Slushflow Questionnaire

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ABSTRACT

Questionnaires concerning slushflows were distributed globally. The purpose of the questionnaire was to determine the geographic distribution of slushflow activity as well as to collect information concerning most common nomenclature, release conditions, period of occurrence, type of terrain upon which they occur, the characteristics of starting zones, paths and run out zones, geomorphic activity, type of damage and hazard control.

Persons who have first hand experience with the slushflow process are identified. The answers have definitely established that slushflows occur in lower latitudes as well as in the arctic, and that slushflow hazard has not received the emphasis deserved. Heavy rainfall may cause slushflows at any time during winter, especially in areas with a marine west-coast type of climate. Stream channels and shallow depressions are the most common location of starting zones, while slushflow frequency seems to be related to the permeability of the substratum. Slushflows are a significant geomorphic agent, and there is an increasing encroachment of human activity into potential slushflow zones.

INTRODUCTION

There exists a general impression that slushflow activity, i.e. rapid mass movement of water-saturated snow, is confined primarily to arctic and high subarctic regions. This is partly due to the numerous accounts of the occurrence of this phenomena in these regions. Slushflows were first cited in modern literature by Washburn and Goldtwaite (1952). However, knowledge of slushflow activity has a much longer history. Osborn (1852) described slushflow activity near Barrow's Strait in the Canadian arctic

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and slushflow occurrences have been recorded by the Japanese for over 300 years (So Amma pers. comm.)

Recent work by Hestnes (1985) reported slushflow activity in southern Norway. These events in lower latitudes encouraged the authors to conduct a global survey concerning slushflow occurrence and characteristics. Questionnaires were sent to 950 universities, research centers, engineering institutes, and individuals in 44 countries (Table 1). Most addresses were selected from mailing lists obtained from the International Glaciological Society, International Snow Science Workshop Committee, the American Association of Avalanche Professionals, and the publication World of Learning.

Although responses to the questionnaire were fewer than anticipated, 130 questionnaires were returned. Of these 81 have been analysed. The remaining 49 respondents had little or no knowledge of slushflows. Another 18 were returned due to wrong addresses etc. Much of the information contributed indicates both institutional and national understanding concerning slushflows.

Responses to the questionnaire regarding geographic location indicate that the geographic distribution of slushflows is much broader than generally expected. Although the greatest number of occurrences are still reported in the higher latitudes (polar and subpolar regions), there are an impressive number of slushflows documented in the lower latitudes of Europe, Central Asia, China, Japan and North America, as well as in the southern hemisphere. Location of slushflow occurrences reported in the questionnaires are shown in Figure 1.

This information broadens the area of interest and raises many questions concerning factors which initiate slushflow occurrence. Initially, higher latitudes appeared to harbour environments most conducive to slushflow activity. This conclusion was based solely on the number of events reported. It now appears that the accelerated rate of snowpack melting due to intrusion of warm air masses and twenty-four hours of radiation input (Onesti 1987) are not the only factors which can induce slushflows. New questions, or at least other questions, now enter into the field of slushflow research.

Table 1. Distribution and Response

		Sent	Response	Analysed	No info
Scandinavia:	Denmark	9	3	2	1
	Finland	9	5	2	3
	Iceland	12	1	1	
	Norway	33	7	7	
	Sweden	15	3	2	1
Europe:	Austria	38	12	6	6
	Belgium	7	1	1	
	Bulgaria	3			
	Czechoslovakia	9	2	1	1
	East Germany	8	2		2
	France	37	3	2	1
	Great Britain	54	7	5	2
	Greece	4			
	Holland	8	3	1	2
	Hungary	6			
	Italy	26	5		5
	Liechtenstein	1			
	Poland	15	4	1	3
	Portugal	4	2	1	1
	Romania	4	1	1	
	Spain	18			
	Switzerland	29	7	2	5
	USSR	61	8	8	
	West Germany	48	5	2	3
	Yugoslavia	9			
Asia/Oceania/ Africa:	China	5	1	1	
	India	7	1		1
	Iran	1			
	Japan	36	2	2	
	Pakistan	1			
	Turkey	9	2	1	1
	Australia	1			
	New Zealand	24	7	7	
	Kenya	2			
North/South America:	Canada	55	6	3	3
	U.S.	323	26	21	5
	Argentina	6			
	Bolivia	1			
	Chile	6	3	1	2
	Columbia	1			
	Ecuador	2			
	Mexico	1			
	Peru	1			
	Venezuela	1	1		1
TOTALS:		950	130	81	49

