A regional early warning – for slushflow hazard

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1 Introduction

Slushflows annually pose a major natural hazard in Norway and elsewhere, threatening people and infrastructure. Historically the damages and economical cost in Norway were equally caused by slushflows and snow avalanches (Hestnes, 1998). More than 1550 fatalities in the country were caused by snow related hazards, including slushflows, during the last ~150 years (Hisdal, 2017). Here we present the operational regional Slushflow Early Warning assessment method (SEW) currently used in Norway. Its main purpose is to initiate and facilitate measures aimed at preventing damage to health and infrastructure.

Figure 1: Example of a slushflow path and runout, close to Krossbu, Jotunheimen, Southern Norway 19 May 2013. It released at the outlet of a lake and has eroded the ground. It is not uncommon that slushflows initiate in sunny weather due to snowmelt only. Photo: Kjell Nyøygard.

Slushflows are rapid mass movements of water-saturated snow (Washburn and Goldthwait, 1958; Nobles 1966; Hestnes, 1985; Fig. 1). Although not well known and often associated only with the Arctic, slushflows are observed and pose a hazard in snow- covered areas globally (Onesti and Hestnes, 1989). As an example, 88 fatalities were caused by a single slushflow event in Japan in 1945 (Kobayashi et al., 1994). We have used the definition of slushflows agreed on internationally in 1992 (Hestnes, 1998) which covers a range of slushy appearances such as slush avalanches, torrents, etc. (Gude and Scherer, 1998).

Slushflows are generally released in low to moderately sloping terrain (<30°), unlike snow avalanches, landslides and debris flows. The flowing mixture of snow and water initiates in depressions, gentle slopes, and in the transition zone between steep- and low-grade terrain, but is also released during ice breakup of streams and rivers.

The initiation mechanism and flow dynamics may partly resemble that of debris flows (Statens vegvesen, 2014). The flow paths are characterized by long distances, up to several kilometres (e.g., Hestnes, 1998; Pérez-Guillén et al., 2019). The fluidity of slushflows also enables flow around obstacles and thus they may not follow straight runouts as commonly seen in snow avalanches and landslides. The mass movements often continue farther downward steep slopes and may transform into debris flows. Due to their high water content, slushflows have large erosional forces (Rapp, 1960; Onesti and Hestnes, 1989). They often erode the ground along their path and accumulate mass by incorporating rocks, debris, and other materials. High density makes the damage potential substantial, both for infrastructure and geomorphology. Stones deposited 20 m above riverbeds and debris coverage of vegetated areas have been observed in Greenland (Washburn and Goldtwait, 1958).

Slushflows are reported to have occurred in a variety of weather situations, spanning from cyclonic activity with heavy rainfall and rapid snowmelt, to situations with snowmelt only due to solar radiation (Hestnes and Sandersen, 1987; Scherer et al., 1998; Decaulne and Sæmundsson, 2006; Jaedicke et al., 2013). The latter, a sunny weather type that many do not associate with danger, can thus pose a hazard. During the winters of 2010 and 2011, there were eight fatalities purely due to slushflows in Norway. One of the situations occurred during sunny weather conditions, possibly viewed as harmless by the public, but resulted in the deaths of four people (Hestnes et al., 2012).

Physical mitigation measures are expensive if feasible at all. In some areas they are difficult to implement due to the nature of the slushflows (Hestnes and Sandersen, 2000; Tómasson and Hestnes, 2000). Therefore, an early warning system EWS including slushflow hazard is an asset both to protect lives, buildings, roads, and railways and as an incentive to take precautions and safety measures.

EWSs comprise four different elements spanning: knowledge, monitoring and warning service, dissemination and communication, and response capability (UN/ISDR, 2006). For several natural hazards, such as floods and snow avalanches, regional early warning and forecasting has been developed through many decades (e.g., Föhn, 1998; Krøgli et al., 2018). Krøgli et al. (2018) present development of the Norwegian Landslide Forecasting and Warning Service (NLFWS) in more detail. Early warning of slushflows is a necessity for infrastructure but is also beneficial to, e.g., hikers and skiers (Gude and Scherer, 1998). Local slushflow forecasting has to some extent been carried out for four decades (Hestnes, 1998). Due to the range of initiation factors and processes, assessment of slushflow hazard is much more complicated than that of avalanche hazard (Onesti, 1985; Onesti and Hestnes, 1989, Hestnes, 1998).

In this paper we focus on the method developed for operational regional slushflow early warning assessment established and used within the NLFWS. We present the foundation and development of the hydro-meteorological method of the regional SEW. Furthermore, we examine the implications the nature of slushflows has on data collection and outline the possibilities for application of the method to other areas.

2 Background

2.1 Previous work

As previously mentioned, the release mechanism of slushflows differs from that of snow avalanches. As liquid water content (LWC) increases in the snowpack, the pore pressure increases, and snow crystal bonds weaken. The gravity component may be small in low sloping terrain (Hestnes, 1998). The dynamics of slushflows resemble that of debris flows in that the high water content enables great mobility. This means that the masses have little firmness and therefore behave like a viscous liquid (Statens vegvesen, 2014).

In 1983 the Norwegian Geotechnical Institute (NGI) started developing objective forecasting criteria for slushflow hazard, on a local scale. Hestnes (1985) defined three types of slushflow release based on terrain types: drainage channels, water-saturated embanked snow through narrow outlets, and bogs.

Critical stability of the snowpack and slushflow release during snowmelt and rain depends on a complex interaction between several factors: impermeable ground conditions, rate and duration of water input, snow structure, specifically the permeability of the snowpack layers, the number and strength of the bonds between snow particles, as well as the slope angle determining the pressure head (Hestnes et al., 1994; Hestnes, 1998; Hestnes and Bakkehøi, 2004).

Relative water saturation of the snowpack occurs within two regimes, with low or high saturation respectively: (a) The pendular regime, when air is continuous throughout the pore space between individual grains. This typically occurs up to 7 % volumetric LWC. (b) The funicular regime when liquid water is connected throughout the pore space, and air space is reduced (Colbeck, 1973). The snow structure controls the transitional range between pendular and funicular regime. For old, coarse-grained snow it is typically between 7–12 % LWC, while new snow is saturated at 13–18 % LWC (Denoth, 1982). Furthermore, the degree of wetness can be separated into very wet snow estimated at 8–15 % LWC) and soaked snow at > 15 % LWC (Fierz et al., 2009).

To saturate a snowpack, impermeable ground that impedes the water percolating through the snow from infiltrating the ground, is required. This requirement is met when the snowpack covers a thick ice layer, bare rock, or frozen ground (Hestnes, 1985), but may also occur on saturated unfrozen ground (Gude and Scherer, 1995; Hestnes, 1998).

Hestnes and Bakkehøi (1996) studied slushflow conditions systematically. They found that cohesionless new snow and porous, coarse grained snow types are most prone to start flowing when the snow is completely saturated. A stratified snowpack with layers of crust and ice are more stable. Dense, icy snow layers were found to withstand more than three days of submersion. Depth hoar at the base of the snowpack covered by coarse grained snow facilitates large slushflows (Hestnes, 1998). On a regional scale, the properties of the snow are assumed to be of great importance (95 %) to assess in regional early warning, , while the significance is reduced (> 50 %) for local assessments and is smallest (> 35 %) in assessment of specific slushflow tracks (Hestnes and Bakkehøi, 2004).

Water supply to the snowpack is controlled by precipitation and snowmelt. Snowmelt is determined by the energy balance at the snow surface, where important components are turbulent energy exchange from sensible and latent heat, and the radiation balance. Humid, strong winds, high air temperatures, and a high amount of incoming solar radiation, such as under midnight sun conditions, will facilitate intense snowmelt (Hestnes, 1998). According to Hestnes et al. (1987), if the relative air humidity is less than 28 % no melting will take place, but some snow will evaporate.
Reliable estimates of snowmelt are essential in the forecasting of slushflow hazard. Solar radiation as a component to snowmelt is found to be an important factor for the release of slushflows and wet snow avalanches in certain situations (Jaedicke et al., 2013; Mitterer and Schweizer, 2013). Scherer et al. (1998) state that the meltwater flow through the snowpack influences the release of slushflows.

