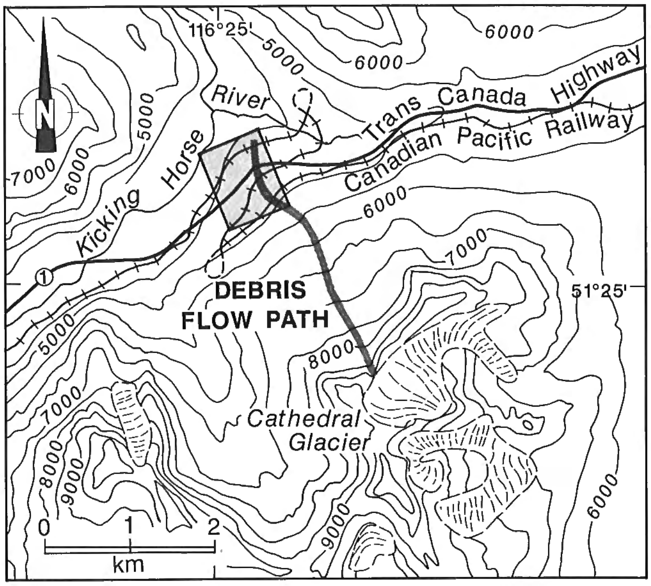


Figure 35. Extent of the debris flow in Kicking Horse River valley resulting from the Cathedral Glacier jökulhlaup of September 6, 1978. Topographic contour interval: left = 20 m; above = 500 feet (152 m). (Modified from Fig. 1 and 3 of Jackson et al., 1989).

Figure 36. Debris flow deposits covering the Trans-Canada Highway and the Canadian Pacific Railway mainline in Kicking Horse River valley, September 7, 1978. Note the derailed and partially buried locomotives. (Photo by Calgary Herald, courtesy of Glenbow Archives, Calgary, Alberta).

Moraine dams and many landslide dams consist of granular materials of low strength that are highly susceptible to erosion. Most moraine dams have relatively low width-to-height ratios, thus the lakes impounded by them drain very rapidly. Generally, however, an unusual event, such as an icefall, is required to initiate failure, and many moraine-dammed lakes have been stable since they first formed in the nineteenth and early twentieth centuries. In contrast, dams created by landslides in Quaternary sediments fail soon after they form (typically within hours or days). Width-to-depth ratios of such dams are relatively high, thus when they are overtopped, much more material is present for water to erode before a full breach is developed than is the case for moraine dams. Available data suggest, however, that this does not necessarily result in reduced peak flood discharges (Costa, 1985; Evans, 1986b; Costa and Schuster, 1988).

The form, material characteristics, and failure mechanisms of glacier dams are fundamentally different from those of moraine and landslide dams. Most glacier dams are much larger than the lakes they impound, and floodwaters must travel long distances through ice. Failure generally involves the enlargement of englacial or subglacial tunnels; wholesale collapse and overtopping failures are unusual (see Clague, 1987, however, for an example of the collapse of a glacier dam). Enlargement of ice tunnels by heat transfer and other processes is a slower process than overtopping and incision of sediment dams, thus glacier-dammed lakes generally drain more slowly than moraine- and landslide-dammed lakes.

Table 5. Historical debris flows, Cathedral Mountain, British Columbia

Date	Area covered (m^2)	Total volume (m^3)
August 5, 1925	40 000	80 000
August 16, 1946	50 000	90 000
July 1, 1962	12 000	24 000
September 6, 1978	77 000	136 000
August 18, 1982	5 000	7 000
August 27, 1984	5 000	5 000
August 29, 1984	52 000	87 000

[a] From Jackson et al. (1989, Table 1).

Flood discharges

The size of a flood caused by the failure of a natural dam is controlled by many factors, the most important being the volume of water in the reservoir, the height, width, internal structure, and texture of the dam, the mechanism of failure, and downstream topography and sediment availability. A variety of empirical equations have been proposed, based on documented outburst floods, to estimate peak discharges (Table 6). The most common variables in these equations are reservoir volume (V) and potential energy of the impounded lake water (PE). Potential energy can be calculated as the product of dam height, reservoir volume, and the specific weight of water.

