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Operational regional slushflow early warning

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Abstract

Slushflows are observed worldwide in areas with seasonal snow cover. A regional early warning for slushflow hazard was established in Norway in 2013–14 as the first in the world of its kind and has been operational since. This paper presents a methodology using water supply – snow depth ratio by snow type, employing grid values and data from historical slushflows, to assess regional slushflow hazard. In Norway slushflows pose a significant natural hazard. Hazard prediction and early warning is therefore crucial to prevent casualties and damage to infrastructure. A benefit with this approach is that it can be implemented in other regions with slushflow hazard where the necessary input data are available.

Slushflows are rapid mass movements of water saturated snow. They release in low to moderate slopes (< 30°). Due to their high liquid water content, slushflows usually have long runouts, and they can transform into debris flows. A complex interaction between several factors is the key to slushflow initiation. Impeded infiltration of the ground is a prerequisite. Porous snow structures are most prone to destabilization. Rate and duration of water supply, due to rain on snow and/or intense snowmelt, is crucial.

The daily assessment of slushflow hazard is based on information on snow cover and hydro-meteorological conditions. Four main variables are central: ground conditions, snow properties, air temperature, and water supply to snow. A wide range of meteorological and hydrological parameters from multiple sources, together with real-time data from automatic stations and observations from the field, are assessed. The data is provided from the decision-making tool Varsom Xgeo, presenting outputs from model simulations as gridded maps (1x1 km). A first water supply-to-snow depth ratio for different types of snow has been developed using grid values and data from historical slushflows.

Short summary

Slushflows are rapid mass movements of water saturated snow, releasing in gentle slopes (<30°), often unexpectedly. Early warning is crucial to prevent casualties and damage to infrastructure. A regional early warning for slushflow hazard was established in Norway in 2013–14 and has been operational since. We present a methodology using the ratio between water supply and snow depth to assess slushflow hazard. This approach can be used in other regions with slushflow hazard as well.

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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; Fig. 1). 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: Slushflow, close to Krossbu mountain lodge, Jotunheimen, Southern Norway 19 May 2013. It runs through gently sloping terrain, has a high liquidity, and has eroded the ground. It is not uncommon that slushflows initiate in sunny weather due to snowmelt only. The mountain Store Smørstabbtinden is seen in the background right of the upper middle. Photo: Kjell Nyøygard.

Slushflows are rapid mass-movements of water-saturated snow (Washburn and Goldthwait, 1958; Nobles 1966; Hestnes, 1985). 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 (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 released in low to moderate slopes (<30°), unlike snow avalanches, landslides and debris flows. The initiation mechanism and flow dynamics may partly resemble that of debris flow (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 appear unexpectedly. The mass-movements often continue

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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 are 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 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 weather conditions possibly viewed as harmless by the public but resulted in the deaths of four people (Hestnes et al. 2012).

Natural hazard mitigation measures can generally be divided into three different groups, spatial planning, early warning and physical mitigation measures. Within spatial planning and for construction of physical mitigation measures numerical modelling of snow avalanches and debris flows is widely used (e.g. Christen et al., 2010; Mikos and Bezak, 2021). This is not a straightforward task for slushflows. Jaedicke et al. (2022) states that the mixture of water and snow gives slushflows unique properties that affect the movement and effects of pressure. This leads to completely different dynamic effects compared to for example snow avalanches, but also compared to debris flows. Experiments with dynamic slushflows in have only been carried out in a few trials (Jaedicke et al., 2008).

There are, to our knowledge, currently no dynamic models specifically developed for calculating the broad range of slushflow dynamics. Models developed for other flow-like processes, e.g RAMMS::DEBRISFLOW (RDF), contains sets of friction parameters recommended for calculation of debris flows. A study carried out by Skred AS (2021) hypothesised that RDF can also be used for calculation of slushflows, with an assumed higher water content and mobility than in the case of debris flows if the friction parameters are adapted. Finding slushflows with sufficient data quality, was a challenge. A few were found and enabled set up of RDF and gave a reasonable opportunity to test whether the model results agree with observations. Different sets of friction parameters, location of initiation areas, volume in initiation areas and use of the erosion module were tested. The modelling results were compared with observed speeds, path and slushflow runout.
The study showed that it is to some extent possible to use RDF to post-calculate the events, but that slushflows have significantly greater mobility than the standard friction parameters for debris flows. Several reservations and approximations were made. The values were very uncertain due to poor data amount and quality.

For RAMMS(::DF) the best applicable values will partly depend on the composition of the slushflow, which will vary from slow slushflow to slushflow (e.g. depending on the water content, and thus the mobility). Although numerical modelling of runouts is much more developed for snow avalanches and landslides, it is currently not a part of the early warning system (EWS) for the hazards in Norway.

Physical mitigation measures are expensive if possible. 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 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. Various EWSs, both site-specific and regional exist for rapid mass movements (e.g. Stähli et al., 2015; Guzzetti et al., 2020, LandAware). There are various challenges for the different hazards. For Rock falls the exact time of occurrence may be difficult to predict, while the location of possible events could be determined quite precisely and thus site-specific. While for floods in general, both time of occurrence and location currently can be determined quite precisely. Snow avalanches and landslides are somewhere in between. The time of release could also be forecasted quite accurately. As with rock falls, they initiate in steep terrain, and thus some terrain types could be ruled out for potential hazard. Slushflows are unique as they initiate in gentle slopes, but the runout could continue along almost flat terrain, or proceed in steep terrain once released. The initiation, however, can be forecasted reasonably well.

EWSs comprises of four different elements, spanning knowledge, monitoring and warning service, dissemination and communication and response capability (UN/ISDR, 2006). Krøgli et al. (2018) discusses the Norwegian Landslide Forecasting and Warning Service (NLFWS) in a in more detail. Early warning of slushflows is a necessity for the road- and railway administrations but is also a benefit, to e.g., hikers and skiers (Gude and Scherer, 1998). Local slushflow forecast has to some extent been carried out (Hestnes, 1998). Due to the range of initiation factors and processes, evaluation of slushflow hazard is considered to be much more complicated than evaluation of avalanche hazard (Onesti, 1985; Onesti and Hestnes, 1989, Hestnes, 1998). In this paper we focus on the method developed for 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. Finally, we discuss challenges in determining the consequences of climate change have on slushflows.