Hestnes et al. (1994) analysed 80 slushflow events. During periods of cyclonic warm fronts snowmelt contributed with 5–45 % of the total water input. Based on five major situations between 2008 and 2013, Jaedicke et al. (2013) found that the rain-induced slushflows typically occurred during the first half of the winter season when solar radiation was low. The springtime examples of widespread slushflow activity were found to be caused by intensive snowmelt only. Scherer et al. (1998) found that for snowmelt-induced slushflows, the timing of energy input is crucial.

Even though slushflows can occur anywhere globally with seasonal snow cover given the right combinations of factors (Onesti and Hestnes, 1989), no standardized national or international method for regional forecasting of slushflow hazard has been developed. The need for such a service, improving the safety of rail and road traffic, but also for backcountry activities , was pointed out already in the 1990s (Barsch et al., 1993; Gude and Scherer, 1998). The lack of further development may have several reasons: some assumed that slushflows only occurred in restricted parts of the world, slushflows are often misclassified, and sufficient regional data input has not been available, even though the phenomenon has been known for more than 300 years (Onesti and Hestnes, 1989).

2.2 Establishment of regional early warning of slushflow hazard

In 2009, the Norwegian Water Resources and Energy Directorate (NVE) was assigned the responsibility of establishing national EWSs for natural hazards (including the previous organizational unit in NVE, the division for floods, expanding to snow avalanches, landslides, and rock falls). This was part of a political effort to improve prevention of water-related natural hazard risk. The Norwegian Landslide Forecasting and Warning Service (NLFWS) was officially launched in autumn 2013 (Krøgli et al., 2018). From 2014, this service also officially included forecasting slushflow hazard. The organizational decision to include slushflow along with landslide forecasting was mainly based on three reasons: a) slushflows are water-related, and the ground conditions are also part of the hazard assessments, b) slushflows can also occur during periods when the snow avalanche warning service is not operative (June – Nov.) and c) slushflows release in gentle slopes and may therefore also occur in areas other than those normally covered by the Norwegian Avalanche Warning Service (NAWS) (Engeset, 2013).

It is important to distinguish between local and regional forecasts. Locally, factors that are specific to the place, such as cirque formation, are decisive, as they may induce local melt conditions. Regional forecasts must recognise weather conditions that are valid for a larger area, as well as differentiate between different danger levels. As for regional landslides and snow avalanches, regional slushflow forecasts are not intended to be site-specific, i.e., they do not indicate the location of possible slushflows. The regional SEW does not cover single slushflow events caused by external triggers, such as snow avalanches damming a river or human activity that blocks drainage. The danger level is communicated through a bulletin that is updated at least once a day at www.varsom.no (Krøgli et al., 2018).

It must be noted that during method development it was an overall requirement that the resulting method for assessing regional slushflow hazard should use the same approaches as and fit into the existing framework already developed for NVE's other natural hazard EWSs, in particular that of landslide. This overall objective put some constraints on the methodological approach, the definition of the danger levels and hence the evaluation of the issued warning bulletins. The slushflow hazard is subjected to the same scale and definitions as flood and shallow landslides, built across the same concept as meteoalarm (http://www.meteoalarm.eu/) (Krøgli et al., 2018) and is thus not the same as the snow avalanche hazard scale used in Norway and Europe.

Unlike warnings issued by NAWS, the regions for landslide and slushflow hazard are not predefined, only constrained by municipality borders. The minimum size of a warning area is set to approximately 7500 km^2. This approach enables identifying exposed areas, e.g., along the coast.

The NLFWS assessments are based on analysis of automatic meteorological and hydrological monitoring stations, a database of historical landslides, hydro-meteorological models, and simulations (Krøgli et al., 2018). The NAWS also benefit from in situ snow observations in slopes (Engeset, 2013). These are mainly carried out in steep terrain.

The NLFWS bulletins are divided in four colour-coded danger levels (Krøgli et al., 2018): green (1), yellow (2), orange (3), and red (4). Green indicates generally safe conditions and is the level that occurs most frequently. Yellow level is the lowest of the levels for which an early-warning bulletin is issued. Orange level indicates high landslide hazard and red level indicates extreme hazard. Note that the nature of slushflows makes it possible for them to occur both in flat and steep terrain. The current regional early warning is thus not to the same degree as snow avalanche early warning a mean of pinpointing safe terrain types in detail. Still, the different danger levels to some extent give a clue to where the hazard mainly could be expected.

At yellow (2) level the expected appearance of slushflows is mainly restricted to terrain formations particularly prone to slushflows, such as narrow outlets (cirques, funnel shapes) that enhance accumulation of water. Yellow danger level may be valuable to the municipalities, where local knowledge about the most susceptible geomorphic features in the area can be applied. For areas with vulnerable infrastructure and buildings this is a signal to initiate mitigating measures. At orange (3) level the expected slushflow hazard is high, and many slushflows are expected. Red level (4) is an extreme situation, and emergency response authorities should implement emergency plans and mitigation measures for carrying out possible evacuations and other contingency responses.

3 Methodology of regional slushflow early warning assessment

Our methodological approach to regional SEW is based on the combination of factors that have previously been found to be decisive in the triggering process. However, in the regional approach, the geomorphic terrain features will be of less importance in the assessment, as the size of the area ensures their presence. Nevertheless, they are to some extent reflected in the yellow danger level. The variables for regional assessment of slushflow hazard can then be narrowed down to ground conditions, snow properties, and water supply. The daily operational routines and bulletin distribution is described in detail by Krøgli et al. (2018). Here we concentrate on the assessment method for regional SEW, developed since 2013.

3.1 Setting, hydro-meteorological data, tools, and assessment process

The area of the Norwegian mainland (Scandinavian peninsula) covers an area of 324 000 km^2, spans latitudes from 58°N to71°N and comprises widely different climate types. The country currently has a real-time network of approximately 600 hydrological and ca. 500 meteorological (precipitation and temperature) stations. In addition, there are ca. 530 locations with snow depth measurements and ca. 20 snow pillows.

For forecasting purposes, the relatively poor coverage of stations is supplemented by hydrological models that provide forecasted hydro-meteorological variables. The country is divided into 1 km^2 grid cells which are displayed in the open access analysis and decision-making webtool Varsom Xgeo (www.xgeo.no hereafter referred to as Xgeo). The development of observational and simulated weather grid data, covering the whole country at 1 × 1 km resolution, enables regional approaches to early warning. Development and limitations of the maps in Xgeo are explained in https://senorge.no/Models?lang=no%20 (accessed 13 May 2023). The different variables are shown as various maps that are manually evaluated by the forecasters.

The daily slushflow assessment is standardized and based on the following: a) information about hydro-meteorological conditions derived from real-time measurements, model simulations, and forecasts assembled as nationwide gridded thematic maps and data time-series. b) quantitative gridded forecasts of precipitation, temperature, wind, and air humidity, supplied by the Norwegian Meteorological Institute (MET).

The forecasted hydro-meteorological variables are obtained by a distributed version of the hydrological HBV model (Beldring et al., 2003) and the seNorge snow model (Saloranta, 2016). The model runs four times daily, and the results are presented in tabs, such as water supply (rain and snowmelt), soil water saturation, groundwater level, and soil frost, available at Xgeo (Krøgli et al., 2018 and references therein). Simulated variables are compared with real-time station data to evaluate the model's performance. The assessment process is shown schematically in Fig. 2 and information and variables used, in Table 1. The different steps are described further in the following subsections.