Table 6. Selected published regression equations for peak discharges of floods from landslide-, moraine-, and glacier-dammed lakes and artificial reservoirs

Type of dam	Equation[a]	Coefficient of determination (r^2)	Source
Landslide	$Q = 0.0158PE^{0.41}$	0.81	Costa and Schuster, 1988
Moraine	$Q = 0.0013PE^{0.60}$	0.78	Costa and Schuster, 1988
Glacier	$Q = 0.0000055PE^{0.59}$	0.80	Costa and Schuster, 1988
	$Q = 75V^{0.67}$	0.96	Clague and Mathews, 1973
	$Q = 105.6V^{0.58}$	0.95	Desloges, 1984[b]
	$Q = 113V^{0.64}$	0.80	Costa, 1988
Earth- and rockfill	$Q = 0.0184PE^{0.42}$	0.75	Costa and Schuster, 1988
	$Q = 0.72V^{0.53}$	0.84	Evans, 1986b

[a] PE = potential energy of reservoir in joules; it is the product of dam height (m), reservoir volume (m^3), and specific weight of water (9800 newtons/m^3). V = reservoir storage (x 10^6 m^3, except in equation of Evans (1986b), where V is m^3). Q = peak discharge (m^3/s).

[b] Equation modified by Desloges et al. (1989) to correct for bias introduced by back transformation of logarithmic coefficients during regression of log-log relationship: $Q = 179V^{0.64}$.

Plots of Q (peak discharge) vs. V and Q vs. PE (Fig. 37) show considerable scatter, reflecting the diverse characteristics of dams and flood paths, as well as errors in estimating peak discharges. Direct measurements of flood discharge are virtually impossible, thus a variety of indirect methods commonly are used to estimate peak discharges, including drawdown rates and measurements based on hydraulic formulae or postflood 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 generally are too small because floods attenuate away from their source.

Notwithstanding these problems, the data in Figure 37 clearly show that there are differences in peak discharges for the three types of dam failures. For the same potential energy, glacier dams produce the smallest floods. Landslide dams produce smaller peak discharges than moraine dams, probably because they are relatively low and wide.

Jökulhlaup discharges have been estimated by applying a physical model first formulated by Nye (1976) and later elaborated by Spring (1979) and Clarke (1982). This model is based on hydraulic and heat transfer principles and assumes that escaping waters melt and thus enlarge the tunnel through which they flow. It requires as input a number of physical and geometric parameters, including the length of the drainage tunnel, the thickness of ice at the tunnel entrance, the distance of the lake surface above the tunnel outlet, lake volume, lake bathymetry, lake water temperature, and the Manning roughness coefficient in the tunnel. This model, at best, can give only approximate estimates of peak discharge because some of the input parameters (e.g. Manning coefficient) are poorly known and the morphology of the model outflow tunnel undoubtedly is too simple.

HAZARD ASSESSMENT AND MITIGATION

General considerations

Peak discharges of floods from landslide-, moraine-, and glacier-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. First-order estimates of peak discharges of outburst floods may be obtained from empirical relationships such as those shown in Figure 37 and Table 6. 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. 37).

