WEATHER AND SNOWPACK CONDITIONS ESSENTIAL TO SLUSHFLOW RELEASE AND DOWNSLOPE PROPAGATION

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ABSTRACT

Rapid mass movement of water-saturated snow, usually known as slushflow or slush avalanche, is a major natural hazard in Norway. Slushflows occur in winter during heavy rainfall, as well as due to intense thaw in spring. The basic interrelations between ground conditions, snowpack properties and water supply, critical to slushflow release and downslope propagation, has been studied. The analytical approach to these problems and the major conclusions are summarized.

Altogether 31 slushflow periods and more than 80 slushflow sites, critical to human activity and located close to meteorological stations, were examined. The geomorphic and vegetational site characteristics, snowpack development and flow path morphology were established by field work as well as interpretation of maps and meteorological records. Estimation of precipitation and meltwater were based on meteorological data transformed to the starting zones.

Drainage channels and water-saturated snowfields are the typical starting zones of slushflows. Slushflows due to cyclonic activity are normally released within 24 hours of rain and snowmelt. Five main combinations of winter snowpack and current weather were identified to characterize the slushflow periods. Cohesionless new snow and coarse grained snow are most liable to start flowing, and tend to spread out downslope. The most favourable conditions for large slushflows are coarse grained snowpacks with depth hoar at the base, and when water is in abundance during spring break-up. Acute hazard may be predicted based on meteorological records and weather prognosis.

INTRODUCTION

Flowing mixtures of water and snow are a major natural hazard in Norway (Fig 1-3). Numerous terms have been used by scientists and practitioners when describing these phenomena. You may have characterized them by terms such as: Water-snow flow, rain-on-snow event, slushflow, slush avalanche, "odd-ball" avalanche, wet snow avalanche or maybe flood ? The participants in the Circum Arctic Slushflow Workshop in Kirovsk, Russia in 1992 decided to recommend the name slushflow when dealing with these phenomena.

Slushflows are released when the gravity component parallel to the slope exceeds the basal friction and the tensile strength of the snowpack. Whether the snowpack will reach a critical stability during rain and snowmelt depends on the relative rate of formation and discharge of free water at the base of the snowpack, which is basically governed by the ground conditions, the texture and structure of the snowpack, and the rate of water supply (Fig. 4-5). The critical pore pressure may also form above an impermeable layer in the snowpack.

Slushflows may sometimes be released as wet slab avalanches. In those cases liquefaction may occur instantaneously or when the snow mass reaches snowfields of higher water content. The possible size of slushflows seem almost unlimited. The impact of large slushflows may sometimes create destructive flood-waves in fjords and lakes (Fig. 6).

In Norway, districts exposed to high cyclonic activity during winter are most exposed to slushflow hazard. This includes both West and North Norway. Slushflows released during the spring break-up are also common. They primarily affect inhabited areas in North Norway, as well as the settlement of Longyearbyen on the island of Spitsbergen at 78° north (Fig. 7-8).

Slushflows are primarily a threat to housing, constructions and communication lines (Fig. 9-12). According to historical documentation, slushflows and snow avalanches are almost equally responsible for damage and economic loss in Norway.

When the extensive consequences of slushflows were realized in the early 1980's, a research programme on slushflows was started at the Norwegian Geotechnical Institute (NGI). The main scientific purpose was to develop objective criteria to identify hazard areas and methods for slushflow prediction and control.

The present paper summarizes the analytical approach to the basic interrelations between ground condition, snowpack properties and water supply, critical to slushflow release and downslope propagation.

METHODS OF INVESTIGATION

Sampling

The snowpack development prior to 31 slushflow periods have been analysed. Altogether more than 80 slushflow sites, critical to human activity and located close to meteorological stations, were examined. The reference periods and sites were intentionally selected to cover a representative variety of weather, snow and ground conditions. A varying number of events are recorded during the different slushflow periods, and two periods have a large regional representation.

The analyses are based on data from more than 80 meteorological stations run by the Norwegian Meteorological Institute (DNMI). All slushflow sites were within a distance of 40 km from a synoptic station recording 3 or 4 times a day, and less than 20 km from a precipitation station. In most cases the distances were less than 20 km and 10 km, respectively.

Fig. 1 A huge slushflow released from a low-grade snowfield of high water content on the mountain slope has destroyed the farm buildings at Fivelstad, Stranda 05.02.1990 (Photo K. Kristensen, NGI)

Fig. 2 A small slushflow has run into the town of Hammerfest at 71° and demolished two houses 15.02.1994. (Photo K. Lied, NGI)

Fig. 3 The slushflow in Hammerfest was released in a drainage channel due to rain and snowmelt 15.02.1994. (Photo K. Lied, NGI)

Fig. 4 The water level in the central part of this sloping snowfield is 1.3-1.4 meters, Telemark 28.04.1984. (Photo E. Hestnes, NGI)

Fig. 5 The water table in this drainage channel is between 1.2-1.5 meters, Rana 27.04.1994. The drainage is atop the snowcover. (Photo E. Hestnes, NGI)

Fig. 6 A destructive flood wave was created in Vetlefjorden by the impact of a huge slushflow 28.04.1994. The slushflow was 600 meters wide by the fjord. (Photo E. Hestnes, NGI)

Fig. 7 A slushflow has run into the settlement of Longyearbyen, Spitsbergen at 78°, 14.06.89. (Photo K. Anthonsen, Svalbardposten)