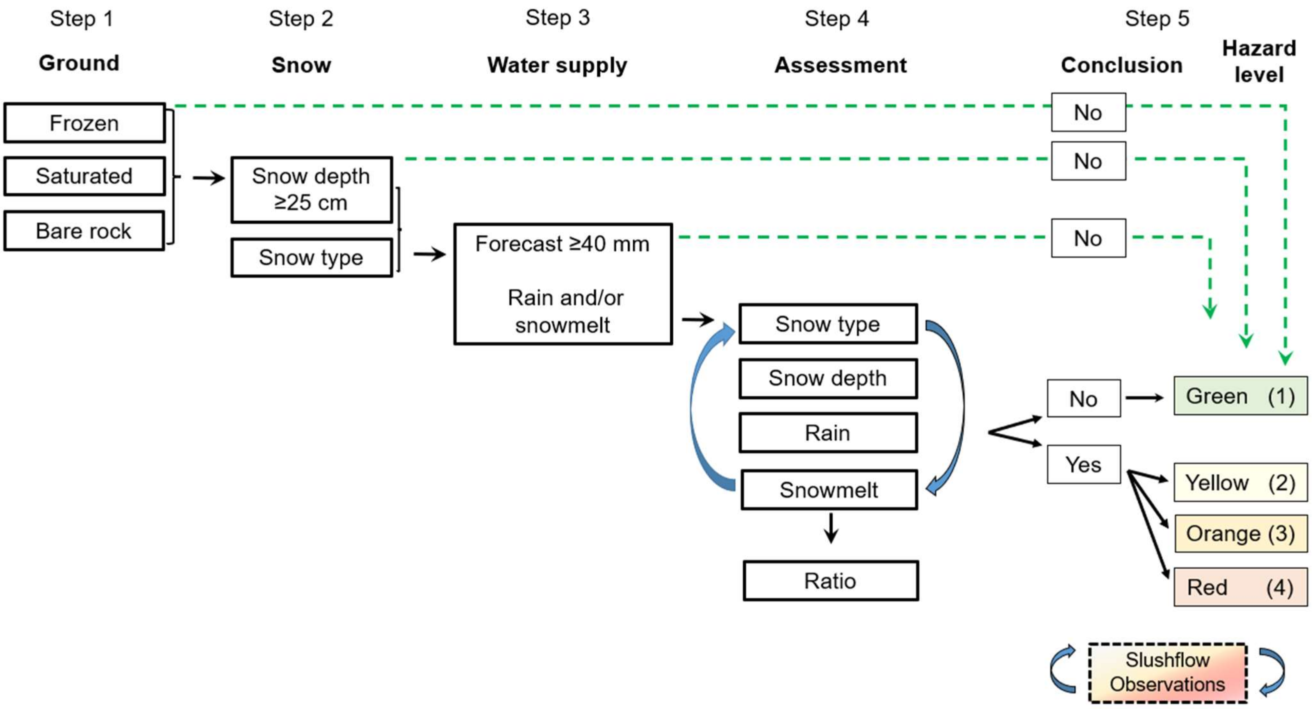
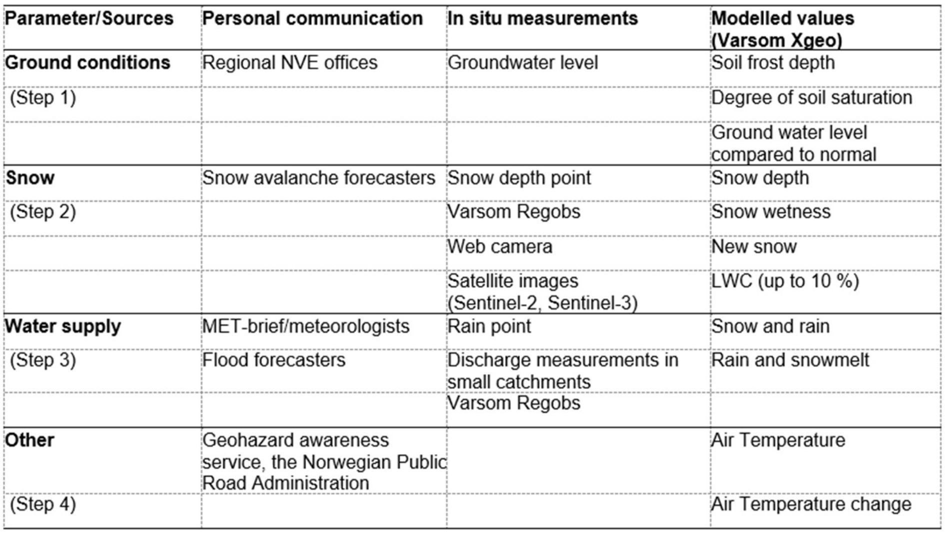


Figure 2: The steps in the forecasters'slushflow hazard assessment process. Simulations of the different variables run automatically and are presented in Xgeo.no, while the forecasters manually verify the variables, check the snow type, and assess their regional interactions.

Table 1: Overview of information and variables used in the assessment



Parameter/Sources	**Personal communication**	**In situ measurements**	**Modelled values (Varsom Xgeo)**
Ground conditions	Regional NVE offices	Groundwater level	Soil frost depth
(Step 1)			Degree of soil saturation
			Ground water level compared to normal
Snow	Snow avalanche forecasters	Snow depth point	Snow depth
(Step 2)		Varsom Regobs	Snow wetness
		Web camera	New snow
		Satellite images (Sentinel-2, Sentinel-3)	LWC (up to 10 %)
Water supply	MET-brief/meteorologists	Rain point	Snow and rain
(Step 3)	Flood forecasters	Discharge measurements in small catchments	Rain and snowmelt
		Varsom Regobs	
Other	Geohazard awareness service, the Norwegian Public Road Administration		Air Temperature
(Step 4)			Air Temperature change

3.2 Impeded infiltration of the ground

Impeded infiltration of the ground is a prerequisite for water saturation of the snowpack. Modelled ground properties, such as soil frost, soil saturation, and ground water level, are all included in the assessment. For modelling purposes the soil in Norway on a regional scale is defined as till , although there are variations. Thus, the same model parameters for soil conditions are used nationwide (see Krøgli et al., 2018 for more details).

Soil frost depth is simulated using the Motovilov et al. (1999) approach within the spatially distributed version of the hydrological HBV model (Beldring et al., 2003). The soil frost depth calculation is based on the physics of heat conduction in the soil matrix and in the snow cover above the ground. It is used with air temperature data and precipitation data as input. The simulation only gives a rough estimate, as in nature the soil frost depth varies locally due to many factors, including snow depth, water content, and soil properties and structure. Vegetation also influences this process. Experience shows that the simulation performance is more reliable in autumn, when the soil frost depth is increasing, than late in spring. On the other hand, spring conditions often encompass a high degree of water saturation. Observational data for comparison is a valuable asset.

The degree of water saturation in the ground is simulated with a distributed version of the HBV model. High degree of water saturation indicates that the soil pores are filled with water and the infiltration to the ground will therefore be impeded and the criterion met.

An approximate groundwater level is also simulated with the spatially distributed version of the HBV model in Xgeo and shows the groundwater level in relation to the average groundwater level on the same date for the reference period 1981–2000. A network of ~65 groundwater stations around the country is also used for comparison with the model simulations (Li et al., 2015). High groundwater level is not sufficient to determine impeded infiltration of the ground in an area. It is, however, an indication that the ground conditions are approaching a level where the infiltration capacity is low. The simulations only give estimates. They do not account for, for example areas with talus with space for water infiltration into the ground even when frozen.

Bare rock and bogs also represent areas with impeded infiltration, at least on a local scale (Hestnes, 1998). Currently, few areas in Norway (Nordland and Agder counties) are considered to have large enough areas of bare rocks for this criterion to be met regionally and included in the assessment.

In rare situations, a thick ice layer in the snowpack can also work as an impermeable layer and facilitate slushflows, provided it is covered with enough snow. Several ice layers will instead strengthen the snowpack against slushflows (Hestnes, 1998).

Model simulations of soil frost, ground water level, and water saturation are evaluated by the forecasters and compared with observations e.g. from the regional NVE offices (Table 1), if available. An important part of the assessment is to resolve whether the possible conditions are regionally or only locally present.

