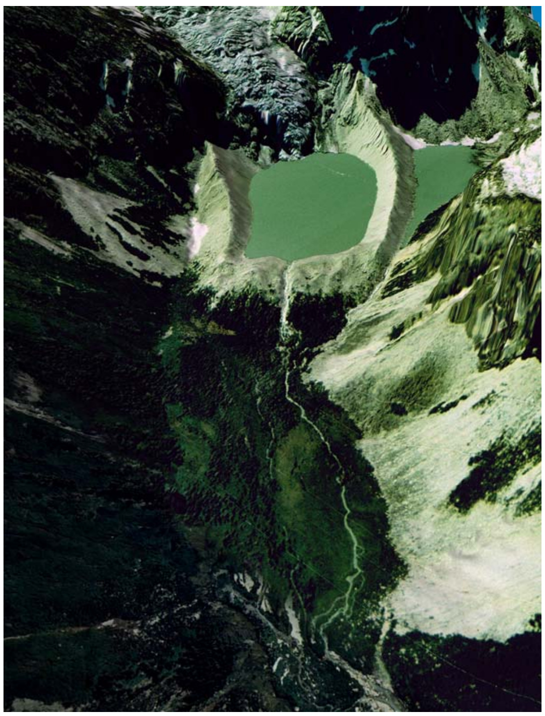
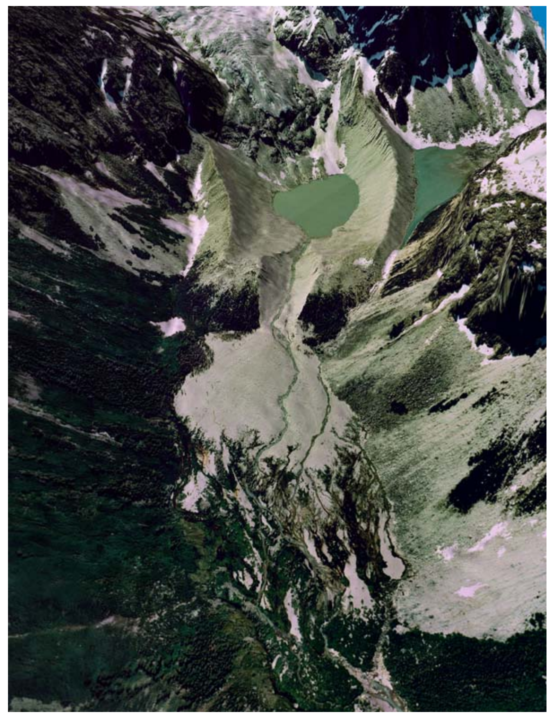
CLIMATE CHANGE AND GEOMORPHOLOGICAL HAZARDS IN THE CANADIAN CORDILLERA; THE ANATOMY OF IMPACTS AND SOME TOOLS FOR ADAPTATION

Scientific Report 1999-2001 – Summary of Activities and Results

Climate Change Action Fund Project A099

S.G. Evans (Project Leader)





Cover illustration : virtual views created by draping digital orthophoto over a digital elevation model of moraine-dammed lake Nostetuko Lake, Coast Mountains, British Columbia. Left image is pre-outburst using an 1981 orthophoto and right image is post-outburst using a 1994 orthophoto. The outburst took place in July, 1983 when about 6.5 M cubic metres of water escaped through a breach in the moraine dam. Breaching was initiated by a wave train generated by a glacier avalanche from the toe of Cumberland Glacier. The terminal moraine probably dates from the mid-nineteenth century and Nostetuko Lake formed behind the moraine-dam during subsequent twentieth century retreat of

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1. THE PROBLEM: HAZARDS AND CLIMATE CHANGE

Background

In the wake of recent natural disasters (e.g. Hurricane Mitch, the Saguenay Flood) it has been commonly supposed (e.g., *The Economist, April 13, 1999*) that there has been an increase in frequency of catastrophic events and their severity, and that this is directly due to climate change. Indeed, in its annual (1999) study of natural catastrophes, *The Munich Re-Insurance Company* goes as far as to say that "there are more and more indications of a climate-related accumulation of extreme weather events."