2 Background

2.1 Previous work

The release mechanism of slushflows differ from that of snow avalanches. The flowing mixture of snow and water is released during breakup of streams and rivers, but also initiate in depressions, gentle slopes, and in the transition zone between steep- and low-grade terrain. 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).

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, snow structure, and rate and duration of water input (Hestnes et al., 1994; Hestnes, 1998; Hestnes and Bakkehøi, 2004).

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 to 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 facilitate water saturation of a snowpack, basal impermeable or saturated 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 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 had better stability. 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 have > 95 % significance, locally > 50 % and in specific slushflows > 35 % (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 the midnight sun conditions will facilitate intense snowmelt (Hestnes, 1998). If the relative air humidity is less than 28 % no melting will take place, but some snow will evaporate (Hestnes et al., 1987). Reliable estimates of meltwater production 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 meltwater 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 and meltwater 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 forecast of slushflow hazard has been developed. The need for such a service, with utility value for road and rail, but also for outdoor life, was promoted 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 division for flood, expanding to snow avalanche, landslide and rock fall). This was part of a political effort to improve water-related natural hazard risk prevention. NLFWS was officially launched in autumn 2013 (Krøgli et al., 2018). From 2014, this service also officially included forecasting slushflow hazard. This was due to several 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 hazard levels.

As for landslides and snow avalanches, regional forecasts are not intended to be site-specific and indicate the location of possible slushflows. The slushflow release mechanism is the decisive factor for the types of slushflows included. 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 hazard level is communicated through a bulletin updated minimum once a day at www.varsom.no (Krøgli et al., 2018).

Unlike the predefined areas used by NAWS, the regions for landslide and slushflow hazard are dynamic, 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 development of the method for assessing regional slushflow hazard had to fit into the existing framework already developed for NVE's other natural hazard EWSs, putting some constraints on the approach. The NLFWS assessments are based on 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 warnings bulletins are divided in four colour-coded hazard levels: 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. Red indicates extreme hazard. 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.

Our methodological approach to regional SEW is based on the combination of factors that are previously found to be decisive in the triggering process. Yet 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. The variables for regional assessment of slushflow hazard can then be narrowed down to ground conditions, snow properties and water supply.

3 Methodology of regional slushflow early warning assessment

3.1 Setting, hydro-meteorological data, and tools

The area of the Norwegian mainland (Scandinavian peninsula) covers an area of 324 000 km^2, spans wide range of latitudes (~58° – 71°N) and experiences large climatic variations. The country currently has a real-time network of ca. 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) (Table 1). The development of observational and simulated weather grid data, covering the whole country at 1 km^2 resolution, enables regional approaches to early warning. Development and limitations of the maps in Xgeo are explained in https://senorge.no/Models?lang=no (accessed 13 May 2023).

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
			Degree of soil saturation
			Ground water level compared to normal
Snow	Snow avalanche forecasters	Snow depth point	Snow depth
		Varsom Regobs	Snow wetness
		Web camera	Fresh snow
		Satellite images (Sentinel-2, Sentinel-3)	LWC (up to 10%)
Water supply	MET-brief/meteorologists	Rain point	Snow and rain
	Flood forecasters	Discharge measurements in small catchments Varsom Regobs	Rain and snowmelt
Other	Geohazard awareness service, the Norwegian Public Road Administration		Air Temperature
			Air Temperature change

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 4 times day^{-1}, 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.

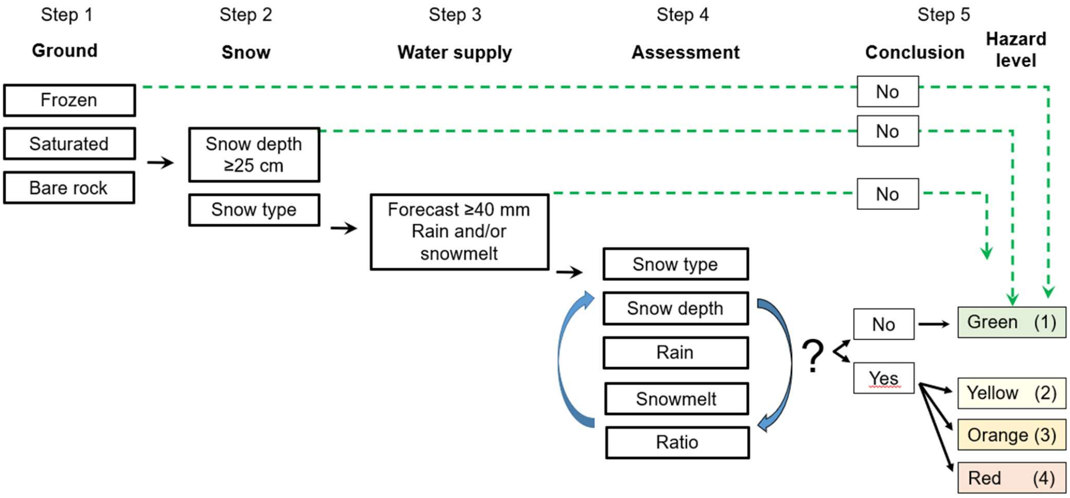

Figure 2: Flow chart of the slushflow hazard assessment process

3.2 Impeded infiltration of the ground

Impeded infiltration of the ground is a prerequisite for water saturation of the snowpack. Ground properties such as soil frost, soil saturation, and ground water level are all included in the assessment. For model purposes the soil in Norway is considered to be till on a regional scale, although there are variations. Thus, the same model parameters for soil conditions are used nationwide.

Soil frost depth is simulated using the Motovilov et al. (1999) approach within the spatially distributed version of the hydrological HBV model. The simulation only gives a rough estimate, as the soil frost depth varies locally due to many factors like 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

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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 (Beldring et al., 2003). High degree of water saturation indicates that the soil pores are water filled 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 there the infiltration capacity is low. The simulations only give estimates. They do not account for, e.g., 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, at least when compared to the model grid size of 1 km^2.

