Extreme precipitation on dry ground in western Norway – characteristics of induced landslides call for adaptation of the Norwegian practice in landuse planning

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Abstract. Following a particularly dry summer, a torrential rain event struck Western Norway on Tuesday 30 July 2019. The resulting floods and shallow landslides caused one fatality and severe damages to public and private infrastructure in the former Jølster municipality. Building on earlier work, in which we identified characteristics of the shallow landslides induced by torrential rains on unsaturated soils, we here present suggestions for adaptation of the Norwegian practice in landuse planning.

1 Introduction

Historically in Norway, the majority of shallow landslides occur after prolonged and/or intense rainfall, sometimes combined with snowmelt; commonly during spring and autumn [1,2]. Whilst more research is needed, it is generally assumed that shallow landslides in Norway are primarily released in fully saturated soils as slope-specific porewater pressure thresholds are exceeded [3]. In contrast, during the Jølster event soils were not fully saturated, instead failures largely occurred due to locally high porewater pressures at depth, as short intense rainfall on dry ground led to surface water infiltration in open cracks in the surface cover, often at soil-bedrock or soil-boulder contacts [4].

1.1 The Jølster event

In July 2019 the weather in Western Norway was relatively warm and dry, resulting in low to very low groundwater levels in areas not affected by snow or glacier melt [5]. Unusually warm air masses dominated Southern Norway in the week prior to the extreme event on 30 July, whilst colder air masses approached from the east and northeast the day before the event. This created atmospheric instabilities which intensified as the air masses moved westwards and absorbed humidity from the glaciated and still snow-covered areas in the southern Scandinavian Mountains [6]. The rain gauge at Haukedalen, 16 km south-southeast of Vassenden, recorded 43.6 mm in 3 hours, exceeding the 200-year event magnitude [6]. However, weather-radar data suggest much higher intensities in the mountains above Slåtten and Vassenden (Fig. 1A) focused to a narrow time window from 3 to 5 pm.

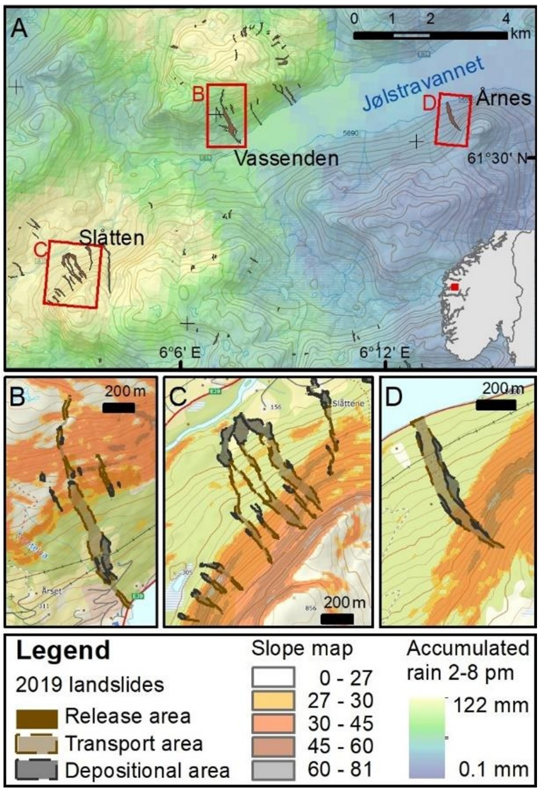

Fig. 1. Landslides and rainfall in Jølster 30 July 2019. A: Accumulated rainfall estimated from weather radar 2-8pm with shallow landslides [7] B-D: Close-up of terrain and slope angles with detailed mapping of the largest shallow landslides [4].

The intense deluge triggered >120 landslides and floods which damaged public infrastructure and private property in a 10 km radius around Vassenden (Fig. 1A). The extreme event resulted in one fatality, 150 people evacuated from the area and the closure of Highway E39 for several hours. Following the event, 17 million kroner (ca. 1.65 million euro) were spent on debris removal and building of safety measures; payments from private insurances not counted.