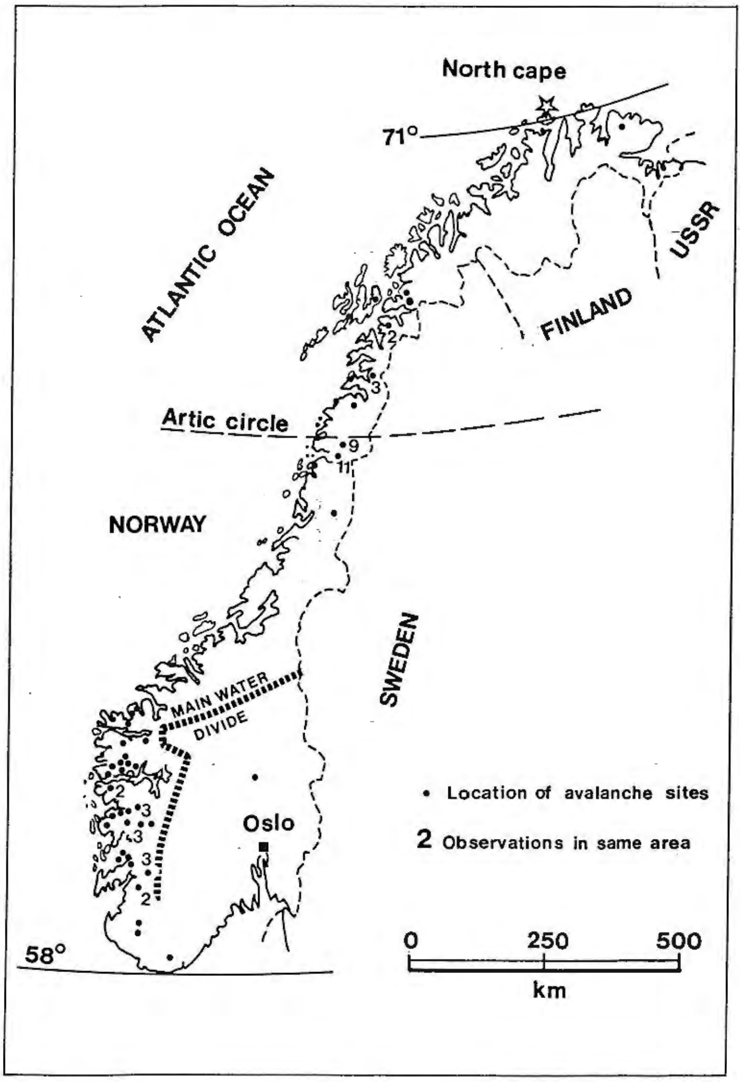


Fig. 8
Location of the investigated slushflow sites.

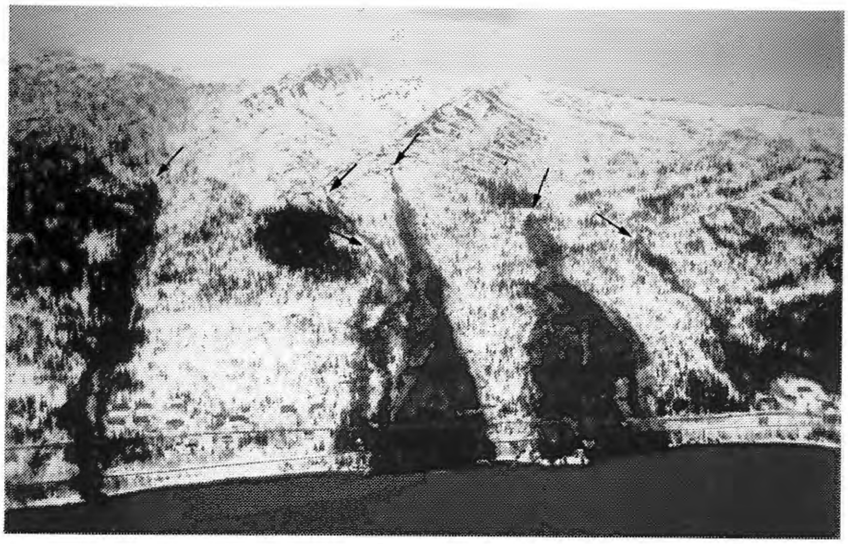


Fig. 9
The slushflows on this sparsely forested hillside in Sjånesheia, Rana, 27-28.01.1981, closed the road and the railway between South and North Norway for 2 and 4 days, respectively. The arrows indicate the starting zones of six slushflows.
(Photo O.I. Tysnes, Dagbladet)

Fig. 10 Cars waiting for the road to be opened after the first blockage, were hit by the second slushflow and thrown off the road, causing 3 fatalities and 5 badly injured. Sjånesheia, Rana, 27.01.1981. (Photo S. Bakkehøi, NGI)

Fig. 11 The rescue team are searching for two victims in one of the demolished houses covered by frozen slush. Sjånesheia, Rana, 29.01.1981. (Photo S. Bakkehøi, NGI)

To drept av snøras i Steira — fire våningshus og tre fjøs tatt

Two fatalities due to slushflows in Steira - 4 houses and 3 cowstables destroyed. (3 adults and 3 children were injured.)
Handnesøya, Nesna 16.01.1967.
(Photo B. Madsen, Rana Blad)

Fig. 12
Newspapers have been an important source of information about historical slushflows in this century.

Site characteristics

The geomorphic and vegetational characteristics of the slushflow sites and interfering environment were evaluated by interpretation of topographical and economical maps, scale 1:50 000 and 1: 5 000 respectively, aerial photographs and comprehensive field work. Vegetation survey maps and vegetation classification indexes have been used when available.

Quantitative and qualitative aspects of landforms and ground conditions related to slushflow activity have previously been presented by Hestnes (1985) and Hestnes & Sandersen (1987).

Snowpack development

The snowpack properties at the time of slushflow release are a result of the contemporary ongoing changes of snowpack through the winter, and the weather condition during the critical warm front passage(s) (Hestnes & Sandersen 1987, Hestnes et.al 1987).

Deduction of the snowpack development during winter, and the texture and structure of the ultimate snowpack, was done by comprehensive analysis of the meteorological records. Classification sheets including both quantitative and qualitative data, as well as time-profiles based on data from the nearest or most relevant meteorological stations, were useful analytical tools. Altogether 185 time-profiles were drawn (Fig. 13-14).

In the analysis it proved helpful to divide the winter prior to slushflow release into a 'winter period' and a 'current period'. The winter period is defined to start with the snow accumulation (W_o) and last until the start of the thawing weather (W_t). The current period is identical with the critical warm front passage(s) or critical snowmelt period in spring (C_o - C_t) (Fig. 13-15). The winter period and current period may almost coincide when slushflows occur in early winter. Later in the season the two periods will normally have a few days of overlap. When slushflows occur during spring break-up the two periods may not have overlap at all.

It also proved helpful to divide the current period into an 'initial stage' (snow) and a 'final stage' (water). The final stage is the time of rain and meltwater supply to snowpack, and is thus the period conducive to slushflow release.

Transformation of weather parameters

The amount of snow, rain and snowmelt received per unit area in the starting zones during the current period were estimated, based on the records of the nearest meteorological stations transformed to the actual slushflow sites.