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).

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 do 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 focuses 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 is 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. 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 ratio developed to reflect the regional hazard level.

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 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, 2005). 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.

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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.

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 brief provided by the Norwegian Meteorological Institute enables adjustments in the model interpretation of the 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 model (EB). The combined rain and snowmelt values tab 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. Solar radiation is found to be a major factor for the release of wet snow avalanches, i.e., production of meltwater (Mitterer and Schweizer, 2013). 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 latter model EB solar radiation and turbulent heat fluxes are incorporated. The EB is only simulated 48 h ahead, and for technical reasons not combined with rain values. The EB simulations are satisfactory at 3 hourly time steps. At daily resolution 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 process of breakup of streams and rivers. 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 the synergy of close cooperation with the flood forecasting service.

3.5 Slushflow observations, validations, 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. Secondly, observations are used in the post evaluation of the assessment. Underreporting of slushflows is a weakness, however. Thirdly, quality-controlled events are important in the development of statistical decision-making tools. Finally, the development of e.g. RAMMS applications for slushflows also suffer from lack of data (Sect. 1). There is currently ongoing work at other institutions and departments to meet the needs for better modelling of this natural hazard.

3.5.1 Slushflow observations

There are several challenges in the data collection of slushflow events. One is insufficient observer knowledge, causing misinterpretation of slushflows as snow avalanches or debris flows. Several different terms have been used for slushflows (e.g., slushers, slush avalanche, rain-on-snow-event) and has previously distorted the classification and establishment of an accountable 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 slushflow evidence may disappear rapidly.

Next, is the fact that 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 25 February 2021 exemplifies this problem. Initially only one, later two, slushflows that hit the road was reported. Photos taken from a helicopter at the date of occurrence revealed there were at least additional 13 slushflows, totally 15 within an approximate area of only 2 km^2 (Fig. 3).

Figure 3: Some of the slushflow paths identified in the review of images from 25 February 2021, Fauske, northern Norway. Photo 330 squadron.

3.5.2 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 constrains on the temporal and spatial resolution of satellite images. 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. Only for one of the 13 slushflows, the interpretation was reasonably certain. Investigating an extraordinary slushflow situation in Greenland, several slushflows were detected using Sentinel-2. Yet, 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 approaches. To some extent, the spatial distribution of the slushflow is also a challenge. The spatial resolution must e.g., be sufficient to detect rather confined changes in brooks. Furthermore, the nature of slushflows also may restrain methods using 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 restrained for many slushflows. In slushflows flowing across 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 enable flow across almost all types of terrain. This hampers the possibility of masking out certain terrain areas 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 to some extent meet this shortage.

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 is not very easily spotted (Fig. 4).

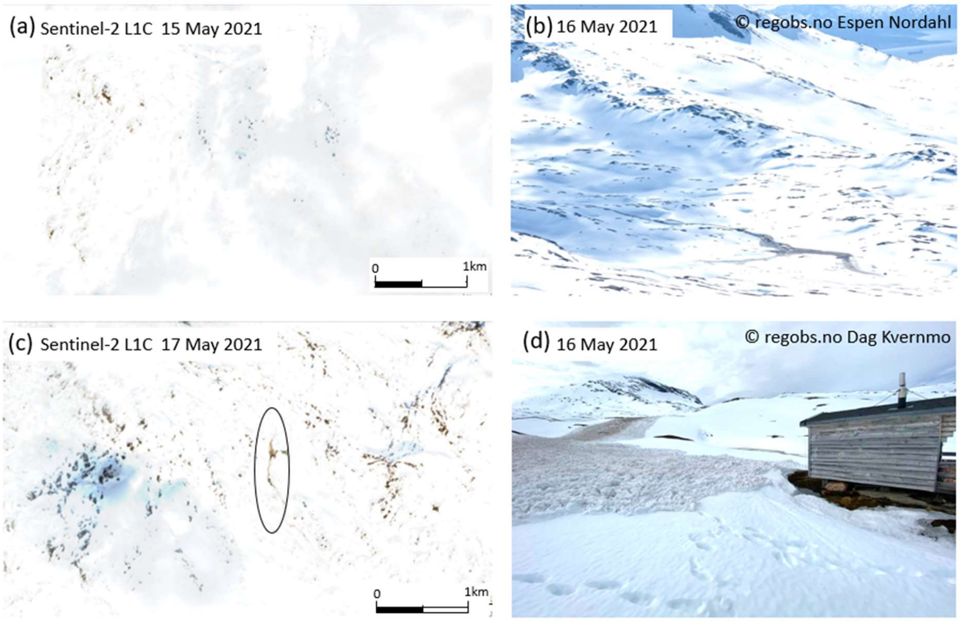

Figure 4: Snowmelt situations generally cause substantial changes of the snow cover and slushflows are often challenging to extract from multi-temporal satellite images. The slushflow at Leigassletta, Nordland, Norway 16 May 2021 is an exception with its long runout and distinct shape. It also occurred 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) Copernicus Sentinel-2 L1C satellite image 17 May 2021, the slushflow in black oval. (c) The slushflow released on 16 May 2021, seen from distance Photo: Espen Nordahl, Regobs.no (d) Close up of the slushflow on 16 May 2021 Photo: Dag Kvernmo, Regobs.no

3.5.3 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 have mainly been registered by NGI prior to NVE's assignment of slushflows prevention responsibility. In the last years, also the Norwegian public roads administration has started a more systematic collection of slushflow data.

The current database contains over 800 reported slushflows from the year 1600 until now. Around half of these have undergone quality control and are categorized as A, B, C, or D. Events classified as A have 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.

