Response from the authors (in blue) to the comments by referee Ivan Vergara (in black), updated 9. April 2021.

[Line numbers in blue refers to the new version of the manuscript: Bondevik_Sorteberg_Groundwater fluctuations_revised_marked_up.docx]

GENERAL COMMENTS:

The manuscript "Groundwater fluctuations during a debris flow event in Western Norway – triggered by rain and snowmelt" analyses the behaviour of the groundwater level during the occurrence of a debris flow and compares it with the behaviour during other extreme events and with the typical groundwater situation. It is considered that the research is novel because the analysis of these data is not common and the results are very important for the study of shallow landslides by allowing to know the situation of the ground before, during and after the failure. Moreover, the manuscript is well written and has fine and clear figures. Then are some comments that could improve understanding of the work.

We appreciate that you find our paper well written with fine and clear figures, and also that you have provided many suggestions, listed below, that will improve our paper. We will comments on each of them below.

SPECIFIC COMMENTS:

L19-20. Saying that Storm Dagmar did not generate debris flows without giving the reason does not provide much information to the reader. I think the sentence is missing a conclusion.

The sentence gives the reader the important information that in spite of a very similar groundwater situation, a debris flow or slide was not triggered during the storm Dagmar. Unfortunately, we do not know the reason for that and cannot give it. In the discussion section of the paper this is somewhat discussed, but are not able to come up with a specific explanation.

L82-87. It would be useful to describe somewhere in the manuscript (perhaps here) some other important characteristic of the study area... E.g., Mean annual precipitation, climate, vegetation.

Yes, we have now included a paragraph that describes the vegetation and climate in the area (line 98-101).

L234-237. I don't understand the relationship between this sentence and Fig. 6. On the other hand, I do not understand the arguments to infer that the peak occurred before 23 o'clock... If the intensity of the rain and the air temperature did not change, it would not be explained either because the groundwater reached the peak between 8:30 p.m. and 9:30 p.m. and then it started to decrease.

Sorry, there is a type error here in our text, it should not say "*see Fig. 6"* in our text, but it should be "*see Fig. 8*." This has now been changed (line 263).

L237-238. In Fig. 8 this extrapolation is not plotted... It is important to plot it.

Yes, we agree, good idea. We have now plotted the extrapolation in Fig. 8 as a stippled line.

L269-272. Is there any hypothesis why this event did not generate landslides? There is some information throughout the manuscript that could explain the non-occurrence and it could be useful to comment on them in the same paragraph (e.g., the 2013 peak could have been greater, the distance between where the debris flow is triggered and where the groundwater is measured, artesian conditions).

Yes, we agree, there must be a reason for this that has to do with local conditions in the slope. After reading the review the first time we agreed to give some possible explanations in our text, but we now feel it will just be speculations. We think it is more honest to say that we do not know. So, after thinking about this for some time we have decided to leave this paragraph as it is.

TECHNICAL CORRECTIONS:

L14-16. I think it should talk about precipitation and not rain, considering that until 3:00 p.m. the precipitation fell in a solid state; and only if it is possible (considering that in the Abstract each word counts) to clarify that a fraction of the melted snow came from the same event of precipitation.

Yes, agree. We have changed from "*rain"* to "*precipitation"* – and included a sentence that says that a fraction of the precipitation first came as snow (line 15).

L38-39. "The mean(?) maximum rainfall intensity was 80–100 mm in 24 hours, locally up to 129 mm." Currently the sentence is contradictory to me.

Yes, we see that this phrasing is not good, and we have rephrased it (line 40-42).

L39. "Most of the landslides were debris slides and flows" is clearer. Slide is a type of movement of landslides (Hungr et al. 2014) and using it as a synonym for Landslide can be confusing. . . The comment applies to the whole text.

Yes, we have replaced the word "slides" to "landslides" here (line 41) – but also at other places in our text where such a change was appropriate.

L41-42. In order not to use the word "slide" and not repeat "landslide" it could be said something like this: "The number of mass movements makes this one of the largest landslide events in Norway during. . ."

Yes, we agree, we have replaced slide with “mass movements” in line 45.

L44-47. Many people are unfamiliar with Jan Mayen Island. With Fig. 3 it is clearer what its position should be, but it could be clarified in the text at least that it is an island.

Thanks for pointing this out. Instead of relating the location of the low atmospheric pressure to the island Jan Mayen, we refer to Iceland, most people are familiar with the location of Iceland. We have replaced Jan Mayen with Iceland in our text (line 49) and also in the figure text (line 84).

L92. Is it necessary to clarify the brand?

Maybe not. It is important to give information about the equipment used here in the method section. We do not think it is a necessary to mention the brand of the data logger we used, but it does not hurt to mention it either. Our sentence is not changed: “*The data logger, a mini-diver (DI 501) manufactured by Van Essen instruments, was attached to a wire and inserted into the pipe.*”

L160. I understand that it is explained below but I don’t think it is convenient to describe the shape ("much sharper") and not describe the difference in amplitude. I think it is better to either describe the two characteristics at the moment or just mention that they have different characteristics and then detail them in the following sentences.

We agree. We have changed the sentence to:

“The peaks and troughs of the oscillations occur simultaneously upslope and in the valley bottom (piezometer at the weather station), but the peaks upslope are much sharper and have higher ~~vary in~~ amplitudes (Fig. 7).” (line 181-182)

L168. Perhaps a more technical term than "the big picture" can be used... Such as "the typical/mean annual cycle".

Yes, we agree, we have replaced the words “the big picture” (line 190).

L252-253. Do you define peak duration as the time the groundwater was less than 50 cm from the ground? I think it is important to clarify.

Yes, we agree – this is important to clarify. We have inserted “when groundwater was less than 50 cm from the surface” in line 278-279 to clarify how we define the duration of the peak.

L261-263. It may be helpful for the reader to indicate the date May 26 in Fig. 6.

Yes, good idea. We have indicated May 26 in our revised Fig. 6.

Figure 1. Snow avalanches are not landslides and it is better to use the full terms. . . Landslide instead of slide and rockfall instead of rock.

Yes, we agree. We have changed the legend in Fig. 1.

Figure 1. A minor issue in the legend: the precipitation is a continuous number. This should also be reflected in the legend. Better write: 0-30; >30-60; >60-90;. . . etc.

Yes, we agree, we have changed this in the revised Fig. 1.

Caption Figure 1. “114 debris flows and slides”.

Yes, we agree. We have changed from “114 debris flows, slides,….” to **“**114 debris flows and slides” – as suggested (line 57).

Figure 2. To respect the structure: “Photo: Jan Helge Aalbu on 16 November 2013.”

Yes, we have changed the structure (line 63) and included a new Table (Table 1) with some more information about the landslides in the photos in Fig. 2.

Figure 4. Try to improve the sentence so as not to repeat "aerial photo". One possibility is: “Map and aerial photo from 2018 of the site near Anestølen. A. The contour interval is 100 m. B. The eastern slope is prone to. . .”

Good idea. We have replaced as suggested (Line 155-156).

Figure 5B. It is not necessary to clarify that the rocks are solid.

Agree – we have changed from “Solid rocks” to “Boulders” in Figure 5B.

Response from the authors (in blue) to the comments by anonymous referee (in black), updated 9. April 2021.

[Line numbers in blue refers to the new version of the manuscript: Bondevik_Sorteberg_Groundwater fluctuations_revised_marked_up.docx]

GENERAL COMMENTS

The manuscript provides continuous data about precipitation, air and groundwater temperature, snow depth, pore-water pressure, monitored on a site in Western Norway that in November 2013 was involved in a weather-induced debris flow after a storm that caused about 142 landslides and 7 snow avalanches in the same region. The reported data allow, in particular, to compare the weather and piezometric conditions responsible of the debris flow with those occurred in the past not able to induce any failure. The paper is well written and contains very accurate figures.

We are glad you think the paper is well written and has accurate figures. We appreciate all your suggestions that will improve our paper. Below we comment on each of these and show how we have revised our manuscript.

The availability of information exactly during the landslide event represents undoubtedly a valuable aspect not to be overlooked. However, as also correctly recognized in the text by the Authors, two evident limitations exist: i) the pore-water pressure data are measured only by one piezometer (located upslope); ii) information about the properties of the involved soils are absent. Of course, the first aspect, that prevents to model the piezometric regime along the slope, can not be solved. On the contrary, I hope that some data about the physical, hydraulic and mechanical soil properties should be added because a full comprehension of the landslide is very hard without them. In particular, the absence of information regarding the shear strength parameters makes impossible analyzing the slope stability conditions. Some specific suggestions, aimed to improve the quality of the manuscript, are reported in the following section.

