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HILLSLOPE STABILITY AND SEDIMENT YIELD IN THE MOUNTAIN RANGES OF BRITISH COLUMBIA, CANADA

A REPORT ON A LITERATURE STUDY AND ASSISTANCE ON A MASS MOVEMENT AND LAKE SEDIMENTATION RESEARCH, DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

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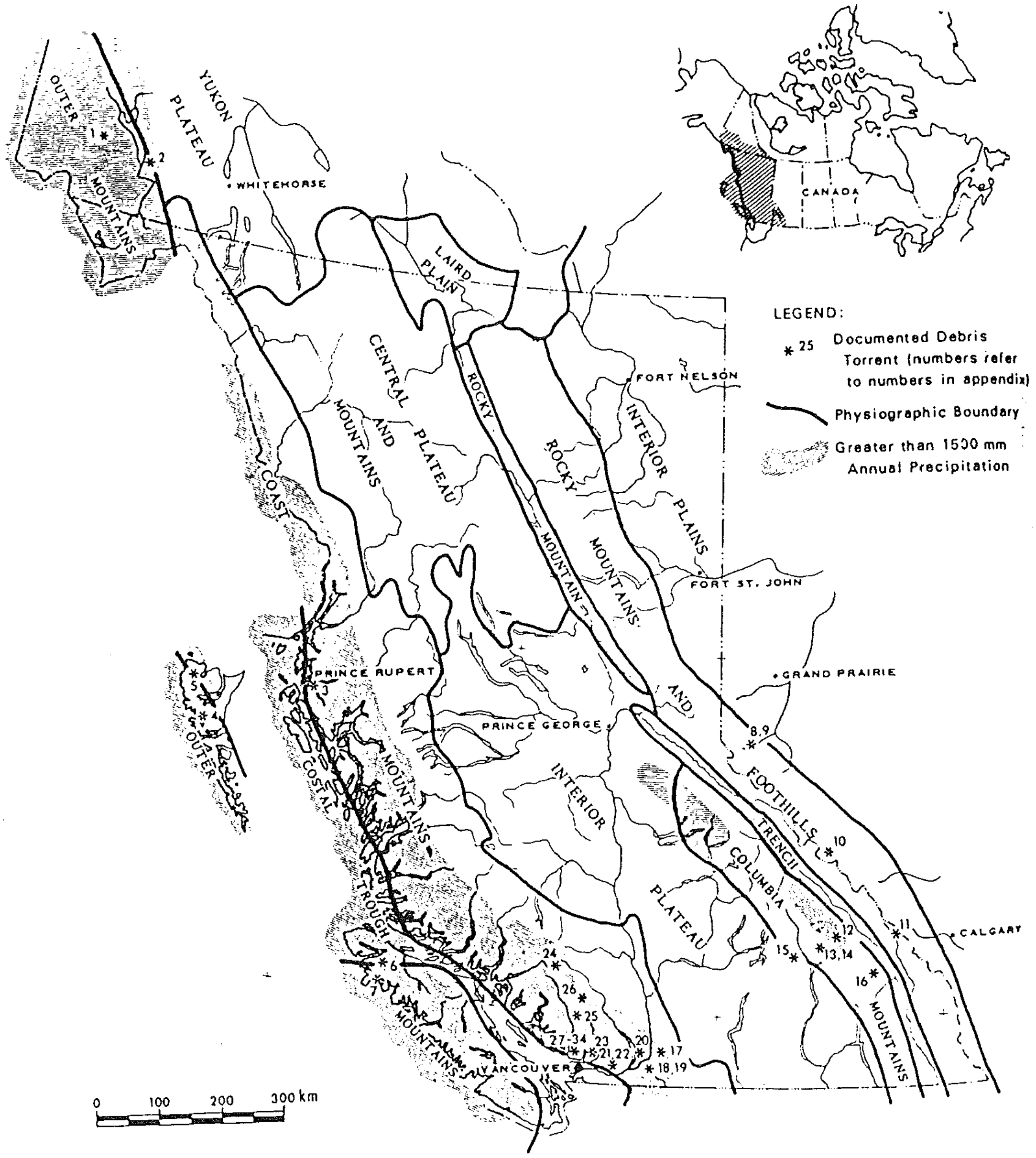


Figure 1: Map of mountain ranges in British Columbia (VanDine, 1984)

INTRODUCTION

This paper deals with mass movements resulting from hillslope instability and sediment yields of mass movements, derived from evidence of sedimentation rates in lakes. The purpose of this paper is to look into and compare different mass movement and lake sedimentation researches and to gain knowledge of the geomorphology of some mountain ranges in British Columbia, with an emphasis on the southern Coast Mountains.

The paper will first present and discuss results of different articles which were examined. These articles dealt mainly with mass movements, especially debris flows and landslides in the Coast Mountains and sedimentation in lakes in southwest and south central British Columbia. Research on debris flows, landslides and lake sedimentation will be looked into separately. After this, two specific researches that were attended by the author will be described. One deals with landslide mapping in the Capilano Watershed north of Vancouver and the other deals with sedimentation rates in Green Lake near Whistler. These researches are both performed by graduate students from the University of British Columbia in Vancouver, Canada. Assistance for the fieldwork-part of these two researches was given by the author from June to October 2000, as part of the undergraduate program of Physical Geography studies at the University of Utrecht in the Netherlands. In the last part of the paper, the attended and studied researches will be compared with previous researches and discussed, followed by some conclusions.

PART 1: LITERATURE STUDY

The many mountain ranges of British Columbia have been categorized by many different workers (VanDine, 1984; Slaymaker, 1990b). The main ranges can be recognized as followed; from west to east; the Coast Mountains Ranges on the Vancouver and Queen Charlotte Islands and the Coast Mountain Ranges on the mainland, the Columbia Mountains and the Rocky Mountains on the border with Alberta (figure 1).

The Coast Mountain region around Vancouver are mostly made up of granitic rocks like (quartz-) diorite and granodiorite and are locally covered by glacial till, especially at lower elevations (Slaymaker, 1990a). To the east in the Cascade Ranges, the gneissic and granitic rocks alternate with folded sedimentary rocks with deformation decreasing to the east (Slaymaker et al., 1987). Further to the east, the Columbia and Rocky Mountains consist mostly of folded sedimentary rocks.

The mountain ranges strongly influence the distribution of precipitation from the Pacific Ocean to the province of British Columbia. The Coast Mountains receive an annual precipitation of about 3-4000mm on the westside of the Island Ranges and 1.5-2000mm on the mainland, leaving the Interior Plains dry. Further to the east precipitation increases again in the Columbia and Rocky Mountains. The fraction of snow from total precipitation significantly increases with elevation and also towards the interior. The elevations for lower permafrost limits decrease from the Coast Mountains to the interior (from about 2300m to 1000m), whereas the tree line (at about 1800m at Garibaldi NP) lies at higher elevations in the Rocky Mountains (about 2300m) (Slaymaker, 1990b).