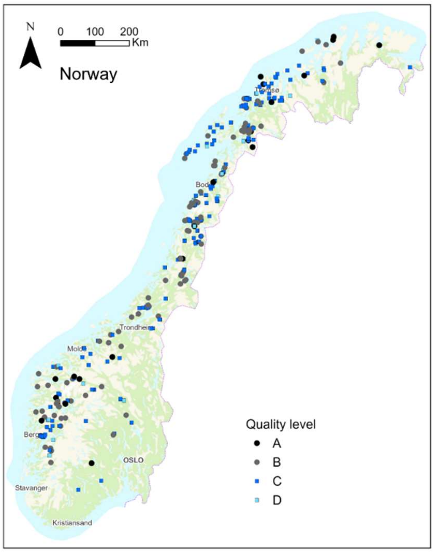

Figure 5: Reported and quality-controlled slushflows in Norway in the period 2013-2023. There are 152 events of quality A and B and totally 394 slushflows (Source: www.skrednett.no. Assessed 12 June 2023). Map source: The Norwegian Mapping Authority, Geovekst – Geodata AS.

3.6 Water supply – snow depth ratio by snow type

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).

Initially our methodological approach was 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 a ratio table (Table 2) for the four snow types used (FC/DH, PP, MF, OTH).

We used data from quality-controlled slushflow events to make the ratio tables. The table is based on values in www.xgeo.no (Accessed in April 2023). Retrieving the snow type was probably the most 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 needed 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 was decisive. Thus, higher snow depth mainly contributed 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: Water supply – snow depth ratio by snow type and slushflow hazard level

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
0-25	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

One day	Yellow (2)	Orange (3)	Red (4)
SD [cm]	FC/DH	FC/DH	FC/DH
0-25	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

PP – precipitation particles/new snow
FC/DH – faceted crystals or depth hoars near the ground
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 which 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 more slushflow prone snow types are still expected to generate a larger number of slushflows.

It is important to note, however, that table 2 is still to some extent 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 metamorphosed 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 values in Table 2 are subject to continuous improvements, as new quality-controlled slushflow data becomes available.

4 Operational assessment

Since autumn 2013, regional slushflow early warnings have been issued in Norway, and the practice went official in January 2014. Many of these warnings have been in a combined bulletin with debris flows, as a result of 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 is issued alone.

The operational slushflow hazard assessment procedure follows a checklist according to the workflow in figure 2. One of the main considerations is to determine how well the modelled variables reflect the situation. Real-time data from stations, web cameras and reports from Regobs are very useful in this respect. Another important consideration is their regional representativeness. During the daily morning-brief the simulations from variables constituting water supply are scrutinized against the meteorologist's evaluation of the situation. Afterwards, a collective 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 brief and provides updates from the road network. There is also a synergy effect from working close with the flood forecasters. For example, situations such as possible increases in water discharge in small catchments is discussed. An analysis of the interaction between the different variables (step 4, Fig. 2), follows, and Table 2 comes into effect. Finally, the appropriate hazard level is determined. During an ongoing situation reports on slushflow observations from Regobs are also important input to evaluate if the hazard level in the issued bulletin is correct.

An advantage of this method 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.

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

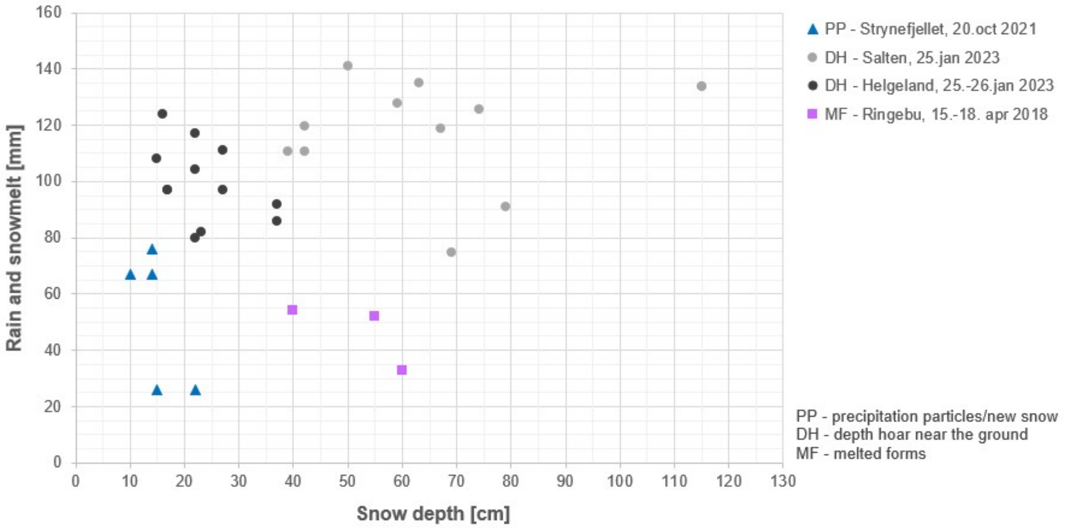

Figure 6: Distribution of reported slushflows according to snow type, and modelled snow depth and water supply (i.e., rain and snow melt) 1-3 days before the events.

In January 2023 there was intense rain and snowmelt on a snowpack with facets and depth hoars (FC/DH) near the ground snow in parts of Nordland County. In Salten the 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 of 141 mm corresponded with a snow depth of 50 cm, giving a water supply-to-snow depth ratio of almost 3 (red level, Table 2). At higher warning levels most of the lower-level ratios are expected to be represented within the warning area as well. For Helgeland the 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 water supply-to-snow depth ratio was even higher, with more than 4 on average. The values were typically extracted from the most pronounced 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 the 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 to 76 mm. This corresponds to an average water supply-to-snow depth ratio 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 consider as snowmelt could be accumulated several days ahead. 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. 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 40-60 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.

Jaedicke et al. (2013) used 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 day^{-1} for snow depths of at least 50 cm in mixed situations with rain and snowmelt, while intense rain situations were set to 50 mm day^{-1}. The overall picture fits well with our results. They also estimated that as water input intensity increases, the importance of snow properties decreases.

5 Application to other areas

While shallow landslide and debris flow thresholds 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, realized 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.

In December 2022 several communities on the Faroe Islands were hit by what turned out to be numerous slushflows, fortunately without fatalities. The islands are characterized by a thin layer of soil covering the underlaying rocks, 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, totally 45 mm) 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.