About the properties of the involved soils:

Ideally, it would be very nice to present the properties of the soils on the slope in a table. However, we do not have such data, such data are not available from other studies of the area, and the material on the slope varies a lot, both laterally and with depth, that makes it difficult. In the paper we present the information we have about the properties of the slope deposits that allow the reader to have some understanding of the slope and the soil. Below is line 93-95 in the method chapter:

> *"The lower part of the slope is covered by slide deposits and till and the average slope angle is 25 °– 26 °. The sediment-covered slope tapers off upwards into steeper and exposed bedrock and cliffs (Fig. 5A). From the outcrops of the slide scar of the 2007 slide event (Fig. 4B), we found that the thickness of the deposits on the slope varies, probably between 2 and 5 m.*

And also in line 103-104:

> *We drilled through boulders and relatively firm deposits down to 2.4 m below the surface using a hammer drill powered by compressed air (Fig. 5B).*

In the caption to Fig. 5B (line 165-169) we say:

> *"Average steepness of the sediment-covered slope is 25°–26°. The stippled line indicates where we believe the boundary between till and bedrock is located, based on observations from the 2007 slide scar (Fig. 4B). B. The mini-diver (sensor) is suspended from a wire in the piezometer and anchored 1.64 m below the surface. The top 60 cm of deposits consists of organic soil and weathered till, with firm till below that. We drilled through boulders at depths of ca. 1 m and 1.5 m."*

And, in the discussion chapter we say (line 250-252):

> *"The slope is covered by till and colluvium, deposits that vary widely in composition and grain size. Thus, observations from one borehole may not be representative of other areas on the same slope."*

In order to provide accurate data about the soil properties, especially data for cohesion and friction angle (the shear strength parameters), and data of the hydraulic conductivity etc., we would need to do a new study of the slope. Because of the heterogeneity of the soil, we would need information from several locations along the slope and also from different depths. On an ideal slope with homogeneous soils such data would be very useful, and possible also available. In addition, in this paper, we do not perform any calculations or simulations of stability or of the slide movement. We believe that the information given is sufficient for the reader to get the information of the soils on the slope to understand the work and data we present about the groundwater fluctuations during the debris flow event.

SPECIFIC COMMENTS

Line 30. The availability of real-time water level data during rapid landslides are effectively rare, but, on the contrary, many papers provide the pore pressure in slopes involved in active slow landslides, cyclically reactivated by seasonal weather events. Therefore, the sentence "rare because it is difficult to predict which slope will fail" should be replaced by "rarely provided during rapid landslide events".

We agree, thanks for this suggestion, we have replaced as suggested (line 30).

Lines 39-40.

Snow avalanches are not landslides. Therefore, the sentence "Most of the slides were debris slides and flows (114), but rockfalls (28) and snow avalanches (7) also occurred" should be replaced by "Most of them were debris slides and flows (114), but rockfalls (28) also occurred. Some snow avalanches (7) were observed too".

We agree. We have changed "slides" with "mass movements". The sentence have been changed to (line 42-43):

> *"Most of the ~~slides~~ mass movements were debris slides and flows (114), but rockfalls (28) and snow avalanches (7) also occurred (Fig. 1).*

Figure 1. The term "slides" in the legend can not be used to indicate at the same time the three types of phenomena. It should be replaced by a term like "Events". Moreover, I suggest to indicate them according to the following order: i) Debris flow and slide; ii) Rockfall; iii) Snow avalanche.

Yes, we agree and have changed it as you suggested here, both in figure caption (line 56-57) and on the revised figure (legend).

Caption Figure 2.

I suggest to simplify it, inserting in a table (to be cited in the text) all the provided information regarding the three shown landslides: date and hour of the occurring events, landslide length, upslope and downslope altitudes, mean slope inclination, range of thickness, etc.

It is a good idea. We have provided a Table (Table 1, Line 70-75) with this information and simplified the caption to Fig. 2 (line 62-70).

Section 2.

This section should contain a table reporting the available information (eventually deriving them by other papers) about the mean values of physical, hydraulic and mechanical properties of the involved soils: grain size, in-situ porosity and degree of saturation, unit weight, hydraulic conductivity, strength parameters. Such values are very important to allow a full understanding of the infiltration and seepage processes and, as a consequence, of the induced landslide mechanism.

See comment above under the heading "About the properties of the involved soils."

Line 90.

Indicate at which altitude and distance from the toe of the landslide the piezometer has been installed.

OK, we have added a sentence that gives that information in line 104-105.

Line 125.

Indicate the total length of the debris flow.

OK, added a sentence that gives the length of the debris flow (line 145). This length can also be found in the new Table 1.

Figure 5A. Clarify which “Distance” is reported in the X-axis. Is it the distance from the toe of the landslide ?

No, it is the distance from the road on the flat valley bottom and upslope to the borehole, at 90° to the slope, and parallel to the slide scar of the 2007 landslide. We have indicated the location of the profile on the aerial photo in Fig. 4B, as a stippled line, that will clarify better the location of the profile.

Figure 6. According to the results, the influence of the snow cover melting on the water level is particularly important. Therefore, I suggest to insert in this figure the data about the snow depth (shown only by the supplementary Figure S9) and about the air temperature (partially shown in Figure 8).

We have moved the snow cover figure from the supplements and included it into the revised Figure 6 (lower diagram). We also tried to include the air temperature graph, but that made figure 6 too messy. We think the snow cover figure works nicely in Fig. 6 and we think it is fine to keep the air temperature graph for the whole year in the supplements. However, air temperatures for the days around the slide event are shown in Fig. 8.

Caption Figure 7. Indicate at which depth and altitude the piezometer of the weather station has been installed.

The altitude of the weather station (and piezometer) is given in the method section of the paper.

Figure 8. Due to the important role of the snow melting, I suggest to insert in this figure the data about the snow depth (shown by the supplementary Figure S9).

Melting of snow has an important role, but we are uncertain that the measurements from the snow pillow at the day the slide happened, with so low values, can be fully trusted. The snow pillow show 0.020 m of water equivalent before the event, and during the event rises to 0.024 m. This value is a combination of snow that was on the ground before the event, new snow that fell during the first phase of the event and water from the change in precipitation to rain. Since the snow pillow cannot be trusted with such low values, we have decided not to include it in such details as the data in Fig. 8 is presented.

Line 222.

The second important weak point of the manuscript regards the absolute absence of information about the soil properties. As already suggested, I hope that you are able to provide them. For instance, some information about the strength parameters could help (at least) estimating the slope stability conditions.

Again, see comment above under the heading “Information about the properties of the involved soils”

Lines 265-266.

Differently from what observed in November 2013, the piezometric peaks monitored in April and May 2013 were caused only by rainwater infiltration (and not by snow melting). Why do you consider such evidence so relevant to not induce sliding ? The corresponding measured peaks of 33 cm (measured in April) and 28 cm (measured in May) below the ground surface are very close to the critical estimated value of 30 cm in November 2013 (such value was extrapolated from the groundwater level curve measured from 19:00 and 23:00, as clarified in Lines 237-238). As a consequence, being the local shear strength approximatively the same at the onset of the three attained maximum water levels, the corresponding local slope stability conditions should be essentially the same too. Unfortunately, the availability of only one piezometer does not allow to make a reliable evaluation of the general slope stability conditions, therefore your consideration seems rather rash. Please make some comments.

We agree; the very high peaks in May and April is essential the same values as the critical peak in November 2013, but we now think, thanks to this review comment that encouraged more thinking about this, that the soil on the slope was probably (partly) frozen in April and May, that could have prevented effective drainage of groundwater downslope. The thawing of the frozen soil, melting of snow on the ground and the rain episodes caused the high piezometric peaks. In spite of the high pore pressures in the borehole, the slope was maybe <u>not</u> unstable, because part of the soil on the slope was still frozen, and a frozen pore space would give higher shear strength. The air temperatures in April and May was low, most of the nights were below freezing until May 5, that would prevent the thawing of the ground and refreezing of the surface water during nights.

We have rewritten this paragraph (line 286-293) and enlightened this possibility of frozen soils in April and May.

Lines 276-279.

The emphasis of provided considerations is rather strange. It's well known that the initial conditions are crucial to determine the weather-induced effects. Once given an initial monitored piezometric value, the main challenge should be, of course, associating a landslide hazard to a forecasted weather event. At the same time, associating a very low landslide hazard to severe weather event if the initial measured groundwater level is located below a "safe" value should be also very useful for the implementation of an early warning system. I encourage the Authors to make some comments about this topic.

Yes, we have added a new paragraph (line 320-327) about the early warning system in Norway and suggested here that there might be a good idea to include piezometers from slopes susceptible to debris flows to the warning system.

TECHNICAL CORRECTIONS

Title. Is the hyphen "-", between "Norway" and "triggered", necessary ?

It is not necessary for us to use "–", a comma instead would also work. However, using "–" (em dashes) to replace commas makes the reader focus a bit more on this information that is set inside the em dashes "–". We have thus kept the em dashes in the title.

Caption Figure 1. “114 debris flows, slides” should be replaced by “114 debris flows and slides”

Yes, we have changed accordingly.

Line 109.

The word “from” at the end of the line should be replaced by “carried out”.

? We do not understand this comment ….“carried out”… and have not replaced the word “from” in our revised text.

Line 163.

The sentence “has also been” should be replaced by “already”.

OK, replaced “has also been” with “already”.