Aerological diagrams always served as a base for transformation of the recorded temperature values (Fig. 16). The wet adiabatic laps rate was used, if in accordance with the aerological observations. The humidity is calculated by using the observed water vapour pressure and the corrected temperature.

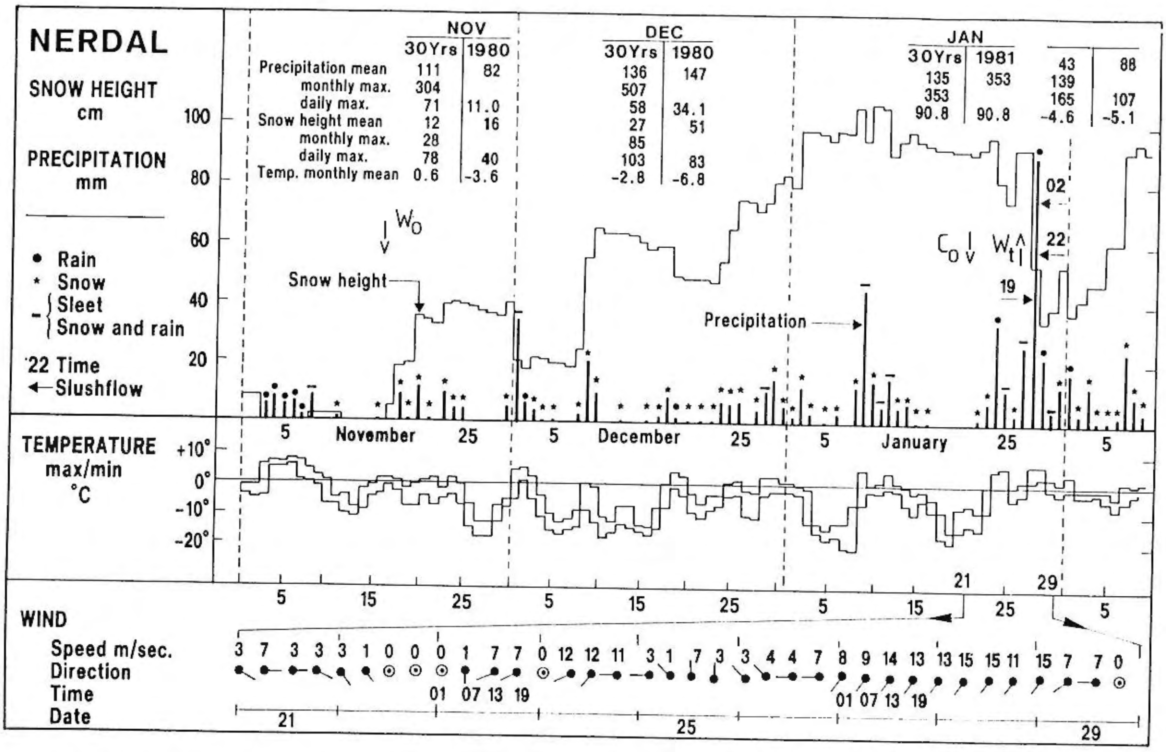


Fig. 13 The winter and current weather conditions leading to the catastrophic slushflows, in Sjånesheia, Rana 27-28.01.1981. Weak cohesionless winter snowpack of coarse grains. Daily records from the DNMI observation station 7940 Nerdal, 2.5 km away.

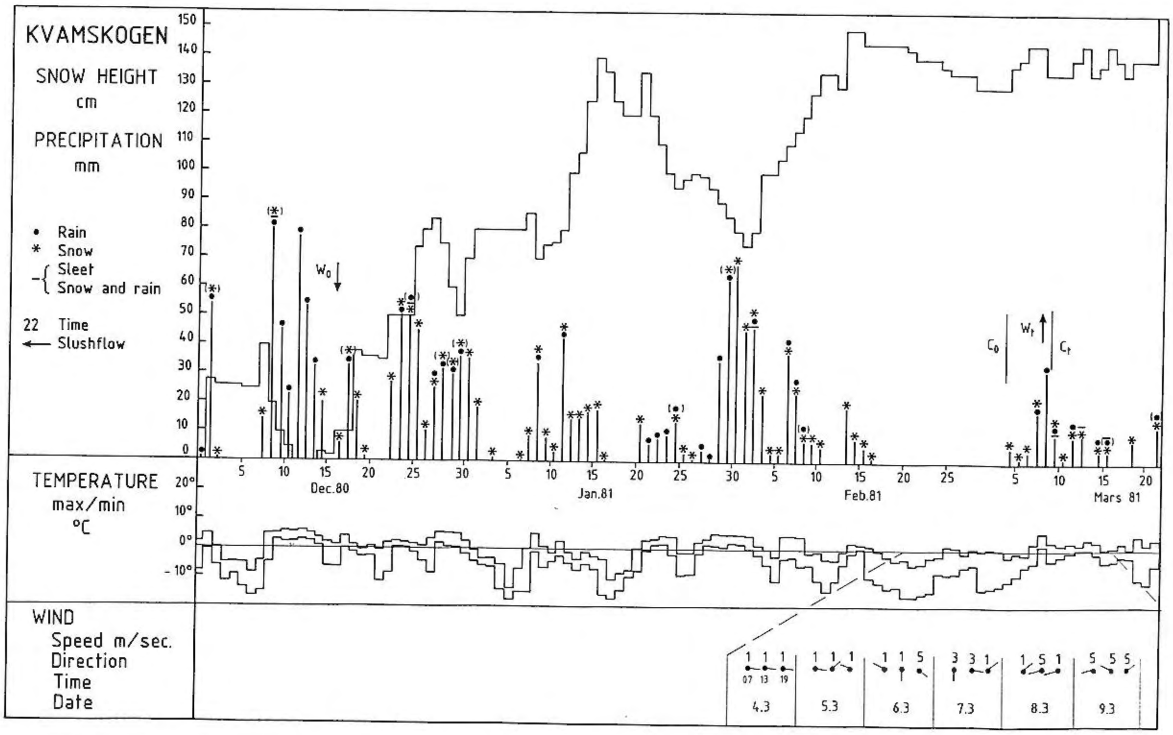


Fig. 14 The winter and current weather conditions leading to the slushflow at Kvam (Fig. 18). Stratified and relatively stable winter snowpack. Current period characterized by some snowfall and moderate supply of rain and meltwater. Daily records from DNMI observation station 5030 Kvamskogen, 22 km away.

