ASSESSING LANDSLIDE OCCURRENCE WITH SNOW DATA AND OTHER SITE INFORMATION

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INTRODUCTION

In early April 1985, large landslides occurred at several low elevation forested locations in southcentral British Columbia (B.C.), causing significant off-site damage to properties and other resource values (Figure 1). The determination of the causes of these landslides have significant economic and legal implications with regard to who should be paying for the repair costs associated with the damage. Two landslides that have caused damage to fish habitats and rehabilitation in Quesnel Lake, B.C., were reported by Watt and Cheng (1985). The present study assesses the causes of another landslide near Vavenby, B.C. that had led to traffic stoppage of the Canadian National (CN) railway track immediately below by covering it with a large amount of soil, rock and forest debris. The results are discussed in relation to the findings of Watt and Cheng (1985).

METHODS

The Vavenby landslide site was inspected on October 16, 1985 by walking from top to bottom. During the ground inspection, observations were made on topographic features such as slope gradient and configuration, soil materials, moisture and wind-firm condition of trees. The location of the landslide relative to harvested units, logging roads and skid trails was also noted and assessed. Attempts were made to obtain climatic information relevant to the occurrence of the landslide. This includes data from the climate station at Vavenby, snow-course station at Blue River and three snow-pillow stations in the general vicinity.

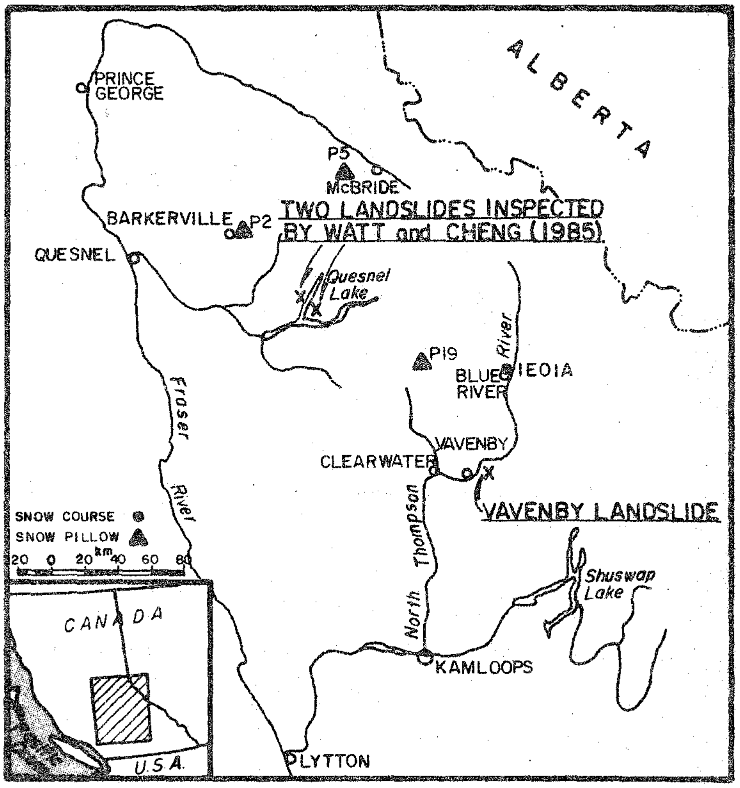

Figure 1. Location of the Vavenby landslide, two other landslides inspected by Watt and Cheng (1985), and snowcourse and snow pillow data stations.

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RESULTS AND DISCUSSION

Description of Landslide

The landslide site is located on the east bank of the North Thompson River at about 500 m elevation, approximately 15 km north of Vavenby, B.C. (Figure 1). According to the report by CN engineers, this landslide occurred on April 12, 1985. The mean annual precipitation at the site is estimated to be about 900 to 1000 mm (Cheng and Reksten, 1986) with approximately 40 to 50 percent occurring as snow. The dominant tree species are a mix of Western Red Cedar and Douglas-fir. The landslide is located in gneiss, granite and granodiorite types of bedrock formation (Kowall, 1980).