DEBRIS FLOWS

Debris flows, better known in North America as debris torrents (which are coarse-grained, channelized debris flows) are a common feature in most mountain ranges in the province of British Columbia, in particular in the Coast and Rocky Mountains. Since their impact on structures like roads and railways can be large, much research has been done to gain a better understanding of these features.

Debris flows in British Columbia occur during different time periods throughout the year as can be seen from figure 2, partly because they are triggered by different mechanisms; mostly by snowmelt and heavy precipitation storm events in autumn and summer (VanDine, 1985). Therefore, the initiation mechanisms and occurrence of debris flows of different regions requires its own specific, separate approach. Because of this the debris flows in British Columbia will be dealt with in two

Figure 2: Frequency of occurrence vs. time of year for western Canadian debris torrents (VanDine, 1984)

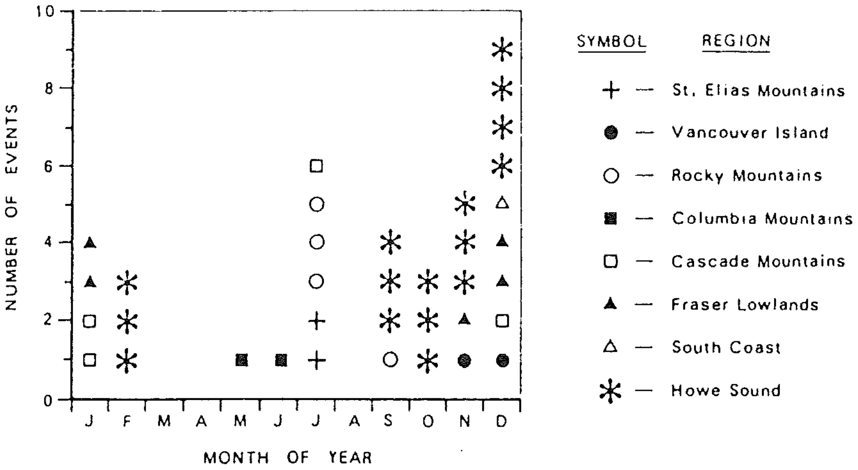
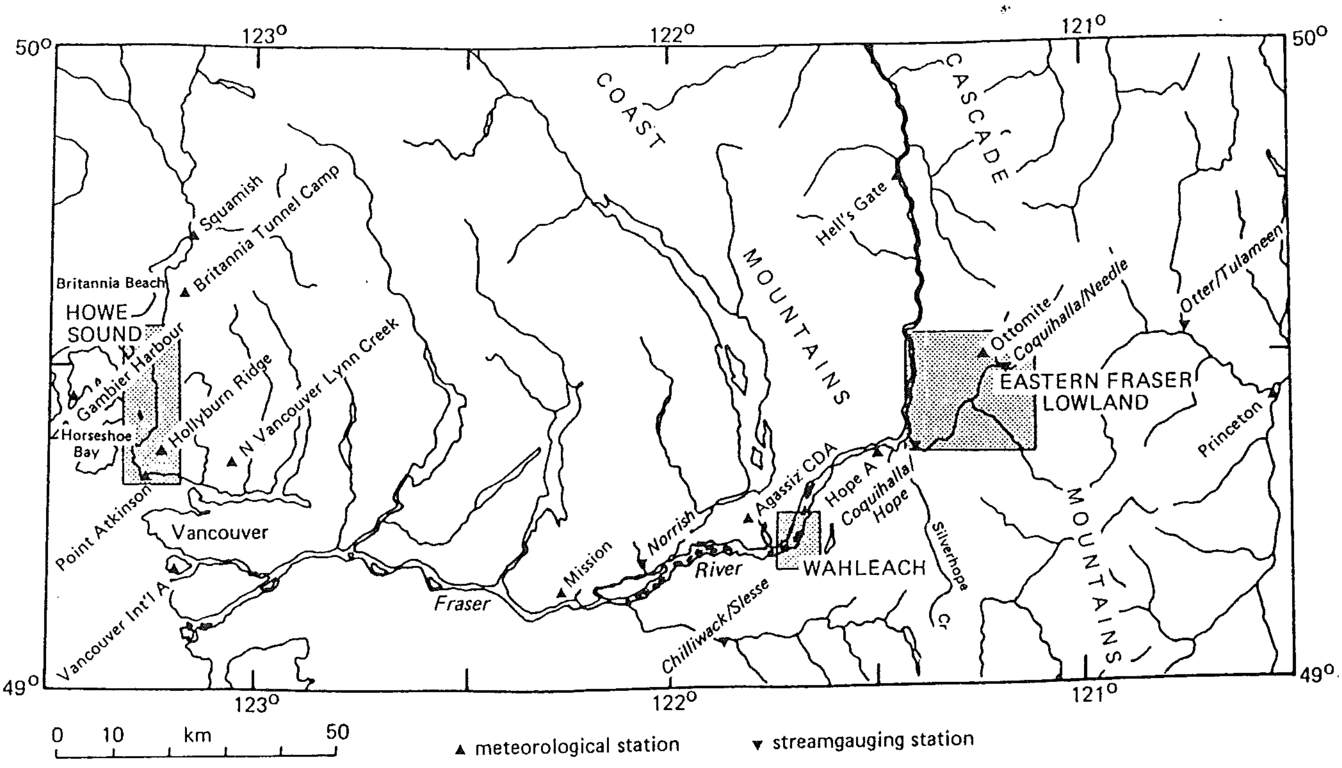


Figure 3: Map of southwestern British Columbia, showing Howe Sound area and Cascade Ranges (Church & Miles, 1987)



groups; first the debris flows of the Rocky Mountains will be considered and than the debris torrents of the Howe Sound and the Cascade Ranges in the Lower Mainland.

