Discussion of “Operational regional slushflow early warning”

AUTHOR RESPONSE TO REFEREE COMMENT 1

Sund et al.

18 July 2023

Responses to Referee #1 (Harpa Grimsdottir)

General comment

Referee comment: *The paper gives a good overview of the operational slushflow regional forecasting system in Norway, which is probably unique in the world. It gives some good background information on slushflows and what kind of situation may lead to slushflow danger in general, based on previous papers on slushflows. The paper is of importance to all who are dealing with this problem, forecasting for and warning against slushflow danger.*

Author comment: We are grateful for your positive review and constructive suggestions for improvements.

Detailed comments

1. **Referee comment:** *According to our experience, slushflows can initiate in slopes that are quite steep in general, however the starting point might be in an area with inclination <30°. The starting point can be in a small „step“ in the slope, or at the lower part of a high and steep mountain where the slope starts to ease off. I feel that sometimes, the risk of slushflows may be underestimated in areas where the slope in general is considered to be too steep for slushflows but still includes areas where slushflows can initiate.*

Author comment: Thank you very much for shedding light on this aspect. We fully agree and have experienced the same in Norway as well. It is also included in our internal information about slushflows. However, in many cases we do not have sufficiently evidence to be 100% sure, as this kind of slushflows are often documented only at far distances. The increased use of unmanned aerial vehicles (UAVs) will help meeting this shortage. It is slightly mentioned in L118, but we will highlight this aspect better.

2. **Referee comment**: *It is mentioned that physical mitigation measures are expensive if possible, and in some areas difficult to implement. Therefore, EWS is important. It is also stated that the initiation of slushflows can be forecasted reasonably well. In my opinion it is important to consider physical mitigation especially in places where slushflows pose serious threat to settlement. There is great uncertainty associated with forecasting the time and location of a slushflow. In some slushflow paths the complication and cost is not as high as for typical dry snow avalanche mitigation measures, but in other areas it is more complicated.*

Author comment:

We agree that physical mitigation is important in populated areas, and it is a part of the mitigating measures against natural hazards. However, this paper concentrates on and presents *one* of the possible mitigation measures, namely early warning and not all mitigation measures for slushflows in general. The cost of permanent physical mitigation measures in Norway is very high, and all areas can therefore not be protected physically. Thus, not least with increasing hazard due to climate change, it was decided to establish an early warning system against natural hazards in Norway. In other countries this may appear differently.

Generally, the permanent physical mitigation measures in Norway are established in areas where they serve as against multiple natural hazards including debris flows and snow avalanches, Thus the knowledge about the effect against slushflow specifically is less known. Although studies have been performed in Alpine regions the Norwegian conditions are not identical. In Norway settlements are not confined to a few areas but are spread along the entire country.

Yet, there are locations along the railway where sheds are built (Hestnes and Sandersen, 2000) for protection against slushflows, only.

In Longyearbyen, Svalbard there is also currently ongoing work to establish a permanent physical mitigation measure against slushflows, after a comprehensive study. This is being built in Vannledningsdalen, a confined channel draining a wider valley and large drainage basin. With a long and well-known history of slushflows. Until now the hazard has been managed by a deflecting dam for protection of houses and by trenching the channel every spring with a bulldozer to drain the snowpack. Currently flexible net barriers are being established. It is however suggested that further work should be carried out to establish reliable numerical models of the interaction between slushflows and the barriers (e.g., Kalland, 2022).

In our experience forecasting the time of slushflows is much more feasible than location, especially at the higher warning levels. The exceptions are areas with known recurring slushflow event history. This is the background for L91 and onward.

L 91 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.

3. **Referee comment**: *In Figure 2 (flowchart) the hazard level becomes automatically green (1) if the ground is not frozen, saturated or a bare rock. Earlier in the paper it is, however, stated that requirement of water saturation can also be met with unfrozen ground and when a thick ice layer is covered with snow. Perhaps slushflows occurrences in such conditions are so rare that they are not taken into account?*

Author comment:

In Norway the experience so far is that these conditions are rather rare on a regional scale. Nevertheless, it is included in the daily checklist, and which is updated each season according to new experiences and tools.

Our aim with Fig. 2 was to provide a rough overview of the principle, and not least to draw the attention towards the ground conditions as they are also (usually) an important part of the assessment. However, thick layers are in the checklist used for the daily assessment, although the condition is rare in Norway, to our experienced so far.

It will anyway be natural to set up a specific checklist according to the tools available and conditions in the area/country in question.

If desired, we can change the headline instep 1 from “Ground” to “Impeded infiltration” and add thick ice layers within the snowpack.

4. **Referee comment:** *In Table 2 it is a bit unclear to me what SD (cm) stands for. Is it the total snowdepth according to a model in Xgeo? Or does „Sum 1-3 Days“ apply to the snowdepth – is it the accumulated snow within the last 3 days? As I understand it, it is the total snowdepth, but then it is assumed that a total snowdepth of 0-25 cm can lead to danger levels 2, 3 and 4. However, in the flowchart in Figure 2, snowdepth less than 25 cm automatically leads to danger level 1. Does „Sum1-3 Days“ apply to the water supply (rain + snowmelt)?*

Author comment: Thank you for pointing out the missing explanation in Table 2. This should certainly have been explained.