A schematic profile showing the position of the Vavenby landslide relative to its surroundings is presented in Figure 2. The landslide started on the shedding position of a steep west-facing forested slope (>70%) of convergent type above the CN railway road bed. It left a scar approximately 50 m long, 20 m wide and 1 m deep in the form of a spoon-shaped depression downslope. The area immediately above the head of the landslide is forested and stable with no sign of recent erosion (Figure 2). The area further above this forested and stable portion of the steep slope is an area of gentle gradient (< 15%) that had been selectively logged in 1981 with birch being the species left standing. There is an access road with a culvert running through the upper portion of this logged area. Most of the area above this logging road capable of contributing moisture to the landslide site is steeper forested slopes of 20-50%. The snowmelt or the rain storm runoff, after passing through this culvert, will first accumulate in a swamp in the cut block before contributing any surface runoff downslope to the convergent type of slope where the landslide is located.

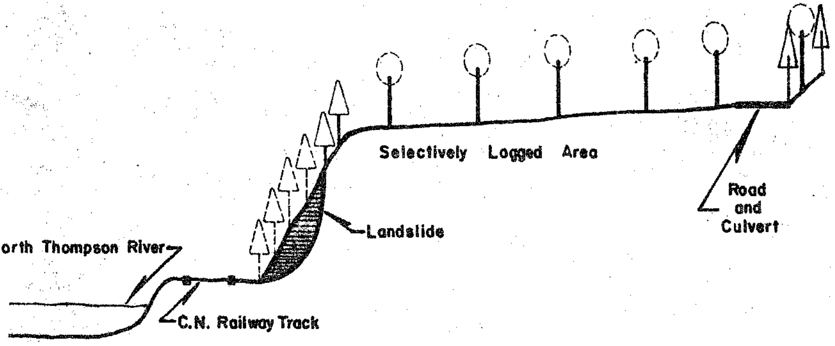

Figure 2. A schematic profile through the Vavenby landslide and terrain above it.

Factors affecting the occurrence of the Vavenby landslide

The site features of the Vavenby landslide suggest that it can be classified as a debris avalanche. Debris avalanches are rapid, shallow downslope movements of inherent soil, rock and forest debris with varying water content from hillslope areas. A debris avalanche often becomes a debris flow downslope because of substantial increase in water content (Baily, 1971, Burroughs *et. al.*, 1976).

Debris avalanches are caused most frequently when a sudden influx of water reduces the shear strength of earth material on a steep slope as a result of heavy rainfall (Baily, 1971) and/or snowmelt. As the saturation zone in the soil rises in response to rapidly infiltrated water from heavy rainfall and/or snowmelt, the bouyant uplift force of water reduces the interlocking force on the soil particles and this, in turn, reduces the frictional resistence to sliding. In addition, the downslope movement of seepage water also exerts a drag force on each individual soil particle along its path thus contributing to the driving force that tends to move masses of soil downslope. Generally, under the same groundwater conditions, a thinner soil mantle has a greater potential for sliding than a thicker soil mantle (Baily, 1971, Burroughs *et. al.*, 1976).

Debris-avalanche prone areas are characterized by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle, convergent topography on bedrock or glacial till surfaces (Swanston and Swanson, 1976). For example, the steep bow-shaped headwall areas of ephemeral streams, or the 0-order streams as described by Tsukamoto (1982) are where debris avalanches frequently occur. Because debris avalanches are shallow failures, factors such as root strength, anchoring effects and the transfer of wind stress to the soil mantle are potentially important influences. Factors that govern antecedent soil moisture conditions and the water supply rate to the soil by snowmelt and rainfall also have significant control over when and where debris avalanches occur (Swanston and Swanson, 1976, Swanston, 1984). The evaluation of field observations and pertinent hydrometeorological information indicates a combination of all or most of the following factors was most likely responsible for the occurrence of the Vavenby landslide on April 12, 1985.

a. Slide-prone site

The surficial material consists of gravelly, loamy sand materials on 70 to 80% slope. Minor bedrock outcropping also occurs. At the depth of 100 cm there is a transition layer between the permeable soil and impermeable sublayer that appears to be the failure phase. Tree root density is generally high in the permeable surface layer but root growth is restricted at the transition sub-soil layer due to the high density materials. This makes it a site with high windthrow susceptibility. There is evidence of windfall at and around the landslide site. The surface slope angle (70-80%) on the site is high enough for potential failure. As well, the convergent type of slope and the high density subsoil with low permeability is highly susceptible to increased pore water pressure due to snowmelt and/or rainfall that might have contributed to the system.