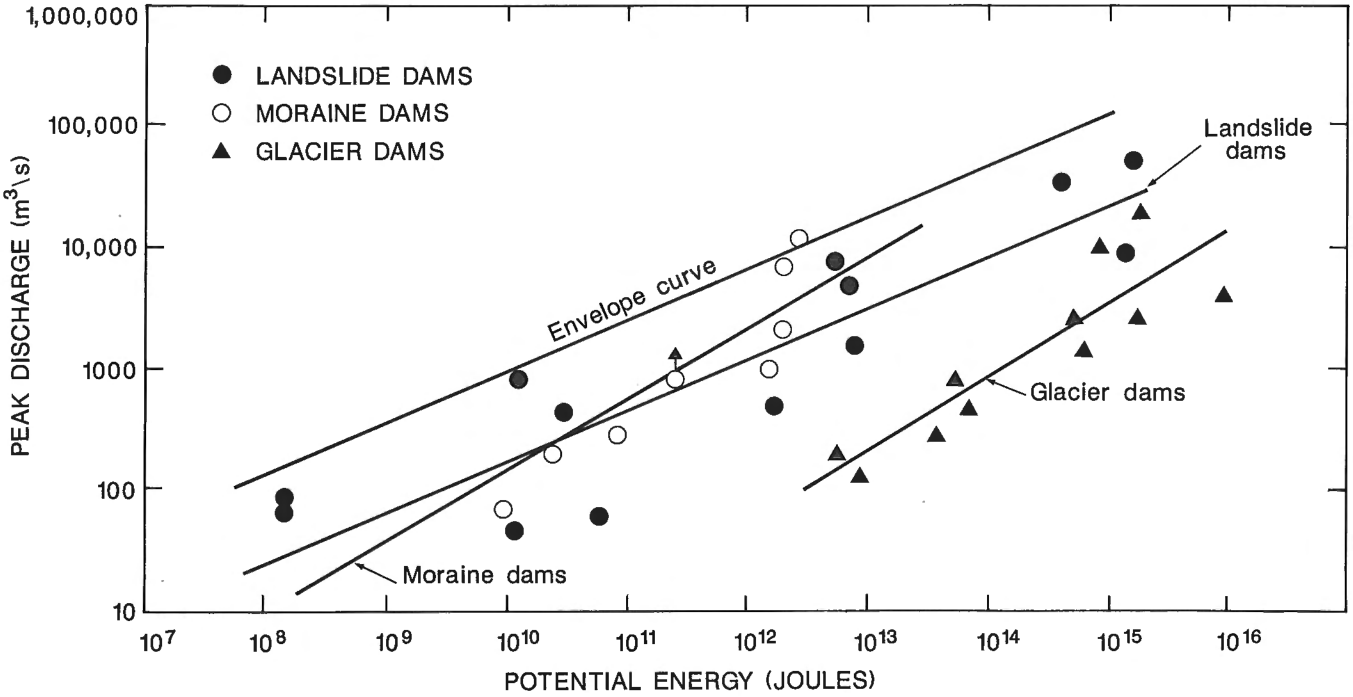


Figure 37. Plot of potential energy of lake water versus peak discharge for selected failures of landslide, moraine, and glacier dams. Least-squares regression lines for the three types of dams and the envelope curve encompassing all plotted data ($Q = 0.063\ PE^{0.42}$) are also shown. (Modified from Fig. 12 of Costa and Schuster, 1988).

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. Flood attenuation is greatest, and sediment entrainment least, where floods traverse low-gradient floodplains. In contrast, floods may travel considerable distances and attenuate slowly in steep narrow valleys. Sometimes, discharges may increase substantially due to the 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, during the jökulhlaups from Cathedral Glacier between 1925 and 1984 and also when Klattasine Lake drained in the early 1970s. Historical examples indicate that debris flows can only form and be sustained on slopes steeper than 10-15° (Fig. 38), and only if there is an abundant supply of sediment downvalley of the dam. Moraine and landslide dams themselves contain large volumes of sediment, but additional material generally must be picked up below the dam to form a full-fledged debris flow. Bulking of flood flows with sediment and plant debris has important consequences for the assessment of outburst flood hazards, but this phenomenon remains poorly understood.

Most historical floods from moraine- and glacier-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.

In contrast, large landslides may dam rivers in presently settled valleys. Some strategic transportation and communication corridors in the Canadian Cordillera, such as Fraser and Thompson valleys, are vulnerable to such damming. Upstream development may be inundated as the reservoir fills, and downstream development may be damaged or destroyed if the dam fails. Such large landslide-damming events, however, are far less common than small dam failures that occur in steep mountain watersheds during rainstorms. Floods from small landslide-dammed lakes, in fact, may pose a greater overall hazard to people and property in the Cordillera than larger, although far less frequent, outbursts from moraine- and glacier-dammed lakes.