Debris torrents in the Rocky Mountains

In the Rocky Mountains, Jackson (1987) researched debris flows in three study areas: the Kananaskis Valley (south of Banff N. P.), the Elk River Valley (northeast of Fernie) and the Kicking Horse Pass area (in Yoho N.P.). He mapped 44 debris torrent fans in the field and another 59 through air photo interpretation in order to establish past debris flow activity and evaluate the debris torrent hazard. Hazard can be assessed from textural evidence and evidence from fan morphology, basin morphometry and geomorphology. In the field, soil samples (grain size distribution, tephra layers, organic material), tree corings were taken and injury assessments of trees were made. From the aerial photographs relief differences between highest point in the basin and fan head, mean basin area and mean basin slope above fan head were estimated. The frequency calculated from this data is the minimum, since man induced activities are likely to increase the activity of debris torrents.
Jackson et al. (1989) found that debris flows in the Cathedral Mountains (south of the Kicking Horse Pass in Yoho, N.P.) were mostly triggered by jokuhlhaups (outbursts of lakes behind moraine dams) and not heavy precipitation events. The required amount of water for failure was calculated using the volume of mobilized debris and the water content. Since the pumping of the lake by the Canadian Pacific Railway in 1985 no jokuhlhaups have occurred (the lake was drained and never reformed).
Saczuk & Gardner (1998) built a model for hazard ratings for sites in Banff N.P (the Bow, Mistaya and Saskatchewan Rivers area). They constructed a debris flow recurrence interval model to establish the hazard of sites. Digitized aerial photographs were used to estimate channel geometry and amount of available debris in gullies. Erosion rates, threshold debris volumes, annual sediment yield and triggering rainfall intensity were taken from previous literature to calculate critical threshold values leading to events. Of the 22 sites, 14 were rated as "high hazard", having recurrence intervals of about once or twice in 50 years. Errors from the air photo interpretation were calculated and input variables were varied to evaluate the reliability of the model. The erosion rate seemed to have the largest effect on the outcome: changing input values from 0.0005 to 0.0007 m^3/yr resulted in a decrease of 30%. The major trigger mechanism for debris flows at this site was found to be intense rainfall and snowmelt events. The water saturated the loose debris in the channel and mobilized according to the "fire hose effect". This trigger mechanism is similar to that found in the Howe Sound area.

Debris torrents in the Howe Sound & Cascade Ranges

The area of the Howe Sound is renowned for the many debris torrents that took place during the early eighties (Eisbacher, 1983; Skermer, 1984; Hungr et al., 1984). In addition, the area to the east in the Cascade Ranges has also had an increase in events for that time period (Slaymaker et al., 1987; Church & Miles, 1987; Evans & Lister, 1984). Figure 3 shows a map of the Howe Sound and Cascade Mountains. Since the events in the eighties, much research has been done in the area in order to develop remedial measures against the debris torrents like structures and warning systems (VanDine, 1987; Kellerhals & Church, 19??; Hungr et al., 1984).
Figure 4 (Bovis & Dagg, 1989) is a map of the Howe Sound area with the creeks most prone to debris torrents. Alberta, Charles, Newman, Magnesia and M Creek have experienced the most or largest events. The events in the Howe Sound Creeks since 1958 and triggering rainfall intensities, measured at nearby weather stations are summed up in table 1. Many debris torrents were triggered during rainstorms during the years 1981-1984. Oddly enough, the flow-events were not triggered by extremely high precipitation events, but the five-year period from 1980 to 1984 recorded the highest annual precipitation at Vancouver International Airport (Church & Miles, 1987). The debris flows reported from the area initiate from small, steep catchments and are triggered by locally intense rainfall, snowfall, rain-on-snow events, which occur dominantly from September through February. These precipitation events are the result of convection cells of about 1-5km^2 that collide with the steep mountain walls of the Coast Ranges (Church & Miles, 1987). Antecedent moisture has a large influence on whether an event will occur or not, as can be concluded from the events in the eighties.

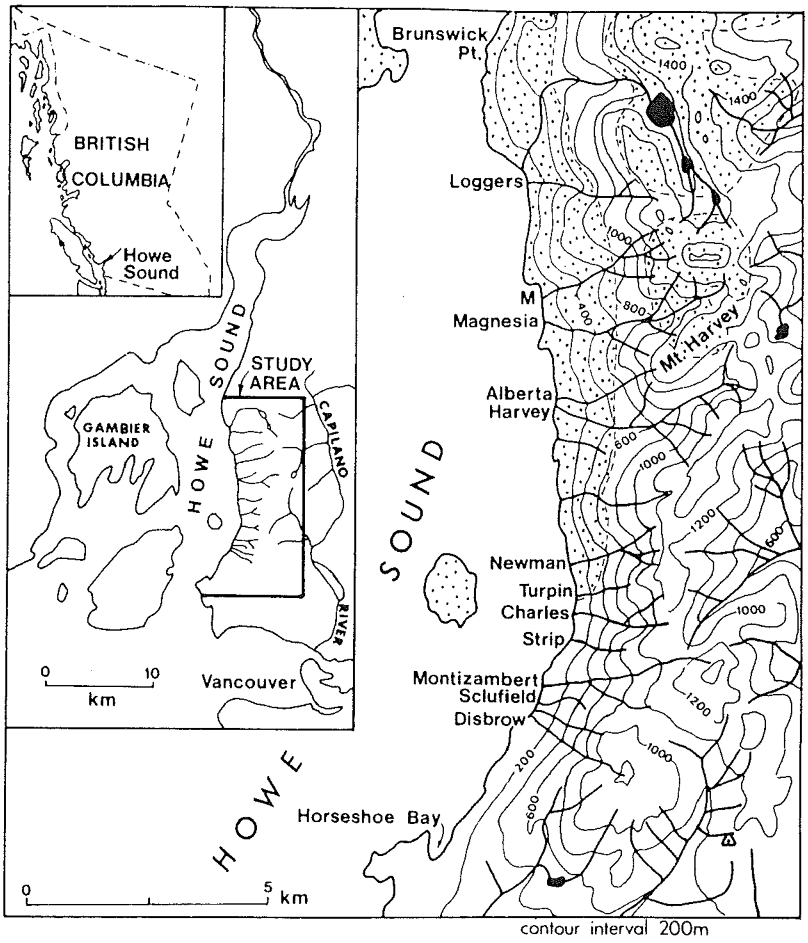
	SOUTH											CREEK											NORTH				
	Disbrow	Unnamed 1	Sclufield	Montizambert	Strip	Charles	Turpin	Newman	Lone Tree	Rundle	Harvey	Alberta	Magnesia	M Creek	Loggers	Deeks	Brunswick Point	Bertram	Kallahne	Unnamed 7	Unnamed 8	Furry	Unnamed 9	Daisy	Thistle	Britannia	24-hr Precipitation* Hollyburn Ridge (mm)	Prior 7-day Precipitation* (mm)
Fall, 1960													O															
Early 1960s																			O					O				
Oct. 12, 1962**													●														24	132
Dec. 22, 1963																										O	125	146
Sept. 18, 1969						●		●			O																59	90
?, 1972																O												
Nov. 3, 1972						●																					52	81
Nov. 7, 1972						●																					46	195
Dec. 15, 1972											O																56‡	36
May 23, 1973											O																71	28
1976/77																						O						
Sept. 9, 1978											O																30	64
Dec., 1979	O																											
Oct. 28, 1981													●	●					●								44	41
Oct. 31, 1981																						O					72	227
Dec. 4, 1981						●		●				O															18‡	58
Oct. 6, 1982						●		O																			27	76
Dec. 3, 1982												●															82	147
Feb. 11, 1983							●	●				●															80‡	175
Nov. 15, 1983				●		●		●														O					130	207
Oct. 8, 1984											O																31	136
Dec. 14, 1984			●																								26‡	154

*Indicative only; amounts vary greatly locally.
**Huricane Freda.
‡Plus significant snowmelt.

