

SLUSHFLOW FORMATION, FLOW REGIMES AND CONSEQUENCES (Short version)

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ABSTRACT: The term 'slushflow' was introduced by Washburn and Goldthwait (1958). Eight people perished in slushflows during the winters 2010 and 2011 in Norway, five in backcountry, two in their home and one truck-driver. Buildings, cars, bridges, power-lines etc. were destroyed, roads blocked and many narrow escapes reported. The premises and consequences of these widespread slushflow occurrences have been examined. Problems related to collapse of transportation, vulnerability of power lines, land-use planning, backcountry travel etc. are elucidated. Important aspects on slushflows not previously focused in the literature, are summarized. New dimensions to our knowledge of slushflows have been acquired.

Keywords: Slushflow, snowpack, water level, formation, flow regimes, runout, hazard assessment

1. INTRODUCTION

Numerous names have been used by scientists and practitioners describing "flowing mixtures of water and snow". However, the term 'slushflow' was defined by Washburn and Goldthwait (1958) and the Circum Arctic Slushflow Workshop in Kirovsk, Russia 1992 resolved on using 'slushflow' as a generic term (Onesti 1992).

Slushflows are released when a critical water pressure is attained in the snowpack due to rain and/or snowmelt, depending on a complex interaction between geomorphic factors, snowpack properties and the rate and duration of water supply (Hestnes et al. 1994; Hestnes and Bakkehøi 1996, 2004; Hestnes 1998).

An extraordinary spring-thaw situation occurred in northern Norway in mid-May 2010, while western Norway was hit twice by intense cyclonic activity in 2011 (Fig. 1). Eight persons died in fatal slushflows, four in each year, several survived in miraculous ways. Evacuations, search and rescue operations, destroyed power-lines, collapse of transportation due to extensive road closures etc., were the overall picture, putting the knowledge, skill and experience of authorities and experts to the test (Hestnes 2010 a-b; Jónsson 2010; Pettersson 2010; Sandersen and Domaas 2011; met.no 2009/2010/2011; Newspapers 2010/2011).

The premises and consequences of these widespread slushflow occurrences have been examined and important aspects not previously

discussed in the literature are summarized. Among this are time-series of slushflows in motion and water level fluctuation in snowpack on uneven sloping ground (Figs. 2-3).

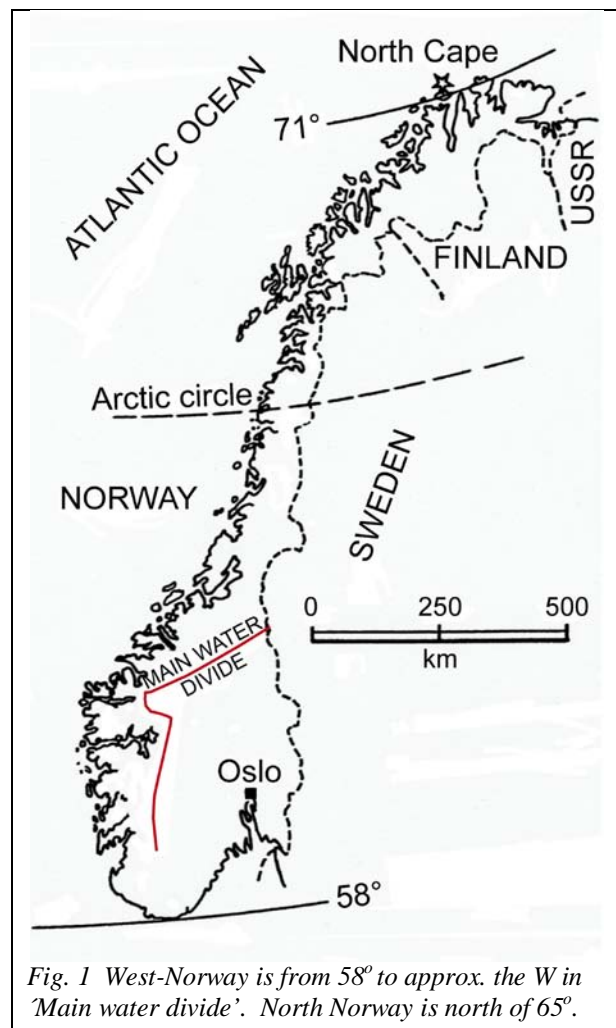


Fig. 1 West-Norway is from 58° to approx. the W in 'Main water divide'. North Norway is north of 65°.