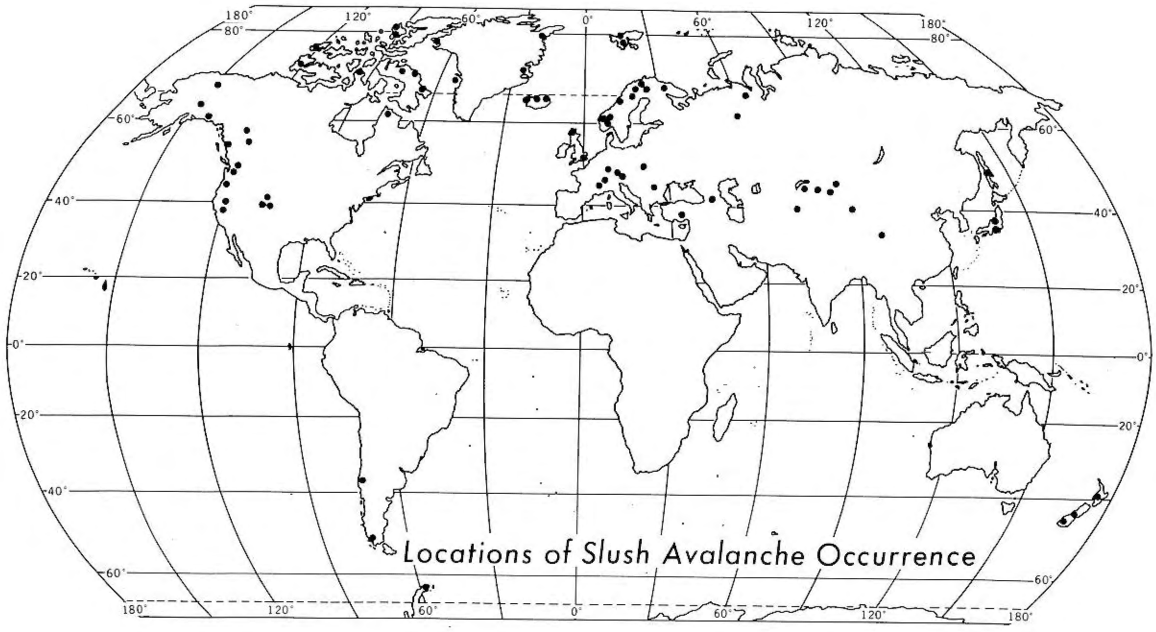

Fig. 1. Geographic distribution of slushflow occurrence.

<u>NOMENCLATURE</u>

In an attempt to determine which English or international terms were most commonly used when referring to slushflow-like phenomena, the following list was provided:

- Wet snow avalanche
- Slush avalanche
- Slushflow
- Mountain torrent
- Wildback
- Other

Responses were grouped into categories according to the number of similar answers as follows:

1)	Slush avalanche Slushflows	39%
2)	Wet snow avalanche Slush avalanche Slushflow	25%
3)	Wet snow avalanche	12%

It was difficult to interpret some questionnaires since it was problematic for the informants to differentiate between slushflows and wet snow avalanches. Several questions are raised by the above responses. Are there characteristic differences between wet snow avalanches and slush avalanches or slushflows? If so, what are the differences and can they be quantified?

In the literature "slushflows" and "slush avalanche" have been used synonymously and the term "wet snow avalanche" sometimes appears presumably with the same meaning. Nyberg (1985) suggests that the term "slush avalanche" might be restricted to major events, while "slushflow" could be applied also to small scale stream breakups. (In these cases the snow is saturated). The term "wet snow avalanche" could better be reserved for avalanches with lower free water content.

METEOROLOGICAL CONDITIONS RELATED TO SLUSHFLOW RELEASE

The questionnaire asked if the process was initiated by intense thaw (snowmelt), heavy rain, or other causes. The responses are indicated in Table 2.