120 shallow landslides triggered by this torrential rainfall event were identified based on Sentinel-2 NDVI (Normalized Difference Vegetation Index) images in a 10 km radius around the town of Vassenden (Fig. 1A; [7]). 52 of these, including the most destructive debris flows and avalanches (Fig. 1B-C), were studied in greater detail and presented in [4]. The findings are shortly summarized in the following paragraph.

1.2 Characteristics of landslides induced by torrential rain on unsaturated soil

Commonly, autumn and spring storms can induce shallow landslides spread over larger areas in Norway [2]. In contrast the torrential rainfall in Jølster triggered a multitude of shallow landslides in a spatially confined area (< 160 km^2) during the warm summer month.

The landslide source areas in Jølster are situated in the upper hillslopes, often at the transition between bare bedrock and thin (< 0.5-1 m) soil cover and primarily at or above the tree line. Many landslides are initiated at the foot of larger or smaller cliffs. Notably, and importantly, many of the starting points were not recognized in existing susceptibility and hazard zone maps. These maps are all based on combinations of field observations of deposits and tracks from previous events, scattered historical records and computer models based on digital terrain data. While some landslides were subsequently channelized into known flow paths, several landslides paths occurred very unexpectedly considering geomorphology and known previous events.

Some open fissures observed in the topsoil around and directly above 2019 backscarps could traditionally be interpreted as retrogressive soil failure, but fissures were also observed further away from the backscarps and between landslides. Therefore, we argue that they likely initiated prior to the event, due to the prolonged dry spell. The time from rain shower onset until triggering of the majority of shallow landslides was barely 1-2 hours, suggesting that only the topsoil (0.1-0.3 m) was saturated and that intense surface runoff instead infiltrated directly through pre-existing fissures. This mechanism facilitated rapid water infiltration and localized build-up of water pressure at depth corresponding to typical observed scarp thickness (0.6-1.2 m), at stratigrahic transitions, as well as soil-bedrock and soil-boulder contacts.

Point field observations and subsequent volume analyses from pre- and post-landslide terrain models further indicate that landslide surface sediment entrainment outside the main channels was restricted to roughly 0.2 m below original surface. This may be related to the depth of transition from saturated to unsaturated topsoils. Due to the low sediment entrainment, the water-to-solid ratio of the mobilised landslide/debris flow material remained high. The observed shallow landslides are thus more liquid, have longer runouts and are slightly less destructive compared to counterparts released in fully saturated soils.

Many landslide paths were densely forrested illustrating the rare occurrence of mass movements on those slopes. Therefore, timber was an important ingredient of the total landslide masses. In the Slåtten area (Fig. 1C) logs accumulated during the first more viscous pulse functioned later to protect the settlement from a second, more liquid, landslide pulse. Landslide deposits from the larger Jølster landslides were very diverse: from thin diamicts with angular boulders, over thin unsorted to layered diamicts, to almost isolated freshly eroded cobbles and boulders with basically no sediment matrix deposited on relatively undisturbed topsoils and vegetation. The last category differs significantly from the normally recognised landslide deposits, and may after few years likely be misinterpreted as rockfall deposits rather than shallow landslides.

2 Natural hazards in Norwegian landuse planning

Considerations of natural hazards in Norwegian landuse planning are regulated through the Planning and Building Act §§ 28-1 and 29-5 [8] and in Regulations on technical requirements for building works (TEK17) § 7 [9]. The toolbox for natural hazard evaluation in spatial planning consists of i) seamless national *susceptibility maps* establishing potential danger and ii) local *hazard zone maps* which verify and quantify real danger based on mass movement probability. Since 2009 hazard zone evaluation has been required for planned building projects within a susceptibility zone. The Norwegian Water Directorate (NVE) works on hazard zone mapping of the most densely populated areas within selected municipalities; currently only 2.6% of Norway's surface area is analysed.

Hazard zones in Norway are defined based on the largest nominal probability for a mass movement hitting and damaging individual buildings:

i) For infrastructure belonging to safety class S1 (garages, boat houses) annual probability must be ≤ 1/100.
ii) In safety class S2 (residential houses with max. 10 units, work and residential houses for a max. of 25 persons) annual probability must be ≤ 1/1000.
iii) In safety class S3 (residential houses with more than 10 units, work and residential houses for more than 25 persons, schools, kindergartens, nursing homes and institutions for emergency preparedness) annual probability must be ≤ 1/5000.