b. Heavy snowmelt

Heavy snowmelt and/or heavy rainfall in the area (500-800 m elevation) of about 100 ha tributary to the landslide site can trigger slope failure such as debris avalanches by providing a large volume of water to the soil. As described earlier, this will subsequently cause the development of high pore-water pressure over an impervious layer, a condition very favourable for initiating debris slides. Based on data supplied by the B.C. Ministry of Environment, the snowpack water equivalent of 382 mm on April 1, 1985, as measured by the Blue River Town snow course (670 m) was among the highest on record (Table 1, Figure 3). However, the unusually high temperatures from April 7 to 12, completely melted the snow pack at low elevation areas in southcentral B.C., including the landslide site (Figure 4). This was in great contrast to snowmelt patterns of 1972, 1974 and 1982, three years with April 1 snow water equivalents similar to or higher than the 1985 value. However, the snowmelt volume between April 1 and May 1 in these three years were at least 200 mm less than the 1985 value (Figure 3). In fact the 1985 snowmelt between April 1 and May 1 broke the highest snowmelt record established over the previous 14 years. The calculation with temperature data from the AES climate station at Vavenby indicates that the available energy was sufficient to melt the snow at the landslide site completely by April 12, 1985 (Martinec, 1976).

Table 1. Summary of 1971-85 Snow Survey Measurements at the Blue River Town Snow Course Station (1E01A).

Elev. 670 metres Lat. 52°08' Long. 119°15' Drainage: NORTH THOMPSON

JANUARY 1			FEBRUARY 1			MARCH 1			APRIL 1			YEAR	MAY 1			MAY 15			JUNE 1			JUNE 15		
DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm		DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm	DATE	SNOW DEPTH cm	WATER EQUIVALENT mm
01-01	61	124	02-01	99	229	02-28	104	277	03-31	109	325	1971	05-01	30	107	05-15	0	0	06-01	0	0			
01-02	86	175	01-23	175	284B	02-27	155	381	03-29	107	434	1972	04-30	66	290	05-12	18	79	05-28	0	0			
01-01	66	168	01-31	97	224	03-01	89	279	04-01	76	290	1973	05-01	18	66	05-15	0	0	06-01	0	0			
01-01	84	208	01-31	132	373	02-28	142	409	03-31	102	356	1974	04-30	46	193	05-14	0	0	06-01	0	0			
01-02	86	170	02-01	99	279	03-01	127	345	03-31	114	371	1975	05-01	48	198	05-15	0	0						
01-02	53	97	01-29	97	244	03-01	107	310	03-31	89	264	1976	04-29	30	119	05-15	0	0						
12-31	51	117	02-01	61	147	02-28	63	178	03-28	58	196	1977	04-25	0	0	05-15	0	0						
01-03	74	190	01-31	99	269	02-24	89	277	04-01	71	226	1978	05-01	0	0	05-15	0	0						
01-01	63	116	01-26	74	148	02-25	107	249	03-29	73	234	1979	04-27	31	127A	05-14	0	0						
12-26	68	148	01-30	83	198	02-27	93	262	03-26	87	287	1980	04-30	0	0	05-15	0	0	06-01	0	0			
01-01	82	211	02-01	77	240	03-01	79	278	04-02	62	246	1981	05-02	17	62	05-15	0	0	06-01	0	0			
01-01	53	106A	02-02	129	277	03-06	128	373	04-01	117	387	1982	05-01	58	211	05-15	16	63	06-01	0	0			
									03-31	61	236	1983	05-02	0	0	05-15	0	0	05-31	0	0			
01-07	65	118A	02-03	85	206A	02-29	99	267	03-29	68	220	1984	05-01	0	0	05-15	0	0	06-01	0	0			
12-30	104	200	01-29	105	281	02-26	122	354	03-28	107	382	1985	04-29	0	0	05-15	0	0	06-01	0	0			
				100	240		99	284		85	286	NORMAL		23	91									
	71	153		95	240		107	303		87	297	MEAN		23	92		2	9		0	0			