Imprinted on a possible climate-driven increase in extreme events is an increase in vulnerability linked to societal factors, such as population growth and wealth distribution, which partly accounts for the massive recent increase in insurable losses world-wide (van der Vink et al., 1998).

These converging trends point to the need to develop a more resilient society through adaptive measures. Nowhere is the need greater than in mountainous terrain where catastrophic geomorphic processes (landslides, river floods, and glacier outburst floods;) are heavily influenced by climatic factors such as precipitation and temperature, and are thus sensitive to climate change (Watson et al., 1996; Evans and Clague, 1993, 1994, 1997).

Climate-related geomorphological hazards in the Canadian Cordillera

The Cordillera of western Canada is susceptible to a wide range of climate-related geomorphological hazards including landslides, river floods, and glacier-related outburst floods (Evans and Clague, 1994, 1997). These hazards have caused significant loss of life (Evans, 1997) and property damage in the historical period (Septer and Schwab, 1995), which, for the purposes of this study, is taken to be 1850 to the present. This period corresponds broadly to the period of dramatic climate change currently under intense public and scientific discussion. Catastrophic geomorphic processes have also impacted on the economic infrastructure of the region (transportation, energy, and forestry), resulted in a loss of productive forest lands, and have adversely affected the quality of water supplies. They have also impacted on the Pacific Salmon Fishery and on the viability of recreation and tourism developments. The region is experiencing sustained economic growth and an increase in population that is rapidly extending the settled areas of the Cordillera.

In assessing the impact of climate-driven catastrophic processes and developing tools for adapting to their possible increased occurrence, a number of key gaps are evident in our knowledge as follows;

- a lack of precise data on whether the frequency and severity of hazard events has increased in the historical period
- a lack of rigorous research on whether this possible increase is climate driven
- a lack of precise data on the nature of the climate – hazardous processes linkage, both with respect to precipitation and temperature

- a lack of precise data on the extent to which vulnerability has increased

There has been only very limited consideration given to the development of adaptive tools that allow the impact of these processes to be mitigated.

In the research summarized below we attempted to fill some of these gaps.

Objectives of project

Work in the project was carried out in general accordance with our proposal dated May 1999. In the proposal three major tasks were identified viz.

Task 1: Historical documentation of impacts – the anatomy of impacts 1
Task 2: Analysis of site and regional events; the anatomy of impacts 2
Task 3: Simulation of rapid landslides: a tool for adaptation

As the work developed minor changes were made in the conduct of the project to take into account the occurrence of 6 major climate-driven events, which took place in the Canadian Cordillera in 1999. This led to a re-alignment of focus of Task 2 exclusively toward rainfall-triggered events and the prioritizing of data capture from the 1999 events.

The conduct of the work also had to be modified because of unavailability of two team members due to illness and leave of absence.

2. PROJECT TEAM

The Project team was a collaboration of the Geological Survey of Canada, University of British Columbia, Simon Fraser University, British Columbia Ministry of Forests, and Septer Consulting of Whaletown, British Columbia. The team is led by Dr. S. G. Evans, an expert on landslides and glacier-related hazards at the Geological Survey of Canada and consists of Professor J.J. Clague, Quaternary Geologist and Natural Hazard Specialist, Earth Sciences, Simon Fraser University, Burnaby, B.C.; Dr. O. Hungr, an expert in the analysis of landslides in the Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, B.C.; Mr. M. Geertsema, Forest Geomorphologist, British Columbia Ministry of Forests, Prince George, B.C.; and Mr. D. Septer, Geomorphologist, Septer Consulting, Whaletown, British Columbia.

Two graduate students were initially involved in the project and carried out work towards their post-graduate degrees. These students were Jane Kershaw (M.Sc. student, Simon Fraser University) working under the supervision of Dr. J. Clague, and Dana Ayotte (Ph.D. student, University of British Columbia) who worked under Dr. O. Hungr (University of British Columbia). Ms. Ayotte left her studies after the Summer of 2000.

3. TASK 1 – HISTORICAL DOCUMENTATION OF IMPACTS – THE ANATOMY OF IMPACTS 1

<u>Sub-task 1A : Rainfall and floods in southern British Columbia</u>

Activities 1999-2000 : Part 1 of this sub-task was completed by D.Septer. A comprehensive report covering the period 1808 –1950 was submitted in March 2000. *Activities 2000-2001*: Part 2 of this sub-task was completed by D.Septer. A comprehensive report covering the period 1950 – 1995 was submitted in September 2000.