Hazard assessment

An assessment of hazards associated with natural dams commonly begins with an airphoto search for potentially unstable lakes. At this stage in the investigation, all glacier and moraine dams should be considered potentially unstable, although subsequent field study may indicate that many are unlikely to fail. In contrast, most existing landslide dams in the Cordillera can be considered stable unless ground investigations indicate otherwise. The likelihood that a particular dam will fail can be assessed, at least qualitatively, by studying 1) the morphology and internal characteristics of the dam,

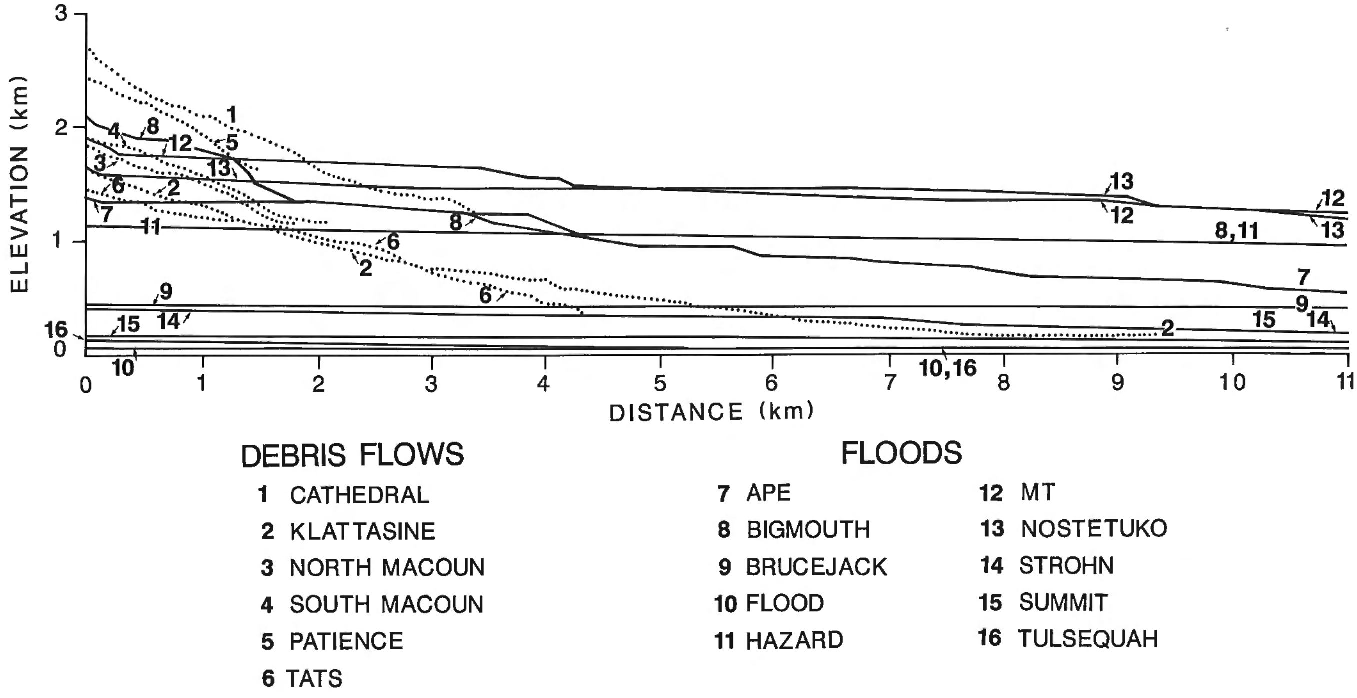


Figure 38. *Profiles of the paths of historical floods (solid lines) and debris flows (dotted lines) caused by failures of moraine and glacier dams in the Canadian Cordillera. Debris flows are only generated and sustained on slopes steeper than 10-15°.*

2) the size, character, and hydrology of the reservoir, and, in the case of moraine dams, 3) the proximity of the reservoir to slopes that are susceptible to rockfalls or icefalls.