Although Table 2 is based on modelled values, it gives an indication of the suitable ratios and hazard levels and could be used for assessments elsewhere. Obviously, some kind of assessment must be done regarding ground properties. In the case of snowfall, such areas will most likely be subject to conditions rapidly changing from snow to rain and snowmelt.

Our approach could also be utilized in areas with rare snowfall, as the snow most likely will fall within the PP category. 26 July 2019 a snow/hailstorm hit stage 19 Col de l'Iseran, France during Tour de France. The impermeable and 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 the snow 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 validity of right combinations of factors.

Although Table 2 has a basis from modelled values it gives an indication of the suitable ratios and hazard level and could be used for assessments elsewhere. Obviously, some kind of assessment must be done regarding ground properties. However, as demonstrated by the example from Col de l'Iseran, roads could be sufficient on a more local scale. In the case of snow fall, such areas will most probably be subject to conditions rapidly changing from snow to rain and snowmelt.

The main part of our assessment was also successfully used by NVE to forecast slushflow hazard and timing for contingency operations outside at the meso-scale in Longyearbyen and surroundings in the high-Arctic Archipelago of Svalbard as an emergency measure for a period following 2016.

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, where the large-scale weather systems may differ from those commonly occurring in Norway. Conversely, data from other areas could be used to improve the dataset used for SEW in Norway.

At our 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 hazard 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.

We observe that the initial areas where slushflows occur are often the marginal zones of snow-covered areas as the water supply – snow depth ratio increases in these areas first. From this we can draw that there is a potential within the method for a more tailored use at lower entry values of smaller areas according to the specific need of other communities and areas.

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6 Future work and climate change

The awareness and knowledge about slushflows are increasing and 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.

A considerable challenge is that registration of possible slushflow events is missing in large areas. Even though slushflows hitting roads and infrastructure are considered most important, all observations are crucial for the development of an index, as the example from the Fauske area showed (Sect. 3.5.1, Fig. 3). With the unprecedented availability of spatial and temporal high-resolution satellite images and continuous development of 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. In the future improvements of both the regional slushflow early warning method and numerical modelling of runout could enable a confinement of the regional approach to a more detailed local warning.

6.1 Expanding the data set for a statistical slushflow index

Slushflow data from other countries also contribute to expand the slushflow data set lay the groundwork for a statistically generated slushflow index. For the early warning of landslides there are enough quality-controlled events (>200) with corresponding modelled variables (water supply and soil saturation degree) in Xgeo to establish of 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 was too poor to ensure sufficient reliability for this approach. The ongoing work with expanding the number of quality-controlled slushflows and related data is therefore essential.

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, 1998; Hestnes, 1998; Scherer et al., 1998).

Knowledge about the triggering location 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 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 hazard levels.

6.2 Climate change

Due to the previously mentioned limitations in the historical slushflow data collection, it is difficult to use the current data set for precise historical comparisons on, e.g., changes in frequency due to climate change.
There is some debate on whether the changing climate will cause more or fewer slushflows. Already in the 1990s, Gude and Scherer (1995) stressed the possibility of increased slushflow activity. Siderova et al. (2001) estimated that there will be a slight decrease in slushflow activity in northern Europe in 2050, based on the most dynamic climate change scenarios at that time. In a 10–20-year perspective, natural variations will largely dominate over changes in the climate in Norway, as an example. Within this time horizon, the advantages of using updated observations rather than projections are believed to outweigh the disadvantages (Hanssen-Bauer et al., 2017).

Climate change studies indicate a future climate in Norway with higher temperatures, increasing amounts of precipitation and increasing frequency and intensity of short-term precipitation. This is thought to result in an increased frequency of, among other things, slushflows in large parts of the country. Rising temperatures could lead to change from wet snow avalanches to slushflows (Hanssen-Bauer et al., 2017).

The first prerequisite for slushflow initiation is impeded infiltration of the ground below the snowpack. Projections of seasonal soil frost in a warmer climate generally indicate that the total area experiencing seasonal soil frost will be reduced, and the penetration depth will decrease. Chen et al. (2022) detected this trend for the northern hemisphere for the period 1986-2005. However, winter climate change alters snow cover and depth that will influence the soil frost dynamics. A reduction in soil frost may also enhance water saturated ground conditions. Development of gridded nation-wide projection maps of ground temperatures is challenging and currently there are not sufficient data to assess this question (Nilsen et al., 2020).

The next prerequisite is snow. Processes in snow and its properties are greatly affected by frequent temperature changes around 0°C. Warm spells during winter are projected to occur up to three times more frequently in the next 50–100 years than in the reference period of 1985–2014 (Vikhamar-Schuler et al. 2016). A trend analysis for projected days with zero-degree crossings (DZC) in Norway indicate that temperatures will rise above 0°C for a larger part of the year in cold seasons and regions, such as inland regions during winter and Finnmark in spring (Nilsen et al., 2020).

Hestnes and Jaedicke (2018) assume that more frequent switches between rain and snow will form more ice and crust layers in the snowpack and thus increase the stability against slushflows. Yet, temperatures and DZC alone are not sufficient to access the influence on changes in the snowpack and other processes involved in the release of slushflows. Diurnal temperature variations are important, but currently even daily values may be challenging to project correctly (Nilsen et al., 2020).

If an exposed snow type is subject to long-lasting air temperatures above 0°C in addition to rain, the slushflow hazard will be higher compared to a situation where the air temperature throughout the day varies around 0°C. The average air temperature alone is therefore not a sufficient indicator. It is also currently unclear to what extent weather situations where new snow falls straight on bare ground, followed by rain and/or snowmelt conditions, will increase in Norway.

Water supply is the final factor, also subject to large uncertainties. Projections on precipitation amounts as rain are probably better than estimates on snowmelt. Estimating correct values of snowmelt is challenging also as present-day assessments.