O Flood
● Debris torrent

Table 1: Recorded events in Howe Sound since 1958 (Church & Miles, 1987)

Figure 4: Map of the Howe Sound region. Unshaded areas are underlain by late Cretaceous diorites. Dots denote the approximate extent of Gambier Group rocks (Bovis & Dagg, 1988)



△ Hollyburn Ridge Weather Station
⛶ Gambier Group rocks (other areas mainly dioritic rocks)

Compared to debris flows reported from other regions over the world, the material of the debris flows of the Coast Mountains consists of coarse-grained clastic debris, with little organic debris and little clay content; less than 5% silt and clay-sized particles (Hungr et al., 1984). These characteristics lead to certain typical debris flow behaviour. This debris flow behaviour can best be described by the viscous Newtonian flow model, which describes its laminar behaviour or by the dilatant model by Bagnold (1954), which approaches the flow by looking into the dispersive forces, caused by grain contacts in the fluid. Transitions of these two models are also possible and may be useful describing the differences in flow behaviour of different parts of the debris flow in one single event. For instance, debris flows usually have a bouldery, laminar flowing front followed by a finer-grained, more turbulent tail and surges may occur within the flow. These surges are also coarser-grained and occur as pulses and have been described in detail by Davies (1985). Pulsing debris flows can be explained by the shearing behaviour of viscous flow, which provides shear strengths large enough to support the large boulders in the surge. Bouldery surges can also be the result of the dispersive pressures in the flow, which result from the intense grain contact of clay-sized particles in the slurry flow, that support the larger particles. Both theories show that this grain shear, necessary to support the clasts is extremely erosive, which is often observed in the field when intensive scouring of the channel bed has deepened the channel. Other flow behaviour can move towards more turbulent or more shearing flow and can be described by the Bingham visco-plastic model or various other modified versions of it (Hungr et al.,1984; Davies, 1986; Innes, 1983; Jordan, 1988).

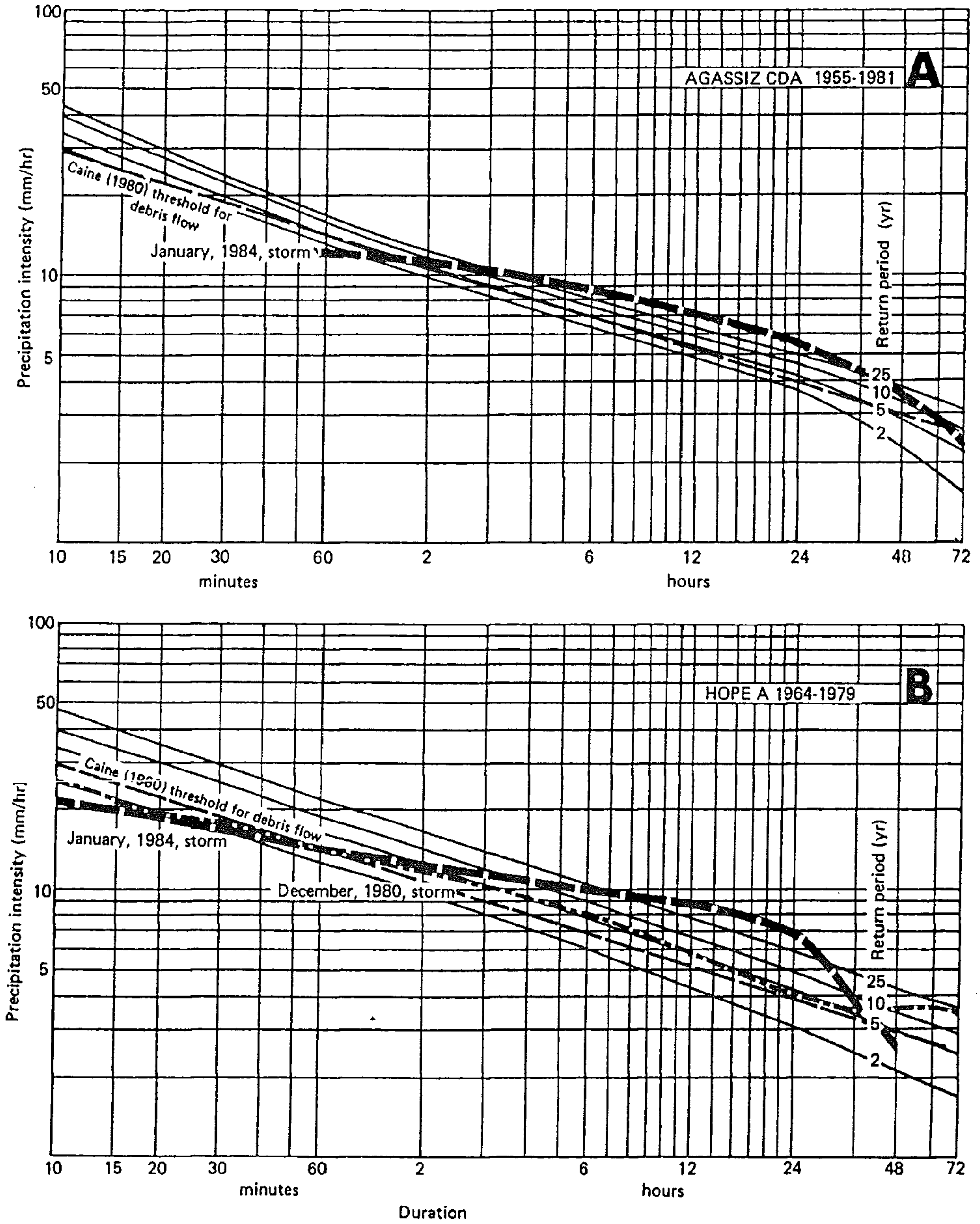
The debris torrents in the Coast Mountains can start from two trigger mechanisms. The torrents can be triggered by slope failures such as rock falls or small slides or result from the re-mobilization of loose debris that has gathered in gullies over time. The mechanics of landslide failures resulting in debris torrents have been described by Iverson et al. (1997). The mechanism that causes the soilmass to fail and convert into a debris flow is the result of, (a) liquefaction from a rapid rise in pore pressures in the soil, (b) widespread Coulomb failure within the rock mass, (c) conversion of landslide translational energy to inertial vibrational energy (increase of granular temperature) or (d) a combination of the above. Liquefaction from high pore pressures seem to be a characteristic of all debris flows, since debris flows are able to move around structures without damaging or displacing them (Iverson et al., 1997). An increase in granular temperature will "dilute" the flow and enhance its fluidity. If the increase in granular temperature at a slip surface is passed on to adjacent soil, the slip can become more widespread and cause the transition into a debris flow.