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 low; 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 frequent rockfalls.

The stability of a glacier dam depends on the location of the lake relative to the glacier that dams it, the size of the lake, and the regimen, internal structure, and hydrology of the glacier. The recent history of the lake may be a good indicator of its future behaviour. Lakes that have drained catastrophically in the recent past are likely to do so in the future, at least until such time as the glacier recedes sufficiently that it no longer impounds water or until it advances and forms a stronger seal. On the other hand, a lake with no prior history of jökulhlaups may suddenly begin a cycle of outburst floods if the glacier that dams it thins and retreats past a critical threshold. Some glaciers may pass through this threshold in the near future as climate warms in response to rising concentrations of greenhouse gases in the atmosphere. This warming may also cause some presently unstable, glacier-dammed lakes to disappear, but it is likely that other new lakes will form and, in some cases, threaten downstream development.

Once the likelihood of dam failure is known, the downvalley effects of an outburst flood can be predicted. Peak flood discharges can be estimated using the empirical equations mentioned earlier. Discharge attenuation and bulking, however, must be taken into account when predicting the height of the flood wave at various points downstream from the dam. The possibility that the flood could transform into a debris flow must also be considered. These phenomena are largely dependent on the physical characteristics of the valley and on the availability of erodible sediment and trees along the flood path.

Although existing landslide-dammed lakes can be identified easily on airphotos, the sites of future landslide dams are virtually impossible to predict, with the exception of sites where mine wastes might fail. Detailed geotechnical, geomorphic, and other studies are required to determine the likelihood that specific slopes might fail, producing landslides capable of blocking streams and thus impounding lakes. Once such a dam forms, quick action is required to minimize possible flood damage. This is because the reservoir generally fills rapidly and then empties due to overflow and incision of the dam.

Hazard mitigation

Remedial and control measures have been applied to three natural dams in the Canadian Cordillera. Since 1985, water has been pumped from the lake on Cathedral Glacier in the Rocky Mountains to prevent jökulhlaups and debris flows (Jackson et al., 1989). Rock-lined channels with weirs have been constructed across the Clinton Creek and Wolverine Creek landslide dams in Yukon Territory to control erosion and prevent flooding (Stepanek and McAlpine, 1992).

In other parts of the world, more extensive efforts have been made to prevent, or minimize the effects of, destructive outburst floods (Lliboutry et al., 1977; Yesenov and Degovets, 1979; Eisbacher, 1982; Eisbacher and Clague, 1984). Remedial and control measures that have been applied to moraine-dammed lakes include excavation of tunnels to lower or empty reservoirs, construction of paved revetments and low earthen dams to stabilize outlets and increase freeboard, and construction of downvalley retention basins to trap floodwater and debris. The only effective measure that can be taken to prevent jökulhlaups or reduce their size is to lower or drain the lake. This can be done, for example, by constructing a tunnel through the glacier dam or a channel at its margin. In the case of newly formed landslide dams, it may be necessary to construct an armoured overflow or bypass channel and to evacuate people below and above the obstruction.

REFERENCES

Blachut, S.P. and Ballantyne, C.K.
1976: Ice-dammed lakes – A critical review of their nature and behaviour; McMaster University, Department of Geography, Discussion Paper 6, 90 p.

British Columbia Hydro and Power Authority
1983: Homathko development; memorandum on glacial lakes and debris flows; B.C. Hydro and Power Authority, Hydroelectric Generation Projects Division, Report Geo 18/83, 22 p.

Blown, I. and Church, M.
1985: Catastrophic lake drainage within the Homathko River basin, British Columbia; Canadian Geotechnical Journal, v. 22, p. 551-563.

Brooks, G.R. and Hickin, E.J.
1991: Debris avalanche impoundments of Squamish River, Mount Cayley area, southwestern British Columbia; Canadian Journal of Earth Sciences, v. 28, p. 1375-1385.

Carter, N.M.
1932: Exploration in the Lillooet River watershed; Canadian Alpine Journal, v. 21, p. 8-18.