Groundwater fluctuations during a debris flow event in Western Norway – triggered by rain and snowmelt

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Abstract. Pore pressure is crucial in triggering debris slides and flows. Here we present measurements of ground water pore pressure and temperature recorded by a piezometer 1.6 m below the surface on a slope susceptible to debris flows in Western Norway. One of the largest oscillations in data collected over four years coincided with a debris flow event on the slope that occurred during storm Hilde on 15–16 November 2013. More than 100 landslides were registered during the storm. Precipitation ~~Rainfall~~ totalled about 80–100 mm in 24 hours, locally up to 129 mm, and an additional trigger factor for the landslides was a rapid rise in air temperature that caused snowmelt. In the studied slope a fraction of the precipitation first fell as snow. On 15 November, the groundwater level in the hillslope rose by 10 cm per hour and reached 44 cm below the surface. At the same time, air temperature rose from 0 °C to over 8 °C, and the groundwater temperature dropped by 1.5 °C. The debris flow probably occurred late in the evening of 15 November, when the groundwater level reached its peak. Measurements of the groundwater in the hillslope in the period 2010–2013 show that the event in 2013 was not exceptional. Storm Dagmar on 25–26 December 2011 caused a similar rise in groundwater level, but did not trigger any failures. The data suggest that during heavy rainstorms the slope is in a critical state for a landslide to be triggered for a short time – about 4–5 hours.

1 Introduction

It is well known that groundwater pore pressure is crucial in triggering shallow debris slides and flows (e.g. Iverson, 1997), but how exactly does pore pressure vary in a hillslope during a rainstorm? How much and how rapidly does the groundwater level rise before a landslide is triggered? And, for how long during a rainstorm is the slope landslide-prone? We try to answer these questions using groundwater level data logged by an automated piezometer installed in a borehole on a hillslope in western Norway, where a debris flow occurred during heavy rainfall and snowmelt in November 2013.

Such instrumental data are rarely provided during rapid landslide events ~~because it is difficult to predict which slope will fail~~. Several studies have measured the hydrologic response to rainstorms in hillsides prone to shallow slides (e.g. Collins et al., 2012; Fannin and Jaakkola, 1999; Johnson and Sitar, 1990; Sidle, 1986), or measured the response to artificial sprinkling of water over a slope to force a landslide to occur (e.g. Harp et al., 1990; Reid et al., 1997). Only a few studies provide instrumental data directly from a natural debris flow event (Montgomery et al., 2009; Reid et al., 1988). Here, we present continuous groundwater level measurements from a hillside susceptible to shallow debris slides and flows for the period 2010–2013. The data include the day when a debris flow occurred in this particular slope during the storm named Hilde on 15–16 November 2013.

During this storm, the intense rainfall and snowmelt triggered more than 100 landslides in Western Norway. The ~~maximum~~ storm ~~rainfall intensity~~ generated relatively large amounts of precipitation. Near the coast, on the western slopes of the mountain range, precipitation was 90–120 mm pr. 24 hours, farther inland precipitation was lower (30–90 mm) but fell first as snow on higher ground~~was 80–100 mm in 24 hours, locally up to 129 mm~~. Most of the mass movements ~~slides~~ were debris slides and flows (114), but rockfalls (28) and snow avalanches (7) also occurred (Fig. 1). Many roads were damaged, a bus got stuck, people were evacuated, and houses and cars were damaged by slide material, but fortunately no one was killed (Fig. 2). The number of mass movements ~~slides~~ makes this one of the largest landslide events in Norway during the last two decades (Krøgli et al., 2018).

The storm was a classic extreme precipitation event on the west coast of Norway. A warm mature front, partly occluded, passed southern Norway on 15 November. The pressure configuration, with a very low-pressure system northeast of Iceland~~Jan Mayen~~ and a high-pressure center southwest of the UK, generated a strong north-south pressure gradient and induced a southwesterly flow of moist warm air towards western Norway (Fig. 3). It rained heavily as the moist air was lifted by the warm front. The precipitation further intensified as the flow ascended over the mountains of western Norway. This weather situation leads to the formation of narrow plumes of intense high-level moisture, often referred to as atmospheric rivers. These cause most of the extreme precipitation events on the west coast of Norway (Azad and Sorteberg, 2017).

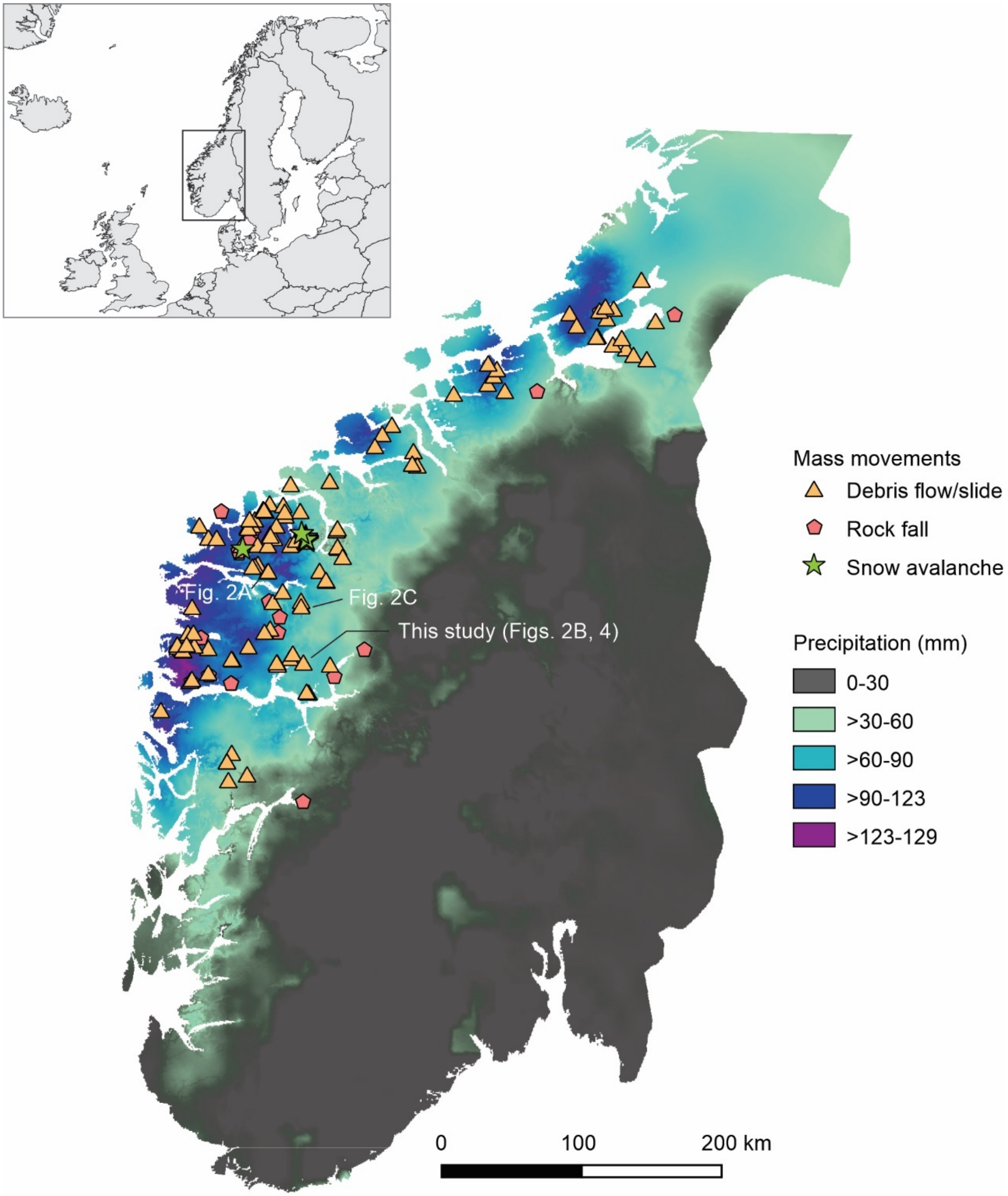


Fig. 2A
Fig. 2C
This study (Figs. 2B, 4)
Mass movements
Debris flow/slide
Rock fall
Snow avalanche
Precipitation (mm)
0-30
>30-60
>60-90
>90-123
>123-129
0
100
200 km