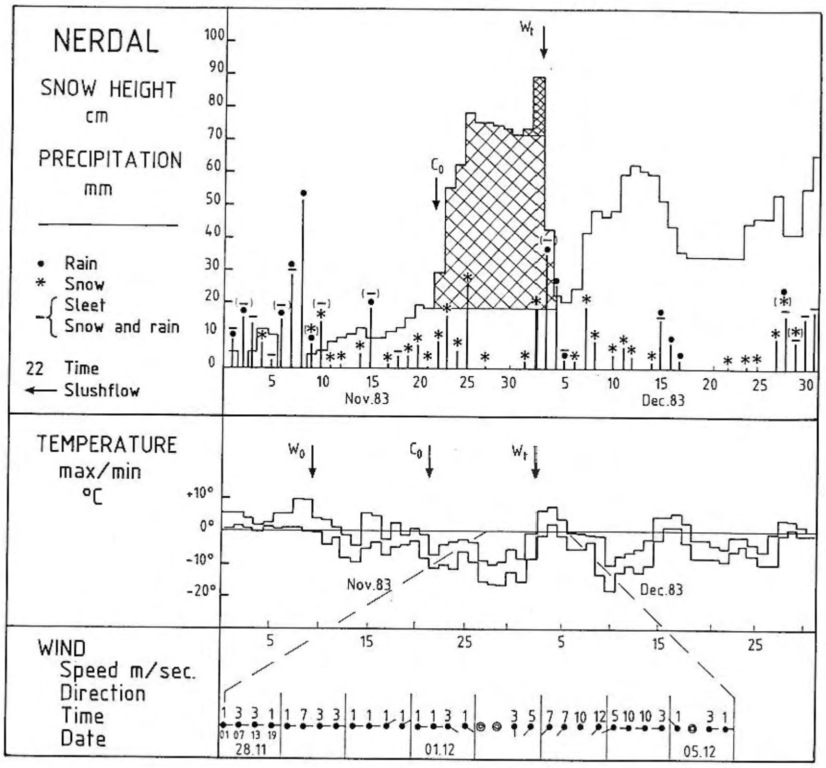


Fig. 15
The winter and current weather conditions leading to the slushflow in Sjånesheia, Rana 03.12.1983. Weak early winter snowpack. Cohesionless dry new snow of current period on top. The winter period and current period almost coincides. Daily records from the DNMI observation station 7940 Nerdal, 2.5 km away.

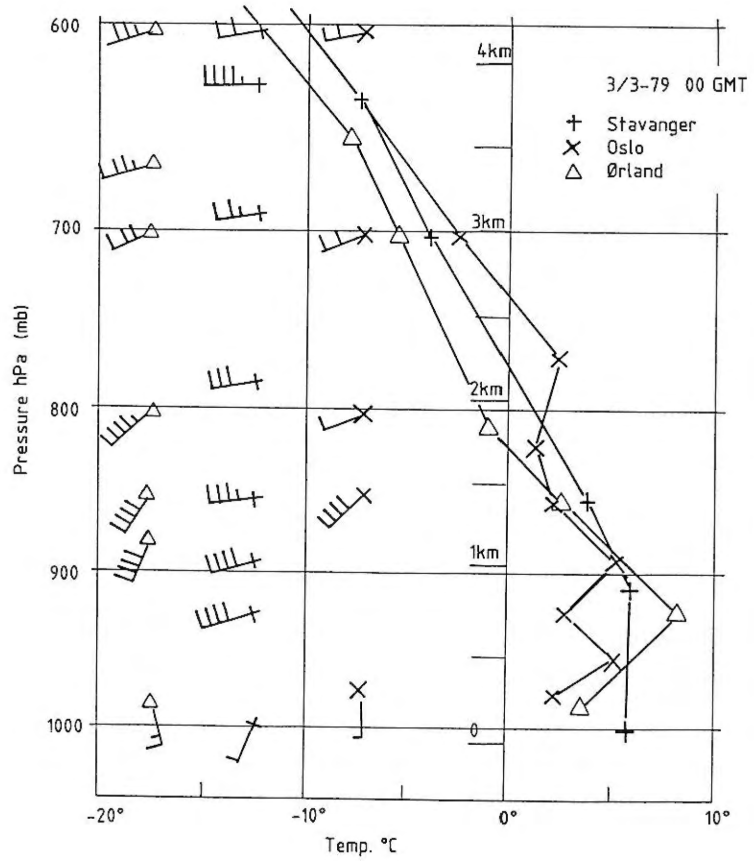


Fig. 16
Aerological diagrams at 00 GMT 03.03.1979 of Oslo, Stavanger and Ørland. Weather conditions with inversion or constant temperature below 1000 m is very frequent, and have to be considered when estimating precipitation and meltwater.

The type and amount of precipitation is estimated based on the transformed temperature values, recorded precipitation characteristics, topographic conditions and subjective judgements.

Correction of wind speed is also normally required. The recorded wind speed is then transformed to the slushflow sites by an empirical formula involving distance, height differences and roughness parameters. Sometimes the windfield also has to be corrected due to convergence or divergence (Nordseth 1986). The complete formula and the parameters involved are defined below (Fig. 17).

$$\bar{v}_h = \bar{v}_{10} \cdot f_1 \qquad f_1 = \left(\frac{h}{10}\right)^{\overline{n_1}} \qquad \overline{v_h} = \overline{v_H} \quad \frac{H}{z_o} = \left(\frac{L}{z_o}\right)^a \cdot b \quad \Rightarrow \quad H = \left(\frac{L}{z_o}\right)^{0.76} \cdot 0.48 \cdot z_o$$

$$\bar{v}_{10sz} = \bar{v}_H \cdot f_2 \qquad f_2 = \left(\frac{10}{H}\right)^{\overline{n_2}} = \left(\frac{10 \cdot z_o^{\,0.76}}{L^{0.76} \cdot 0.48 \cdot z_o}\right)^{\overline{n_2}} \qquad \bar{v}_{2sz} = \bar{v}_{10sz} \cdot f_3 \qquad f_3 = \left(\frac{2}{10}\right)^{n_3}$$

$$\bar{v}_{2sz} = \bar{v}_{10} \cdot f_1 \cdot f_2 \cdot f_3 \cdot K = \bar{v}_{10} \cdot \left(\frac{h}{10}\right)^{\overline{n_1}} \cdot \left(\frac{10 \cdot z_o^{0.76}}{L^{0.76} \cdot 0.48 \cdot z_o}\right)^{\overline{n_2}} \cdot \left(\frac{2}{10}\right)^{n_3} \cdot K$$