Compared to other countries' legislations, these are long return periods to consider and consequently consultants have less use of modern climate and event databases to inform evaluations. Geological and geomorphological observations thus become increasingly important for mass movements with very long return periods. Unlike the Swiss practice in landuse planning [10], intensity or energy at impact and damage potential are only considered indirectly.

2.1 Uncertainties in identification of source areas

The current methodology for shallow landslide *susceptibility mapping* in Norway [11] identifies potential starting points based on three topographic characteristics: slope angle, planar curvature and upslope catchment area. The national terrain model which was used for the present dataset had variable original resolution of 5, 10 and 25 m, subsampled to a 10 m raster dataset. The National quaternary geological dataset at varying scale of 1:250 000 to 1:50 000 was used as additional criteria together with a very generalised regionalisation of morphological traces of previous events. The fact that Jølster event starting points were largely not recognized is probably due to a combination of the following: i) many shallow landslides occurred in areas mapped as bare rock in the quaternary map, ii) several shallow landslides were released from hillslope with little planar curvature (> -0.5 per 100 m) and iii) some shallow landslides do not fulfil the requirements regarding upslope catchment (> 5 000 m^2). The low general resolution of the terrain model used (10 m) will also make detection of smaller topographic features inaccurate and some potential starting points may not be detected at all.

Identification of potential source areas for shallow landslides in *hazard zone mapping* according to Norwegian TEK17 is done based on study of historic events, climate analyses, GIS-based terrain analyses (based on Lidar-derived terrain models) and fieldwork. However, looking in greater detail, many of the Jølster event source areas would still not be considered typical landslide starting zones based on the thin soft-sediment cover (< 0.5-1 m) often on narrow ledges or on open slopes, and might not have been investigated further during hazard evaluation. The Vassenden debris flow (Fig. 1B) is a good example of such an unexpected starting zone high up on an open slope without obvious catchment or initial sediment. Many of the Jølster landslides had comparably small starting volumes, but due to exceptionally rainfall intensities and runoff over steep to very steep upper transport areas (30-45 and 45-60 degrees, see Fig. 1B-D), momentum was nevertheless sufficient to sustain large debris flows and avalanches down to the valley bottoms.

2.2 Uncertainties in landslide paths prediction

According to Norwegian TEK17 *hazard zones* must reflect areas where mass movements potentially harm humans or hit and damage buildings, but little guidance is provided on how much damage may be acceptable. In addition to field observations and the study of digital map sources, consultants are obliged to simulate landslide paths with dynamic models, in many cases with RAMMS::Debrisflow. Taurisano [12] has used the Slåtten shallow landslides as one of eleven case studies to determine the best set of parameters in RAMMS for non-channelized shallow landslides in Norwegian conditions. He concludes that the use of standard Voellmy parameters (ξ=200 m/s^2; μ=0.2) and consideration of erosion in densely packed sediments (erosion rate 0.013 m/s) produces the overall best results. For the Slåtten case conservative Voellmy parameters (ξ=3000 m/s^2; μ=0.05) and no erosion gave more realistic results which is consistent with highly liquid debris flows subject to very low frictional resistance and restricted sediment entrainment due to dry soil. If consultants simulate with different starting zones and sets of parameters corresponding to rain-on-dry-ground vs rain-on-saturated-soil scenarios, such modelling results could give indications for the construction of maps which show the intensity or energy at impact.

Landslide paths with long return periods are commonly densely forested. Whilst modelling would have central role in quantifying runout length and intensity, it should be mentioned that any heterogeneity in the landslide mass, and in particular timber, will complicate landslide flow dynamics. In Jølster, we have seen examples of how logs function as a barrier, both through uprooting of single trees and as log walls in the deposition zone. Resulting changes in landslide path direction are near impossible to predict. In other historic events in Norway logs created the biggest damage in otherwise harmless clay-rich landslides, stressing the unpredictable nature of landslide masses with high timber content.