On a global scale, there are various opinions about how the slushflow frequency will be affected. Relf et al. (2015) suggest that climate change can lead to more slushflows hitting infrastructure, and that more mitigation measures are needed. Hestnes and Jaedicke (2018) postulate that, globally, the slushflow frequency may increase in early winter, while the frequency generally is reduced as a result of cyclonic activity.

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 only to study how the individual factors will change, but also necessary to assess their combined interaction once satisfactory data becomes available.

7 Conclusion

The regional slushflow early warning (SEW) in Norway officially went operational in 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 existing framework of the Norwegian Varsom Xgeo grid-based tool. We believe that this novel method developed for regional slushflow hazard assessment could be of benefit also in other countries.

During the 10 seasons (starting 2013–2014) of regional slushflow hazard early warning, there has been 359 reported slushflows in the country of which 152 have been of good - fairly good quality (A and B category).

We have established a relationship between snow types, snow depths and water supply to the snowpack for various levels of regional slushflow hazard. The water supply – snow depth ratio by snow type for a snow depth of up to 50 cm, range from 1.0 from most susceptible snow types at yellow hazard level to 4.0 for the least susceptible snow types at red hazard level.

Awareness and knowledge about slushflows are increasing. The introduction of crowdsourcing tools in Norway has also provided higher quality and increased amount of data. Currently the most important task for further development of SEW is to continue ongoing work collecting essential slushflow data to improve the robustness of statistical findings. Increased good quality registration of events is not only a benefit to the improvement of the early warning method, but also for the development of numerical calculations of slushflow runout.

Our approach for assessing slushflow hazard on a regional scale, using a combination of hydro-meteorological variables, could be applied in other areas as well. Conversely, data from other areas can also contribute to a better foundation for a future slushflow index encompassing snow type, snow depth, and water supply across various hazard levels.

Weather conditions vary widely and are also expected to change further due to climate warming. Slushflows are the result of a complex series of coinciding events. Thus, projection of climate change impact on slushflows needs to include the synthesis of the factors involved for the regions in question. At present the projections are not sufficiently accurate for all the individual variables, which impedes e.g., frequency estimates. Once such data are available, they could also be used as proxy or for frequency calculations.

Data availability

The data used in this study are mainly open access data from links in Sect. 3 Methodology of regional slushflow early warning assessment.

Author contribution

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

Competing interests

The authors declare that they have no conflict of interest.

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References

Abermann, J., Eckerstorfer, M., Malnes, E., and Hansen., B. U.: A large wet snow avalanche cycle in West Greenland quantified using remote sensing and in situ observations, Nat. Hazards, 97, 517–534 https://doi.org/10.1007/s11069-019-03655-8, 2019.

Barsch, D., Gude, M., Mausbacher, R., Schukraft, G., Schulte, A. and Strauch, D.: Slush stream phenomena - process and geomorphic impact. Z. Geomorphol., Supplementband 92, 39-53,1993.

Beldring, S., Engeland, K., Roald, L. A., Sælthun, N. R., and Voksø, A.: Estimation of parameters in a distributed precipitation-runoff model for Norway, Hydrol. Earth Syst. Sci., 7, 304–316, https://doi.org/10.5194/hess-7-304-2003, 2003.

Bellaire, S., van Herwijnena, A., Mitterer, C., and Schweizer, J.: On forecasting wet-snow avalanche activity using simulated snow cover data, Cold Reg. Sci. and Technol., 144, 28–38, 2017.

Brun, E., Martin, E., Simon, V., Gendre, C. and Coleou, C.: An energy and mass model of snowcover suitable for operational avalanche forecasting, J. Glaciol. 35, 333– 342, 1989.

Christen, M., Kowalski, J., and Bartelt, P.: RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. Cold Reg. Sci. Technol. 63, 1–14. https://doi.org/10.1016/j.coldregions.2010.04.005, 2010.

Christiansen, H. H., Blikra, L. H. and Mortensen, L. E.: Holocene slope processes and landforms in the northern Faroe Islands. Earth Environ. Sci. Trans. R. Soc. Edinb., 98, 1-13, 2007.

Chen, C., Peng, X., Frauenfeld, O.W., Zhao, Y., Yang, G., Tian, W., Li, X., Du, R., Li, X.: Comprehensive Assessment of Seasonally Frozen ground Changes in the Northern Hemisphere based on Observations, J. of Geophysical Research: Atmospheres, Vol. 127, e2022JD037306. https://doi.org/10.1029/2022JD037306, 2022.

Colbeck, S.: Theory of Metamorphism of Wet Snow, CRREL, Special Report, 1-11, 1973

Decaulne, A. and Sæmundsson, Th.: Meteorological conditions during slushflow release and their geomorphological impact in Northwestern Iceland: A case study from the Bíldudalur Valley, Geogr. Ann. A: Phys. Geogr. 88(3), 187-197. Doi 10.1111/j.1468-0459.2006.00294.x, 2006.

Denoth, A.: The pendular-funicular liquid transition and snow metamorphism J. Glaciol. 28 (99), 357-364, 1982.

Eckerstorfer, M., Vickers, H., Malnes, E., and Grahn, J.: Near-Real Time Automatic Snow Avalanche Activity Monitoring System Using Sentinel-1 SAR Data in Norway, Remote Sens.-Basel, 11, 2863, https://doi.org/10.3390/rs11232863, 2019.

Ekker, R., Kvaerne, K., Os, A., Humstad, T., Wartiainen, A., Eide, V., and Hansen, R. K.: RegObs – Public Database for Submitting and Sharing Observations, in: Proceedings of the International Snow Science Workshop, 7–11 October 2013, Grenoble, France, 461–465, 2013.

Engeset, R. V. 2013. The Norwegian Avalanche Warning Service, in: Proceedings of the International Snow Science Workshop, 7–11 October 2013, Grenoble, France, 301–310, 2013.

Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Green, E., McClung, D. M., Nishimura, K., Satyawali, P. K., and Sokratov, S. A.: The international classification for seasonal snow on the ground, IHP-VII, Technical Documents in Hydrology N83, IACS Contribution N1, UNESCO-IHP, Paris, 2009.