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Fig. 2 Skarmodalen, Hattfjelldal. Three successive slushflows were released in the same basin. Top picture: The first on May 15 22:30, crown at arrow. The second released further to the right on May 16 08:41. Bottom picture: The third on May 16 09:27. A highly turbulent flow is documented both in the second and third flow, and a time-series of 22 pictures of the third slushflow exists. The top picture shows clean white snow within the track of the second slushflow, and no sign of a potential starting zone where the third flow was released. (Photo L. Fontain, Skarmodalen)

2. THE DISASTROUS SLUSHFLOWS OF 2010

In mid-May 2010 the lowland areas of the 1000 km long region of North Norway were without snow and for the rest a snowline of varying height, when a stable high pressure system brought extraordinarily warm air from Russia to Scandinavia. The temperature rose rapidly to a maximum around 20



Fig. 3. A picture from a time-series of water level fluctuation in snowpack on uneven sloping ground. Snow-height variation 1.5-3 m. NGI field station May 16 20:24, 2010. (Photo K. Kristensen, NGI)

°C, causing abnormal melting with a peak runoff after 3-4 days. Some meteorological stations reported the highest May temperature measured in 150 years. Some hydrological stations reported a corresponding exceptional peak runoff, solely caused by snowmelt, despite the fact that May is the driest month of the year (Pettersson 2010; met.no/dnmi.no 2010).

The water level in the snowpack rose above snow-height along drainages and on level ground, and was even seen on open sloping terrain (Figs. 3-4). Slushflows occurred in numbers, sizes and locations never observed before. Recurring events in the same path were common, and slushflows in motion were documented by unique time series (Fig. 2) (Hestnes 2010a-b; Jónsson 2010).

Towns, villages and farms were affected by slushflows and floods. However, due to limited amounts of snow if any in the inhabited areas, the consequences were much less than expected, even though material damage and hampering of traffic were widespread. Evacuations were effected where slushflows threatened human activity (Fig. 5).

Most roads in the mountainous parts were closed, partly due to damage to roads and bridges, and partly due to concern for the safety of the road users. Before roads could be reopened the hazard had to be evaluated and roads and bridges

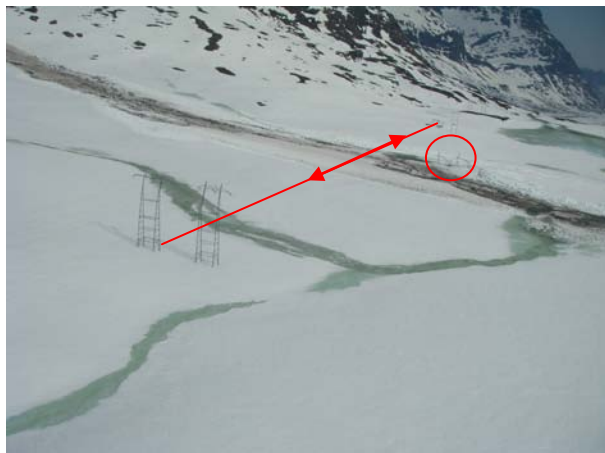


Fig. 4 Melhusskaret, Bardu. The twin 132 kV-lines are hit twice and moved 30-40 m by slushflow. Repair had to be postponed due to the high water level and critical stability of the snowpack. Both access route and working locations were unsafe. The slushflow path was 200 metres wide where the lines were broken. Only the central part of the path has dark and dirty snow with traces of mineralogical material. (Photo Statnett, Bjerkvik)

inspected and repaired (Fig. 6) (Jónsson 2010; Newspapers 2010).