(after B.C. Ministry of Environment, 1985b)

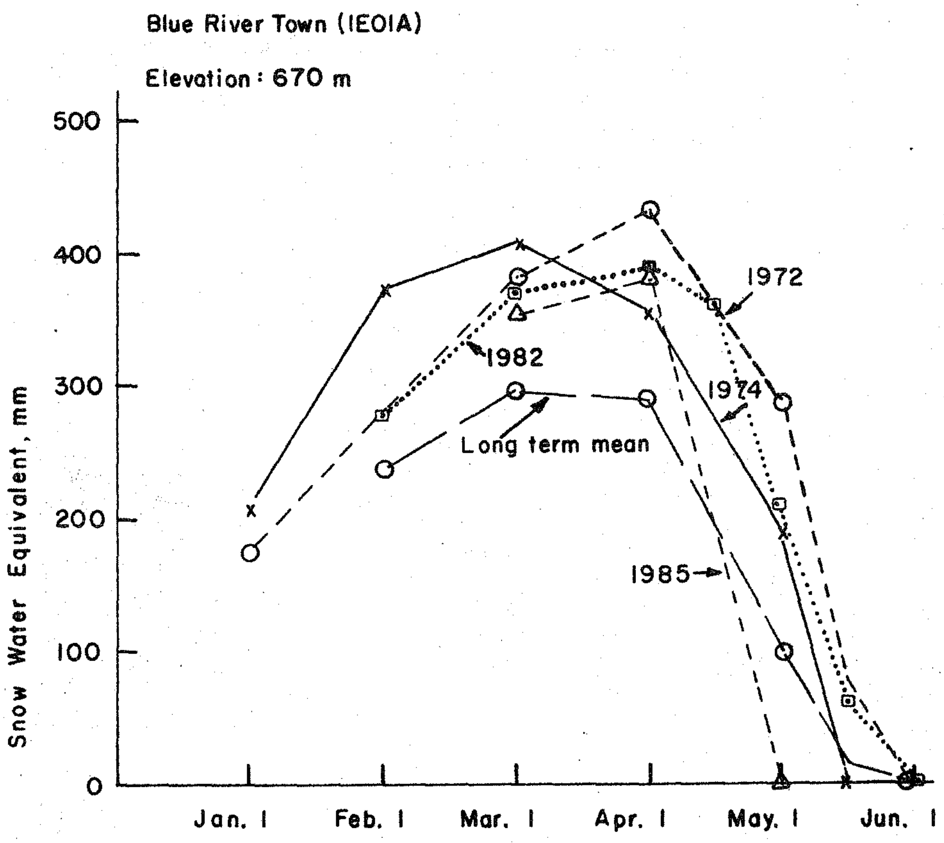

Figure 3. Snow water equivalents at the Blue River Town snow course for the years of 1972, 1974, 1982 and 1985 as compared to the long-term (15 years) means.

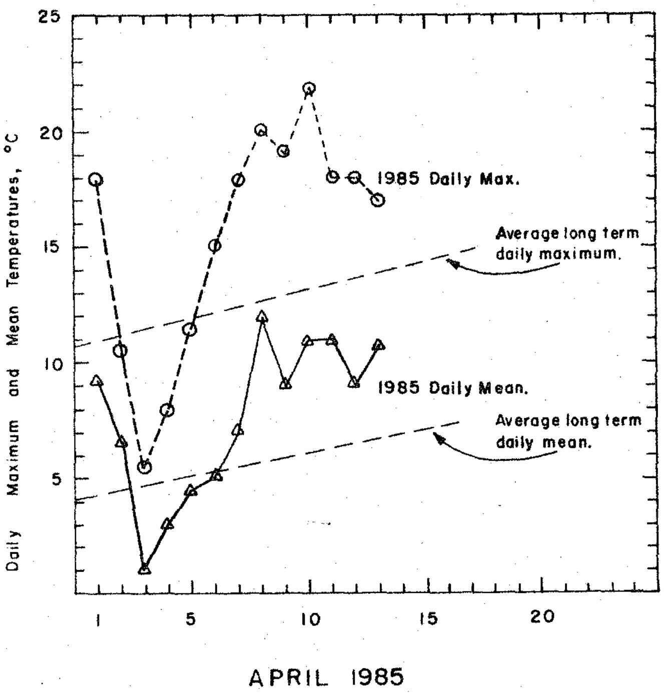

Figure 4. Maximum and mean temperatures at the Vavenby climate station for early April, 1985 as compared to the long-term (30 years) averages.