Clague, J.J.
1982: The role of geomorphology in the identification and evaluation of natural hazards; in Applied Geomorphology ("Binghamton" Symposia in Geomorphology: International Series, no. 11), (ed.) R.G. Craig and J.L. Craft; George Allen & Unwin, London, p. 17-43.
1987: Catastrophic outburst floods; GEOS, v. 16, no. 2, p. 18-21.

Clague, J.J. and Evans, S.G.
1992: A self-arresting moraine dam failure, St. Elias Mountains, British Columbia; in Current Research, Part A; Geological Survey of Canada, Paper 92-1A, p. 185-188.

Clague, J.J. and Mathews, W.H.
1973: The magnitude of jökulhlaups; Journal of Glaciology, v. 12, p. 501-504.
1992: The sedimentary record and Neoglacial history of Tide Lake, northwestern British Columbia; Canadian Journal of Earth Sciences, v. 29, p. 2383-2396.

Clague, J.J. and Rampton, V.N.
1982: Neoglacial Lake Alsek; Canadian Journal of Earth Sciences, v. 22, p. 1492-1502.

Clague, J.J. and Shilts, W.W.
1993: Two landslide-dammed lakes in the Cascade Mountains, southwestern British Columbia; in Current Research, Part E; Geological Survey of Canada, Paper 93-1E, p. 47-54.

Clague, J.J., Evans, S.G., and Blown, I.G.

1985: A debris flow triggered by the breaching of a moraine-dammed lake, Klattasine Creek, British Columbia; Canadian Journal of Earth Sciences, v. 22, p. 1492-1502.

Clarke, G.K.C.

1982: Glacier outburst floods from "Hazard Lake", Yukon Territory, and the problem of flood magnitude prediction; Journal of Glaciology, v. 28, p. 3-21.

1989: Paleohydraulic modelling of outburst floods from Neoglacial Lake Alsek, Yukon Territory, Canada [abstract]; Annals of Glaciology, v. 13, p. 295.

Clarke, G.K.C. and Mathews, W.H.

1981: Estimates of the magnitude of glacier outburst floods from Lake Donjek, Yukon Territory, Canada; Canadian Journal of Earth Sciences, v. 18, p. 1452-1463.

Clarke, G.K.C. and Waldron, D.A.

1984: Simulation of the August 1979 sudden discharge of glacier-dammed Flood Lake, British Columbia; Canadian Journal of Earth Sciences, v. 21, p. 502-504.

Clarke, G.K.C., Mathews, W.H., and Pack, R.T.

1984: Outburst floods from glacial Lake Missoula; Quaternary Research, v. 22, p. 289-299.

Costa, J.E.

1985: Floods from dam failures; U.S. Geological Survey, Open-File Report 85-0560, 54 p.

1988: Floods from dam failures; in Flood Geomorphology, (ed.) V.R. Baker and P.C. Patton; John Wiley and Sons, New York, p. 439-463.

Costa, J.E. and Schuster, R.L.

1988: The formation and failure of natural dams; Geological Society of America Bulletin, v. 100, p. 1054-1068.

Davis, W.M.

1882: On the classification of lake basins; Boston Society of Natural History, Proceedings, v. 21, p. 315-381.

Desloges, J.R.

1984: Ape Lake excursion, October 26-31, 1984; University of British Columbia, Department of Geography and Department of Geophysics and Astronomy, unpublished report, 10 p.

Desloges, J.R., Jones, D.P., and Ricker, K.E.

1989: Estimates of peak discharge from the drainage of ice-dammed Ape Lake, British Columbia, Canada; Journal of Glaciology, v. 35, p. 349-354.

Drysdale, C.W.

1914: Geology of the Thompson River valley below Kamloops Lake, B.C.; Geological Survey of Canada, Summary Report 1912, p. 115-150.

Eisbacher, G.H.

1982: Mountain torrents and debris flows; Episodes, v. 1982, no. 4, p. 12-17.