An additional activity was undertaken at GeoCanada 2000 when climate-induced landslide/geotechnical disasters at the Britannia Mine site were discussed in a paper given in a symposium on natural hazards at the millennium national geoscience meeting in Calgary (Evans, 2000). The now-abandoned Britannia mine site is located on Howe Sound, north of Vancouver in southwest British Columbia.

Results; Work in this sub-task was completed by the submission of an extensive 2-volume report by Septer Consulting, Whaletown, British Columbia (Septer, 2000 a,b). The work centred on archival research and the analysis of hydroclimatic data and produced an extensive historical event list for all climate-related hazard events in the southern Cordillera.

Analysis of this massive dataset is not yet complete but initial analysis shows no obvious trend toward more intense and more frequent heavy rains. Indeed, a leader in the newspaper *British Columbian*, June 21, 1873 declared "Is our climate changing? Never before, within the memory of the oldest resident, has there been so much rain in June. Indeed, a fall of rain after the middle of May has been the exception rather than the rule."

An analysis of the Britannia Mine landslide/geotechnical disasters in 1915 and 1921, which led to the death of a total of 93 people, showed that the first disaster was triggered by a dramatic warming spell which initiated the melting of a heavy snow cover and the second was caused by the 24 hour rainfall of record.

<u>Sub-task 1B : Geomorphic hazards conditioned by twentieth century glacier retreat in the Coast and St. Elias Mountains</u>

Activities 1999-2000: A contract was let to J. Peets who produced a glacier retreat map for parts of the southwest Coast Mountains in the region of the Upper Lillooet River basin. Work on a similar topic in the St. Elias Mountains was not completed for technical reasons.

Research on moraine-dammed lakes in the upper Nostetuko (see cover illustration) with a focus on the Queen Bess Lake moraine-dammed lake outburst continued. Large-scale maps made. Most work was undertaken by J. Kershaw (Simon Fraser University) for her M.Sc. thesis due to be completed in 2002.

Research continued on rock avalanches from recently debutressed rock slopes adjacent to glaciers. A paper on rock avalanches onto glaciers in British Columbia was given at the 1999 Vancouver Geotechnical Society Annual Conference (Evans and Clague, 1999). Aerial photographs were procured for Kendall Glacier rock avalanche. Maps procured. Scanning and digital capture of Tim Williams Rock avalanche.

Activities 2000-2001: Research on the Queen Bess Lake outburst continued. Extensive field investigations were undertaken by J.Clague and J. Kershaw (Simon Fraser University) at Queen Bess Lake and downstream sites. The work is part of Kershaw's M.Sc. thesis due to be completed in 2002. Research continued on rock avalanches from recently debutressed rock slopes adjacent to glaciers particularly with respect to the analysis of digital elevation models. Field work was also undertaken at the 1999 Kendall Glacier rock avalanche. Paper on moraine-dammed lake failures submitted and accepted by *Quaternary Science Reviews* (Clague and Evans, 2000). Aerial photography procured for Telkwa Pass-Fubar Glacier rock avalanche.

Nice Symposium, 2001. At the XXVI General Assembly of the European Geophysical Society held in Nice, France, March 2001, the project leader (S.G. Evans) convened an international symposium on *Moraine-dammed lakes: outburst events, risk assessment and mitigation strategies*. In the symposium two papers arising from the project were given (Evans and Clague, 2001) and Kershaw et al. (2001). The symposium also included papers dealing with case histories in Nepal, Bhutan, and the Andes.

Results

1. **Upper Lillooet River Glacier Ice Loss** – the analysis of successive aerial photographs dating from 1951 to 1994 show a consistent and synchronous glacier retreat from Little Ice Age limits that are visible on the aerial photographs. The synchronous retreat was mapped for about 30 glaciers in a region covering 1330 km^2 in the Upper Lillooet River basin, Coast Mountains, southwest British Columbia. This represents a regional ice loss for the period since the Little Ice Age maximum (taken to be about 1850) and during the period 1951-1994. During this process mountain rock slopes were debutressed, distal lakes formed, and braided reaches of major streams developed.