c. Windthrow

Wind forces transmitted to the soil are often considered as a probable triggering factor for debris slides on shallow soil. When trees sway in the wind, the ground is loosened or the trees may fall, thus possibly inducing landslides. In addition, the soil cavities created by uprooted trees tend to intercept surface and subsurface runoff and cause higher pore-water pressure in the downslope soil layer. Evidence of recent windthrown trees adjacent to the landslide site strongly suggests that wind swaying might have been a factor in causing the Vavenby landslide near the CN railway track.

d. Selectively logged cutblock on the landslide site

The evapotranspiration reduction in the selectively logged area of about 30 ha might result in a higher soil water content. The amount of increased soil water depends on the proportion of trees removed. However, once the soil is recharged early in the snowmelt season, i.e. spring, the effect of a reduced ET on soil water becomes negligible (Satterlund, 1972). The culvert was located where the logging road crosses the natural drainageway. There was no sign of excessive runoff passing through the culvert and contributing to the landslide site during the April snowmelt event.

The selectively logged cutblock, with elevation ranging from 520 to 580 m, above the landslide site, could be considered a clearcut with regard to snow accumulation and melt during winter and early spring because the remaining birch trees were leafless. With no interception of snow by tree branches and leaves, generally more snow is deposited in a clearcut than in the forest. In general, snow also melts slower at a forested site than at a large clearcut site because of shading of the forest and the higher wind speeds in the open that increase snowmelt through condensation and convection (Reifsnyder and Lull, 1965).

Discussion

A field inspection after the landslide occurrence can usually only provide clues useful for interpreting the nature of the landslide. The triggering mechanisms can then be inferred by using information on the site factors and climatic conditions related to landslide occurrence. Landslides are often initiated by the combined effects of several site factors and exceptionally high rainfall and/or snowmelt events with or without additional impacts from land use practices. It is often difficult to pinpoint the relative contributions of each factor due to the complex nature of landslide initiation mechanisms.

The Vavenby landslide near the CN railway track on April 12, 1985 occurred on a forested area. Therefore, it did not involve the loss or the reduction of the major beneficial impact of soil binding by tree roots on slope stability. By field observations and analyses of relevant climatic data, this landslide was considered to have been mainly caused by a record-breaking snowmelt event associated with one of the highest snowpacks on record and subsequently unusually high temperature in early April. This extreme climatic event had provided an extremely high volume of water into a slide-prone site due to steep and convergent slope, shallow soil and existence of ground scars resulting from uprooted windfall trees. The important role of exceptional storms or snowmelt events has often been documented in the literature (Swanston and Swanson, 1976, New Zealand Forest Research Institute, 1982, Sidle et. al., 1985).

Increased snowmelt rate and reduced evapotranspiration would normally cause increased soil water in the selectively logged area. However, in comparison to moisture contribution generated by the record-breaking snowmelt event, any increase in moisture contribution from the selectively logged area to the landslide site would likely be relatively small and insignificant in initiating or in enlarging the magnitude of the landslide. This is because the logged portion only represents about 30% of the total tributary area to the landslide site. Moreover, snowmelt and associated discharge peaks naturally occur earlier at lower elevations. This might cause a desynchronization effect (Goodell, 1959, Anderson, et. al., 1976, Lee, 1980) on the peak moisture received at the landslide site because of the possible difference in timing of peak moisture contributions from the higher elevation portion (580-800 m) of the total tributary area.