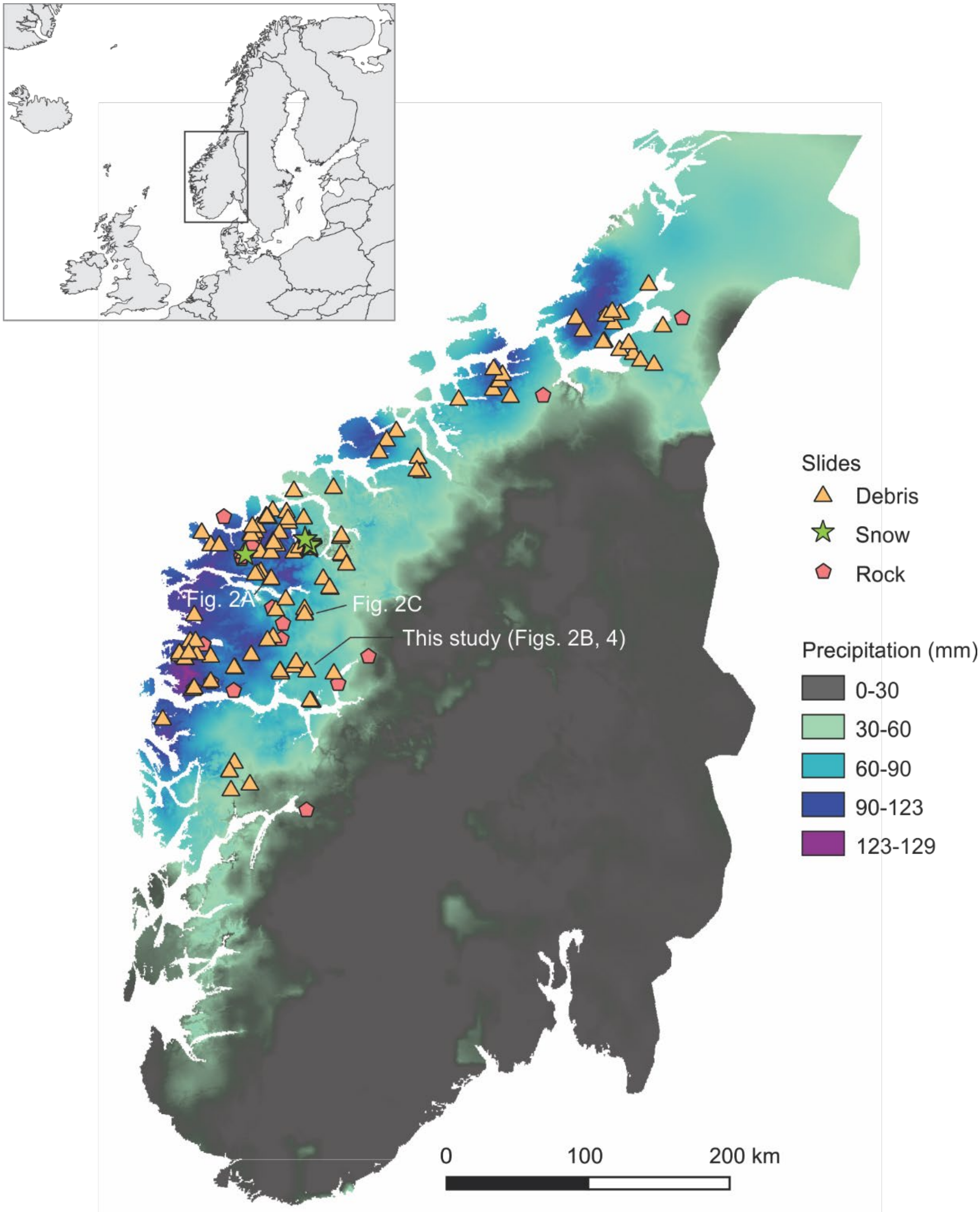


Figure 1: Mass movements~~Landslides~~ that occurred on 15 and 16 November 2013 during storm Hilde in Western Norway – 114 debris flows and~~,~~ slides, 28 rockfalls and 7 snow avalanches and~~ 28 rockfalls~~. Data retrieved from the Norwegian landslide database: https://gis3.nve.no/link/?link=SkredHendelser. Precipitation is interpolated from observations and shows the amount in mm per 24 hours, collected at 06:00 UTC 16 November (08:00 local time), data retrieved from http://www.xgeo.no/.

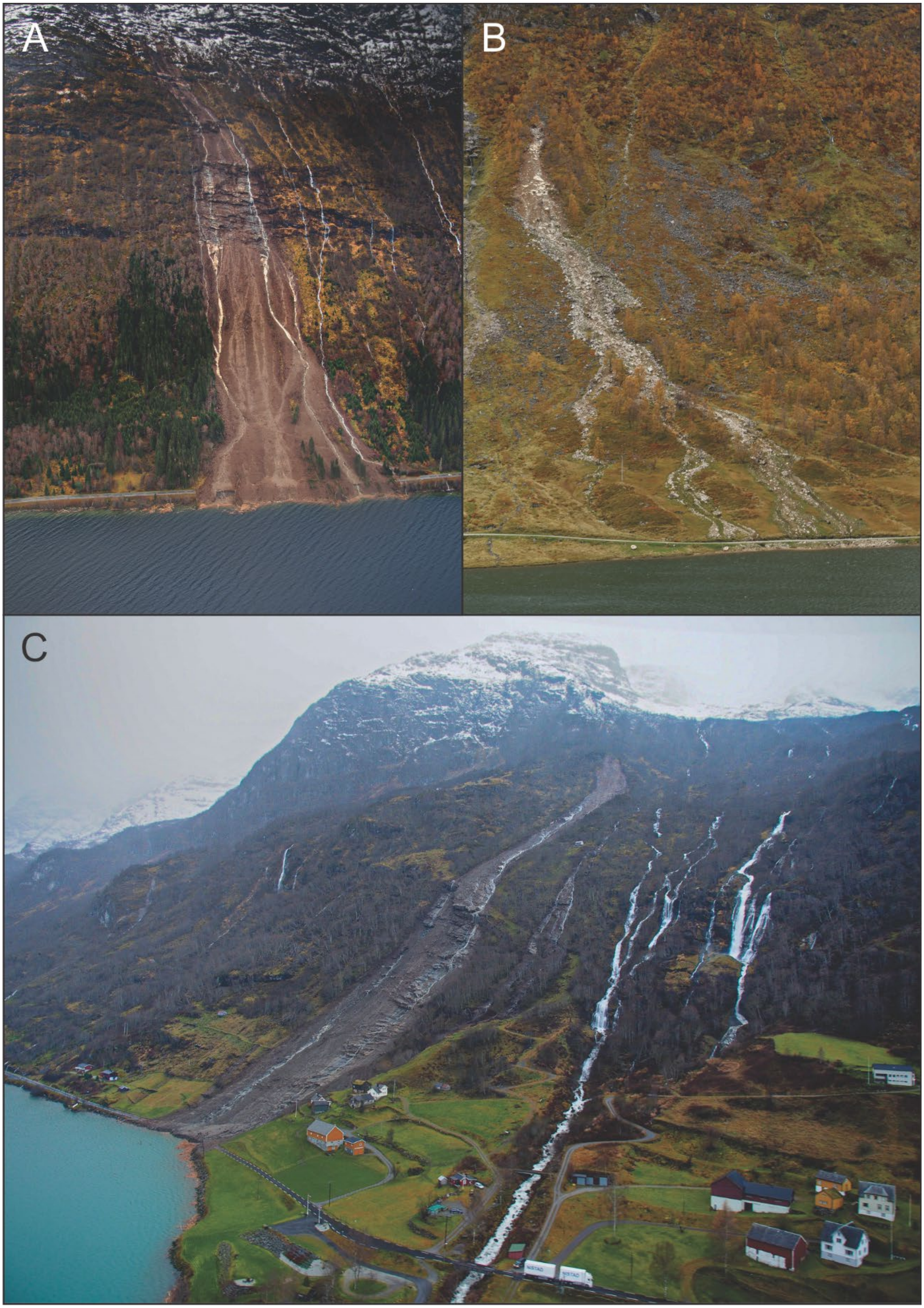

A
B
C

Figure 2: Photos of landslides that occurred during storm Hilde in 2013, see table 1 for details.
A.~~:~~ Skredestranda,~~.~~ ~~The slide occurred at around 21-22 on 15 November, was triggered at an altitude of 620 m, covered about 250 m of the road and continued into lake Hornindalsvatnet (altitude 53 m).~~ p~~P~~hoto~~:~~ Jan Helge Aalbu, 16 November 2013.
B.~~:~~ Anestølen, this study, ~~. P~~photo~~:~~ Kevin Saurin, 6 October 2014.
C. ~~:~~ Oldedalen at Yri, ~~. The slide occurred around 23 on 15 November, started at about 350 m above sea level, and continued into lake Oldevatnet (altitude 34 m).~~ p~~P~~hoto, Jan Helge Aalbu, ~~on~~ 16 November 2013. ~~The slides in A and C both generated small tsunamis.~~

Table 1. Information of ~~to~~ the landslides shown in Fig. 2A, 2B and 2C.

Figure	**Location**	**Date**	**Hour**	**Top altitude**	**End altitude**	**Length slide**	**Mean slope**	**Comment**
2A	Skredestranda, south of the lake Hornindals-vatnet, Nordfjord.	15 Nov	21–22	620 m	53 m	830 m	34°	The landslide continued into the lake Hornindalsvatnet (53 m altitude), covered 250 m of the road. Road was closed for several days. Triggered small tsunami < 1 m (NVE; Søgnesand, 2018).
2B	Anestølen, Sogndal – this study.	15 Nov	19–23?	700 m	439 m	550 m	25°	See details in this paper.
2C	Oldedalen, Yri, Nordfjord.	15 Nov	~ 23	480 m	33 m	780 m	30°	The largest of three slides that occurred around the lake Oldevatnet (33 m altitude). Damaged road and took out electricity. Triggered tsunami in the lake (NVE).

