Identification of slushflow situations from regional weather models

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ABSTRACT: Slushflows are known phenomena that cause significant problems for settlements and infrastructure in Norway. Even though single events in the same location are rather rare compared to avalanches, slushflows do occur annually on a national scale. Both intensive snowmelt events as well as high amounts of rain on the snow cover can cause slushflows during the whole winter season. In recent years eight fatalities and widespread problems for infrastructure in Norway have increased the focus on slushflows. Early warning criteria based on readily available meteorological, hydrological and snow data need to be identified to allow a nationwide monitoring of potentially critical situations and corresponding locations that might lead to slushflow events. Earlier work focused on input data from meteorological stations. These stations are often located at sea level and give little information on the meteorological conditions in the release and drainage areas in the mountains. During the last decade, regional weather models have been developed that deliver weather prognosis every hour with up to 4 km grid resolution. In Norway, observed precipitation and temperature are interpolated to a one-kilometre grid and used to model snow conditions and snowmelt. This study aims at analysing the available data to identify critical meteorological elements and their thresholds for the release of slushflows. Examples from recent years will be studied also taking into account the development of the snow cover prior to the slushflow events. The results indicate that the available data has a promising ability to identify critical situations on a regional level.

KEYWORDS: Slushflow, avalanche warning, weather models, forecasting

1 INTRODUCTION

Slushflows are destructive natural phenomena that occur in all countries with a seasonal snow cover (Onesti and Hestnes, 1989). A special combination of snow, weather and terrain formation has to be present to create conditions for slushflow release (Hestnes et al., 1994). Once a slushflow is released it often destroys everything in its path due to its high velocities and densities (Jaedicke et al., 2008). Slushflow can erode and entrain significant amounts of sediments and rocks on their way. Therefore, they are often misclassified as debris flows or torrents, since their depositions may show similar features, once the snow and ice has melted (Hestnes and Kristensen, 2010). Terrain forms combined with knowledge of weather and snow conditions are used to map hazard areas and to establish early warning service. The importance of the snow cover development through the entire winter season poses a significant challenge for early warning. Physical mitigation measures can be used to protect infrastructure and people from the effects of slushflows.

During the last five years, a number of large slushflow events, some with fatal consequences (Hestnes et al., 2012), have increased the awareness of the phenomena and society demands a more active approach for managing the hazard. The objective of this study is to compare observations to results from regional weather forecast models and to see whether such models can give indications for slushflow forecasting.

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Figure 1. Slushflow at Standalseidet 27.11.2008.

2 MATERIALS AND METHODS

2.1 Recent slushflow events

We have selected five events from recent years that will be studied in more detail in this paper. Some are single events, but in most cases, it is likely that several slushflows happened in the region even though they were not reported (Figure 2).

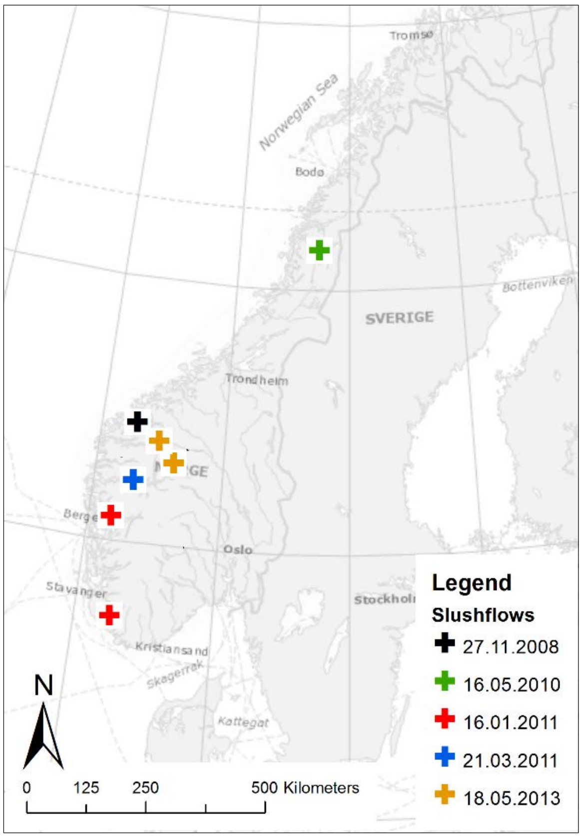

Figure 2: Map showing the analysed events

(1) An intensive warm spell, after an early snow fall, lead to several slushflows in the Ørsta-Volda region around 27. Nov. 2008 (✚ in Figure 2). Pictures of a major slushflow at Standalseidet show the enormous forces involved in these events (Figure 1).