3.3 Snow properties

The properties of snow change through time and are subject to large variations. This also influences the distribution and rate of water routing through the snowpack. Nevertheless, for a regional approach it is necessary to make simplifications and generalizations. Data on the regional snow types and structure are supplied by the NAWS. These data only cover the most rugged part of Norway and focus on conditions in slopes. Real-time observations, containing information on the latest development of the snowpack during the ongoing situation, are retrieved through the crowdsourcing tool Varsom Regobs www.regobs.no (Ekker et al., 2013) (hereafter referred to as Regobs).

Since 2013, a minimum of one weekly observation of the snowpack has been carried out in many regions in Norway (Engeset et al., 2013). Regional snowpack updates are also provided directly from NAWS, daily when necessary. For regions with less observational data, data from the other regions and comparisons with Xgeo simulation data are used to extrapolate the snow conditions.

Several snow cover models, such as CROCUS (Brun et al., 1989), later integrated within the framework of SURFEX (Vionnet et al., 2012), have been developed. They aim to provide information on snow depth and stratigraphy where spatial and temporal observations are sparse. In recent years, the physically based SNOWPACK snow cover model has been applied to simulate LWC for the forecast of wet snow avalanches (Bellaire et al., 2017). However, wet snow avalanches are triggered in a pendular regime (3–7 % LWC) and thus at a lower LWC than the funicular regime of slushflows. Snow models still have too poor performance for preferential flow and ponding to be used operationally in regional slushflow forecasting. Meanwhile, observational data on snow moisture and wet snow avalanching reported in Regobs, as well as the simulated snow wetness index, give an indication of the LWC in the region.

The snow stratigraphy and texture, based on the abovementioned observations, are, for slushflow assessment, divided into four snow types, all with emphasis on the lowermost 0–1 m of the snowpack. Snow types prone to slushflows listed from high to low susceptibility are: facets/depth hoar (FC/DH) at or near the ground, new snow (PP) deposited on an impermeable layer, melt forms (MF), and all other snow types (OTH). The division is based on previous studies (Hestnes, 1998) and empirically from regional information during the 10 years of our service. This is a rough differentiation based on the data available. Here we used "new snow" meaning relatively recently deposited snow, with limited influence from wind drift. Snow with various properties that are less slushflow-prone are grouped under "all other".

Snow depth and snow wetness values are provided from Xgeo and are validated from observations via Regobs. The grid values represent a larger area (1 km^2) and thus do not reflect the specific snow depth, locally. They do, however, provide an adequate input to the water supply – snow depth by snow type ratio developed to reflect the regional danger level (Sect. 3.5). The effect of snow wetness is added to the forecasted water supply before the water supply – snow depth ratio is assessed.

The Xgeo-variable snow wetness is an indicator of the ripening status of the snowpack towards isothermal conditions when runoff from snowmelt is initiated. The snow wetness assessment is based on both observations (Regobs) and simulations of the wetness (up to 10 % LWC) throughout the snowpack.

3.4 Water supply

Slushflows normally occur during situations with air temperatures above freezing. They are often associated with steep air temperature increases above 0°C (e.g., Decaulne and Sæmundsson, 2006). Diurnal air temperature variations are important for assessing the water supply to the snowpack (e.g., Techel and Pielmeier, 2011). Fluctuation around 0°C mutes the rate of water supply to the snowpack. Situations where the temperature is more stable during day and night, e.g., due to midnight sun like in northern Norway, are more favourable for the water supply rate. Xgeo provides an overview of changes in diurnal variation in air temperature for several days, both as observed values and forecast.

The length and intensity of positive degree days prior to slushflow initiation influence both snow metamorphosis and thus snow type, as well as meltwater production. Even though intense rain and/or snowmelt situations often have been highlighted, sufficient water may accumulate in the snowpack when there is constant water supply through several days, even though the rates are relatively low. Special attention is therefore paid to such weather forecasts. During assessment the forecasters evaluate whether the simulated rain and snowmelt variable is over- or underestimating values and to what extent the regional distribution is reliable. This is strongly based on the meteorologist's briefing. As an example, the elevation of zero degrees Celsius is often a decisive factor for both, but it may also be encumbered with large uncertainties.

3.4.1 Rain on snow

In the following sections, mentions of rain are consistently in the sense of rain on snow (ROS). In the calculation of water supply, rain is less subjected to errors than snowmelt. However, there are uncertainties in observations and forecasts. The precipitation type simulation in Xgeo is based on a temperature limit, and the actual type of precipitation may differ from this. The daily meteorology briefing provided by the Norwegian Meteorological Institute enables adjustments in the forecaster's interpretation of the model simulations. Real-time measurements and observations from, e.g., webcams are also an asset in this respect.

3.4.2 Snowmelt

Snowmelt is simulated both through the distributed HBV model (Rain and Snowmelt), and by the snow melting Energy Balance (EB) model. The simulated combined rain and snowmelt in Xgeo do not account for snowmelt due to solar radiation and turbulent heat fluxes. The water input is, therefore, underestimated in this model simulation. Jaedicke et al. (2013) found that the highest recorded solar radiation measurement during snow season coincided with a slushflow event in the same region. In the EB model solar radiation and turbulent heat fluxes are incorporated. The EB model is only simulated 48 h ahead, and for technical reasons not combined with predicted rain values. The EB simulations are satisfactory at 3 h time steps. At daily resolution, however, they tend to overestimate the snowmelt rates when compared to rates at snow pillow stations (Skaugen and Saloranta, 2015). Thus, both simulations are currently used in the assessment.

Many slushflows commonly occur during the ice breakup process of streams and rivers in spring. A steep water discharge gradient could therefore be a good indicator of increasing slushflow hazard (Hestnes, 1998). Water discharge data from monitoring stations could be useful for an early indication. In Norway, however, there are very few stations in small catchments (< 50 km^2), hampering the use in a regional approach. The assessment therefore relies on observations of rapidly increasing water discharge reported in Regobs and a close cooperation with the flood forecasting service.

3.5 Water supply – snow depth by snow type ratio (WSR)

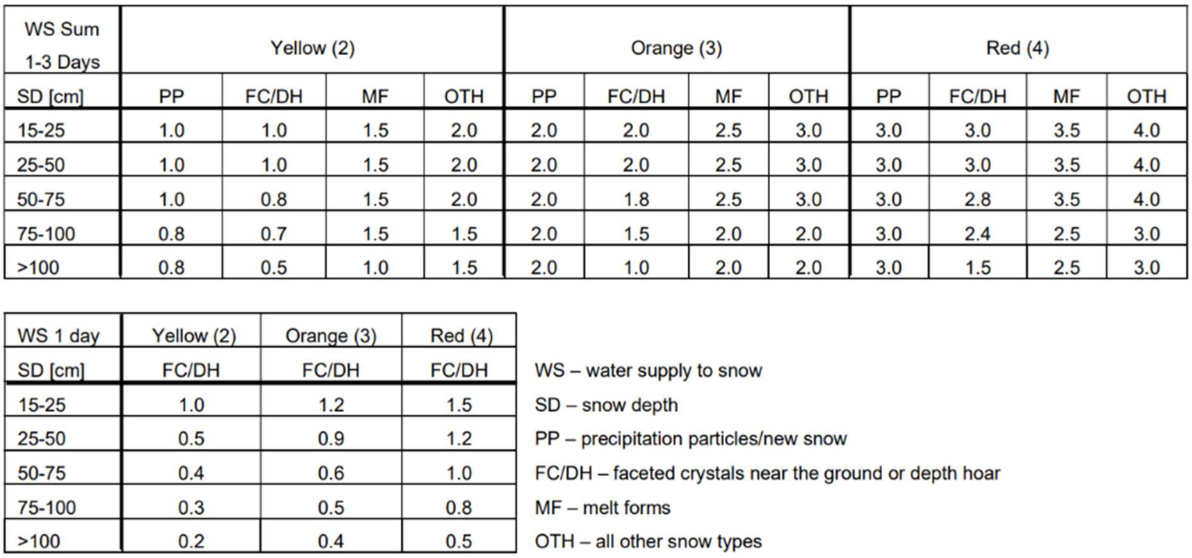
Hestnes and Bakkehøi (2004) investigated the connection between exposed snow types and slushflows. Studies investigating the connection between snow type, snow depth and the associated water supply for slushflow release, are very sparse (Skuset, 2018).