Gude, M., and Scherer, D.: Snowmelt and slush torrents – preliminary report from a field campaign in Kärkevagge, Swedish Lappland. Geogr. Ann. 77A(4), 199-206, 1995.

Gude, M., and Scherer, D.: Snowmelt and slushflows: hydrological and hazard implications. Ann Glaciol. 26, 381-384, 1998.

Guzzetti, F., Gariano, S. L., Peruccacci, S., Brunetti, M. T., Marchesini, I., Rossi, M., and Melillo, M.: Geographical landslide early warning systems, Earth. Sci. Rev., https://doi.org/10.1016/j.earscirev.2019.102973, 2020.

Hanssen-Bauer, I., Førland, E. J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, A., and Ådlandsvik, B.: Climate in Norway 2100 – a knowledge base for climate adaptation. Norwegian Centre for Climate Services, Report 1/2017, available at: https://www.miljodirektoratet.no/globalassets/publikasjoner/M741/M741.pdf (last accessed 3. June 2023), 2017.

Hendrikx, J., Murphy, M., and Onslow, T.: Classification trees as a tool for operational avalanche forecasting on the Seward Highway, Alaska. Cold Reg. Sci. Tech., 97, 113- 120, 2014.

Hermanns, R. L., Hansen, L., Sletten, K., Böhme, M., Bunkholt, H. S. S., Dehls, J. F., Eilertsen, R. S., Fischer, L., L'Heureux, J.-S., Hægaas, F., Nordahl, B., Oppikofer, T., Rubensdotter, L., Solberg, I.-L, Stalsberg, K., and Yugsi Molina, F. X.: Systematic geological mapping for landslide understanding in the Norwegian context. In: Eberhardt E., Froese C., Turner K., and Leroueil S. (Eds.): Landslides and Engineered Slopes: Protecting Society through Improved Understanding, 265-271, Taylor & Francis Group, London, ISBN 978-0-415-62123-6, 2012.

Hestnes, E.: A contribution to the prediction of slush avalanches, Ann. Glaciol., 6. 1-4, 1985.

Hestnes, E.: Slushflow hazard – where, why and when? 25 years of experience with slushflow consulting and research. Ann. Glaciol., 26. 370 – 376, 1998.

Hestnes, E., and Bakkehøi, S.: Observations on water level fluctuations in snow due to rain and snowmelt, in: Proceedings of the International Conference on Avalanches and Related Subjects, September 2-6, 1996, Kirovsk, Russia, 115-120, 1996.

Hestnes, E., and Bakkehøi, S., Slushflow hazard prediction and warning. Ann. Glacial. 38, 45- 51, 2004.

Hestnes, E., and Jaedicke, C.: Global warming reduces the consequences of snow-related hazards, in: Proceedings of the International Snow Science Workshop, 07-12 October 2018, Innsbruck, Austria. 493-497, 2018.

Hestnes, E., and Kristensen, K.: The diversity of large slushflows illustrated by selected cases, in: Proceedings of the International Snow Science Workshop, 17-22 October, Squaw Valley, CA, 2010.

Hestnes, E., and Sandersen, F.: Avalanche formation, movement and effects, IAHS Publ. N162,1987.

Hestnes, E., and Sandersen, F.: The main principles of slushflow hazard mitigation. International Symposium Interpraevent 2000, Villach, Austria. Tagungspublikation, Band 2, 267-280, 2000.

Hestnes, E., Bakkehøi, S., and Kristensen, K.: Slushflows – a challenging problem to authorities and experts. Data of Glaciological Studies, Moscow. Publication N1, 74-87, 2012.

Hestnes, E., Bakkehøi, S., Sandersen, F., and Andresen, L.: Meteorological significance to slushflow release. NGI 582000-5. Symposium on Snow and Glacier Research, Lom, Norway, 1987.

Hestnes, E., Bakkehøi, S., Sandersen, F., and Andresen, L.: Weather and snowpack conditions essential to slushflow release and downslope propagation, in: Proceedings of the International Snow Science Workshop, Snowbird, 30 October – 3 November, UT, 40-57, 1994.

Hisdal, H., Bjordal, H., Engeset, R. V., Colleuille, H., and Steinvik, K.: Evaluering av snø- og jordskredvarslingen, NVE report 38-2017, available at: http://publikasjoner.nve.no/rapport/ 2017/rapport2017_38.pdf (last accessed 24 April 2023), 2017.

Jaedicke, C., Lied, K., and Kronholm, K.: Integrated database for rapid mass movements in Norway, Nat. Hazards Earth Syst. Sci., 9, 469–479, https://doi.org/10.5194/nhess-9-469-2009, 2009.

Jaedicke, C., Høydal, Ø. A., and Midtbø, K. H.: Identification of slushflow situations from regional weather models, in: Proceedings of the International Snow Science Workshop, 7–11 October 2013, Grenoble, France, 177-182, 2013.

Jaedicke, C., Kalsnes, B., and Solheim, A. Sørpeskred. Egenskaper, historikk og sikringsløsninger, Report series Klima 2050/38, available at: Norwegian Geotechnical Institute (NGI) Digital Archive: Sørpeskred. Egenskaper, historikk og sikringsløsninger (unit.no), 2022.

Jaedicke, C., Kern, M.A., Gauer, P., Baillifard, M.-A., and Platzeret, P.: Chute experiments on slushflow dynamics, Cold Regions Science and Technology 51 (2008) 156–167, 2008

Kobayashi, S., Izumi, K. and Kamiishi, I.: Slushflow disasters in Japan and its characteristics, in: Proceedings of the International Snow Science Workshop, 30 October – 3 November, UT, 657-665, 1994.

Krøgli, I. K., Devoli, G., Colleuille, H., Boje, S., Sund, M., and Engen, I. K.: The Norwegian forecasting and warning service for rainfall- and snowmelt-induced landslides. Nat. Hazards Earth Syst. Sci., 18, 1427–1450, 2018.

LandAware: Glossary and catalog of LEWS – LandAware (last assess: 5 July 2023).