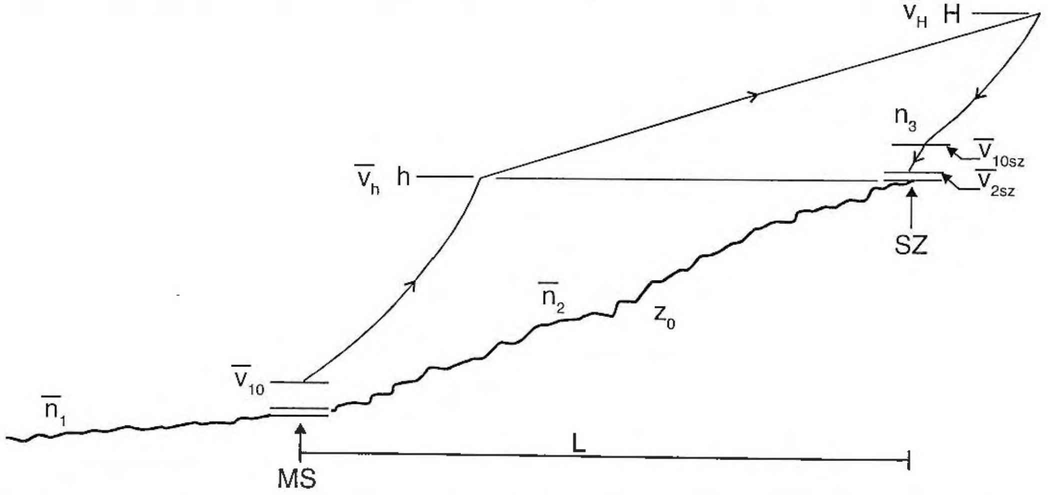


Fig. 17 Principle of transformation of recorded wind speed at meteorological station to starting zone.

v_{10} - wind speed 10 m above ground at meteorological station (MS)
v_h - wind speed at boundary layer/elevation of starting zone (SZ) above MS
h - elevation (m) of SZ above met. station
H_{sz} - elevation (m) of new boundary layer above SZ
$v_{Hsz} = v_h$ - wind speed at new boundary layer above SZ
v_{10sz} - wind speed 10 m above ground in SZ
v_{2sz} - wind speed 2 m above ground in SZ
n_1 - roughness constant of terrain prior to met. station
n_2 - roughness constant of terrain between met. station and SZ
n_3 - roughness constant of starting zone
L - horizontal distance (m) between met. station and SZ
z_o - roughness parameter (m) of terrain between met. station and SZ
a,b - constants related to reference height and roughness, respectively
K - wind speed correction constant due to convergence/divergence

Roughness constants, wind speed corrections and distances have been based on maps and vegetation classification indexes, aerial photographs and field work.

Meltwater estimation

The complete energy exchange for a snowpack can be written

$$Q_M + Q_I = Q_H + Q_E + Q_N + Q_G + Q_R$$

Q_M - energy consumption for snowmelt
Q_I - changes in internal energy of snowpack
Q_H - sensible heat flux from the atmosphere
Q_E - latent heat flux from the atmosphere
Q_N - net radiation of the snow cover
Q_G - heat flux from the ground
Q_R - energy gained from rainwater

Generally Q_I, Q_G and Q_R are negligible and can be disregarded. In bad weather with heavy cloud cover, the radiation term is also small compared with latent and sensible heat.

Calculation of snowmelt is primarily based on an energy balance model outlined for western Norway (Harstveit 1984). The rewritten model (mm day^{-1}) is shown below:

$$Q_M = Q_H + Q_E + Q_N \qquad \text{respectively:}$$

$$Q_H = (K_1 \cdot v_{sz} + K_2) \cdot t_{sz} = (0.8 \cdot v_{sz} + 0.6) \cdot t_{sz}$$

$$Q_E = (K_1 \cdot v_{sz} + K_2) \cdot 1/\gamma \cdot (e_{sz} - e_0) = (0.8 \cdot v_{sz} + 0.6) \cdot 1/\gamma \cdot (e_{sz} - e_0)$$

$$\begin{aligned} Q_N &= Q_S \cdot (1 - \alpha) + Q_{L\downarrow} - Q_{L\uparrow} \\ &= (-0.16(1\text{-}C) + 0.81(1\text{-}C)^{1/2} + 0.07)\, Q_{ex} \cdot (1 + 0.13(1\text{-}C) + 0.05 \ln D - 0.87) \\ &\quad + (0.265\, \sigma\, T_{sz}^4 + 18.4\, C - 23.9) - 81.8 \end{aligned}$$

K_1, K_2 - constants
v_{sz} - wind speed at surface in the starting zone
t_{sz} - temperature at surface in the starting zone
e_{sz} - vapour pressure at surface in the starting zone
e_0 - water vapour saturation pressure (6.11 mb)
γ - wet adiabatic laps rate
α - snow albedo
Q_S - global radiation
$Q_{L\downarrow}$ - incoming longwave radiation
$Q_{L\uparrow}$ - outgoing longwave radiation
Q_{ex} - extraterrestrial global radiation
C - cloud cover in 1/10 parts
D - number of days of exposed snow surface
σ - Stephan Bolzmann constant
T_{sz} - surface temperature (°K) in the starting zone

Multiple calculations were carried out to minimize the error in estimation of the total water supply. The period of water contribution to the snowpack was subdivided into time-intervals of uniform conditions. Each interval had a new set of transformed input values. Rainfall and meltwater estimations were performed within each interval. Total amounts of rain and meltwater were given by adding the estimated values.

The input values of the extraterrestrial solar radiation were adopted from a table by Harstveit (pers. com.) and Lystad (1980), and cover the latitudes 58° - 71° north. The albedo of snow surface was decided on according to guidelines by the Norwegian Meteorological Institute and the deduced character of the snow surface (Nordseth 1986).