1983: Slope stability and mountain torrents, Fraser Lowlands and southern Coast Mountains, British Columbia; Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union, 1983 Joint Annual Meeting, Victoria, B.C., Field Trip Guidebook, No. 15, 46 p.

Eisbacher, G.H. and Clague, J.J.

1984: Destructive mass movements in high mountains: hazard and management; Geological Survey of Canada, Paper 84-16, 230 p.

Evans, S.G.

1984: The 1880 landslide dam on Thompson River, near Ashcroft, British Columbia; in Current Research, Part A; Geological Survey of Canada, Paper 84-1A, p. 655-658.

1986a: Landslide damming in the Cordillera of western Canada; in Landslide Dams: Processes, Risk and Mitigation, (ed.) R.L. Schuster; American Society of Civil Engineers, Geotechnical Special Publication 3, p. 111-130.

1986b: The maximum discharge of outburst floods caused by the breaching of man-made and natural dams; Canadian Geotechnical Journal, v. 23, p. 385-387.

1987: The breaching of moraine-dammed lakes in the southern Canadian Cordillera; International Symposium on Engineering Geological Environment in Mountainous Areas, Beijing, Proceedings, v. 2, p. 141-150.

Evans, S.G. (cont.)

1992: Landslides and river damming events associated with the Plinth Peak volcanic eruption, southwestern British Columbia; in Geotechnique and Natural Hazards; BiTech Publishers, Vancouver, B.C., p. 405-412.

Evans, S.G. and Brooks, G.R.

1991: Prehistoric debris avalanches from Mount Cayley volcano, British Columbia; Canadian Journal of Earth Sciences, v. 28, p. 1365-1374.

Fisher, D.

1973: Subglacial leakage of Summit Lake, British Columbia, by dye determinations; in Symposium on the Hydrology of Glaciers, (ed.) J.W. Glen, R.J. Adie, and D.M. Johnson; International Association of Scientific Hydrology, Publication 95, p. 111-116.

Gilbert, R.

1969: Some aspects of the hydrology of ice-dammed lakes: observations on Summit Lake, British Columbia; M.A. thesis, University of British Columbia, Vancouver, B.C., 93 p.

1971: Observations on ice-dammed Summit Lake, British Columbia, Canada; Journal of Glaciology, v. 10, p. 351-356.

1972: Drainings of ice-dammed Summit Lake, British Columbia; Environment Canada, Inland Waters Directorate, Water Resources Branch, Scientific Series, no. 20, 17 p.

Hutchinson, G.E.

1957: A Treatise on Limnology, Volume 1; John Wiley and Sons, New York, 1015 p.

Jackson, L.E., Jr.

1979: A catastrophic glacial outburst flood (jökulhlaup) mechanism for debris flow generation at the Spiral Tunnels, Kicking Horse River basin, British Columbia; Canadian Geotechnical Journal, v. 16, p. 806-813.

Jackson, L.E., Church, M., Clague, J.J., and Eisbacher, G.H.

1985: Slope hazards in the southern Coast Mountains of British Columbia, Field Trip 4; in Field Guides to Geology and Mineral Deposits in the Southern Canadian Cordillera, (ed.) D.J. Tempelman-Kluit; Geological Society of America, Cordilleran Section, 1985 Annual Meeting, Vancouver, B.C., Field Trip Guidebook, p. 4-1 – 4-34.

Jackson, L.E., Jr., Hungr, O., Gardner, J.S., and Mackay, C.

1989: Cathedral Mountain debris flows, Canada; Bulletin of the International Association of Engineering Geology, no. 40, p. 35-54.

Jones, D.P., Ricker, K.E., Desloges, J.R., and Maxwell, M.

1985: Glacier outburst flood on the Noeick River: the draining of Ape Lake, British Columbia, October 20, 1984; Geological Survey of Canada, Open File 1139, 81 p.

Jones, W.C.

1959: Cheekye River mudflows; British Columbia Department of Mines, Victoria, B.C., unpublished report, 11 p.

Lliboutry, L., Morales Arno, B., Pautre, A., and Schneider, B.