(2) A major disaster struck on 16 May 2010 when four people were killed by a succession of several slushflows while hiking in the mountains (NGI, 2010, (✚ in Figure 2). The slushflow activity was widespread in northern Norway and several roads and power lines were cut during a period of several days with unusual warm and sunny weather.

(3) 2011 started with several slushflows around 16 January in the south-western part of the country (✚ in Figure 2). Two working men, one snowplough driver (NGI, 2011a) and one hydro power technician (NGI, 2011b), were killed in independent events.

(4) Later that year (21. Mar. 2011), further north in the country another significant increase in the temperature, accompanied by intensive rain caused several slushflows in the area around Balestrand in Sogn and Fjordane district (✚ in Figure 2). One slushflow destroyed a house built too close to a minor river, resulting in two fatalities (NGI, 2011c).

(5) During the intensive melt period in May 2013 several slush flows were released in the high mountains in Sogn og Fjordane and Oppland districts (✚ in Figure 2). The event close to the Stryn Summer Skiing area reoccurred in the same location as a similar event in 2005 (Figure 2)

Some basic information about the selected events is given in Table 1, including meteorological observations from stations nearby the slushflow events.

Table 1: Overview over the five selected slushflow events

Date		**27.11.2008**	**16.05.2010**	**16.01.2011**	**21.03.2011**	**18.05.2013**
Area		**Standalseidet**	**Vefsn**	**Egersund**	**Balestrand**	**Stryn/Sognefjell**
Event	Release altitude (m)	600	940	640	600	1520
	Fatalities	0	4	2	2	0
Meteorological station	Name	Ørsta-Volda + Sæbo	Mosjøen Airport	Eik – Hove	Vangsnes	Sognefjell + Skjolden
	Nr	59680 + 59900	77230	43010	53101	55290 + 55300
	Altitude (m)	74 + 21	72	65	49	1413 + 17
	Distance (km)	18 + 7	18	14	6	4 + 24
Meteorological observations	Precip. 72h (mm)	90.3	8.5	69.5	77.4	22.8
	Precip. 24h (mm)	18.8	0	20.6	56.1	0
	Air temp. (°C)	7.3	21.2	3.2	5.2	8.9
	Air temp. corr. (°C)	3.9	15.6	-0.5	1.6	8.2
	Wind direction	SW	SE	S	SW	E
Snow model	Total water (mm)	>100	40 - 60	10 - 20	>100	< 10
ECMWF + 108h	Air temp (°C)	0	15	3	2	6
	Precepitation 24h (mm)	70	0	30	5	0
ECMWF + 24h	Air temp (°C)	-1	16	25	1	6
	Precepitation 24h (mm)	50	0	4	70	0

2.2 Meteorological observations

Meteorological stations from the observation network of the Norwegian Meteorological Institute were selected to illustrate the meteorological conditions before and during the slushflow events. Not all stations observe a full program of the desired meteorological elements (air temperature, wind speed and direction, precipitation and snow height). Therefore, in the case of the events in Standalseidet and Stryn/Sognefjell, two nearby stations were combined to cover both precipitation and wind / air temperature. The stations are relatively closely (6 – 24 km) located to the slushflow events but are often at lower altitudes than the release areas of the events. Therefore, the observed air temperature was corrected to the altitude of the release area of the slushflows using a constant lapse rate of 0.65 ºC/100m. In the Stryn mountains, the weather station at the NGI research station Fonnbu observes additional meteorological elements such as snow temperatures and radiation. All four parts of the radiation balance (both incoming and outgoing short and long wave radiation) are recorded every 10 minutes. Data for the spring 2013 was used to integrate the total energy from radiation for 24 hours.