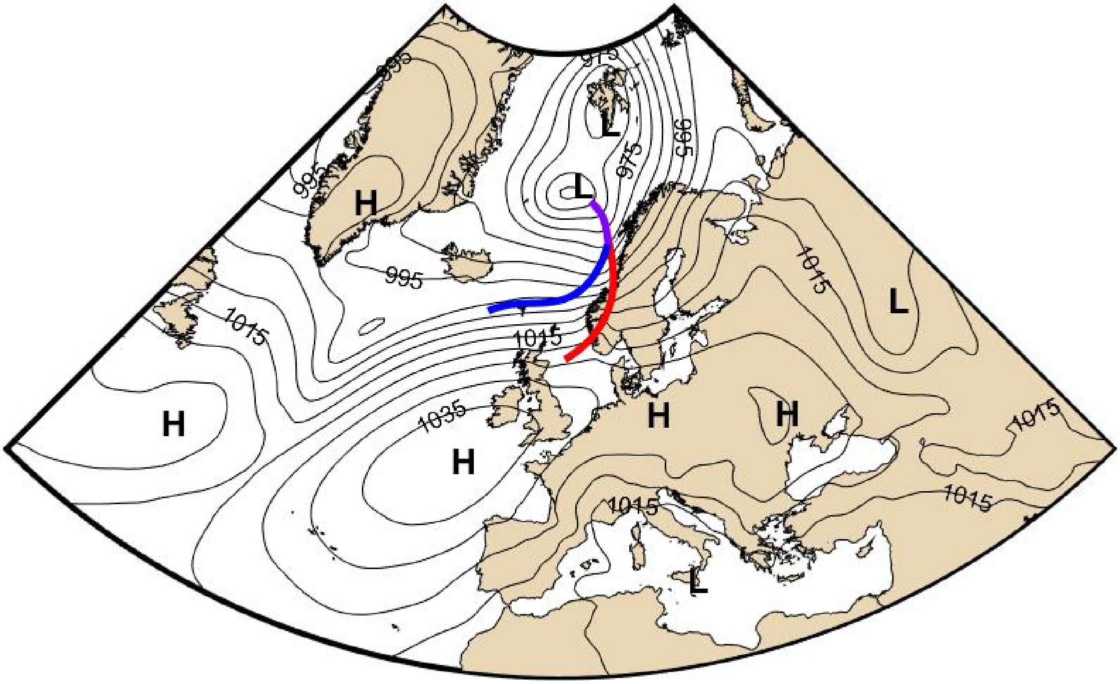


Figure 3: Mean sea level pressure (hPa) on 15 November at 12:00 UTC (14:00 local time). Large amounts of warm and moist air blew towards the Norwegian coast because of low pressure northeast of Iceland~~Jan Mayen~~ and high pressure southwest of England. The air was close to 100 % saturated with water vapor, which precipitated as the air cooled when it rose over the mountains in western Norway. The red line indicates the position of the warm front and the blue line is the cold front. The warm air sector lies between the red and blue lines. The purple line indicates an occluded front, which means that the cold front has caught up with the warm front.

2 The hillside and instrumentation

The hillside we instrumented is typical of Western Norway, and is prone to debris flows and shallow slides. The hillside is near Sogndal, east of the lake at Anestølen (Fig. 4). Recent slide events on this slope occurred on 18 May 2004, 22 September 2007 (Tyssebotn and Velle, 2010) and 15 November 2013 (Olsen et al., 2015) (Fig. 4B). The lower part of the slope is covered by slide deposits and till and the average slope angle is 25 °– 26 °. The sediment-covered slope tapers off upwards into steeper and exposed bedrock and cliffs (Fig. 5A). From the outcrops of the slide scar of the 2007 slide event (Fig. 4B), we found that the thickness of the deposits on the slope varies, probably between 2 and 5 m.

Present-day average temperature range between 10 and 15°C (July) and −1 to −10°C (February), with a mean annual temperature of 0–2°C (1971–2000), see also Fig. S1. The mean annual precipitation is 1655 mm (1991–2020) measured at the weather station at Selseng (Fig. 4A). Maximum average snow depth is between 1 and 2 m (SeNorge). The vegetation is dominated by grass and heath vegetation and small birch trees.

We drilled through boulders and relatively firm deposits down to 2.4 m below the surface using a hammer drill powered by compressed air (Fig. 5B). The borehole is located near the 2007 landslide, 40 m south of the slide scar and about 200 m upslope from the toe of the landslide, at an altitude of 484 m. We pushed and hammered threaded pipes, 1 m long and 32 mm in diameter, down into the borehole. The pipes were subsequently screwed together. The lower pipe (piezometer) has twelve slits, 10 cm long and 2 mm in width, to allow water seepage. The data logger, a mini-diver (DI 501) manufactured by Van Essen instruments, was attached to a wire and inserted into the pipe. The lower end of the mini-diver is at 1.64 m below the ground surface (Fig. 5B). The drilling and instrumentation are described in Tyssebotn and Velle (2010).

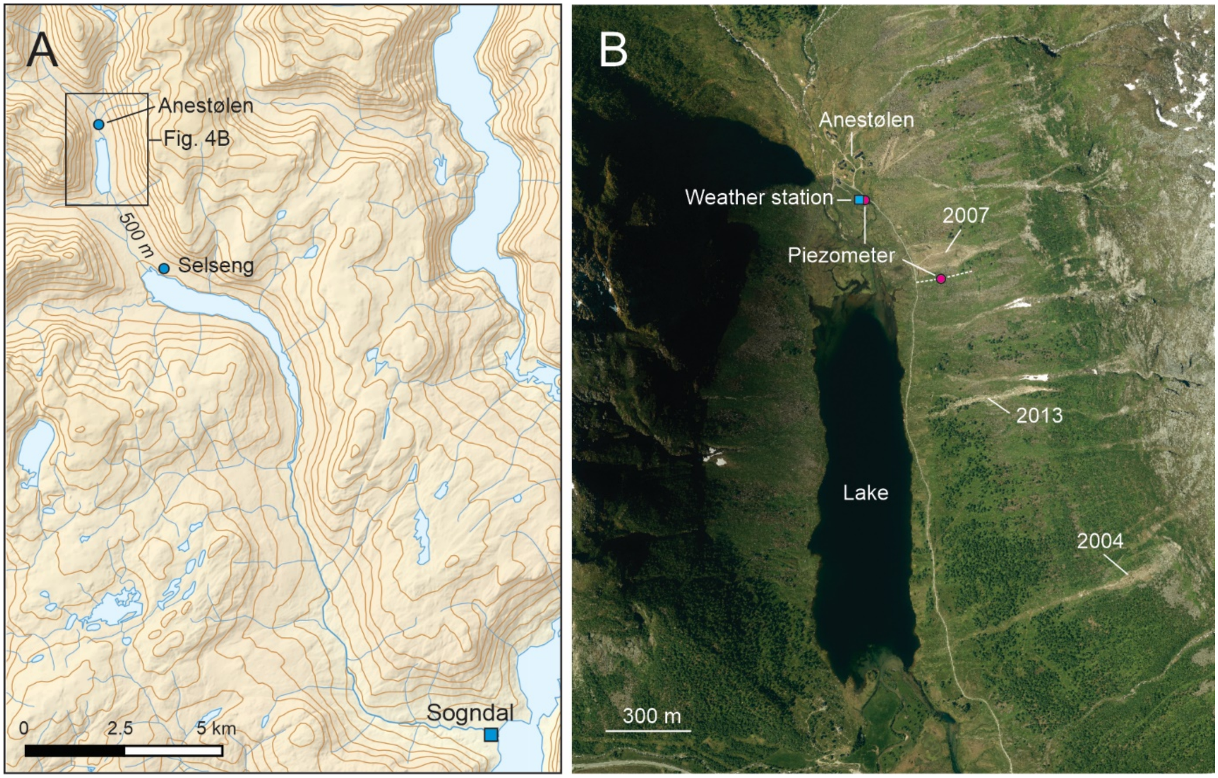
The weather station at Anestølen is operated by the Hydrological Department at the Norwegian Water Resources and Energy Directorate and measures air temperature, precipitation, wind, atmospheric pressure, snow depth and groundwater level (Fig. 4B). Precipitation is measured every 10 minutes, but for periods the bucket that collects the rain was full, and the data are not reliable. However, we found the measurements of precipitation to be reliable around the time of storm Hilde (Olsen et al., 2015). The other precipitation data we present are 24-hour totals measured manually at Selseng (Fig. 4A), 3.5 km south of Anestølen at about the same altitude (station 55730, data downloaded from http://eklima.met.no). Atmospheric pressure and air temperature (Fig. S1) at the weather station are measured every 15 minutes. All data from the weather station are available from http://sildre.nve.no (station no. 77.24.0).