2. **Moraine-dammed lakes in the upper Nostetuko River, Coast Mountains, British Columbia**: poster at GSA Our results are summarized as follows;

Outburst in the upper Nostetuko : Two moraine-dammed lake outbursts of similar magnitude have recently occurred in the glacierised upper reaches of the Nostetuko River watershed in the southern Coast Mountains of British Columbia. Using digital elevation models of the lakes, based on aerial photography flown before and after the outbursts, and extensive field investigations at the sites, we have documented both events in some detail. The first outburst took place at Nostetuko Lake (el. 1632 m a.s.l.) in July 1983, when an avalanche of ice from Cumberland Glacier generated a wave train that overtopped the bulky Little Ice Age moraine dam, releasing 6.5 M m^3 of water. Approximately 1.5 M m^3 of material were eroded from the moraine dam during the breach. The second outburst took place at Queen Bess Lake (el. 1700 m a.s.l.) in August 1997, when a large ice avalanche from Diadem Glacier entered the lake and generated a massive displacement wave that swept over the crest of the moraine dam. The wave triggered a breach of the dam, releasing 6.5 M m^3 of water. In contrast to the Nostetuko event, only 280,000 m^3 of material was eroded from the Queen Bess breach, the depth of which was limited by the presence of a bedrock sill that now impounds the remaining volume of water (ca. 12 M m^3) in Queen Bess Lake. Both moraine dams consist of poorly sorted, bouldery deposits derived from granitic bedrock and were breached after warmer-than-average spells of summer weather. Both outburst floods devastated the valleys downstream from the moraine dams and were recorded at a gauging station located at sea level more than 100 km from the lakes. Glaciers in the upper Nostetuko River basin have undergone dramatic retreat since they reached their Little Ice Age maximum in the middle to late 1800s. Retreat from these limits, which increased dramatically after 1948, the date of the earliest aerial photography of the sites, has not only formed the lakes but also created conditions for their subsequent catastrophic draining.

The 1997 Queen Bess outburst ; On August 12, 1997, moraine-dammed Queen Bess Lake, located in the southern Coast Mountains of British Columbia, partially drained after an ice avalanche from Diadem glacier cascaded into the lake. Sedimentological and morphological evidence downvalley of the moraine dam indicate that the flood consisted of two distinct phases, an initial displacement wave and subsequent breach of the dam. A Water Survey of Canada stream gauge recorded the flood at the mouth of Homathko River, 115 km downstream of Queen Bess Lake. The hydrograph shows only one flood peak, indicating that the interval between the two phases must have been relatively short, minutes rather than hours. The displacement wave overtopped the broad Little Ice Age end moraine and flowed 25 m up the opposite valley wall. Trees were toppled in the direction of flow and other vegetation was removed by the floodwaters. The flow at this time was highly turbulent and deposited small boulders, cobbles, and finer gravel in the upper reaches of the valley before it markedly attenuated. The overtopping displacement wave(s) incised the outlet channel, initiating the second phase of the flood. Sediments deposited during this phase indicate highly erosive and turbulent flow. Large boulders up to 5 m in diameter were carried on top of smaller boulders and cobbles. Flow during this phase dramatically altered the entire planform of the river, straightening and widening the channel. The Queen Bess event falls within a two-end-member continuum of outburst floods from moraine-dammed lakes triggered by ice avalanches. One end member comprises events in which the moraine is overtopped by one or more large displacement waves, without the moraine being breached. The other end member involves events in which the outlet channel of the lake is overtopped, but nearly all the outflow results from incision of the moraine dam. Multiple outburst floods can occur from moraine-dammed lakes that are not breached by overtopping waves or from lakes that partially drain.

3. Rock avalanches onto glaciers in British Columbia; studies on Kendall Glacier, Tim Williams Glacier, Ice Valley Glacier (Mt. Munday; see Fig. 1) Kshwan Glacier, and Fubar Glacier (Telkwa Pass; see Fig. 2), rock avalanches showed that glacier debutressing was important in initial failure and that in general the debris moved further over the glacier ice surface than it would have over a non-glacier ice surface. High density DEMs have assisted in the geotechnical characterization of these rock avalanches and have enabled the calculation of detailed quantitative parameters such as failure volume and run-out distance.