Our methodological approach was established with the assets and parameters available (Sect. 2.2) and was initially based on a 1:1 ratio for water supply (mm) and snow depth (cm) during 24h in the most slushflow-prone snow types. This has further been developed into ratio tables (Table 2) for the four snow types used facets and depth hoar (FC/DH), new snow on saturated or impermeable ground (PP), melt forms (MF), and other snow types (OTH). We used data from quality-controlled slushflow events as a basis to derive the water supply-to snow depth by snow type ratio (WSR) tables. The tables are based on values from precipitation as rain, snowmelt from EB model and snow depth retrieved from www.xgeo.no (accessed in April 2023) corresponding with the initiation areas of the slushflow events. Retrieving the snow type was challenging, as the availability of observations varies. For some of the events previous meteorological data from the same snow season was used to estimate the snow type, and only the most reliable estimates were used.

The events were first sorted by the four snow types, then by five snow depth classes in the estimated initiation area, based on the modelled grid value from Xgeo. Not all snow depth classes were represented in the dataset.

Thus, the remaining depth classes were inter- and extrapolated following a logical approach where larger snow depth to some extent needs more water supply than smaller snow depths. For FC/DH this deviates the most, based on observations. We followed the principle that the FC/DH layer near the ground is decisive. Thus, higher snow depth mainly contributes to delaying the water percolation towards the base of the snowpack, rather than the need for soaking the entire snowpack before a slush flow is released. For a MF snowpack, complete soaking is considered necessary before a slushflow is released.

Table 2: Danger level based on water supply – snow depth ratio by snow type



WS Sum 1-3 Days	Yellow (2)				Orange (3)				Red (4)			
SD [cm]	PP	FC/DH	MF	OTH	PP	FC/DH	MF	OTH	PP	FC/DH	MF	OTH
15-25	1.0	1.0	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	3.5	4.0
25-50	1.0	1.0	1.5	2.0	2.0	2.0	2.5	3.0	3.0	3.0	3.5	4.0
50-75	1.0	0.8	1.5	2.0	2.0	1.8	2.5	3.0	3.0	2.8	3.5	4.0
75-100	0.8	0.7	1.5	1.5	2.0	1.5	2.0	2.0	3.0	2.4	2.5	3.0
>100	0.8	0.5	1.0	1.5	2.0	1.0	2.0	2.0	3.0	1.5	2.5	3.0

WS 1 day	Yellow (2)	Orange (3)	Red (4)
SD [cm]	FC/DH	FC/DH	FC/DH
15-25	1.0	1.2	1.5
25-50	0.5	0.9	1.2
50-75	0.4	0.6	1.0
75-100	0.3	0.5	0.8
>100	0.2	0.4	0.5

WS – water supply to snow
SD – snow depth
PP – precipitation particles/new snow
FC/DH – faceted crystals near the ground or depth hoar
MF – melt forms
OTH – all other snow types

The values in Table 2 reflect our experience that there are differences between snow types with weak versus strong crystal bonding, especially on a regional scale assessment – an assumption that is also supported by previous studies (Hestnes, 1998). Furthermore, when the water supply is sufficiently large and intense, the snow types are less important, although the more slushflow-prone snow types are still expected to generate a larger number of slushflows than the less slushflow-prone ones.

It is important to note, however, that Table 2 is showing an estimate, and some caution must therefore be taken. As an example, consider a modelled snowpack consisting of 25 cm of new snow, which in one day receives half the water supply required to start a slushflow. The following day it receives no additional water. On the third day it receives the rest of the water needed for a slushflow to release. By that time, the snow may have transformed into melt forms, and the calculations need to be reassessed due to the change in snow type. Likewise, some vigilance must be exercised at small snow depths for FC/DH. For direct measurements of these, water discharge measurements in small catchments would be a benefit. Still, the overall regional values also seem to catch this type of slushflow release, as they result from rapid increase in snowmelt and water discharge. - The ratio is based on snow depth, and is thus not an unambiguous quantity. There may be large variations in the snow water equivalent (SWE). On the other hand, SWE do not solve the question about snow type. The values in Table 2 are subject to continuous improvements, as new quality-controlled slushflow data becomes available.

3.6 Slushflow observations detection, and database

Observations of slushflow-related events are important for several reasons. First there is the direct importance for the slushflow hazard assessment. Various signs, such as water ponding atop snow, intense snowmelt, and minor slushflows in streams, may indicate an increasing slushflow hazard (Hestnes, 1998). At times, such observations of increased LWC in the snowpack can be retrieved from Regobs in real-time. They are also used for validation of, e.g., snow wetness simulations. Second, observations are used, both in the weekly post evaluation of the assessment, as well as longer term evaluations. For the long term evaluations, data from the release area becomes important to differentiate between proper debris flows and debris flows initially released as slushflows. Information on release area is also important in the development of WSR and a future index. Underreporting of slushflows is a weakness, however. Third, quality-controlled events are important in the development of statistical decision-making tools. Finally, the development of, e.g., I[illegible]MMS applications for slushflows also suffer from lack of data. There is currently ongoing work at other institutions and departments to meet the needs for better modelling of this natural hazard.

3.6.1 Slushflow observations

After several years of operation of the NLFWS, the verification of landslide and slushflow occurrence is still a difficult and tedious task (Devoli et al., 2021). There are several challenges in the data collection of slushflow events, the main being misclassification and underreporting.

Insufficient observer knowledge, causing misinterpretation of slushflows as snow avalanches or debris flows is still a considerable challenge. Several different terms have been used for slushflows (e.g., slushers, slush avalanche, rain-on-snow-event) which has distorted the classification and establishment of a reliable national slushflow database. (e.g., Onesti and Hestnes, 1989; Hestnes, 1998). On the one hand, the large erosional capacity of slushflows, and possible transformation into debris flows, complicates the interpretation of the deposits (Hestnes and Kristensen, 2010). On the other hand, slushflows that do not erode the ground or incorporate other material than snow are also difficult to verify later. The verification time window after an event is usually limited to the existence of snow and slush, and evidence of slushflows may melt away rapidly.

Historical and media documentation are mostly related to the damage of property and infrastructure and not the frequency of slushflows (Hestnes, 1998). A slushflow situation that occurred close to Fauske, northern Norway on 25 February 2021 exemplifies this problem. Initially only one, later two, slushflows that hit the road were reported. Photos taken from a helicopter at the date of occurrence revealed there were at least 13 additional slushflows, totally 15 within an area of only 2 km^2 (Fig. 3).

Figure 3: Some of the slushflow paths (red lines) identified in the review of images from 25 February 2021, Fauske, northern Norway. Photo: No. 330 squadron Royal Norwegian Air Force.

3.6.2 Remote sensing

Satellite images are a potential source of data on slushflows. Slushflows are, however, triggered under weather conditions where the snow cover is rapidly changing, putting constraints on which temporal and spatial resolution are useful. Using data from Sentinel-1A, Radarsat-2 and Envisat ASAR, Malnes et al. (2016) attempted to detect slushflows that had already been reported. Out of 13 investigated events, seven were found, but the confidence level was low. For only one of the 13 slushflows, the interpretation was reasonably certain. Investigating an extraordinary slushflow situation in Greenland, several slushflows were detected using Sentinel-2 imagery. However, these were larger slushflows causing substantial erosion, making it possible to detect the events two weeks later (Abermann et al., 2019).