We have added SD for snow depth in the legend.

We have also added a topline explaining that 1-3 days and 1 day refers to water supply period.

We have corrected the values from 0-25 cm to 15-25 cm. We will also change the value of snow depth in Fig. 2 accordingly, so they both refers to Xgeo values. Please see the new version below.

Table 2: Water supply – snow depth ratio by snow type and slushflow hazard level

	Water supply Σ1-3 days								
Hazard level	Yellow (2)			Orange (3)			Red (4)		
SD [cm]	PP	MF	OTH	PP	MF	OTH	PP	MF	OTH
15-25	1.0	1.5	2.0	2.0	2.5	3.0	3.0	3.5	4.0
25-50	1.0	1.5	2.0	2.0	2.5	3.0	3.0	3.5	4.0
50-75	1.0	1.5	2.0	2.0	2.5	3.0	3.0	3.5	4.0
75-100	0.8	1.5	1.5	2.0	2.0	2.0	3.0	2.5	3.0
>100	0.8	1.0	1.5	2.0	2.0	2.0	3.0	2.5	3.0

	Water supply 1 day			Water supply Σ3 days		
Hazard level	Yellow (2)	Orange (3)	Red (4)	Yellow (2)	Orange (3)	Red (4)
SD [cm]	FC/HD			FC/HD		
15-25	1.0	1.2	1.5	1.0	2.0	3.0
25-50	0.5	0.9	1.2	1.0	2.0	3.0
50-75	0.4	0.6	1.0	0.8	1.8	2.8
75-100	0.3	0.5	0.8	0.7	1.5	2.4
>100	0.2	0.4	0.5	0.5	1.0	1.5

SD – snow depth

PP – precipitation particles/ new snow

MF – melt forms

OTH – all other snow types

FC/DH – faceted crystals or depth hoars near the ground

5. **Referee comment:** *It would be interesting to include in the paper a bit more about how well the forecasting system has worked in practice. It is important to look at days both with and without slushflow events and check how often these weather, soil saturation and snow conditions occur, without any slushflows being recorded. I realise it is not easy due to the sparse slushflow data, however, some analyses of this has probably been done in Norway?*

Author comment:

We understand that the question is being asked. The challenge is, however, that NVE decided to evaluate early warnings for slushflows together with landslides. These events may often follow one another as slushflows may start in areas with frozen ground and then transform into debris flows where the ground is thawed, but far from always. Particularly in the first years it was also difficult to get sufficient data quality for a certain decision on type of event. This work is now ongoing with reanalysis also back in time.

Øyehaug et al. (2018) did an evaluation of the performance of the combination for the period 2014-2017. They found that 92% of days where slushflow hazard was assessed, were correct, while finding the hazard level (as defined by then) was more challenging. We may include but do not find it fully representative, both due to the combination with landslide and the development since then. We therefore chose not to include the report in Norwegian. There has also been a continuous development (especially in the initial phase), which makes it difficult to make a good comparison. In this paper, it is important to convey a notification method to those who may need it.

We agree that this is also an important topic. Recently it has also been decided to evaluate slushflow separately from landslides. Now that the SEW method is more consolidated, it will be natural to discuss the topic it in a separate article, as also treatment of uncertainties needs special attention.

Minor issues (in pdf attachment)

Referee comment: *Here are a few questions on minor issues mostly related to wording. The numbers refer to the lines in the pdf file:*

6: Would it be better to say: „A regional early warning – for slushflow hazard....“?

Author comment: Thank you for the suggestion. Although the operational aspect is left out, we agree that the flow is better in the suggested title and have decided to change the title accordingly.

44: Would be good to mention what year this slushflow occurred in Japan.

Author comment: Yes, thanks it is now included.

71: „Experiments with dynamic slushflows in have only.....“ Should the word „in“ be skipped? Or is something lacking in the sentence?

Author comment: Thanks, “In” was a typo, it is now removed.

86: What is a „slow slushflow“ ?

Author comment: This was a typo. Thanks for bringing it to our attention.

105: „in a in“. One „in“ too much?

Author comment: Thanks for bringing typo to our attention. “a in” is removed.

105,106: Isn‘t Early warning of slushflows good for settlements as well?

Author comment: Absolutely. We have changed this to “infrastructure”.

561: The sentence is a replication of line 550.

Author comment: Thank you for the correction. We have removed the four sentences in L561-564.

596: Dataset is usually one word?

Author comment: It appears to us that both are possible.

598: Establish of thresholds => establish thresholds

Author comment: Thanks, corrected.

References

Kalland, H. D. 2022. Snow forces, avalanches, and avalanche mitigation methods. MSc-thesis, Norwegian University of Science and Technology.

Øyehaug, G. B., Sund, M. and Colleuille, H. 2018. Sørpeskredfare på regionalt nivå: Treffsikkerheita til varslinga. NVE rapport 17/2018.