Fig. 1 ; Perspective view of the Mount Munday rock avalanche on Ice Valley Glacier, Waddington Range, southern Coast Mountains. This digital image was prepared from aerial photographs flown on August 20, 1997, and consists of a DEM with an orthophoto drape. Note flow lines in the debris. Elevation of the top of the source area is 3000 m.a.s.l. and the lower tip of the debris is at 2100 m.a.s.l. The length of the rock avalanche path is 4.7 km.

IMPACT AND ADAPTATION : THE 1999 FUBAR GLACIER ROCK AVALANCHE, TELKWA PASS, COAST MOUNTAINS, BRITISH COLUMBIA.

In September 1999 a rock avalanche originating above the Fubar Glacier, ran down over the glacier and into the valley bottom of Telkwa Pass (see aerial photograph at left). In doing so, it severed two natural gas pipelines that supplied Terrace and Kitimat. Because of the loss of gas supply four large plants were closed in both towns (see press cutting below from *The Province*, September 13th, 1999). The pipeline was re-laid around possible run-out of a new rock avalanche (see aerial photograph). Aerial photographs were flown specially for the project in August 2000.

Fig. 2; September 1999 rock avalanche at Fubar Glacier, Telkwa Pass, Coast Mountains, British Columbia.

Plants closed by mudslide

By Ian Austin
Staff Reporter

A mudslide has forced four large industrial plants and a number of smaller businesses to shut down in the Prince Rupert area.

The rock and mud sheared two natural gas pipelines Saturday in the Telkwa Pass area between Smithers and Terrace, affecting businesses in Prince Rupert, Kitimat and Terrace.

"We were able to close valves to keep the gas in the lines, so residents haven't been cut off," said Russell Wintersgill, manager of operations for Pacific Northern Gas Ltd.

"But if the businesses continued to use gas, it would drain the system, and cut off everyone."

With 17,000 homes and businesses served by the natural gas lines, bleeding the system dry would put out thousands of pilot lights.

"It's easier to bring up a few dozen industrial and commercial users than relight 17,000 homes," said Wintersgill.

Wintersgill said PNG will fix the break, then relocate the line to a safer route: "We're laying a temporary line across the slide, and later we'll re-lay the permanent line around the slide area."

The PNG rep said the system should be partially restored by the weekend.

But he couldn't say when area workers will be able to return to work. He doesn't know when there'll be enough supply for PNG's four biggest customers — Methanex, Alcan, Eurocan, and Skeena Cellulose.

4. TASK 2 – ANALYSIS OF SITE AND REGIONAL RAINFALL-TRIGGERED EVENTS – THE ANATOMY OF IMPACTS 2

Sub-task 2A : Landslide response to regional rainfall events

Because of the occurrence in 1999 of major site events this aspect of the project was not investigated. It is hoped that work will be resumed on this aspect of the project under future CCAF activities.

Sub-task 2B : Event case histories

Activities 1999-2000: Major efforts were expended to document recent case histories. These included the flying of aerial photography, procurement of digital topographic data, the analysis of this data, and the generation and analysis of digital elevation models (DEMs) for new events at 5-Mile Creek, Nomash River, Clanwilliam and Glacier Bay (Knight Inlet), which occurred in 1999.

Activities 2000-2001: Major efforts continued to be expended to document recent case histories. The landslide at Slocan Valley, British Columbia was investigated in April 2000. Further field work was carried out at 5-Mile Creek debris flow, Banff National Park.

Results

5-Mile Creek debris flow, Banff National Park: In August 1999 a debris flow occurred in the Rocky Mountains at 5-Mile Creek in the Bow Valley, Alberta. The event blocked the Trans-Canada highway for several days at the peak of the tourist season (*The Globe and Mail*, August 6, 1999; Fig. 3). The debris flow was apparently triggered by an afternoon highly localised microburst rainfall, which went unrecorded by the hydrometeorological network. Whilst rainfall-triggered debris flows in the Coast Mountains are well documented, Rocky Mountain debris flows show distinctive characteristics that are not. Some of these characteristics include multiple sources for the debris flow (Fig. 3), sheet mobilization of colluvium and substantial entrainment from channel locations.