It should also be pointed out that the extreme warm temperature in early April 1985 had caused landslides at several other locations including forested sites without any disturbance in their adjacent areas (Watt and Cheng, 1985) and floodings at many places in the low elevation areas in the region (B.C. Ministry of Environment, 1985). The two landslides along the north arm of Quesnel Lake (Figure 1) had site features similar to those of the Vavenby landslide, i.e. steep, convergent slopes with shallow, gravelly sandy soil above a high density sub-layer and at a headwall area of an ephemeral channel in low elevation areas. One of these two landslides is located in a completely forested site remote from any human disturbance. The other landslide has a stable forested area separating it and the newly constructed logging road above. However, field observations had also suggested that this slide was not caused by the logging road. The timing of the regional extreme warm temperature and snowmelt in early April, 1985 agrees well with the data from three adjacent high elevation snow-pillow stations (Figure 5).

The B.C. Snow Survey Program with a network of snow course and snow pillow stations, provides data for water supply, flood control and power generation purposes. These stations are established at selected locations and elevations on major and tributary basins throughout the province. Among approximately 260 stations, only 28 (11%) are located at elevations lower than 800 m, probably due to their relatively insignificant value in water supply and flood control operations (Figure 6). However, as illustrated in this study, the data from these low elevation snow course stations could be very useful in providing early season snow accumulation and melt information for resource management and environmental impact assessment, particularly true if they are used together with other relevant snowpillow and climatic data.

CONCLUSION

Several site features combined to make the Vavenby landslide site and the two landslide sites inspected by Watt and Cheng (1985) very susceptible to mass wasting. These features include steep and convergent slope, shallow soil with high density sub-soil, and the evidence of scars from uprooted trees by previous windthrow. Analyses of snow-course, snow-pillow and temperature data indicate that these landslides were mainly triggered by an extraordinary regional climatic event producing an extremely large amount of snowmelt water to the soil in early April, 1985. The snowmelt event was in fact record-breaking due to very high April 1st snow accumulations and subsequently unusually high temperatures in early April. Increased snowmelt rate and reduced evapotranspiration at the selective cutblock of about 30 ha above the landslide could result in increased soil water available for contributing to the slide site. However, it is believed that, in comparison to an exceptionally large volume of moisture generated by the regional record-breaking snowmelt event, this increased contribution probably had only a relatively minimal role in initiating or in enlarging the magnitude of the landslide. This is because the logged area is only about 30% of the total drainage area above the landslide. Moreover, the faster and earlier snowmelt in this lower elevation logged area might cause a desynchronization effect on the peak moisture received at the landslide site. The data from low elevation snow course stations proved useful in assessing early-season snowmelt events.