Li, H., Xu, C.-Y., and Beldring, S.: How much can we gain with increasing model complexity with the same model concepts? Journal of Hydrology 527, 858-871, http://dx.doi.org/10.1016/j.jhydrol.2015.05.044, 2015.

Malnes, E., Eckerstorfer, M., and Sund, M.: Deteksjon av sørpeskred med radarsatellitt. Utredning av muligheter basert på SAR data fra reelle sørpeskred. NORUT rapport 02/2016, available at: https://norceresearch.brage.unit.no/norceresearch-xmlui/bitstream/handle/11250/2735159/Norut_Tromso_rapport_11-2015.pdf, (last access: 3. June 2023), 2016.

Mikos, M. and Bezak N.: Debris flow modelling using RAMMS model in the Alpine environment with focus on the model parameters and main characteristics. Front. Earth Sci. 8:605061. doi: 10.3389/feart.2020.605061, 2021.

Mitterer, C., and Schweizer, J.: Analysis of the snow-atmosphere energy balance during wet-snow instabilities and implications for avalanche prediction. Cryosphere 7, 205–216. 2013.

Mitterer, C., Techel, F., Fierz, C., and Schweizer, J.: An operational supporting tool for assessing wet-snow avalanche danger, in: Proceedings of the International Snow Science Workshop, 7–11 October 2013, Grenoble, France, 7-11, 2013.

Motovilov, Y. G., Gottschalk, L., Engeland, K., and Rodhe, A.: Validation of a distributed hydrological model against spatial observations. Agricultural and Forest Meteorology (98-99), 257-277, 1999.

Nilsen, I. B., Hanssen-Bauer, I., Tveito, O. E., and Wong, W. K.: Projected changes in days with zero-crossings for Norway. Int. J. Climatol. 2021; 41, 2173–2188. https://doi.org/10.1002/joc.6913, 2020.

Onesti, L. J.: Meteorological conditions that initiate slushflow in the Central Brooks Range, Alaska, Ann. Glaciol. 6, 23-25, 1985.

Onesti, L., and Hestnes, E.: Slush-flow questionnaire. Annals of Glaciology 13, 226– 230, 1989.

Øyehaug, G.: Hydrometeorologiske tersklar for sørpeskredfare, MSc-thesis Geohazards, Institute for Geosciences, Uni. Of Oslo, 1-117, 2016.

Pérez-Guillén, C., Tsunematsu, K., Nishimura, K., and Issler, D.: Seismic location and tracking of snow avalanches and slush flows on Mt. Fuji, Japan. Earth Surf. Dynam., 7, 989–1007, https://doi.org/10.5194/esurf-7-989-2019, 2019.

Rapp, A.: Recent developments of mountain slopes in Kärkevagge and surroundings, northern Scandinavia. Geogr. Ann. Vol. XLII, 71-200, 1960.

Relf G., Kendra, J.M., Schwartz, R.M., Leathers, D.J., and Levia, D. F.: Slushflow: science and planning considerations for an expanding hazard. Nat. Haz. 78, 333-354, 2015.

Saloranta, T. M.: Operational snow mapping with simplified data assimilation using the seNorge snow model. J. Hydrol., 538, 314-325, 2016.

Scherer, D., Gude, M., Gempeler, M., and Parlow, E.: Atmospheric and hydrological boundary conditions for slushflow initiation due to snowmelt. Ann. Glaciol., 26, 377-380, 1998.

Sidorova, T., Belaya, N., and Perov, D.: Distribution of slushflows in northern Europe and their potential change due to global warming. Ann. Glaciol., 23, 237-240, 2001.

Skaugen, T., and Saloranta, T.: Simplified energy-balance snowmelting model. NVE report 31-2015, 1-27. 2015.

Skred AS: Bruk av RAMMS::DEBRISFLOW på kjente sørpeskredhendelser NVE ekstern report 9-2021, available at: https://publikasjoner.nve.no/eksternrapport/2021/eksternrapport2021_09.pdf

Skuset, S.: Utløysing av sørpeskred i ulike snøtypar. MSc-thesis. Institute for geosciences and petroleum. Norwegian University of Science and Technology, 1-117, available at: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2564441, (last access: 3. June 2023), 2018.

Statens vegvesen: Flom- og sørpeskred. (Debris flows and slushflows) Statens vegvesen, Oslo, Norway. N V139, available at: https://vegvesen.brage.unit.no/vegvesen-xmlui/handle/11250/3073176, (last access: 3. June 2023), 2014.

Stähli, M., Sättele, M., Huggel, C., McArdell, B. W., Lehmann, P., Van Herwijnen, A., Berne, A., Schleiss, M., Ferrari, A., Kos, A., Or, D., and Springman, S. M.: Monitoring and prediction in early warning systems for rapid mass movements, Nat. Hazards Earth Syst. Sci., 15, 905–917, https://doi.org/10.5194/nhess-15- 905-2015, 2015.

Techel, F., and Pielmeier, C.: Point observations of liquid water content in wet snow – investigating methodical, spatial and temporal aspects. Cryosphere, 5, 1–14, doi:10.5194/tc-5-1-2011, 2011.

Tómasson, G. G., and Hestnes, E.: Slushflow hazard and mitigation in Vesturbyggd, Northwest Iceland. Nordic Hydrol., 31 (4-5), 399-410, 2000.

UN/ISDR: Developing Early Warning Systems: a checklist, EWC III 3rd international Conference on Early warning, From Concept to action, UN/ISDR, available at: http://www.unisdr.org/2006/ ppew/info-resources/ewc3/checklist/English.pdf (last accessed: 5 July 2023), 2006.

Vikhamar-Schuler, D., Isaksen, K., Haugen, J. E., Tømmervik, H., Luks, B., Schuler, T., and Bjerke J.: Changes in winter warming events in the Nordic Arctic Region, J. Climate, 29, 6223–6244, https://doi.org/10.1175/JCLI-D-15-0763.1, 2016.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J.M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2. Geoscientific Model Development, 5(3): 773-791, 2012.

Washburn, L., and Goldthwait R. P.: Slushflows. Bull. Geol. Soc. Am. 69:1657–1658, 1958.