Table 2. Meteorological Conditions

Thaw or rainfall	46%
Intense thaw (Snow melt)	22%
Thaw with rainfall	21%
Heavy rainfall	4%
Others	7%

The high percentage of slushflows accounted for by intense thaw and/or rainfall could be explained in several ways. Intense melting or heavy rainfall as initiating factors could imply that slushflow occurrence may be controlled by climatic seasonality. Slushflows caused by intense melting take place in early spring and flows due to heavy rainfall take place during the rainy season. The combination of both intense melting and heavy rainfall as major factors suggests a marine west-coast type of climate where warm front intrusions and associated rainfall can be experienced at any time during the winter months. Seven percent of the total respondents indicated causes other than those mentioned above. They are as follows: 1) flow from springs after breakup, 2) snowfall on warm soil followed by rainfall, and 3) rain in addition to other water sources such as a faulty irrigation system.

Slushflows are initiated by the metamorphosis of the snowpack under the influence of rapid infusion of free water through intense thawing (accelerated snowmelt), heavy rainfall, or both. These conditions appear to be the common denominator which links together the vast majority of slushflow releases.

SLUSHFLOW SEASONS

Until recently reports in the international literature associated slushflow activity with the spring breakup period and accelerated snowmelt. Hestnes (1985) and Hestnes and Sandersen (1987) indicated that slushflows also occur during the winter months when associated with heavy rainfall and above freezing temperatures, experienced during the intrusion of low pressure systems and associated warm fronts. Responses to the questionnaire concerning seasonal occurrence of slushflows varied considerably. Two major seasons of slushflow activity did emerge, the spring breakup period and winter. This was seen to be true for both the northern and southern hemispheres. However, the actual months in which the events occurred varied. This variation is both due to latitude and elevation differences. Climatic regions are also a controlling factor.

In general, 48% of all respondents indicated that slushflows normally occurred in the spring. These flows are associated with intense snow melt. However, the spring period ranged from March to July. Slushflows which take place in regions of continental climates in the lower mid-latitudes occur as early as March or April. The spring breakup season for slushflows in high latitude continental climates takes place at a much later date (May, June or July). Elevation is also a significant factor.

Sixteen percent of the contributors reported that slushflows took place during the winter period (December, January, February) and the corresponding southern hemisphere months. In all cases, winter slushflows were associated with areas dominated by a marine west-coast climate.

Slushflows which occur during the summer months account for 18% of those recorded. These data are difficult to interpret since the summer months reported ranged from April to October; however, the majority of the respondents indicated July and August. In most cases the geographic location of summer slushflow occurrences suggests areas of higher elevation, normally on ice caps.

SLUSHFLOW TERRAIN ASSOCIATION

Slushflows were reported to occur in a variety of terrain settings, with no particular type of terrain category dominating. Responses to this section of the questionnaire are presented in Table 3.

Table 3. Slushflow Terrain Association

Mountainous terrain	28%
Glaciers	21%
Forested hillsides/Valley sides	18%
Rural districts	16%
Cultivated land	12%
Urban districts	5%

Clark and Seppälä (1988) indicated that slushflows also occur in non-alpine areas of the arctic and subarctic. Slushflows most likely occur in all terrains when appropriate water input to snowpack and starting zone conditions are available.

STARTING ZONE LOCATIONS

The location of slushflow starting zones is extremely important because of the unique requirements for the initiation of flowage. Reports of slushflow occurrences indicate that prior to release the snowpack in the starting zones has a very high water content or is in a saturated condition, due to excess of water in drainage channels or constrictions, obstructions, or depressions where free water can accumulate or be retained.

Thirty-nine percent of the respondents indicate that the starting zones most frequently are located in stream channels (Table 4). In mountainous terrain these stream channels are low order with steep side slopes, however, slushflows also occur in stream channels on broad open floodplains. Thirty-one percent suggest that slushflows frequently originate from shallow depressions, while 25% indicate that the starting zones were located on open slopes.

Starting zones where slushflows occur less frequently are also indicated by the contributors (Table 4).

Table 4. Starting Zone Locations

	frequently	infrequently
Stream channels	39%	11%
Shallow depressions	31%	14%
Open slopes	25%	31%
Bogs	1%	24%
Others	4%	20%

SLUSHFLOW TRACKS

Recipients of the questionnaire were asked to select the characteristic configuration of the slushflow tracks. Choices were as follows: Channelled (defined), open slope (undefined), or alternating channelled-undefined. The answers are shown in Table 5.