The temporal resolution is still often too low for optical detection. To some extent, the spatial distribution of the slushflow is also a challenge. For instance, the spatial resolution must be sufficient to detect rather confined tracks of slushflow in brooks. Furthermore, the nature of slushflows may also hamper the use of methods involving surface roughness and backscatter signature detection. Wet snow avalanches leave debris in the runout zone enabling detection of high backscatter due to the relatively high surface roughness from the debris (Eckerstorfer et al., 2019). This approach is currently also of limited use for many slushflows. In slushflows flowing over frozen terrain or rocks, the snow masses involved may melt rather than leave debris. When there is no erosion of the ground, there are usually no long-lasting deposits. Finally, the nature of slushflows enables flow across almost all types of terrain. This prevents the possibility of masking out certain terrain types to reduce the amount of data and speed up the processing time during automated tracking, as is possible for automated tracking of wet snow avalanches. Increasing application of unmanned aerial vehicles may alleviate these limitations in the future.

A slushflow on 16 May 2021 at Leigassletta, Nordland, Norway provides an example of close to optimal conditions for detecting such events. There were dependable, in situ observations of the slushflow covering more than 2 km distance in length and sufficient temporal resolution. Low cloud coverage enabled use of optical satellite sensors, such as Copernicus Sentinel-2 L1C provided free from the European Commission’s Copernicus environmental monitoring programme. Still, the slushflow was spotted neither very easily, nor along its entire extent (Fig. 4).

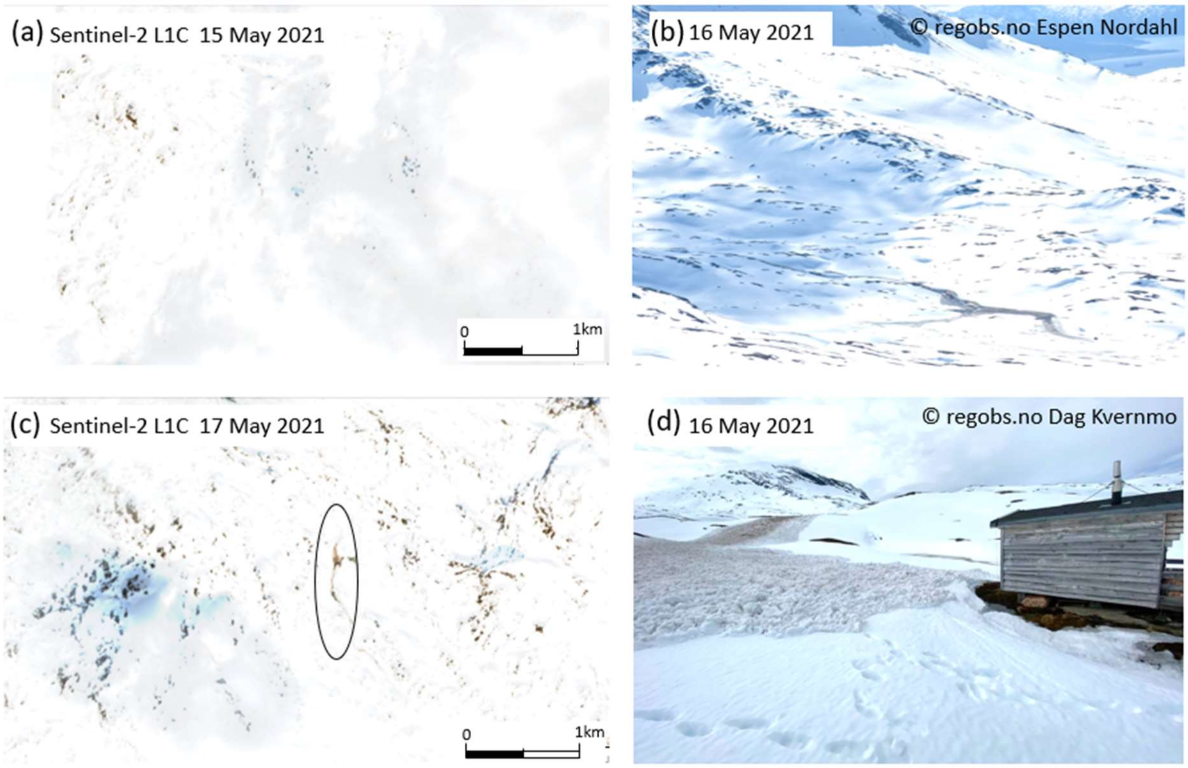


Figure 4: Snowmelt situations generally cause substantial changes of the snow cover and slushflows are often challenging to extract from multi-temporal satellite images. The slushflow at Leigassletta, Nordland, Norway 16 May 2021 is an exception with its long runout and distinct shape. It also occurred at a time of a favourable temporal resolution (of the satellite images). (a) Copernicus Sentinel-2 L1C satellite image 15 May 2021 prior to the slushflow. (b) Parts of the slushflow released on 16 May 2021, seen from a

distance. Photo: Espen Nordahl, Regobs.no (c) Copernicus Sentinel-2 L1C satellite image 17 May 2021, parts of the slushflow in black oval. (d) Close-up photo of the slushflow on 16 May 2021 Photo: Dag Kvernmo, Regobs.no

3.6.3 National database

A national database of rapid mass movements has been established in Norway (Jaedicke et al., 2009; Hermanns et al., 2012). It is available at www.skredregistrering.no and maintained by NVE. It consists of several types of data, raw observations registered directly in the database, observations transferred from Regobs, some quality-controlled, and supplemented later (Fig. 5). Several national sources contribute to the database. The slushflow entries before 2010 were mainly registered by NGI, but also supplied with more information later. In the last years, also the Norwegian public roads administration has started a more systematic collection of slushflow data.

The current database contains over 1000 reported slushflows from the year 1600 to the present (Lunde et al., 2023). Around half of these have undergone quality control and are categorized as A, B, C, or D. Events classified as A have a known date, time, and position. Events falling under category B have a date and time accuracy within ± 1 day and a location accuracy within 50 meters. Unverified reported slushflows are initially categorized as D but may be upgraded to at least C if confirmation of the event being a slushflow is obtained.

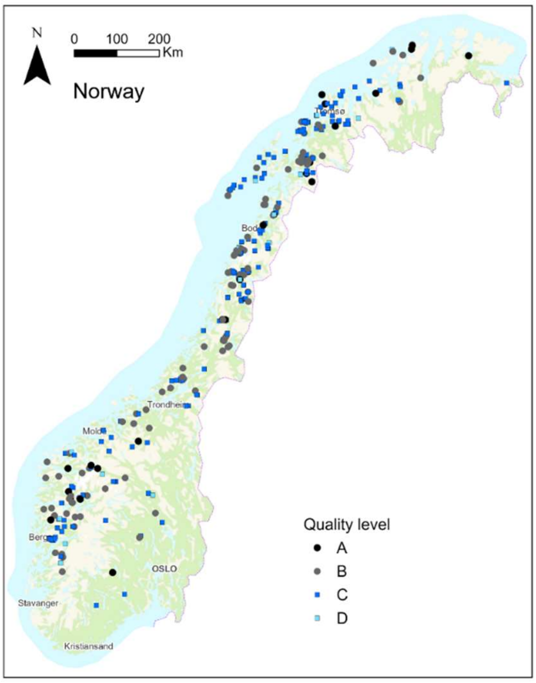


Figure 5: Reported and quality-controlled slushflows in Norway in the period 2013-2023. There are 152 events of quality A and B and totally 394 slushflows (Source: www.skrednett.no. Accessed 12 June 2023). Map source: The Norwegian Mapping Authority, Geovekst – Geodata AS.

3.7 Operationalization

The operational slushflow hazard assessment procedure follows a checklist according to the workflow in Figure 2. An imperative consideration for the forecasters is to determine how well the modelled variables reflect the situation. Real-time data from stations, web cameras, and reports from Regobs, e.g., about abundant water in the snowpack, are very useful in this respect. Another important consideration is their regional representativeness. This is a particularly important part of the assessment, as in many situations there are indications of local hazard only. Thus, it is the forecaster's task to analyse to what extent the simulations are correct and the probability that the situation will not extend into a larger area. Another task, when the interaction between the various factor is of regional relevance, is to delineate the exposed area correctly. This is to a large degree based on the forecasters experience with the model performance. The differences between forecast weather and real weather also play a role, e.g., the exact altitude of the 0ºC isotherm.