A report on 5-Mile Creek debris flow was released as a Geological Survey of Canada Open File (Couture and Evans, 1999) and a paper on the event was read at GeoCanada 2000 in Calgary (Couture and Evans, 2000). Our work on the 5-Mile Creek debris flow raised awareness of the hazard with Banff National Park authorities and led to the convening of a special workshop on this and other landslide hazards in the Park.

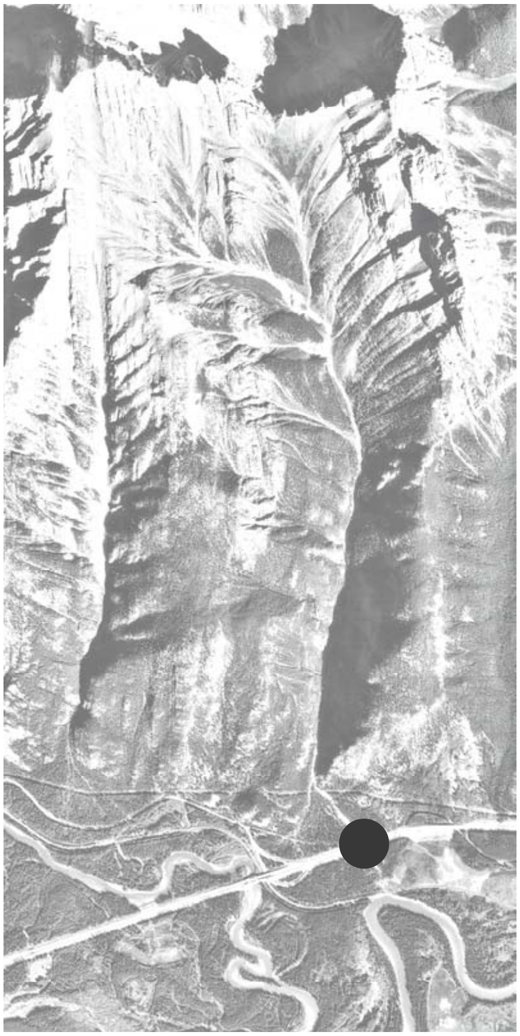

Fig. 3: Aerial photograph flown in September 1999 of % Mile Creek basin, Rocky Mountains, Banff National Park, Alberta. Bow River valley is visible in lower part of the photograph. The August 1999 debris flow originated in multiple locations within the upper part of the drainage and traveled down the creek bed to block the Trans-Canada Highway running right to left. Blockage location is denoted by black spot. The debris flow is thought to have been triggered by a very localized microburst rainfall in the upper reaches of the watershed. The debris flow blocked the Trans-Canada Highway for several days at the height of the tourist season. Aerial photographs flown specially for this project by Foto-Flight, Calgary, Alberta.

5. TASK 3 – SIMULATION OF RAPID LANDSLIDES; A TOOL FOR ADAPTATION

Sub-task 3A : Development of analytical models

Activities 1999-2000: Based on the procurement of detailed digital maps and digital elevation models, a dynamic analysis was carried out of the 1999 Nomash River debris avalanche using a modified version of DAN (Hungr, 1995). Abstract submitted to a special session at the Assembly of the European Geophysical Society, Nice, France.

Activities 2000-2001: Based on detailed digital maps and digital elevation models, the dynamic analysis of the 1999 Nomash River and Clanwilliam debris avalanches was undertaken using DAN. Paper read at special session at the Assembly of the European Geophysical Society, Nice, France (Hungr et al., 2000). The Nomash and Clanwilliam cases also formed part of a paper by Ayotte and Hungr (2000) presented at the 2nd International Conference on Debris Flow in Taiwan.

Despite the fact that a major paper in preparation progress in this Task has been slower than expected because of unavailability due to illness of collaborators during the summer months and the leave of absence taken by D. Ayotte (UBC).

Results

The analysis of the 1999 Nomash rock-slide debris avalanche (Fig. 4) successfully accounted for the erosion and entrainment of material along its path. The development of this capability and its successful calibration is an important step in the use of dynamic analysis as a tool for adaptation.