Both the input data, the analytically determined process values and the calculations are listed in large work sheets. The possible consequences of incorrect input values dealing with meltwater estimation is discussed in Hestnes et.al. 1987.

Flow path morphology

The information on flow path morphology were collected by comprehensive field work and photographic material as well as contributed to by informants. The correlations between snowpack properties and flow path morphology were partly deduced from the snowpack analysis and partly observed in the field. The results are compared with the previous works by Hestnes (1985) and Hestnes & Sandersen (1987).

RESULTS

Site characteristics

The extensive survey revealed a nuanced variety of site characteristics, mainly in accordance with previously documented environmental and geomorphic features (Hestnes 1985, Hestnes & Sandersen 1987). They can be summarized as follows:

Slushflows most commonly comprise a part of the break-up process of drainage channels and streams, but they also start from inclined bogs, depressions and open slopes. Snow-embanked, water-saturated snowfields and lakes are other potential starting zones.

In drainage channels, crown surfaces are normally located either at sloping rock or at local reduction in gradient associated with irregularities in ground conditions. Sloping rock surfaces are typical for the starting zones with highest frequencies (Fig. 18-19).

Slushflows occur within cultivated land, pasture, open forest with grass and bush vegetation, forested hillsides and in treeless mountainous terrain. The landforms and drainage basins vary widely in size, shape and geomorphic configuration.

Slushflows are released at almost any level within drainage basins, and at different levels and ground conditions in the same basin. The average inclination from the crown to the bottom boundary of the main accumulation of slush is observed to vary between 4° and 20°.

Fig. 18 Channelled slushflow track with stones and pools. Starting zone in background. A skier trying to cross the water-saturated snow of the stream channel was caught by the slushflow and perished. Kvam, Øystese. 08.03.1981. (Photo F. Sandersen, NGI).

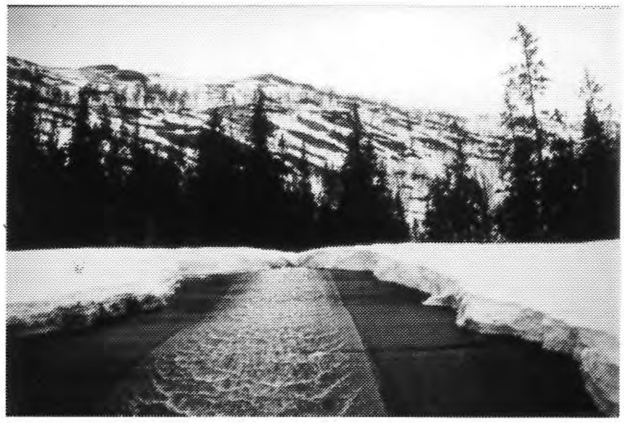


Fig. 19 Starting zone on sloping rock surface in brook. Sjånesheia, Rana, 27.01.1981. (Photo H. Norem, NGI).

The winter snowpack

The investigated slushflows occurred during November - May. Slushflow may, however, also occur in October as well as in June and July in mainland Norway. The length of winter period varied from 23 - 198 days.

The snowpack at the end of the 31 winter periods included a large variety of texture and structure. Less prominent slushflow periods during winter were preceded by fine grained snowpacks or stratified snowpacks. The winter snowpack prior to periods of many slushflows and particularly large slushflows in spring matched with one of the three classes (Fig. 13-15):

- Cohesionless new snow.
  Cohesionless new snow sometimes resting on an icy crust on top of a (thin) snowpack of coarse grains or stratified snow. (Primarily early winter.)

- Coarse grained snowpack.
  Weak cohesionless snowpack of coarse grains sometimes with depth hoar at the base. (All winter.)

- Stratified snowpack.
  Stratified snowpacks of different texture, often with crusts of snow and ice. (Primarily spring thaw.)

The investigation has documented that slushflows do occur on unfrozen ground as well as frozen. The previous classification by Hestnes & Sandersen (1987) has thus been entailed a minor modification according to this fact. Both cohesionless new snow in early winter and older snowpacks might rest on unfrozen ground.

The current period

Altogether 25 of the investigated slushflow periods occurred due to cyclonic activity in winter. The length of these current periods varied from 2-15 days, normally including several front passages (Fig. 20). The duration of the final stage of snowmelt varied from 5 - 36 hours.

The 6 slushflow periods due to spring thaw varied in length from 7 - 28 days. The duration of the snowmelt in these periods lasted from 5 - 16 days. The final stage during spring thaw might, however, sometimes be less than 24 hours.

The warm front passages causing slushflows always started with snow, often huge amounts of snow, before the temperature rose high enough for rain and snowmelt. In contrast, only two of the slushflow periods caused by spring thaw had a small amount of snowfall during the initial stage, but rain and snow in abundance in the final stage. There is a striking difference in estimated water supply between the slushflow periods due to cyclonic activity and spring thaw (Table 1).

Table 1. Estimated precipitation and snowmelt during the slushflow periods

Precipitation	Slushflows due to cyclonic warm fronts		Slushflows due to spring thaw	
	Range mm	Average mm	Range mm	Average mm
Snow	2-155	51	0-13	3
Rain	9-128	59	6-107	59
Meltwater	2-52	21	54-332	141
Total water	21-170	80	109-354	200

Meltwater accounted for 5-45 % of the total water supply in periods of cyclonic warm fronts. Rainfall was observed to contribute less than 5 %, but also as much as 65 % of the water supply during spring thaw situations. Net radiation constituted 20-50 % of the energy budget during spring break-up.

Weather and snowpack by slushflow release

Five main combinations of winter snowpack and current weather were identified to characterize the slushflow situations.

- New snow (early winter).
  Varying amounts of cohesionless dry new snow of current period, resting on ground or icy snow surface. The snowfall followed by intense pouring rain and snowmelt.

- Coarse grained snowpack.
  Weak cohesionless winter snowpack of coarse grains sometimes with depth hoar at the base. Large variety of precipitation and snowmelt during current weather period.

- Stratified snowpack I.
  Relatively stable winter snowpack. Current period charaterized by intense snowfall followed by abundant rain and snow melt.

- Stratified snowpack II.
  Relatively stable winter snowpack. Current period characterized by some snowfall and moderate supply of rain and meltwater.