2.3 Snowmelt

The Norwegian Water Resources and Energy Directorate (NVE) in cooperation with the meteorological institute provides daily maps of snow properties and runoff on a one kilometre grid for the whole country (Engeset et al., 2004; Tveito et al., 2002). The data is based on gridded observational data of air temperature and precipitation, both corrected for elevation and wind direction. The snow modelling is based on the HBV model (Bergström, 1976) and gives information on the total amount of snow, snow wetness and runoff from snowmelt (Saloranta, 2012). For this analysis the total sum of runoff from snowmelt and rain is chosen for the event day of the slushflow or the day prior to the event, depending on which day produced most water.

2.3 Meteorological forecasting model

The aim of this paper is to verify if meteorological forecasting models give indications relevant for the prediction of slushflow events. For this purpose, archive data of 240-hour forecasts from the European Centre for Medium-Range Weather Forecast (ECMWF) was used. The model data is produced every six hours. Forecasts from 108 to 24 hours before the event day from the ground level (2 m height) were consulted to see, if they are able to predict the observed weather on the event day.

3 RESULTS

The five selected slushflow events can roughly be divided into two distinct groups, e.g. good weather and bad weather slushflows, referring to events that include intense rainfall and events during clear sky situations. Figure 3 and 4 show the meteorological observations of the events in Vefsn in 2010 and Balestrand in 2011. There are distinct differences namely the amount of precipitation during the event (0 versus 56.1 mm) and altitude corrected temperature (15.6 versus 1.6 ºC). In addition, the wind direction shows two different systems. While southwesterly flow (Balestrand) usually is associated with low pressure systems from the Atlantic, southeasterly wind often lead to Foehn conditions during the coastal decent of the air masses after passing over the Scandinavian mountain range. In both situations, there is no snow observed at the meteorological stations, due to their low altitude.

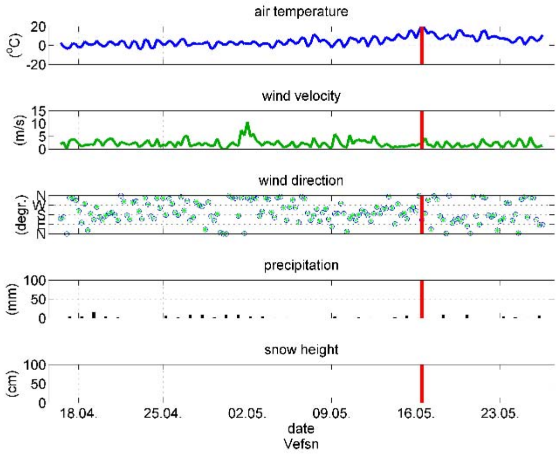

Figure 3. Meteorological record 20 days before and 10 days after the slushflow event in Vefsn 16.05.2010. The red line marks the day of the event.

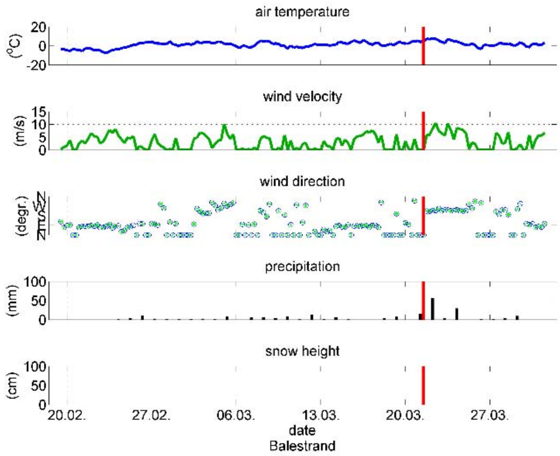

Figure 4. Meteorological record 20 days before and 10 days after the slushflow event in Balestrand 21.03.2011. The red line marks the day of the event.