The initiation of debris flows from loose debris requires two conditions: availability of sufficient water (antecedent moisture and/or intense precipitation) and availability of sufficient debris. Sufficient debris build-up is possible when debris flow events are low frequency, but the adjacent valley walls and upper catchment area have a high erodibility and frequently add debris to channel.Furthermore, channels have enough room for the storage of debris (depth, width, length and steepness). The absence of vegetation as a result of fire, disease or logging and disturbances like road building and logging operations all have a positive effect on the development of debris flows (Church & Miles, 1987).

Prediction of debris flows and counteractive measures

In order to predict debris flow activity certain methods for hazard zoning of catchments and creeks have been developed. First of all, critical threshold rainfall intensity-duration curves have been established. Johnson & Sitar (1990) have summed up several threshold rainfall duration intensities by Caine (1980), Cannon-Ellen (1985) and Wiescorek (1987) in an intensity-duration graph (Johnson & Sitar 1990). For Cannon & Ellen, the two areas with the highest and lowest mean annual precipitation were calculated. Data from research sites is then calculated and plotted in these curves and for some researches the curves seem to agree with the threshold values, but for some studies they may not apply at all. Especially the antecedent moisture in the soil seems to have a large influence on the threshold value. In figure 5 the intensity-duration curves of the December 1980 storm have been plotted against Caine's threshold curve for two sites. The critical intensity was reached after about an hour, when the intensity had a recurrence interval of about 5 years. The 24-hour intensity had a

Figure 5: Magnitude-frequency-duration of rainfall for Agassiz and Hope at western Cascade Ranges. Based on Atmospheric Environment Service analyses to 24hr, thereafter on compilation from British Columbia Ministry of the Environment (Gumbel's extreme value distribution) (Church & Miles, 1987)



recurrence interval of more than 25 years for both locations. This indicates higher magnitude-lower frequency events, but does not imply that these circumstances will actually trigger a debris flow. Ten debris flows had a mean recorded precipitation of less than 100 mm for 24 hours, which is Caine's (1980) threshold criterion. Recurrence-intervals were estimated anyway, critical 24-hour precipitation events were likely to occur every 5 years for the Howe Sound and every 50 years for the Fraser Lowland (Church & Miles, 1987).

Keefer et al. (1987) developed a similar model for the San Francisco region. This real-time warning system is also based on the threshold intensity-duration curves by Caine, Cannon & Ellen and Wieczorek. They used critical water levels and pore pressures (therefore incorporating antecedent moisture) for sites experiencing debris flow activity, which were triggered by landslide events. These critical water levels were plotted against the intensity-duration graphs of Cannon & Ellen, Caine and Wieczorek (Church & Miles, 1987) to find the critical rainfall intensities. These curves may help predict debris flows from data on rainstorms arriving at the coast, but since intensities vary a lot within the storm cells and may be high for very small areas, it is extremely difficult to give accurate predictions.

Another method for predicting debris flow activity has been developed by Thurber Consultants and has been described by VanDine (1984). In order to measure the magnitude of potential debris torrents of a certain basin, the "design torrent" is calculated. The design torrent is the upper limit of the volume of debris that is likely to be involved in a torrent. It can be estimated from several methods, comparative, empirical, unit volume and modified unit volume methods. The unit volume method was used for the Howe Sound area. It estimates potential debris yield of a creek by calculating the volume of debris per unit creek length or multiplying creek width times scour depth per unit creek length. Structure-design and removal of debris in gullies were then based on these design torrent values. Structures are usually in the form of check dams, retention basins or chutes under bridges. The amount of debris to be removed was given by a few times the design torrent.
Kellerhals & Church (19??) used evidence from fans to establish debris flow and avulsion risks in the Howe Sound area. They looked for boulders, logs at certain locations, log jams, scars on trees and differences in vegetation to map debris flow events and assess risk locations. For locations with high-risk several structures and alarm devices (electric fences and wires) were developed to divert and slow down the flow.

Benda & Cundy (1990) found a model from debris flow evidence in northwest USA, an area that compares well with southwestern British Columbia. The model is very similar to that of the design torrent of Thurber Consultants (VanDine, 1984) and uses channel slope and tributary junction angle to calculate travel distances en deposition in channels. Bovis & Dagg (1992) used the same model to calculate the momentum transferred by a hillslope failure (trigger mechanism) in order to estimate whether or not a debris flow will form and continue down slope. These calculations were based on data from the Howe Sound. The estimated volume of the debris flow is calculated by multiplying the average volume of debris in the channels by the length of the channel traveled with a slope above 10 degrees and adding an erosion volume of 8m^3/m times the length (Benda & Cundy, 1990). Critical junction angles (between the contributing slope and creek) were also accounted for in the model.
For the Howe Sound area, Bovis & Dagg (1988) pointed out that variations in hydraulic conductivity and angle of internal friction of the debris might have a large effect on the stability of the debris stored in channels. Channel debris is more stable over time when the angle of internal friction slightly increases and the hydraulic conductivity considerably increases. The increase in hydraulic conductivity and angle of internal friction is the result of water flowing subsurface through the debris deposited in the channel. Because of this increase in stability of the debris larger magnitude, lower frequency events are needed to mobilize the debris, or a major avalanche, slide or fall event is needed to set off the debris flow. On its way, finer-grained particles are mobilized, leaving the debris deposit coarser lag deposit. Especially for the debris torrent event in M Creek on October 28 1981, this is thought to have had an effect, since the debris had been deposited in the channel over a period of six

years and the deposit was not recently wetted before the event. The triggering rainfall was not an extremely high precipitation event. This theory also applies for the February 1983 event in Alberta Creek, although this event was triggered by a large snow avalanche.

LANDSLIDES

Landslides are a different phenomenon than debris flows and are therefore treated in a separate chapter. The landslide fails over a shear plane and then the debris slides or rolls downhill. The failing mass can also, under liquefied circumstances, continue down slope as a debris flow as has been described above. Many larger landslide events reported from British Columbia, however, are typical slide events (Hope Slide, Downie Slide, Dusty Creek Slide). Most articles cover a single slide or landslide prone region. One study, however, has attempted to zonate landslides in the whole province of British Columbia (English, 1995). Several landslide-sensitive site characteristics were mapped (relief, lithology, fracture-structure, precipitation, seismic intensity and freeze-thaw regime) and combined to develop a landslide-hazard map for British Columbia. Three to seven classes per site-characteristic, with each their own index value, were taken from previous literature to zonate landslide-risk. Higher relief, weaker rock, more freeze-thaw cycles, higher fracture densities, precipitation and seismic intensity all promote landslide initiation and were assigned higher index values. From the final riskmap it became evident that the St. Elias, Cassiar and eastern Carbonate Zones are most susceptible to landsliding, and that the Coast Mountains were only ranked forth, despite being one of the most landslide prone regions in British Columbia.