The mini-diver we installed in the hillslope piezometer measure total pressure and temperature. Pressure is measured in cm H_2O to an accuracy of ± 0.5 cm H_2O with a resolution of 0.2 cm H_2O. Temperature is measured in degrees Celsius to an accuracy of ± 0.1 °C, with a resolution of 0.01 °C. The atmospheric pressure was subtracted from the measured pressure to obtain the true water pressure above the sensor in the mini-diver. We used the atmospheric pressure measured at the weather station from 2 October 2012 onwards (data downloaded from http://sildre.nve.no/Sildre/Station/77.24.0). Measurements from before 2 October 2012 were corrected using atmospheric pressure measured at the airport in Sogndal (station 55700, downloaded from http://eklima.met.no). The difference in altitude between the weather station (442 meters above sea level) and the sensor in the borehole at the slope (484 m) is 42 m. This corresponds to a pressure difference of about 5 hPa, which we subtracted from the atmospheric measurements. The difference in altitude between the airport (497 m) and the borehole is only 13 m. For these measurements we ignored the altitude difference. The mini-diver was set to record measurements every 4 hours, and we obtained almost continuous measurements for the years 2010, 2011, 2012 and 2013.

3 The 2013 debris flow

The debris flow ~~slide~~ happened in the evening of 15 November or during the following night. It was first observed by a person driving an all-terrain vehicle to the mountain farm at Anestølen in the morning of 16 November; he found that the road was covered by wet debris, and was unable to proceed (Fig. S2). The driver thinks the flow happened sometime during the night, but cannot exclude the possibility that it was the evening before, on 15 November (Olsen et al., 2015). The nearest landslides to Anestølen (see three triangles in Fig. 1 immediately west of this site), happened on the evening of 15 November, and during the night and early morning of 16 November at 02:00 and 07:30.

The landslide is a typical debris flow with levees and lobes. The flow had a point source at an altitude of 720 m, widened downslope, and continued in a channel with levees on both sides (Figs. 2B, S3). The channel was eroded about 2 to 3 m into the deposits, and exposed the bedrock in certain places. A spillover lobe is evident on the southern side of the flow~~slide~~. Towards the lake, the flow split into three different paths (Fig. 2B) (Olsen et al., 2015), and ended in the lake (439~~41~~ m altitude). Here, a fan and a delta of fine-grained material, mostly sand and organic material, were deposited (Fig. S5~~4~~). The length of the debris flow is about 550 m. We inspected the landslide on 17 November (Fig. S4~~5~~) and found snow inside the very wet slide debris. The entire lake was colored brown by suspended sediment from the debris flow ~~slide~~ that had entered the lake.


A
Anestølen
Fig. 4B
500 m
Selseng
Sogndal
0
2.5
5 km
B
Anestølen
Weather station
Piezometer
2007
2013
Lake
2004
300 m

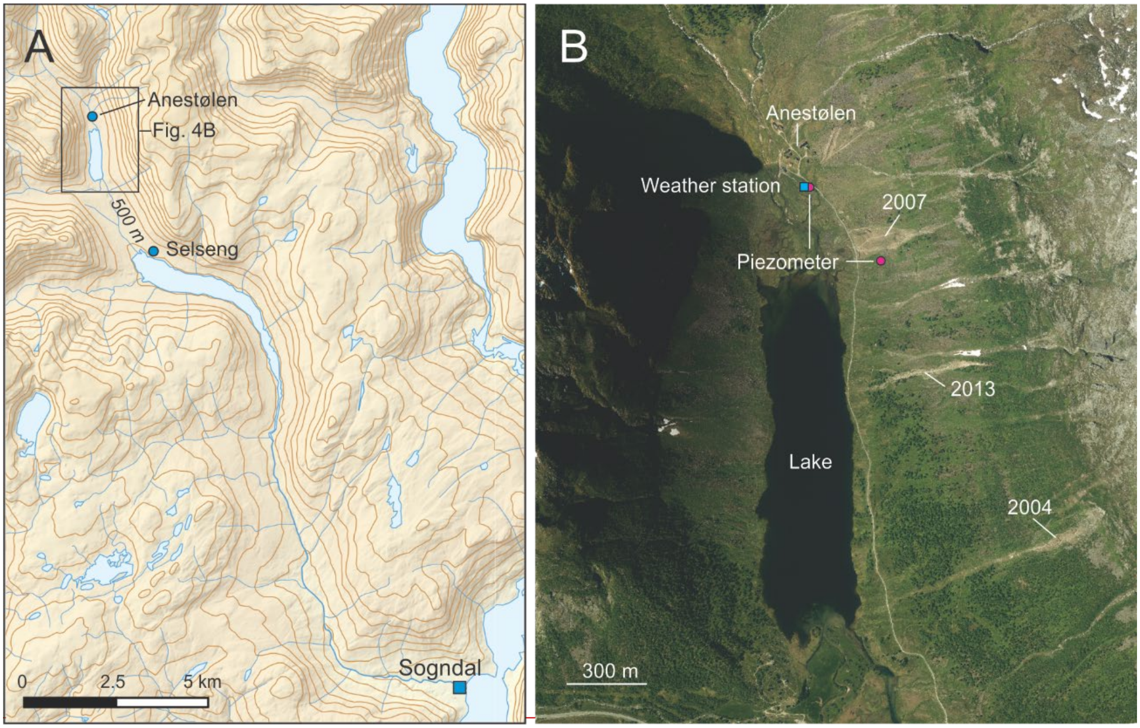
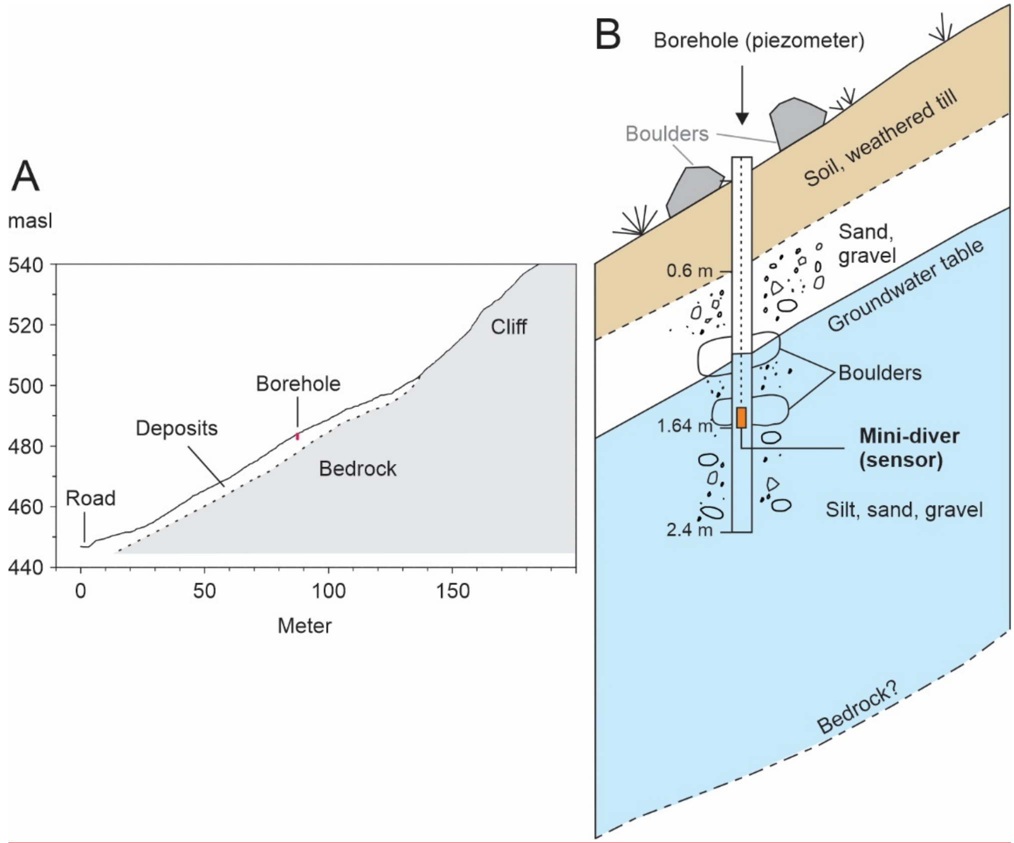


Figure 4: Map and aerial photo from 2018 of the site near Anestølen. A. The contour interval is 100 m. B. ~~Aerial photo from 2018.~~ The eastern slope is prone to debris slides and flows, and the most recent landslides are indicated with the year they occurred. There is a weather station including a piezometer located in the valley bottom, station no. 77.24.0 (https://sildre.nve.no). We installed a piezometer in a borehole on the hillslope close to the southern slide scar of the 2007 slide. The stippled white line across the borehole shows the location of the profile in Fig. 5A © Kartverket/Geovekst (www.kartverket.no).


A
masl
540
520
500
480
460
440
0
50
100
150
Meter
Cliff
Borehole
Deposits
Bedrock
Road
B
Borehole (piezometer)
Boulders
Soil, weathered till
Sand, gravel
Groundwater table
0.6 m
Boulders
1.64 m
Mini-diver (sensor)
Silt, sand, gravel
2.4 m
Bedrock?