1977: Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historic failures of morainic dams, their causes and prevention; Journal of Glaciology, v. 18, p. 239-254.

Marcus, M.G.

1960: Periodic drainage of glacier-dammed Tulsequah Lake, British Columbia; Geographical Review, v. 50, p. 89-106.

Mathews, W.H.

1959: Vertical distribution of velocity in Salmon Glacier, British Columbia; Journal of Glaciology, v. 3, p. 448-454.

1964: Water pressure under a glacier; Journal of Glaciology, v. 5, p. 235-240.

1965: Two self-dumping ice-dammed lakes in British Columbia; Geographical Review, v. 55, p. 46-52.

1973: Record of two jökullhlaups (*sic*); in Symposium on the Hydrology of Glaciers, (ed.) J.W. Glen, R.J. Adie, and D.M. Johnson; International Association of Scientific Hydrology, Publication 95, p. 99-110.

Mathews, W.H. and Clague, J.J.

1993: The record of jökulhlaups from Summit Lake, northwestern British Columbia; Canadian Journal of Earth Sciences, v. 30, p. 499-508.

Matthes, F.E.
1939: Report of Committee on Glaciers; American Geophysical Union Transactions, v. 20, p. 518-523.
Mokievsky-Zubok, O.
1977: Glacier-caused slide near Pylon Peak, British Columbia; Canadian Journal of Earth Sciences, v. 14, p. 2657-2662.
Nye, J.F.
1976: Water flow in glaciers: jökulhlaups, tunnels, and veins; Journal of Glaciology, v. 17, p. 181-207.
Post, A. and Mayo, L.R.
1971: Glacier dammed lakes and outburst floods in Alaska; U.S. Geological Survey, Hydrologic Investigations Atlas HA-455, 10 p., 1:1 000 000 scale map.
Ryder, J.M.
1991: Geomorphological processes associated with an ice-marginal lake at Bridge Glacier, British Columbia; Géographie physique et Quaternaire, v. 45, p. 35-44.
Ryder, J.M. and Clague, J.J.
1989: British Columbia (Quaternary stratigraphy and history); in Chapter 1 of Quaternary Geology of Canada and Greenland, (ed.) R.J. Fulton; Geological Survey of Canada, Geology of Canada, no. 1, p. 43-58 (also Geological Society of America, The Geology of North America, v. K-1).
Ryder, J.M., Bovis, M.J., and Church, M.
1990: Rock avalanches at Texas Creek, British Columbia; Canadian Journal of Earth Sciences, v. 27, p. 1316-1329.
Schmok, J.P. and Clarke, G.K.C.
1989: Lacustrine sedimentary record of ice-dammed Neoglacial Lake Alsek; Canadian Journal of Earth Sciences, v. 26, p. 2092-2105.
Smith, H.R. and Patton, F.D.
1984: Comparison of the Devastation Glacier slide with other high velocity debris flows [abstract]; 4th International Symposium on Landslides, Toronto, Abstracts Volume, p. 96.
Spring, U.
1979: Wasserabfluss durch intraglaziale Kanäle; Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der Eidengenössischen Technischen Hochschule (Zürich), no. 37, p. 127-143.
Stanton, R.B.
1898: The great land-slides on the Canadian Pacific Railway in British Columbia [includes Discussion]; Institution of Civil Engineers, Proceedings, v. 132, pt. 2, p. 1-148.
Stepanek, M. and McAlpine, H.F.
1992: Landslide dams at Clinton Creek; in Geotechnique and Natural Hazards; BiTech Publishers, Vancouver, B.C., p. 291-298.
Thorarinsson, S.
1939: The ice-dammed lakes of Iceland with particular reference to their value as indicators of glacial oscillations; Geografiska Annaler, v. 21, p. 216-242.
1953: Some new aspects of the Grimsvötn problem; Journal of Glaciology, v. 2, p. 267-274.
Yesenov, U.Y. and Degovets, A.S.
1979: Catastrophic mudflow on the Bol'shaya Almatinka River in 1977; Soviet Hydrology: Selected Papers, v. 18, p. 158-160.