One of the largest landslides in British Columbia is probably the Hope Slide from January 1965 which involved an area of about 1.9 km^2 (Mathens & McTaggart, 1969). Since the temperatures at the time were below freezing and there was hardly any precipitation involved, the slide is thought to have been triggered by two small eartquakes. Cracks nearly parallel to the slide plane were found in the head scarp and probably promoted failure. Another large slide is the Dusty Creek Slide near Mount Cayley, north of Squamish, which took place in 1963. This slide also seems to be set off along some fracture planes in the folded volcanic rock of the Garibaldi Complex. The Downie Slide, north of Revelstoke, is an older, post-glacial slide, also of imense magnitude and has been monitored for smaller movement like creep since 1965. This slide probably occurred because of the favourable dip of failure plane, which was smaller than the dip of the slope face.

Smaller slides in British Columbia have also been studied. Landslides in glacio-marine, glacio-lacustrine and till sediments have been studied in the Skeena Region (Evans, 1982), in the Fraser Canyon. Piteau (1976) studied landslides from valley wall opposite of river bends. Landslides in basaltic terrain near Kamloops in British Columbia have been described by Evans (1984). Studies on the sensitive clay region near Ottawa, Ontario appear to be non-applicable for British Columbia as most rock is volcanic and relief mountaineous (Mollard, 1977; Fransham & Gadd, 1977).

Deforestation and landslide initiation

Logging has been an ongoing business in British Columbia and after the effects of it on slope stability became clear in the sixties, attempts have been made to replant logged terrain to regain stability. A lot of research has been done to establish the effects of clearcutting and the building of logging roads on the initiation of slope failures.

Furbish & Rice (1983) designed a probability model for a landslide-sensitive region in northwest California which compared failures from unlogged and logged areas. The results of the study show that most failures occur near stream incisions. Rood (1984; 1990) also compared landslide risk for forested and logged areas, but used a more statistical approach. He mapped all slides and flows in the research area on the Queen Charlotte Islands and established statistically which area had the most frequent and most voluminous events. Logged areas (clearcut terrain and logging roads) were in all cases extremely more sensitive than forested areas, failure volumes, for instance, had increased by a factor 35. There was an especially large increase in logging road-related failures.

Wu & Swanston (1980) and Bishop & Stevens (1965) studied the effect for deforestation on slopes in Southeast Alaska. Bishop & Stevens (1965) found an increase in landsliding of 4.5 times since the initiation of logging in 1953. The slides in this area also seem to be lithology related, there were more slide events on south facing slopes, which were more smooth and concave, compared to the stepped north-facing slopes. For most slides, the glacial till would slide over the bedrock shear plane. The logging of trees was found to promote sliding, because of loss of shear strength in the soil, the loss of root systems to support the soil structure and most of all less infiltrating water was used by the tree. This will very likely also be the reason the increase of slope failures for logged terrain in British Columbia.

LAKE SEDIMENTATION

Evidence for mass movement from hill slopes can be found on slopes and their deposition fans, as seen above, but also in lakes deposition of transported sediment takes place. Shallow deltaic sediments near river mounds and deep-lake sediments supply plenty information on sediment rates and past activities. There are a couple of large lakes draining the Coast Mountains to the east as well as many smaller lakes within the Ranges. The larger lakes are Chilko, Harrison and Lillooet Lake. These lakes have been subject to research for the study of sedimentation rates and sedimentation chronologies. Deslodges & Gilbert (1991) studied deposition rates of many of these lakes. In Harrison Lake they found depostition rates of around 0.1-2mm/a. The lake sediments consist of a transparent upper layer of postglacial age on top of a lower thicker (10-12m) layer deposited from high-energy glacial deposition. The glacial sediments are thicker because they are the result of more intense sedimentation processes; rapid glacial retreat added sediment from the northwest and in the south a delta was build by the Fraser River. Evidence from Chilko Lake (the deepest and largest lake draining the Coast Mountains) shows about the same profile although the lake sediments come from more localized origins and fewer sediment is available than other lakes in the western Cordilerra (Deslodges & Gilbert, 1998). Modern sedimentation rates were estimated at 2.2 mm/a; 210Pb-dating and acoustic results, however suggested rates of smaller than 1 mm/a. This seems to agree better with the faster (2mm/a) sedimentation in Harrison Lake. Unlike Lillooet Lake, Chilko Lake does not have a thick sediment layer from glacial related deposition. This could be due to, erosion of sediment, low sediment concentration of the melt water, extremely rapid deglaciation or limited Holocene glaciation. Lillooet Lake is estimated to deposit sediment varves with a rate of 28-0.9 mm/year (Deslodges & Gilbert, 1994; Gilbert, 1974).

Owens & Slaymaker (1993; 1994) studied Gallie Pond, a small lake north of Pemberton and Whistler. They found two tephra-layers of 6800 years (Mazama tephra from Crater Lake in Oregon) and 2350 years of age (Bridge River tephra from Mt. Meager, BC). The eldest of the two is coarser, since its source is closer to the lake. With the use of these tephra-layers, four different phases in sedimentation were be established. Around 10 500 years BP the glacial period ended leaving glacial tills behind. 10 500 years BP to 6800 years BP was a period of intense redistribution of these sediments by fluvial and colluvial processes (paraglacial sedimentation). This was followed by a warmer and dryer period of peaty wetland, stabilization of slopes and low lacustrine sedimentation, which lasted till 2350 years BP. Mineral contents increased, lake water rose and events were high frequency-low magnitude. Since 2350 years BP cooler conditions have prevailed, accompanied by increased sediment delivery from hillslopes to the lake. Overall the environment has been relatively stable and low energy throughout the Holocene.

Over a smaller scale, the chronology of the past 125 years, from evidence of Lillooet Lake (Deslodges & Gilbert, 1994) shows a higher frequency of "extreme" runoff-sediment yield events during the post 1945 period. Specific laminae correspond to the 1940, 1958, 1980 and 1984-floods. Sedimentation rates were variable for different locations in the lake, the rates from cores taken in the southern part of the lake were 50% lower than those measured in the main basin (Deslodges & Gilbert, 1994). These differences may have been caused by currents and waves in the lake, subaquaous slope failures and rivers entering the lake. Therefore, it is useful to take cores at different locations of lakes. Schiefer (1999) estimated rates of sedimentation for 70 small lake catchments from which single cores were taken. An incredibly large area was covered this way so differences between the lake cathments could be studied. Although a lot of data was gathered this way, the cores might not be representative of the lake, if they are disturbed or not taken in a representative (deeper) parts of the lake.