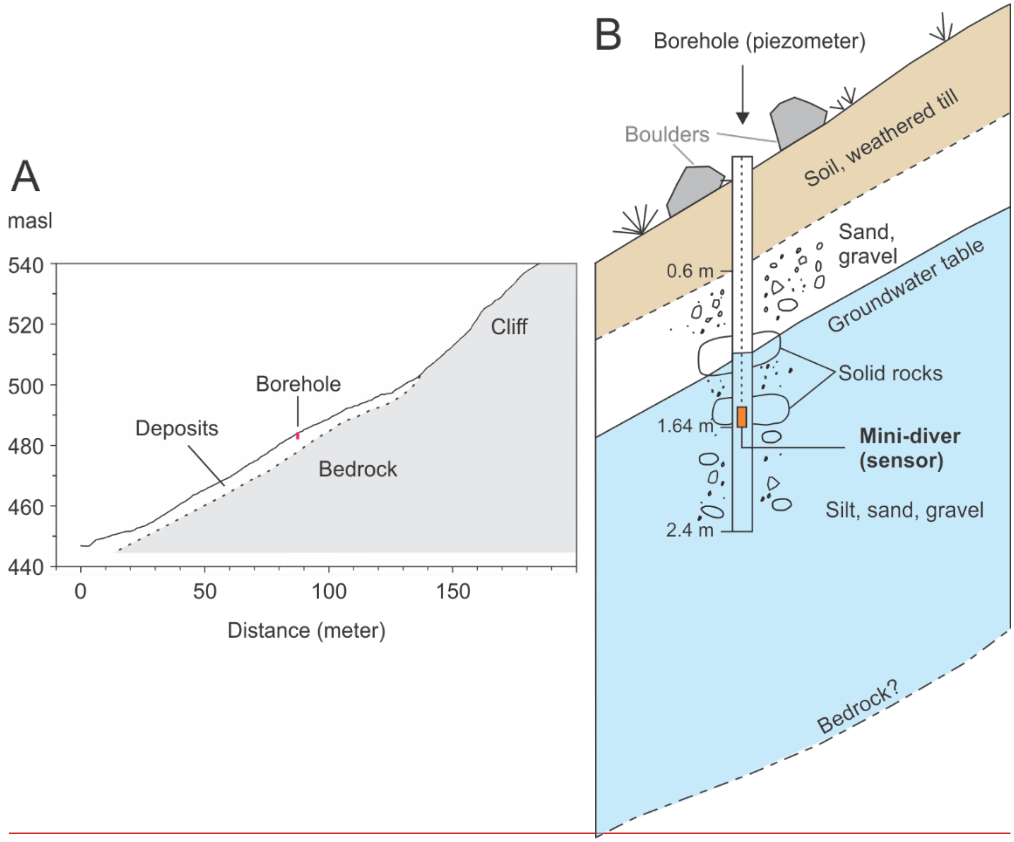


Figure 5: Profile of the hillside just south of the southern slide scar of the 2007 landslide (Fig. 4B) showing the borehole with the instrumented piezometer. A. Average steepness of the sediment-covered slope is 25–26°. The stippled line indicates where we believe the boundary between till and bedrock is located, based on observations from the 2007 slide scar (Fig. 4B). B. The mini-diver (sensor) is suspended from a wire in the piezometer and anchored 1.64 m below the surface. The top 60 cm of deposits consists of organic soil and weathered till, with firm till below that. We drilled through boulders at depths of ca. 1 m and 1.5 m.

4 Results

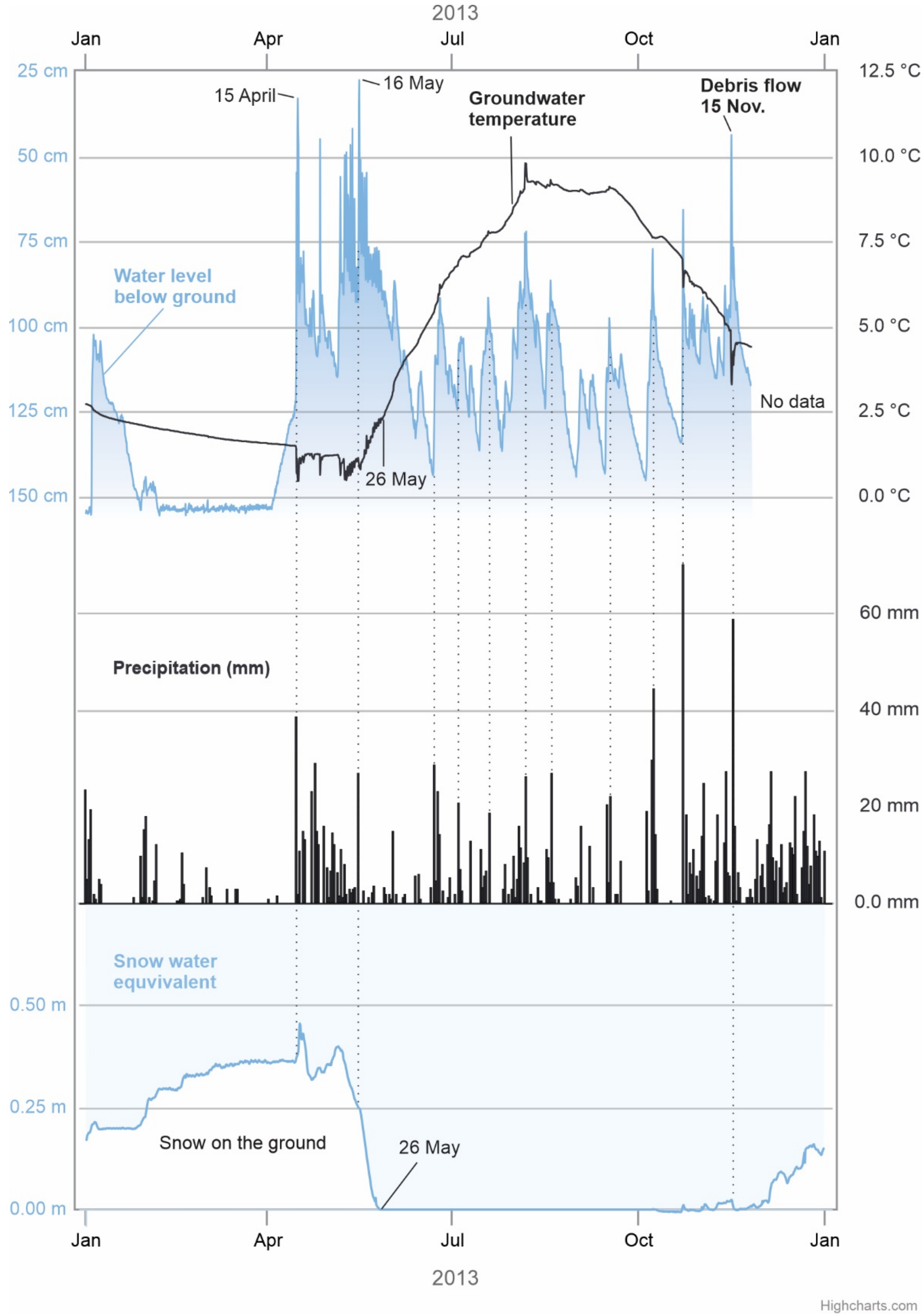
The groundwater level on the slope varies according to season and precipitation. In winter the groundwater table is low, and in 2013 the water level was below the sensor in February and March, apparently because the ground was frozen (e.g. Ireson et al., 2013) (Fig. 6). During spring, from April to June, the groundwater is recharged by snowmelt, rain and thawing of the frozen ground (Du et al., 2019), which cause high peaks and rapid changes. In summer and fall, the groundwater level is controlled by precipitation events, and normally oscillates between 150 cm and 75 cm below the ground (Figs. 6, S7~~6~~–S9~~8~~). A few times in the summer, the groundwater level is lower than the sensor. Most of the oscillations show a rapid, almost instantaneous rise, and a longer, slower, decline – the oscillations are clearly asymmetric (Fig. 7).