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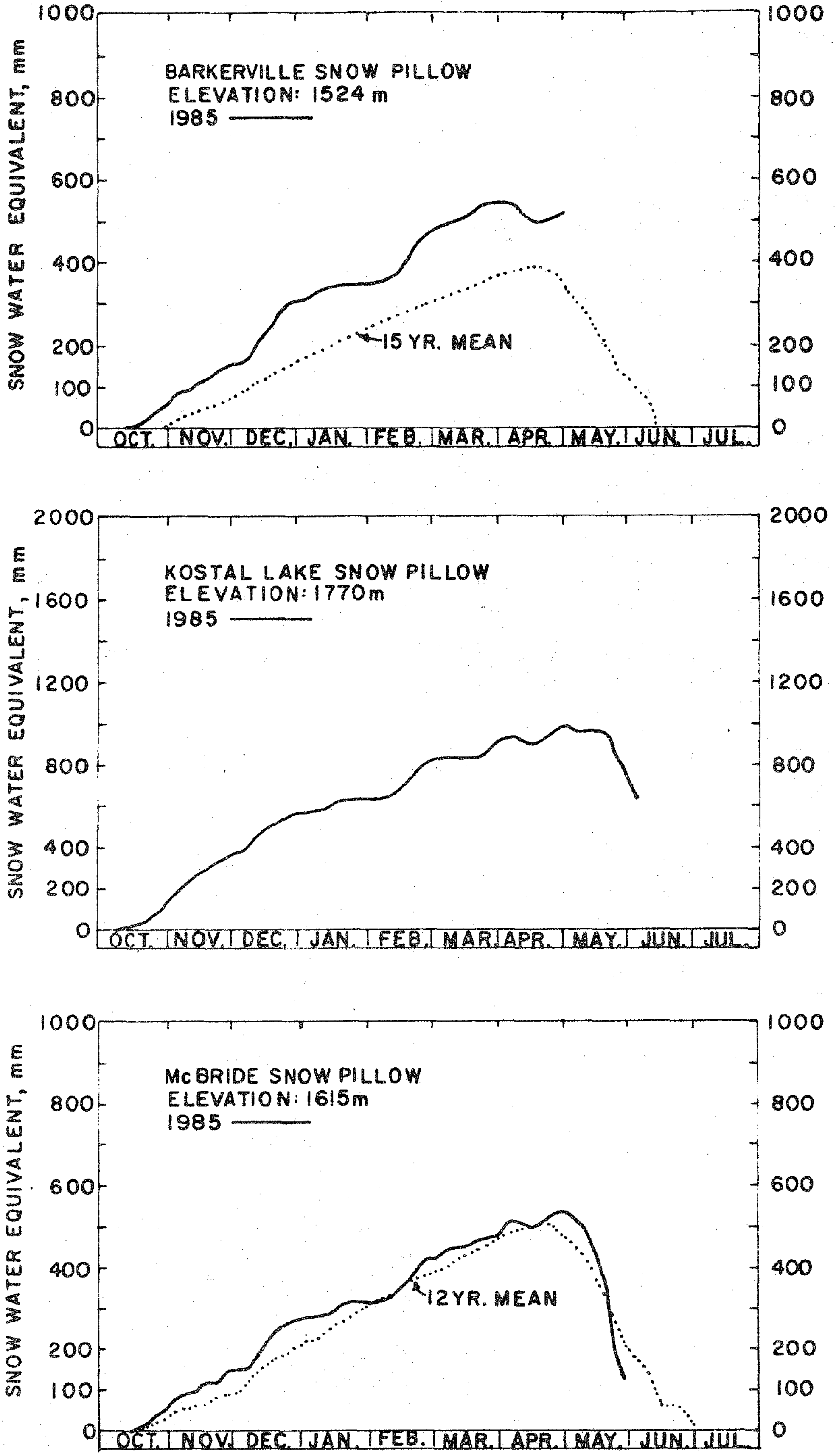

Figure 5. 1985 snowmelt timings as indicated by data from three snow pillow stations in the general vicinity of the Vavenby landslide site.

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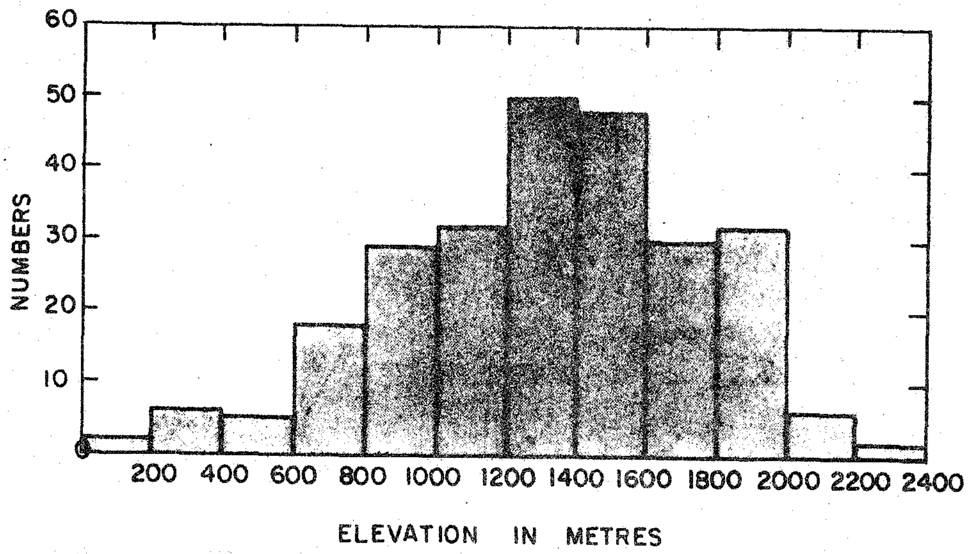

Figure 6. Elevation distribution of snow course stations in British Columbia based on data supplied by the B.C. Ministry of Environment.