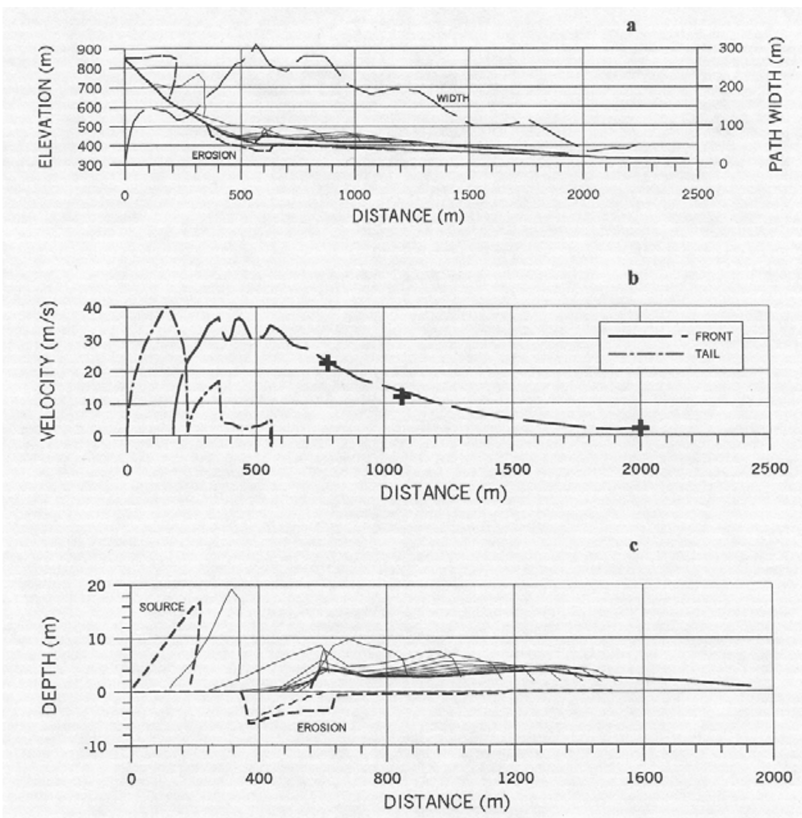

Fig. 4; Simulation of 1999 Nomash River rockfall-debris avalanche using DAN. Model successfully simulates travel distance, velocity (where field estimates were made), and depth of deposit (from Ayotte and Hungr, 2000).

6. SUMMARY

Climate driven catastrophic geomorphic processes are a major hazard in the Canadian Cordillera. Climate-driven catastrophic processes include rockfall, rock avalanches, debris flows and debris avalanches, rockfall-triggered debris avalanches, rapid flow slides in Quaternary sediments, outbursts from moraine-dammed lakes, and the failure of built slopes, such as railway fills or embankments. The nature of climate forcing has two aspects a) climate change or variability at a decadal or century scales that precondition failure situations and b) triggers involving climatic episodes such as rainstorms or rapid warming that lead directly to the event in question. Historical records dating back to 1850 document the occurrence of extreme rainfall events and their effects. There is no first-order evidence that either the frequency or the magnitude of rainfall events has changed with time in the region under examination. This may reflect a number of factors including a sparse hydroclimatic data network in which triggering rainfall events, for example, are not recorded. Despite this, glacier-ice loss was seen to be a synchronous pervasive phenomenon at a regional scale and seems to suggest a pervasive regional response to higher summer temperatures and lower winter precipitation that would result in successive negative annual mass balances for the glaciers in the region. Further, glacier-ice loss was seen to be an important pre-requisite for both catastrophic rock avalanches onto glaciers and catastrophic outbursts from moraine-dammed lakes in glacier forelands.

Detailed analysis of case histories yields data that is vital in understanding processes which in turn is fundamental in developing adaptive strategies. These detailed case histories have been invaluable in calibrating dynamic models that simulate the behaviour of climate-driven mass movements including rock avalanches, debris flows, debris avalanches, and rockfall-triggered debris avalanches. Success in simulating numerous aspects of catastrophic landslide behaviour using dynamic models indicate that these will be useful tools for improving adaptation to climate change.

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