The power supply to the north-easternmost parts became vulnerable when the power-lines through one of the two corridors going north were broken by slushflows. Maintenance of the twin-lines had to be postponed until access route and working locations were safe (Fig. 4). Districts lost their electricity because local lines were cut off (Hestnes 2010a).



Fig. 5 Sørkjosen, Nordreisa, May 16, 2010. Slushflows released far up in the mountains flowed through the village along two streams and closed the main road E6 (foreground). 7-8 houses were evacuated. (Photo W. Bjerkmo, Sørkjosen)

The extraordinary melting and drainage conditions made backcountry travel both difficult and hazardous. This turned out to be fatal to a party of 8 skiers. They had given up on reaching their destination when a slushflow came over a rim less than 100 metres above and hit them within seconds. Four women lost their lives in the accident and two men were injured (Hestnes 2010b; Newspapers 2010).

Other backcountry travellers survived in miraculous ways, among them three family members on a fishing-trip. Just when they were about to enter their tent for the second night, they heard a rumbling noise. They knew what it meant and run towards a slightly elevated spot some 30 metres away. They were stuck by a fence when the slushflow split and went on both sides, masses stopping less than 10 metres from their position (Fig. 7) (Pers. com.).

Some of those who escaped from saturated drainages, rotten snow and slushflows in the backcountry, have told about hazardous travel across brooks, slush-deposits and flooded sections of mountain roads with unknown conditions of road surface and bridges, before they reached back to inhabited areas (Newspapers 2010; Pers. com.).

3. THE WEATHER AND SNOW CONDITIONS

The meteorological elapse of the winter 2009/2010 was fairly similar all over Norway taking into



Fig. 6 Langfjorden, Alta. The E6 by the fiord was closed by slushflows from the plateau above at different locations. It is 800 km detour via Finland when this part is close. (Photo Á. Jónsson, NGI)



Fig. 7 Ranseren, Børgefjell National Park. Approximate location of campsite and the lucky choice of escape route. The slushflow reached the lake on both side of their stand by the fence. .Photo taken two weeks later by G. Prytz, Skarmodalen.

account variations due to elevation, distance from the coast and latitude. In the North numerous freeze and thaw cycles from the end of September until December were followed by cold periods until the end of February. The corresponding record-breaking low amount of snow consequently caused a coarse-grained and very unstable snowpack, unevenly distributed in wind exposed terrain. In contrast, recorded snowfalls in March and April exceeded 200 % of the normal precipitation and were deposited on top of this unstable base (met.no/dnmi.no 2009/2010; yr.no 2009/2010).

The extraordinarily warm air from Russia in mid-May caused an extreme snowmelt accelerated by the contemporary high windspeed. This most extensive slushflow period registered during spring-thaw in Norway coincided with a period of relatively little snow and extreme run-off. However, there is also a causal relationship between the texture and structure of snowpack and the change of character of the snow during the melting period (Hestnes et al. 1994; Hestnes 1998; Hestnes and Bakkehøi 2004).

4. ASPECTS TO EMPHAZISE

A nationwide contemporary spring-thaw is rare in Norway due to the maritime location of the country

and the distance of 2000 km from southwest to northeast (Fig. 1).

The slushflow situation in May 2010 is the only documented spring-thaw situation of regional consequences in one hundred years. It has also documented that snowmelt can be the only water supply. This underlines the importance of taking meltwater contribution into account when predicting slushflow hazard during cyclonic activity in winter as well (Hestnes et al. 1994; Hestnes and Bakkehøi 2004).

Potential hazard often build up in locations and at elevations not observable from the areas at risk. Elevation differences of hundreds of metres without snow and many kilometres in distance may separate starting zones and slushflow prone areas (Figs. 5-6).

Lack of visible signs where people live or travel can be fatal. Lack of records of rare events and often disregard for existing knowledge, is a general problem both in planning and safety work (Figs. 5-6, 8).

The unique time-series of water level fluctuation in the snowpack on uneven sloping ground has verified that shifting wind-loading, snowpack properties and local terrain and drainage conditions, are important factors determining the strength and stability of a water-saturated snow cover (Fig. 3).