- Ripe snow / Spring break-up.
  Coarse grained or stratified winter snowpack supplied with extensive meltwater and varying amounts of rain during the final stage of current period.

The snowpack stability

Cohesionless new snow and coarse grained snow are most liable to start flowing. A fine grained snowpack is stronger than a coarse grained snowpack. Snowpacks that, prior to the current weather period, are compact with hard or icy layers, normally show good stability. Hard crusts and icy layers are observed to withstand more than 3 days of saturation.

Coarse grained snowpacks with depth hoar at the base, provide the most favourable conditions for large slushflows. Large slushflows may also occur in stratified snowpacks and during spring break-up, when water is in abundance (Fig. 1,6 & 9).

Slushflow release

Slopes exposed to wind during frontal passages will normally be most susceptible to slushflows. They receive the highest influx of sensible and latent heat from the atmosphere, and thus the highest amount of melt water, and often the highest amount of precipitation as well.

Slushflow release and downslope propagation are closely related to the ground conditions, height and complexity of the snowpack, and rate and amount of water supply (Fig. 21).

Slushflows with wide regional occurrence have been released after cold periods with strong temperature gradients, forming weak cohesionless snowpacks of coarse grains with depth hoar at the base.

Winter weather characterized by repeated changes between snowfall, rain and cold dry weather, often causes rather different snowpack conditions within short distances mainly due to local variations in topography, precipitation and temperature. Slushflows may therefore occur rather locally and the flow paths are often channelled. However, intense rainfall on newly fallen snow resting on icy crust, has released numerous slushflows within a whole county.

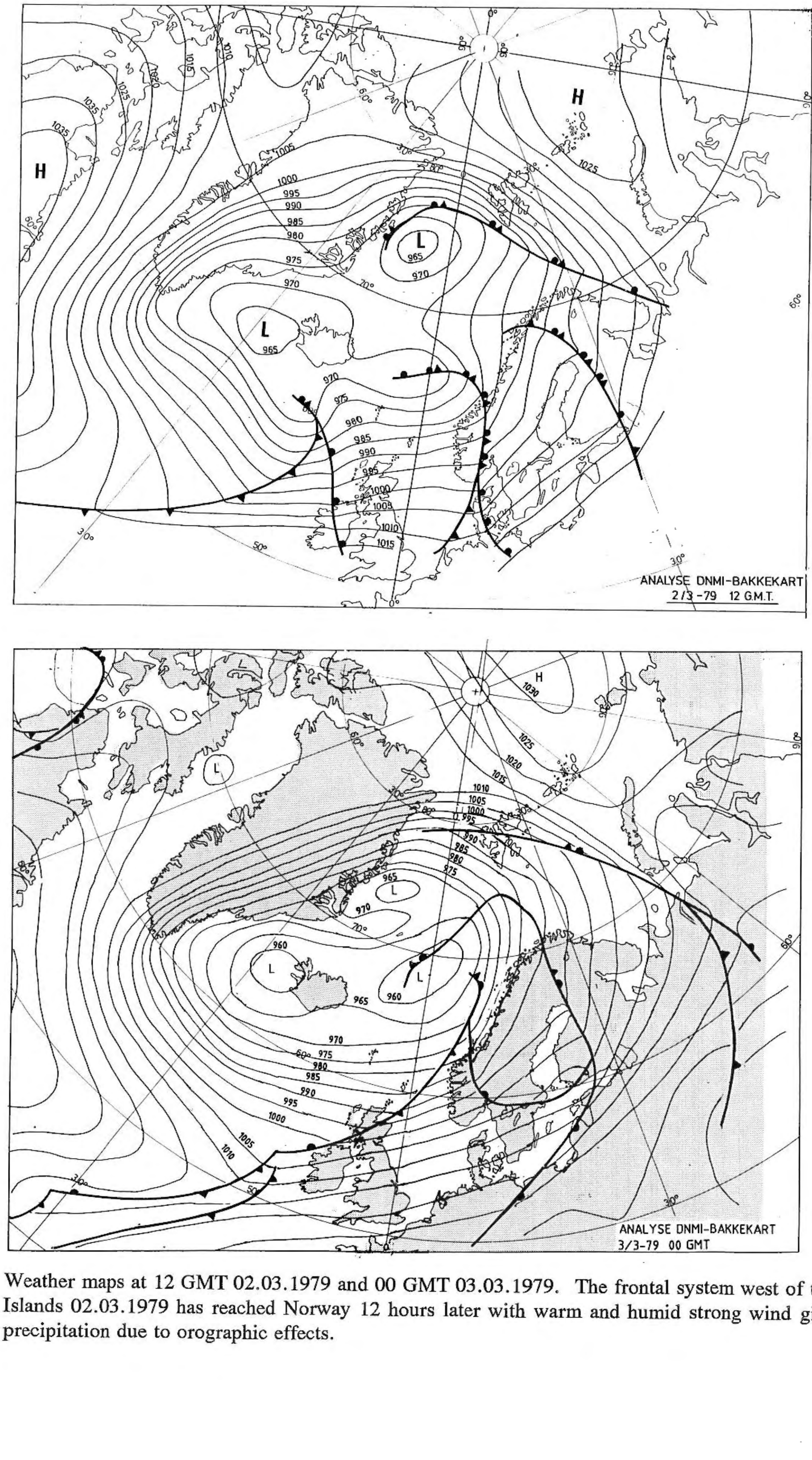


Fig. 20 Weather maps at 12 GMT 02.03.1979 and 00 GMT 03.03.1979. The frontal system west of the British Islands 02.03.1979 has reached Norway 12 hours later with warm and humid strong wind giving high precipitation due to orographic effects.