Table 5. Slushflow Track Characteristic

	frequently	infrequently
Channelled (defined)	55%	18%
Open slope (undefined)	24%	49%
Alternating channelled-undefined	21%	33%

Characteristics of the track are important in examining slushflows in general. The planimetric geometry of the track will be dictated by the configuration of the terrain, and the texture and structure of the snowpack below the starting zone.

When considering only starting zone location where slushflows are normally observed, certain similarities become apparent between the starting zone and slushflow track characteristics (Tables 4 and 5). In stream channels, open slopes and shallow depressions slushflows appear frequently. Although shallow depressions rank second in Table 4 they may be found in both stream channels and on open slopes. The questions the respondents were asked to answer concerning starting zones and flow tracks are most likely interrelated in that they basically reflect the geomorphic setting within which slushflows occur.

GEOMORPHIC ACTIVITY OF SLUSHFLOWS

Rapp (1960) indicated that slushflows have the potential of being a significant geomorphic agent in arctic areas. Nyberg (1985) described in detail several erosional and depositional forms produced by slushflow activity in Northern Swedish Lappland. Evidence of slushflow erosion and deposition is ubiquitous in the Central Brook Range in Alaska (Onesti 1985). Although the literature is quite sparse with respect to the geomorphic work of slushflows, it has been documented.

Response to the questions on the geomorphic activity of slushflows is fairly uniformly distributed. The respondents indicate that erosion, transportation, and deposition are all part of the geomorphic process related to slushflows. Thirty percent indicated that slushflows erode, 35% transport, and 35% deposit (Table 6). The number for erosion is somewhat lower but since transportation and deposition are taking place, it would naturally follow that erosion also occurred. Perhaps the term entrainment rather than erosion could or should have been used.

Table 6. Geomorphic Activity

	frequently	infrequently
Erosion	30%	32%
Transportation	35%	36%
Deposition	35%	32%

SLUSHFLOWS AS HAZARDS

Slushflows have long been recognized as a serious natural hazard (Rapp 1966, Jahn 1967, Hestnes 1987). The impact of slushflows on human activity is probably less than that of snow avalanches, since most reported occurrences have been in relatively remote or isolated areas. However, the questionnaire has revealed that slushflows impose on everyday life in the same countries as snow avalanches, and trends in recent decades indicate increasing encroachment of human activity into existing or potential slushflow zones.

Table 7 presents the number of respondents who indicated damage and the types of damage which they described.

Table 7. Damage Reports

	Reports
Man	15
Buildings	22
Roads/Railways	30
Hydroelectric power lines/Pipelines	10
Others (Heavy equipment/Support structures)	7

It is difficult to estimate indirect economic consequences of slusflows due to loss of lives, disruption of road, rail and utility links, construction costs for defense structures, industrial losses due to power output, delays of commercial traffic and debris removal from transportation routes.

Construction of defense structures in slushflow runout zones was reported by 16 of the respondents while 38 indicated that no safety devices were used whatsoever. The type of control methods reported are typical of those used in snow avalanche areas such as hazard zoning and limiting access, forecasting warning systems, controlled release, and construction of defence structures.

CONCLUSION

Response to this questionnaire revealed information, with respect to slushflow activity worldwide, which was not previously available to the scientific community. The questionnaire also identified respondents who have first hand experience with the slushflow process.

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Slushflow occurrence has a much broader geographic distribution than generally perceived. The bulk of the literature on slushflows suggests that the vast majority of these events take place in the arctic. The questionnaire demonstrates that slushflows occur in subarctic and mid-latitude regions as well.

The geomorphic setting and meteorological conditions which are associated with slushflow activity vary according to latitude, altitude and climatic conditions which are all interdependent.

It appears that slushflows can occur both during the spring and winter months due to the variety of factors or conditions which trigger the process. This variety in initiating factors in turn makes them more difficult to predict than snow avalanches.

The purpose of the questionnaire was to summarize, in a qualitative manner, information from individuals and institutes who had first hand experience with slushflow activity. There is not much quantitative information regarding the slushflow process available and hence from this standpoint more research and resources must be focused on this topic. Considering present and future trends it is inevitable that human activity will encroach more and more into slushflow prone areas for purpose of recreation, mining, utility and pipeline installation, general construction activity, military maneuvers and settlement. The probability of death and property damage will increase.

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