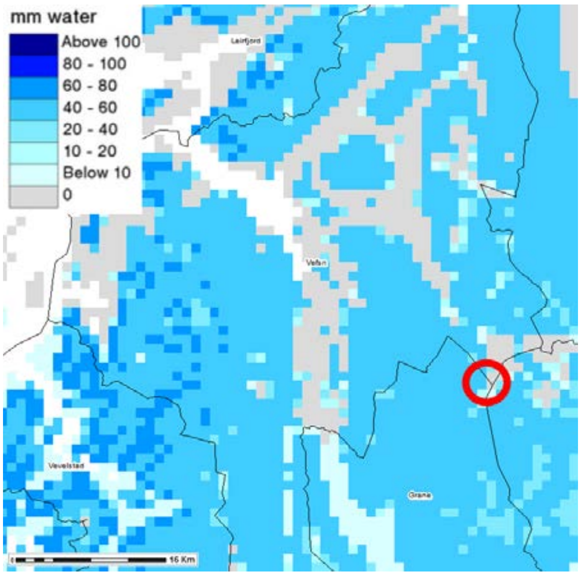

Figure 5: Total amount of available water from rain and snow melt in the Vefsn event 16.05.2010 as modelled by the HBV model. The red circle shows the location of the slush flow.

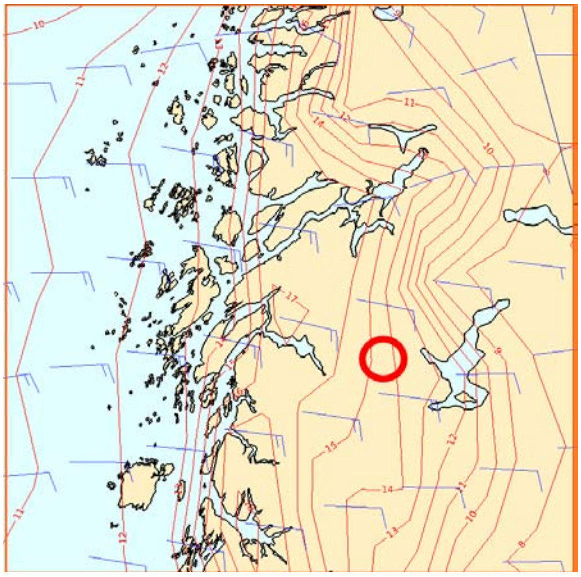

Figure 6: ECMWF 108h prognosis for the 16.05.2010 event in Vefsn. Red lines: Air temperature at 2m, blue arrows: wind speed, green lines: precipitation. The red circle shows the location of the slush flow.

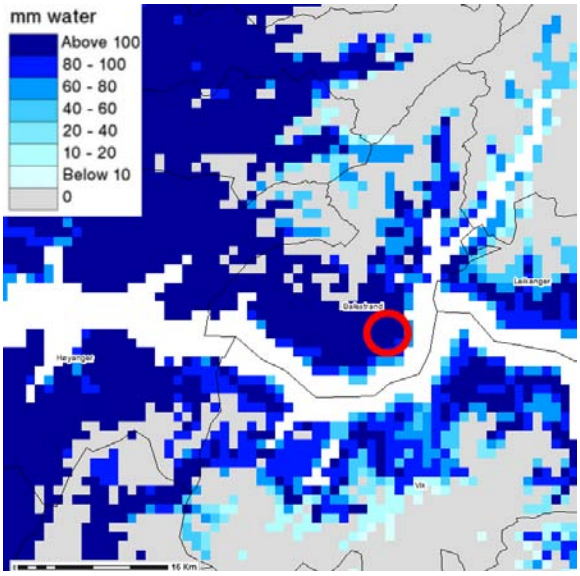

Figure 5: Total amount of available water from rain and snow melt in the Balestrand event 21.03.2011 as modelled by the HBV model. The red circle shows the location of the slush flow.