During the daily morning briefing, the simulated hydro-meteorological variables of are scrutinized against the meteorologist's evaluation of the situation. Afterwards, a discussion is held with the snow avalanche forecasters to determine the predominant snow type in the area of question. The Norwegian Public Road Administration also participates in the briefing and provides updates from the road network. There is also a synergy effect from working closely with the flood forecasters.. An analysis of the interaction between the different variables (Fig. 2, step 4), follows, and Table 2 comes into effect. Snow type is considered an important factor on a regional scale. At the same time, with sufficient water supply, slushflows can occur in all types of snow. It is therefore natural to attach most importance of assessment to the type of snow on yellow and orange danger levels. The challenge is to determine how much water is needed in the various combinations (snow type, snow depth, initial snow condition, intensity of water supply) that can occur. The WSR values (Sect. 3.5, Table 2,) reflects the principle that at equal snow depth, the least water supply will be needed if the snow is already wet and there is a vulnerable snow type.

Representative water supply and snow depths for the area in question are selected and the resulting WSR is extracted. Finally, the appropriate danger level is determined. During an ongoing situation, reports on slushflow observations from Regobs are also important input to evaluate whether the danger level in the issued bulletin is correct.

3.8 Assessment

Since autumn 2013, regional slushflow early warnings have been issued in Norway, and the practice was officially established in January 2014. Many of these warnings have been in a combined bulletin with debris flows, in weather situations where shallow landslides and debris flows also are relevant hazards. In situations with solid ground frost, or with saturated ground but not sufficient water supply for landslide hazard, a slushflow bulletin has been issued alone.

As examples of the variations of snow depth and water supply causing slushflows we present four different slushflow situations in more detail (Fig. 6). These situations happened during different dominating snow types, FC/DH, PP, MF, and OTH respectively. All values are modelled values retrieved from Xgeo (Accessed April 2023).

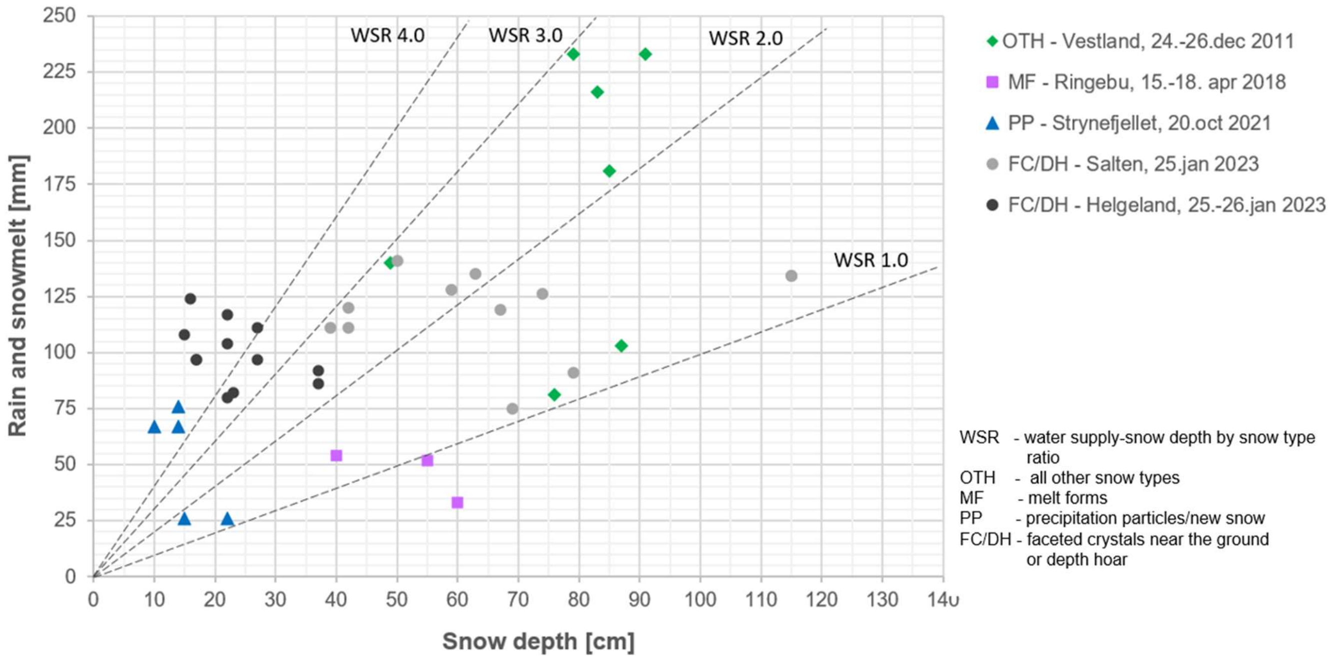


Figure 6: An example, distribution of slushflows according to snow type, and modelled snow depth and water supply (i.e., rain and snow melt) 1-3 days before the events.

In January 2023 there was intense rain and snowmelt on a snowpack with facets near the ground and depth hoar (FC/DH) in parts of Nordland County. In Salten the 3-day water supply varied between 75 mm and 141 mm with an average of 119 mm. The snow depth varied between 39 cm and 115 cm, with an average of 68 cm. The maximum water supply of 141 mm corresponded with a snow depth of 50 cm, giving a WSR of almost 3 (Table 2, red level). At higher danger levels most of the lower-level ratios are expected to be represented within the area of hazard as well. For Helgeland the 3-day water supply varied within the range of the values found in Salten for the reported slushflows (80 mm – 124 mm). Since the snow depth here was considerably lower (15 mm – 37 mm), the WSR was even higher, with more than 4 on average. The values were typically extracted from the most distinct slushflows in the region. In addition, there have been several smaller slushflows possibly with lower ratios.

At Strynefjellet the slushflows occurred when the area received snow (PP) on frozen ground a few days in advance. They were typically reported along the highway Rv15 which runs in a valley in this mountainous area. On 19 October 2021 snowmelt started and was accompanied by rain in the lower areas, before the slushflows were released on 20 October 2021. The modelled snow depths for the reported slushflow sites vary from 10 cm to 22 cm, and water supply from 26 mm to 76 mm. This corresponds to an average WSR of almost 4, with 1.1 as the lowest.

The example from Ringebu shows a situation in spring with melt forms (MF). These situations, with warm and sunny weather, are often challenging to assess because meltwater may accumulate for several days before the slushflow release. Hence, the value that must be taken into consideration is the cumulative water supply (snowmelt) through several days. As the actual in situ snow depth varies, slushflows may release several days in a row depending on when sufficient water supply is reached at different locations. For these three reported slushflows the modelled snowmelt and thus water supply was in the range 33 mm to 54 mm, on snow depths of 40 cm to 60 cm. There are indications that the modelled snowmelt values in Xgeo do not fully account for the effect of solar radiation, and hence the values can be underestimated in this case.

The windstorm called Dagmar swept over Norway on 24 December 2011 and eventually dissipated on 27 December. Strong winds, warm temperatures combined with rain and snowmelt lead to slushflows in the western part of Norway, Vestland county. The registered slushflows represent other snow types (OTH) than the three situations previously described. Since this happened two years prior to NLFWS and NAWS, no slushflow nor avalanche warnings were issued at the time, and there was no organized registration of observed slushflows. Seven slushflows are plotted in Figure 6, but we consider that the number of slushflows were underreported also for this event. The modelled snowmelt and thus 3-day water supply for the seven events was in the range 81 mm to 233 mm, on snow depths of 50-90 cm.