PART 2: RESEARCH ASSISTANCY

Research assistance was given to two researches, one dealing with landslides on forested and clearcut slopes in the Capilano Watershed, the other concerning sedimentation in a lake near Whistler. The area east of the Howe Sound is the Capilano Watershed (near Hollyburn Ridge, figure 3). Whistler and Green Lake lie north of Squamish and is just off figure 3.

RESEARCHES

The first field work was attended during the end of June and the beginning of July and took place in the Capilano Watershed, just north of Vancouver, which is part of the Greater Vancouver Region District. This area has been surveyed for landslides in forested and clearcut terrain by Francesco Brardinoni, who is currently working on his masters research on the impact of timber harvesting on mass wasting here. For this research, mass wasting yield from clearcut and forested slopes in the area were estimated from field survey and remotely sensed survey (aerial photographs of different time periods). The results for clearcut and forested slopes will be compared for the two different techniques.

The second research attended in the field in august, is a study of lake sedimentation rates in Green Lake near Whistler. This research is done by PhD student Erik Schiefer, who looked into accumulation rates as a result of deforestation in different lakes of the Skeena Region in B.C for a masters research. This PhD Research will have the same approach, but will especially deal with differences within the lake.

FIELD WORK

The fieldwork for the landslide research comprised mapping of the area, which was partly already done by the G.V.R.D. Especially evidence of hillslope (in)stability on clearcut and forested slopes was needed, since they will be compared. Maps were available with data on slope, soil and bedrock material, land use, erodibility-index and, in some cases, time of clearcutting. However, these maps were made from aerial photographs (from the 1960's through the 1990's) and needed checking in the field for accuracy of the boundaries of the different mapped aspects. Landslides from after the last air photo series might be encountered in the field. Moreover, landslides which are older and covered by vegetation are often not recognizable on aerial photographs and therefore also needed to be mapped. Clearcut and forested field sites were randomly visited wherever transportation on logging-roads to the site was permitted. For field survey, map boundaries were followed as much as possible, usually cutting straight through the dense temperate rainforest. All the encountered landslides, soilslips, gullies and streams were mapped, and site characteristics like elevation, exposition, vegetation cover and slope angle were checked. At some locations in head scarps soil-samples were taking for further research in the lab. Landslide tracks seemed to be encountered more often at sites which have experienced logging and sometimes continued down slope as debris flow tracks.

The lake sedimentation research at Green Lake involved mainly taking sediment cores, the bathymetry mapping had already been done by taking several cross-section profiles of the lake with a sonar device (Figure 6). The lake consists of some deeper pools (deeper than 30-40 meters), some shallower flats and deltas (about 5-10 meters deep). The biggest delta is build out by the glacier-fed Fitzsimmons River. Cores here tended to be more varved and consisting of coarser sediment, sometimes having organic debris in them. This was visible right after coring since the cores used were three-inch see-through plastic plumbing pipes (Photo 1). In order to move across the lake and be able to drill the cores a raft was build with a hole in the middle. A beam was constructed on top of it with a pulley, in order to sink the cores as vertically as possible (Photo 2 and 3). The cores sunk into the soft sediment by just using a weight and were usually filled for three quarters, when pulling up.
The cores in the deeper pools were a little bit harder to retrieve, since the sediment is farther away. Also, taking cores from shallower flats at some sites was harder, since the sediment was too coarse or there was too much organic debris in it in order to stay in the three-inch pipes. For the deeper parts, two-inch cores seemed to work better.

LABORATORY WORK

The 36 soil-samples taken from the Capilano Watershed were sieved in the lab. Particle sizes smaller than 63 microns were kept separate for fall-velocity measurements. Differences in geology became apparent during the sieving; grain size-distributions were similar for samples of nearby sites, presumably with the same bedrock geology.

So far, 16 sediment cores have been taken at several site in Green Lake, more will be taken in the future.
The cores will be analyzed in the lab for grain size, clay and organic content and also varve-thicknesses will be measured to estimate past sediment yields at different locations in the lake.

DISCUSSION

The debris flow studies show that with some practical research, measures can be taken to decrease the impact of debris flows in British Columbia. Especially studies by Hungr et al. (1984), VanDine (1984), Saczuk & Gardner (1998), Bovis & Dagg (1988, 1992), Benda & Cundy (1990) and Johnson & Sitar (1990) provide some practical techniques for hazard assessment of catchments and torrent creeks. For areas where upper catchments are not too steep, the area can be mapped and critical debris volumes and design torrents can be estimated. For steeper catchments, hazard assessment from field research or air photo interpretation from fans (Kellerhals & Church, 19??) might be safer.

Figure 6: Map of Green Lake (by Schiefer)