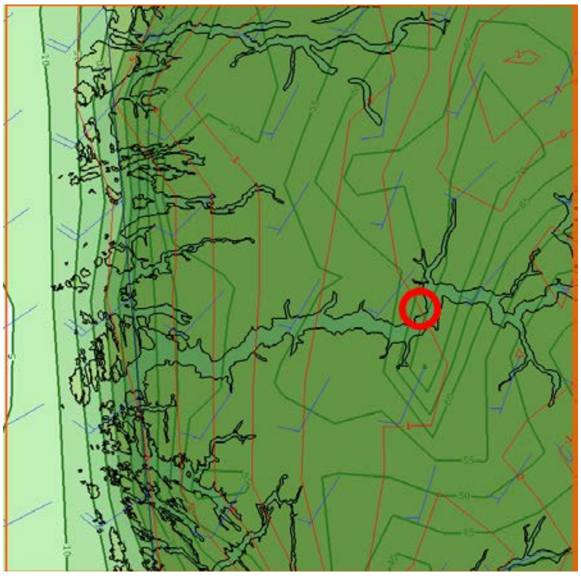

Figure 6: ECMWF 24h prognosis for the 21.03.2011 event in Balestrand. Red lines: Air temperature at 2m, blue arrows: wind speed, green lines: precipitation. The red circle shows the location of the slush flow.

The results of the HBV model for total available water in Figure 5 and 6 show the domination of precipitation in the Balestrand event (total water >100 mm/24h). In Vefsn no precipitation was observed during the event day and snow melt was modelled to amount 40 – 60 mm/24h. This is significant higher than in the 2013 events on Sogne- and Strynefjell where neither precipitation was observed nor snow melt > 10 mm was modelled.

Two model runs of ECMWF data were studied to see whether the model results change and improve as the event approaches. In Vefsn, the 108 hour prognosis shows no precipitation and +15 ºC in the area of the slushflows. In the 24 hours prognosis (Figure 6), there is still no precipitation visible, but the temperature is increased by 1 ºC. The wind direction and velocity remain unchanged with easterly 8 m/s at 2 m height.

The 102 hour prognosis for the Balestrand (Figure 7) event shows air temperatures of +2 °C and 0-5 mm accumulated 24 hour precipitation in the area of the slush flow. The newer prognosis, 24 hours before the event has slightly reduced air temperature (+1 °C) but the 24h precipitation has increased to 65-70 mm. Table 1 gives an overview over the results from all five events.

Net radiation data from the NGI research station Fonnbu show that the total radiation energy tops 8500 kJ/m² on the day of the slushflows in the area (18 May 2013). This is the highest value in the snow covered season (Figure 7). The main component leading to positive net radiation during the night is the unusual high input of incoming long wave radiation. The maximum observed air temperature is +12.3 °C and the snow height is reduced by 13 cm during this day.

4 DISCUSSION

The release of slushflows depends on a long range of processes in a snow atmosphere interaction. Often already the first month of snow on the ground play a decisive role for the development of the snow cover and thus the vulnerability to rain and melt water in spring. Studying the weather just prior to the slushflow is therefore a very rough approach to the phenomena. In a forecasting perspective, the only available data are meteorological observations from a limited number of stations at low altitude and forecasting model data on a rough grid. Information of the snow pack and its vulnerability to slushflows is often unknown. Therefore, the development of forecasting methods based on the available data is desirable to improve.

The five examples chosen in this study may be divided into two groups, slushflows related to rain events and those related to snow melt only.

The rain events typically happen in early to midwinter when solar radiation does not have a major influence on the energy balance. These events are often connected to large scale low pressure systems approaching Norway from the southwest. The meteorological forecasting models generally catch these systems well and in the chosen examples, the amount of precipitation and the temperature development was well forecasted already 102 hours before the slushflow events. Only in the Balestrand situation, the forecasted amount of precipitation increased significantly from the 108h to the 24h forecast. The hydrological model HBV can reproduce the high amount of total available water due to the significant input from the precipitation.

The slushflow events that only involve intensive melt are more difficult to forecast by the models. The meteorological forecasting model reproduces the situation with high air temperature, Foehn and clear sky well. Melting caused by positive net radiation and turbulent energy flux to the