Jaedicke et al. (2013) used 4 × 4 km grid resolution data applied to five major weather situations to study critical meteorological elements for slushflow release. They suggest a minimum of 80 mm water supply per day for snow depths of at least 50 cm in mixed situations with rain and snowmelt, while intense rain situations were set to 50 mm per day^{-}. Their recommendation fits well with our results. They also estimated that as water input intensity increases, the importance of snow properties decreases.

Devoli et al. (2021) investigated the performance of the NLFWS. They found that NLFWS generally has had a high performance (score) of more than 90% correct warnings issued, within the limitations discussed. Due to the organizational decision of evaluating slushflows and landslides jointly (Sect. 2.2), only combined statistics are available. However, not all years presented in the score (Devoli et al., 2021) includes quality controlled slushflows (Lunde et al., 2023). Evaluating issued warnings is challenging due to difficulties in event collection and quality control. This is especially true for slushflows (Sect. 3.6). Misclassification and underreporting complicate danger level assessment. Retrieving information from other sources than media and Regobs can improve the assessment but is resource demanding to collect.

4 Application to other areas

While we have mentioned the limitations of development of SEW within an existing framework, a type of similar delineations will most likely be necessary during an establishment elsewhere. A similar service could find its place both within meteorological forecast service, snow avalanche forecasting or other type of water related slides and avalanche/hazards services.

Rainfall and snowmelt thresholds for shallow landslides and debris flows are specific to the soil properties of the area (e.g., Krøgli et al., 2018). The SEW in this approach is based on the properties of snow, categorized as four different snow types, and the necessary corresponding hydro-meteorological conditions. The SEW method is therefore universally applicable to areas that are subject to snowfall, either frequently or rarely. Although Table 2 is based on modelled values, it gives an indication of the suitable WSR and danger levels and could be used for assessments elsewhere. Obviously, some kind of assessment must be done regarding ground properties and snow type.

The advantage of our method is also a rather simple applicability to other areas with both seasonal snow and to some extent access to hydro-meteorological data. It focuses on the interaction between the different parameters and therefore also enables a more direct adaption of the method to other areas, also where the large-scale weather systems may differ from those commonly occurring in Norway. Conversely, combined snow type, -depth and rain and snowmelt data from other areas could be used as input to improve the SEW in Norway.

In December 2022 several communities on the Faroe Islands were hit by several slushflows, fortunately without fatalities. The islands are characterized by a thin layer of soil covering the underlying rock, facilitating rapid saturation of the ground when soil frost is absent (Christiansen et al., 2007). The ground could therefore generally be considered as meeting the requirement of an impermeable or saturated ground. Simulated meteorological data from www.meteoblue.com for Klaksvik 15−19 December 2022 and snowmelt energy balance graphs (Skaugen and Saloranta, 2015) gives a rough minimum estimate of a water supply (30 mm rain and 15 mm snowmelt, 45 mm in total) to an estimated mean PP snow depth of ca. 30 cm. Even with the very conservative estimate, the resulting minimum ratio of 1.5 is well within the warning range and satisfactorily reflects the situation. The area of Klaksvik is subject to large local variation (personal communication L. Mortensen 6 December 2023) and the values could therefore be regarded as a very conservative estimate.

Our approach could also be utilized in areas with rare snowfall, as the snow will most likely be within the PP category. 26 July 2019 a snow/hailstorm hit Col de l'Iseran, France during Tour de France. The impermeable asphalt was covered by snow and hail that was rapidly saturated by a succeeding intense rain shower. Similar to new snow, hail has poor cohesion between grains. Several slushflows initiated and some also transformed into debris flows as they flowed downhill on unfrozen, debris-covered hillsides. Although this was a rather unpredictable and local event, it shows the importance of the right combinations of factors.

The main part of our assessment was successfully used by NVE to forecast slushflow hazard and to time meso-scale contingency operations in Longyearbyen and surroundings in the High Arctic archipelago of Svalbard. This was done as an emergency measure for a few seasons starting in 2016.

We observe that the initial areas where slushflows occur are often the marginal zones of snow-covered areas as the WSR increases in these areas first. From this we hypothesize that the method has potential for a more tailored use at lower entry values of smaller areas according to the specific need of other communities and areas.

5. Summary and Outlook

5.1 Conclusion

We have presented the method of regional slushflow early warning (SEW) in Norway. The regional slushflow early warning (SEW) in Norway was officially operational from January 2014, probably as the first of its kind in the world. It is based on previous studies and adapted to and further developed within the Norwegian Varsom Xgeo grid-based early warning assessment tool. SEW has been developed within the existing framework for the forecasting of other natural hazards and resources available for this task at NVE.

The different steps, in the forecasters' slushflow hazard assessment process, are discussed as well as the variables used. We have established a relationship between snow types, snow depths and water supply to the snowpack (WSR) for various levels of regional slushflow hazard. The WSR for a snow depth of up to 50 cm, range from 1.0 from the most susceptible snow types at yellow danger level to 4.0 for the least susceptible snow types at red danger level.

An advantage of using WRS is that improvements can easily and continuously be incorporated in Table 2, as more data becomes available from new slushflow events. The procedure's steps remain unchanged, which is a great asset to the forecasters that work in a rotational duty. Sampling of data on snow type and snow depth on site, when available, and their regional representation by the Xgeo grid values will also eventually yield ratios that will be directly applicable both locally and regionally. We believe that this novel method for slushflow hazard assessment could be of benefit to other countries as well.

A considerable challenge is that registrations of possible slushflow events are missing in large areas, as demonstrated in the example from the Fauske area. Even though slushflows hitting roads and infrastructure are considered most important, all observations are crucial for statistical input to the development of a slushflow hazard index for a more automated assessment. With the unprecedented availability of spatial and temporal high-resolution satellite images and continuous development of remote sensing techniques, there is a large potential for future improvements and automated detection of slushflows. This would also be a benefit to the improvement of numerical modelling of slushflow runout.

Although a slushflow hazard index would simplify the assessment procedure, the ratio approach enables a manageable adoptability for other countries and areas with limited data input.

5.2 Future perspectives

For the early warning of landslides there were enough quality-controlled events (> 200) with corresponding modelled variables (water supply and soil saturation degree) in Xgeo to establish thresholds using classification trees (Krøgli et al., 2018). Classification trees have also been used to create a tool for operational snow avalanche forecasting (Hendrikx et al., 2014). Øyehaug (2016) attempted to find slushflow hazard thresholds using classification trees, but the data set at that time was too poor to ensure sufficient reliability for this approach. The increased work during the last years with expanding the number of quality-controlled slushflows and related data has therefore been essential. During the 10 seasons (starting 2013–2014) of SEW, there have been 359 reported slushflows in the country of which 152 (42 %) have been of good - fairly good registration quality (A and B category). The awareness and knowledge about slushflows is increasing, the crowdsourcing tools are improving, and seeing more use. We therefore expect that the data set will gradually grow, and the data quality will continue to improve.

Knowledge about the release area of registered slushflows is important to access the corresponding value for hydro-meteorological data, and to derive better information on the snow type on site prior to slushflow initiation. Better information about the snow depth and snow type in the release area prior to events will increase the accuracy of the WSR values in Table 2. Furthermore, it will provide a more robust dataset suited for statistical analysis, e.g., multivariate analysis, to develop map-based indexes according to snow type, snow depth, and danger levels. A slushflow hazard index must cover situations with cumulative water supply over time. Several situations have been observed to occur after a period with water supply with relatively low daily levels (Decaulne and Sæmundsson, 2006; Hestnes, 1998; Scherer et al., 1998).

Slushflows are the result of a series of coinciding events. For more reliable estimates of the impact of climate change on slushflows, it is not sufficient to only study how the individual factors will change, but also necessary to assess their combined interaction once satisfactory data becomes available.

Data availability

The data used in this study are mainly open access data from links in Sect. 3.

Author contribution

MS designed the method and wrote the manuscript. HAG contributed to the development, testing of the WSR table, SÅS contributed to the testing and of the WSR table. All authors reviewed the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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