Fig. 8 Flesjaelvi, Balestrand March 21, 2011. A couple lost their lives when a house was hit by a slushflow. The house (circle) had been built without the compulsory hazard evaluation required by the Norwegian Building Code. (Photo U. Domaas, NGI)

Slushflows in fully turbulent flow with saltation layer and air-borne part were documented by photo-series (Figs. 2, 9) (Hestnes 2010b, Pers. com.).

Distinct crown surfaces were formed when water-pressure suddenly released slushflows on slopes and fractured deep accumulations of snow located across their paths (Figs. 2, 10).

Two and three separate releases at successively higher elevations or from tributary basins were usual as influx of meltwater continued to accumulate in the snowpack, and they normally reach the same runout zones (Hestnes 1998; Hestnes et al. 1994; Hestnes and Bakkehøi 2004).

Most slushflows were full-depth only in the central part and flowed atop the adjacent snow surface along their flanks and in the runout zones. Clean white deposits were normal far outside areas of dirty deposits, i.e. far beyond future traceable slushflow deposits (Figs. 2, 4, 10) (Hestnes 2010 a-b; Jónsson 2010).

It is also documented that slushflow can reach far beyond any debris flow.

Slushflows reaching below the snowline were normally black from entrained material, and sometimes the original snow might be gone. These circumstances often cause misinterpretation of the genetic origin of deposits. Worth mentioning in this context is the fact that many catastrophic floods in tributary drainages in valleys of Norway have originated from huge slushflows released in the catchment areas (cf. Fig. 9).

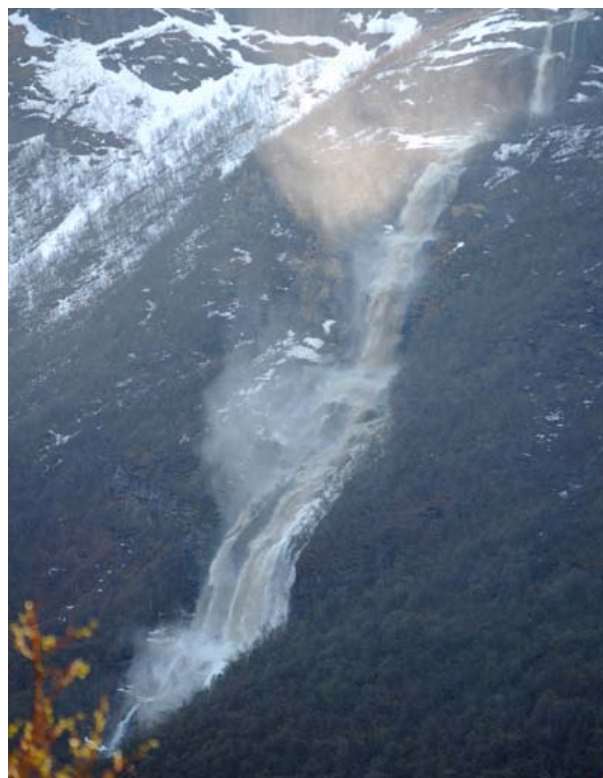


Fig. 9 Okselva, Kåfjord May 16, 2010. "The stream comes often in spring with a big crashing noise and rumble", i.e. slushflow. (Photo P. Lyngstad, Birtavarre)

5. CONCLUSIVE REMARKS

Quantifying slushflow hazard is a major challenge to avalanche professionals. Scenarios based on experience combined with extreme weather analysis and corresponding prognostication of meltwater supply combined with a snowpack stability index, are considered to give the most realistic estimate of slushflow hazard related to the safety classes in land-use planning.

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Fig. 10 Jamtfjellet, Grane. Remarkable crown surfaces across deep snowfields on relatively steep and open slopes were a common feature caused by sudden release due to high water-pressure. There were no indications of where and when such releases would occur. There was normally drainage somewhere under the snow, but the extensive water-supply by melting was probably of vital importance. Slushflows in motion also caused lateral fractures in deep accumulations. These fractures caused quite unforeseen widening of flow-paths on open slopes. (Photo E. Hestnes, NGI)

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