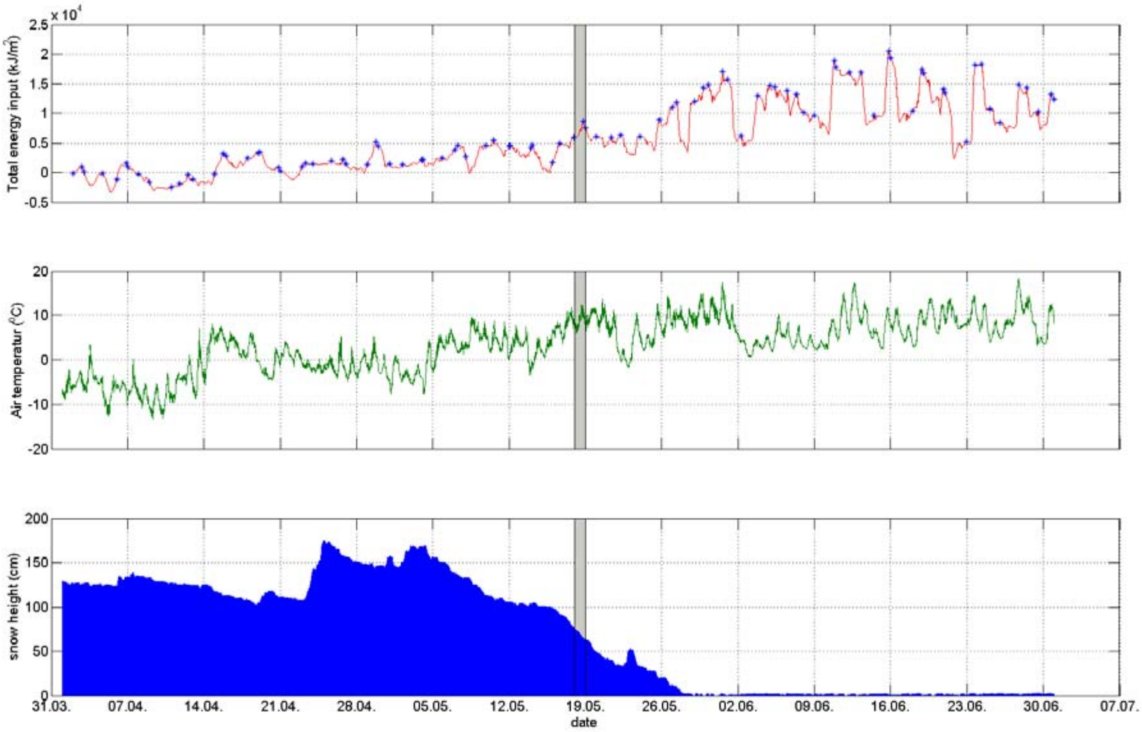

Figure 7: Snow height, air temperature and net radiation energy at the Fonnbu research station in spring 2013. The grey area shows the 18 May, the day of several slush flows in the area

surface is not reproduced by the hydrological model. The snow melt routine in the HBV model is only based on air temperature and a degree day factor depending on the day of the year. Therefore, periods with intensive melting by net radiation and wind will not be covered with this model. Mitterer and Schweizer (2013) found that radiation is a major factor for the release of wet snow avalanches. The results from Fonnbu show that the observed slushflows coincide with the highest net energy in this spring season.

Meteorological forecasts up to three days are available from models with higher grid resolution (up to 4 km). Due to the finer mesh those models presumably will catch more of the local weather development and thus lead to a more realistic forecast for many locations. Available radiation fluxes and turbulent fluxes from such models should also be investigated. Future studies will make use of such models operated at the Norwegian meteorological institute.

The definition of thresholds for the release of slushflows is difficult, but the results suggest a minimum of 50 mm rain within 24 hours with an additional snowmelt of 30 – 50 mm. Most likely, the more water is available in shorter periods of time, the less importance is given to the snow properties. In situations when slushflows are released with little water available, the properties of the snow pack will be more important. The presence of depth hoar is often associated as a prerequisite for slushflows as the coarse structure of the crystals promotes the collection of water under the snowpack. Information on the regional variability of depth hoar might therefore give additional important information.

5 CONCLUSION

Major slushflow events are either accompanied by intensive rainfall or melt events or both in combination. While rain is well predicted by the forecast models, total available water due to rain and melting is less reliable as an indicator. The lack of radiation and turbulent energy fluxes as driver for the snow melt in the HBV model leads to an underestimation of the available water in periods without precipitation and high radiation input. As discussed above finer mesh meteorological models for the first days ahead will probably prove useful and lead to an increased accuracy of the forecast of conditions leading to slushflows. Results from the net radiation measurements at Fonnbu show that radiation data can give decisive information for slushflow forecasting.

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