2.3 Uncertainties in identification of debris flow deposits

In Norwegian *hazard zone mapping*, the mass movement with the longest runout and highest impact is ruling the placement of hazard zone borders, whilst hazard zones are constructed for each mass movement type and then combined to synoptic hazard maps in other countries [e.g. 10]. Thus, field investigations, together with digital map sources and modelling results often inform the decision which mass movement type is determining hazard zoning. As before mentioned, we found a somewhat unexpected category of landslide deposits: almost isolated cobbles and boulders with little or no matrix, sometimes accompanied by tree logs, deposited on undisturbed topsoil and vegetation. Angular boulders will likely be the most long-lived superficial remains of these deposits and may be misinterpreted as rockfall rather than debris flows deposits. In the Norwegian approach for hazard zone mapping a falsely interpretated origin of boulder material may have far-reaching consequences.

2.4 Suggested adaptations of the Norwegian legislation and practice in landuse planning

The Norwegian legislation and practice in landuse planning is developed based on historic mass movement events and has been well suited to tackle debris flow hazard in the past. The Jølster landslides triggered by torrential rain on dry soil can be considered a hitherto rare category of events in Norway which is expected to become more frequent due to a warming climate [13]. In our opinion the Jølster events challenges existing legislation and practice in landuse planning and sheds light on its shortcomings.

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To begin with, we want to address an apparent contradiction in the review of the Norwegian landuse approach presented above. On the one hand, Norwegian legislation demands the consideration of long return periods of 5000-, 1000- and 100-years; it can thus be considered a conservative approach. This is amplified by the current version of conservative susceptibility maps. Hazard zoning restricts building activities in many mountainous municipalities and inhibits local economy and infrastructure development. On the other hand, our analysis of the Jølster event may suggest that the Norwegian approach is not conservative enough to capture this type of landslides induced by torrential rain on dry ground as observed starting points were largely not recognized in susceptibility and hazard zone maps. To resolve this contradiction, we suggest a series of adaptations to the Norwegian legislation and practice in landuse planning.

In our opinion, there is a need to adjust legislation so that the considered return periods for mass movements in steep terrain in Norway are shortened considerably. This would allow evaluations to be based more strongly on climate records and reduce the necessity of expert guessing. Another required change which is already on the way for avalanches and shallow landslides is the production of revised susceptibility maps to make them less area demanding.

The main challenge with debris flows induced by extreme summer rainfall is that we seem to be unable to pinpoint starting points and rather come to the fatalistic conclusion that soil failure must be expected on any slope which is steep enough. Therefore, in the framework of the existing Norwegian approach, we suggest them to be treated more like rockfall. Belonging to the category of mass movements which occur randomly along a mountainside, the probability for a rockfall hitting a property is considered for a 30-meters-wide foothill section. Since the cross-sectional area affected by a debris flow is wider than for rockfalls, the foothill section should be increased to at least 100 meters for landslides in rain-on-dry-ground scenarios. This simple adaptation of the Norwegian practice in landuse planning suggested above, could be set into place promptly.

In the longer term, we suggest more fundamental changes to the Norwegian approach in landuse planning. Landslides induced by torrential rain on dry soil are rare events with long runouts and possibly lower energy at impact. These characteristics could be tackled more adequately with a clear differentiation of the mass movement probability, intensity and resulting hazard. At present probability of the various mass movement types and intensity are only considered indirectly by consultants in one single hazard map showing the combined effect of all mass movement types which have the potential to endanger human lives and health or cause large economic loss. Further, the maximum allowed annual probability is determined based on the function of each individual building in Norway, while countries like Switzerland and South Tyrol follow an aggregated approach in which houses belonging to densely or sparsely populated areas are defined as common objectives. The aggregated approach may help consider rare events more adequately.

A final shortcoming of the Norwegian system that we would like to highlight, is the lack of communication and awareness of the residual risk. Buildings belonging to safety class S3 should be placed outside the three considered hazard zones, where the accepted annual probability is no greater than 1/5000. In the public opinion however, there seems to be a misconception that is no hazard whatsoever beyond these zones.

3 Conclusions

The characteristics of the Jølster event with heavy rain on dry ground highlight the shortcomings of the Norwegian legislation and practice in landuse planning. Many of the Jølster event landslides started outside existing national susceptibility zones and in places not previously known for similar processes. We suggest changes to the legislation as well as short- and long-term adaptations of the Norwegian practice in landuse planning.

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