Photo 1: Samples in transparent plumping tubes

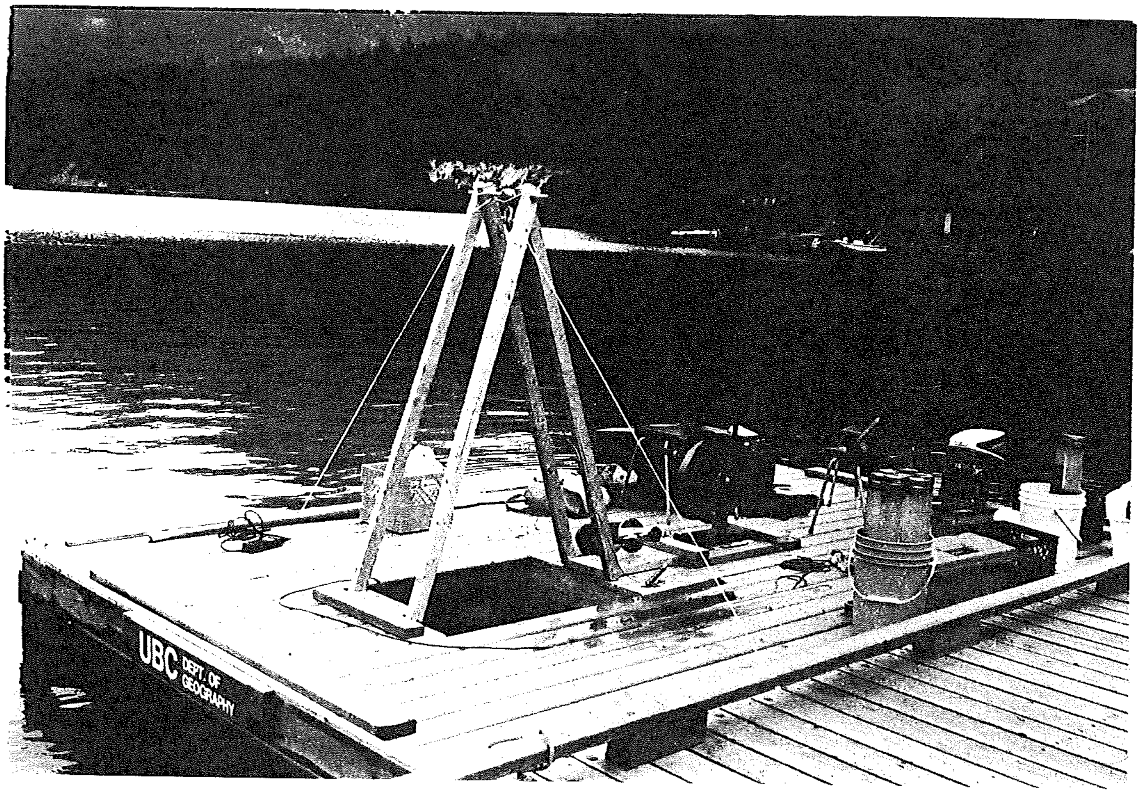


Photo 2: Raft used for research at Green Lake

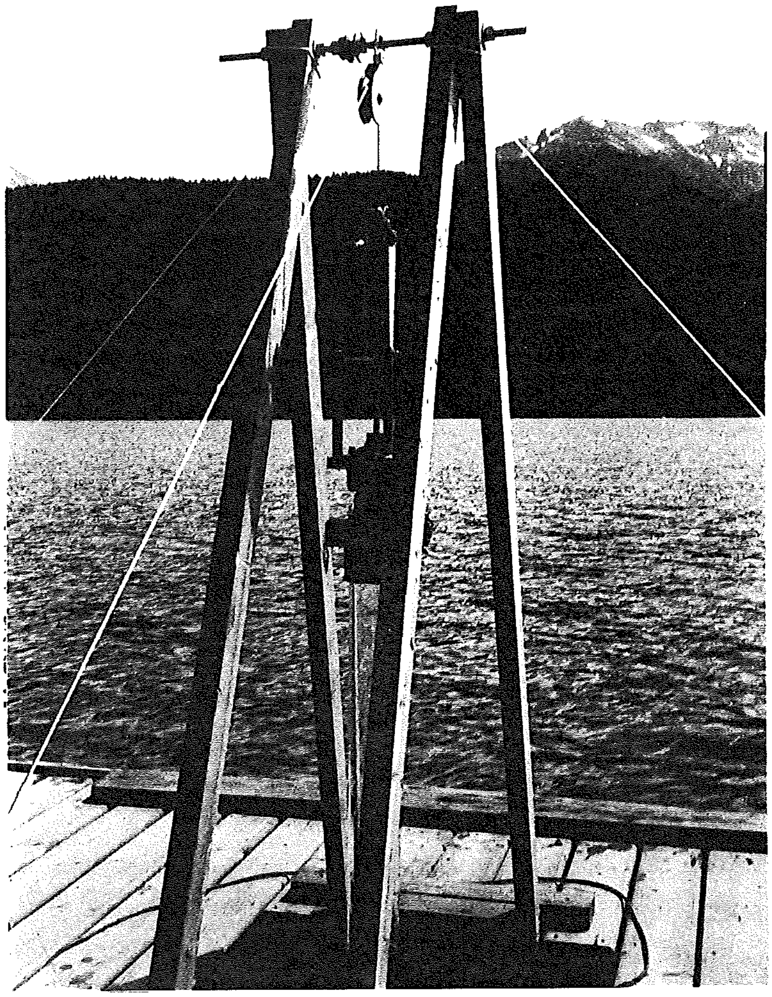


Photo 3: Coring instrument on raft

Statistical risk assessment from recurrence-intervals (Church & Miles, 1987; Johnson & Sitar, 1990) is easily done from past magnitude-frequency data, but possibly not very reliable for the prediction of future events. In combination with meteorological data (precipitation and temperature data), they might be effective in predicting storm events, but it will be hard to predict the exact location of an event, since the storm cells are small and influenced by local topography. These data might be of better use, when used in combination with piezometers in the field, which can provide a warning notice for saturated conditions, necessary for the initiation of failures (Johnson & Sitar, 1990). Recurrence-interval data modified for specific sites (based on magnitudes and frequencies of events (Rood, 1984; 1990)) will be useful in combination with mapping of different site-characteristics for hazard zonation. This applies particularly to differences on clearcut and forested terrain. They will provide necessary information for deciding future logging operations, which should be well chosen. This also applies for the risk assessment of (small) landslides, which in many cases trigger the occurrence of debris torrents as can be seen in the Capilano Watershed. Studies from landslide-triggered debris flows in California (Johnson & Sitar, 1990; Keefer et al., 1987) might be a useful help for monitoring landslides and debris torrents in British Columbia despite the large geological and lithological differences.
The larger landslides (Hope Slide, Downie Slide) seem to be related to fracture-zones in the bedrock and will be hard to predict.

Evidence from sediment yields from lakes display information on past sedimentation rates, which gives information on the overall trend of slope-activity. Events of single years can be studied from varves and might be useful for the calculation of sedimentation by single events. For large events it would be wise to study more lakes in the area, since each lake seems to have a different sedimentation environment. These differences are mainly the result of site-characteristics like lithology and vegetation in the catchment feeding the lake. Most important is probably the extent to which the lake was glacier-fed. Within a lake, differences may be caused by of rivers feeding the lake at certain locations, subaquaous slope failures, currents in the lake and wave action.

CONCLUSIONS

The mountain ranges of British Columbia display a large variety of processes, which erode slopes and deposit in the valleys and lakes. The most common and most studied large erosion events are debris torrents and landslides. Since these hazardous events can take place in urbanized areas (Howe Sound), research has been done to predict their occurrence from past activities (lake sedimentation and debris flow fans), including field research and laboratory research. Several models have been designed, some particularly for a local study area in British Columbia, others are more general and can be applied to regions throughout the world. With the help of these models, several warning systems have been developed from (continuous) measurement of variables significant for triggering events (i.e. continuous measurement of pore pressures, weather forecast warnings systems). Furthermore, several methods have been developed to provide critical measures for failures like, threshold rainfall intensity-duration curves for specific regions, critical junction angles for contributing streams, measurement of design torrents and critical debris accumulation in channels). From this and other data it has been possible to develop structures (check dames, retention basins, debris chutes) which have shown to be able to decrease impacts. For other regions like the Rocky Mountains, with snowmelt and jokuhlhaups related flows and slides, pumping of glacial lakes seems to diminish future disaster.

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