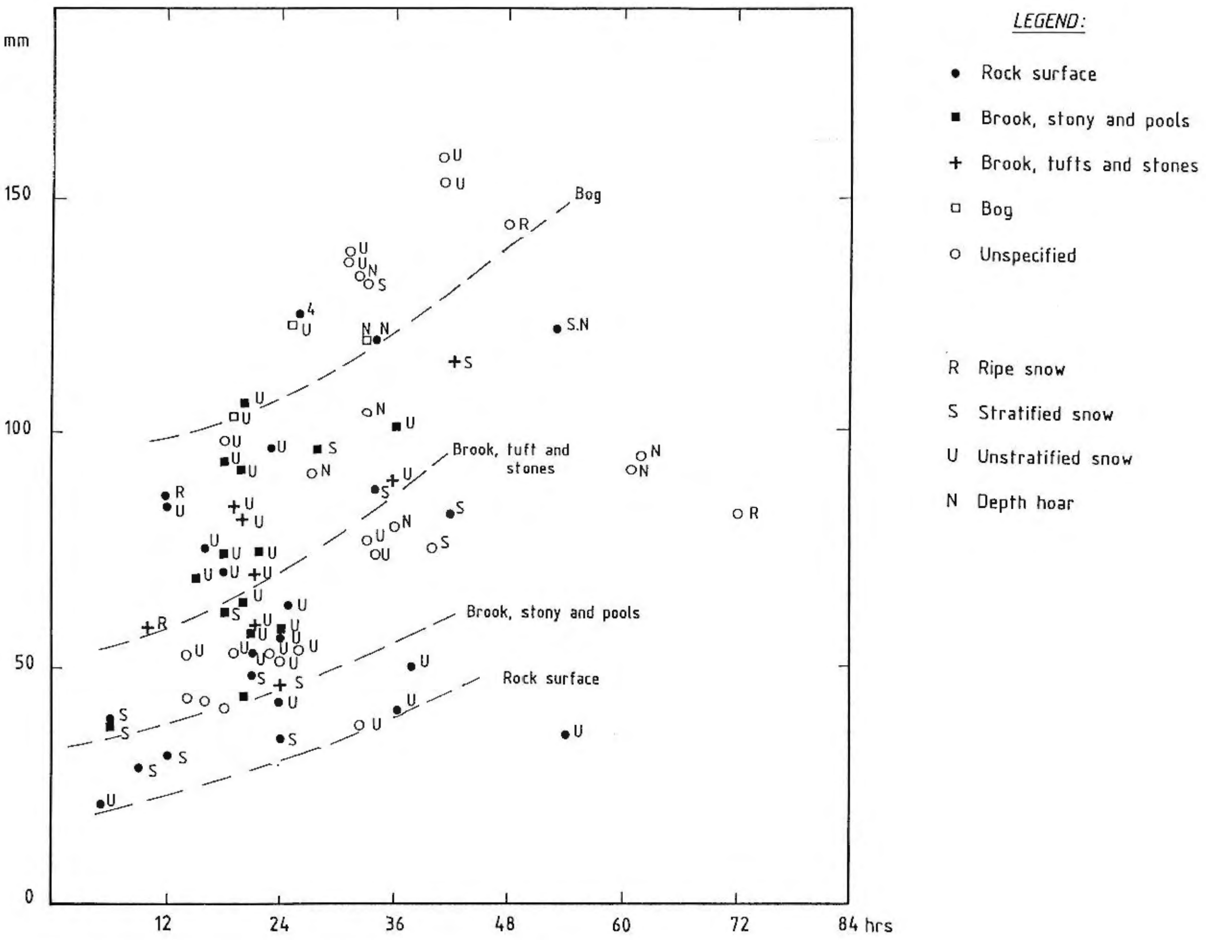


Fig. 21 Slushflow release as a function of total water supply, time and ground condition.

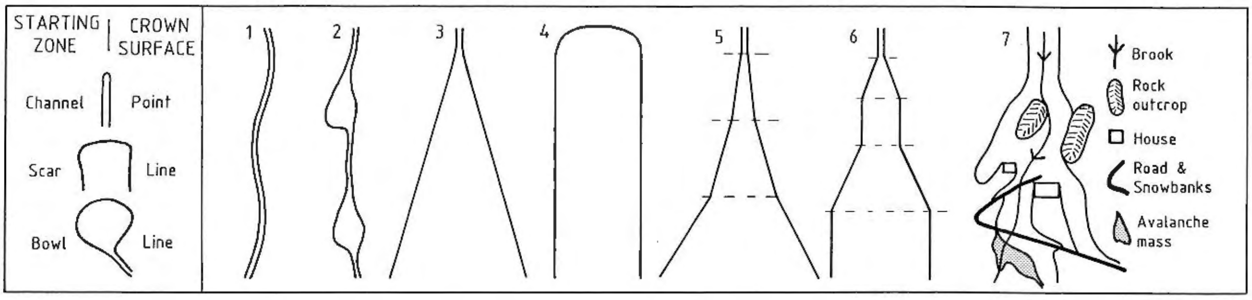
Downslope propagation

Major morphological types of starting zones and tracks are discribed in Hestnes (1985). All the investigated slushflows fit into the classification previously introduced (Fig. 22).

Slushflows in cohesionless new snow and coarse grained snow tend to spread out downwards. The normal downslope progress in dense fine grained snow and stratified snow, forms flow paths with nearly parallel sides if the gradient does not change. Channelled flow paths are primarily connected to drainage channels or low water supply (Fig. 18). They may occur on open slopes.

Scar-like starting zones and broad open paths are typical features of large slushflows. Bowl-like starting zones are typical for slushflows released from snow-embanked saturated snowfields and lakes. Enormous amounts of slush may sometimes drain from such starting zones.

Local topography, vegetation, snowbanks etc. always affect the downslope propagation of slushflows (Fig. 22).



TRACKS: 1. Channelled 2. Channelled - undefined (alternating) 3. Open slope, low - moderate gradient 4. Open slope, moderate - high gradient 5. Stepwise reduction of gradient 6. Alternating gradient 7. Changes due to other influences

Fig. 22 Major morphological types of starting zones and tracks opened in snow cover.

CONCLUDING REMARKS

The complex interrelations between factors essential to slushflow release and downslope propagation have been enlightened.

Apparently, the snowpack properties and water supply at specific slushflow sites can be deduced from the records at the nearest meteorological stations. This implies that criterias for acute hazard prediction at specific locations can be based on meteorological records and weather prognosis. The analysis also indicate that acute slushflow hazard, at least at many sites, can be predicted by a modified 'nearest neighbour method' (Buser et.al. 1987).

A paper dealing with the principles of the snowpack analysis, our decision making system for transformation of the recorded meteorological data to the starting zones and how to decide on the roughness parameters and other constants involved in meltwater estimation, is in preparation.

The next step in our research programme is to test and refine the emperical models for transformation of weather parameters and meltwater estimation, by comparing data monitored at slushflow sites with records from meteorological observation stations (Hestnes & Bakkehøi 1993).

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