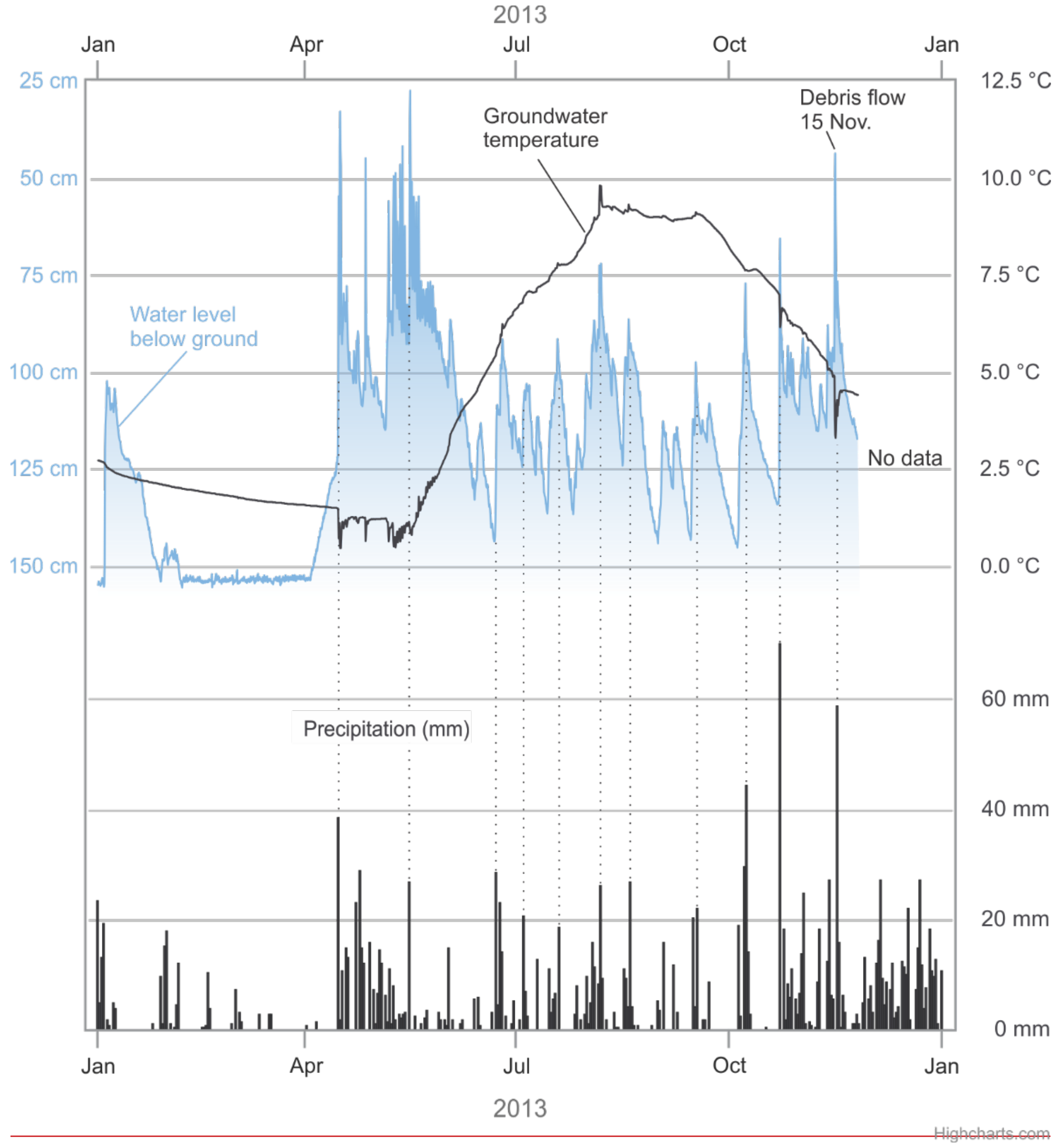
The peaks and troughs of the oscillations occur simultaneously upslope and in the valley bottom (piezometer at the weather station), but the peaks upslope are much sharper and have higher ~~vary in~~ amplitudes (Fig. 7). The valley bottom is saturated almost every time there is a precipitation event. The upslope peaks reach different heights, depending on the amount of infiltration (Fig. 7). Another difference is in the shape of the peaks. The upslope maxima are very sharp, lasting less than 4 hours, while the maxima downslope are broad. The peaks dissipate more rapidly upslope than downslope, as has already ~~also~~ been described elsewhere e.g. Alaska (Sidle, 1984, 1986). The groundwater level starts to decline within hours after reaching peak levels, while the valley bottom peaks last for half a day or more (Fig. 8).

Groundwater temperatures follow the season, but show small, irregular oscillations that reflect infiltration episodes. The temperature curves (Figs. 6, S7~~6~~-S9~~8~~) show~~. The big picture is~~ a steady, slow ~~temperature~~ decline through the winter to about 1.5 ° – 2 °C, an abrupt drop in the spring when temperature reaches its minimum (0.5 ° – 1.2 °C) with wiggles in the temperature curve reflecting meltwater reaching the sensor, followed by a large rise from May to August, up to 9.5 °– 10 °C. In September the groundwater temperatures start a steady decline towards the winter minimum. However, the temperature curves show a number of small anomalies that coincide with peaks in groundwater level. These anomalies are caused by infiltration of surface water that is either colder or warmer than the groundwater. Infiltration episodes between October and May cause the temperature to drop; the largest observed were drops of 1.5 °C and 1.8 °C ~~-~~related to snowmelt (Figs. 6, S8~~7~~). Between May and October, surface water is warmer than the groundwater; infiltration episodes cause temperature rises, the largest recorded being about 1 °C and associated with summer rain events in July (Fig. S8~~7~~) and August (Fig. 6).

One of the largest oscillations in both groundwater level and temperature occurred during storm Hilde on 15–16 November 2013, and triggered the landslide event. In only 8 hours, the groundwater level rose by 46 cm and the temperature dropped by 1.5 °C (Fig. 8). The precipitation at Anestølen began at 08:20 on 15 November and fell as snow until about 14:30, in all 22 mm (3.3 mm/h), because the air temperature was between 0 °and 0.6 °C (blue segment of red curve~~line~~ in Fig. 8). From about 15:00 the air temperature rose quickly and reached 9.5 °C at midnight (Fig. 8), and precipitation was 4.2 mm/h until 22:30 p.m. The response in groundwater level was a rapid rise, 9.5 cm/h (Fig. 9), and a drop in temperature, from 4.9 °C to 3.4 °C between 15:00 and 19:00.

Prior to the storm event, there was a thin cover of snow on the ground. The snow pillow at the weather station measured 20 mm of snow water equivalent before the storm began (Fig. 6~~S9~~). Photos of the landslide the morning after the storm show patches of snow on the ground (Figs. S2-S4). We also observed lumps of snow inside the slide debris. This suggests that there was about 10~~ – ~~20 cm of snow on the ground prior to the arrival of warm, moist air with the storm.


2013
Jan
Apr
Jul
Oct
Jan
25 cm
50 cm
75 cm
100 cm
125 cm
150 cm
12.5 °C
10.0 °C
7.5 °C
5.0 °C
2.5 °C
0.0 °C
15 April
16 May
Groundwater temperature
Debris flow 15 Nov.
Water level below ground
No data
26 May
Precipitation (mm)
60 mm
40 mm
20 mm
0.0 mm
Snow water equivalent
0.50 m
0.25 m
0.00 m
Snow on the ground
26 May
Jan
Apr
Jul
Oct
Jan
2013
Highcharts.com



215 **Figure 6: The upper diagram shows groundwater level (blue curve) and groundwater temperature (black curve) from the borehole on the slope in 2013. The middle ~~lower~~ diagram shows 24h precipitation at the weather station at Selseng (Fig. 4A), station no. 55700, http://eklima.met.no. The lower diagram shows the snow water equivalent measured with a snow pillow at the weather station 77.24.0 (Fig. 4B). The small wiggles in the temperature curve end on 26 May – the same day the snow pillow was free of snow. One of the most pronounced oscillations is on 15–16 November, when a**
220 **debris flow occurred on this hillslope.**

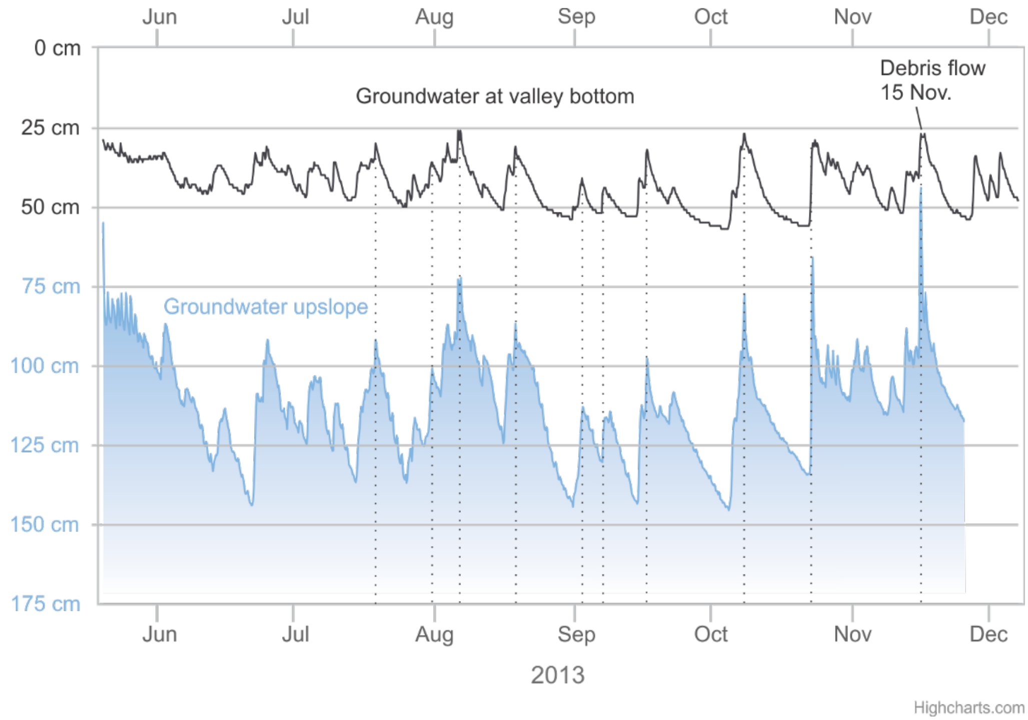
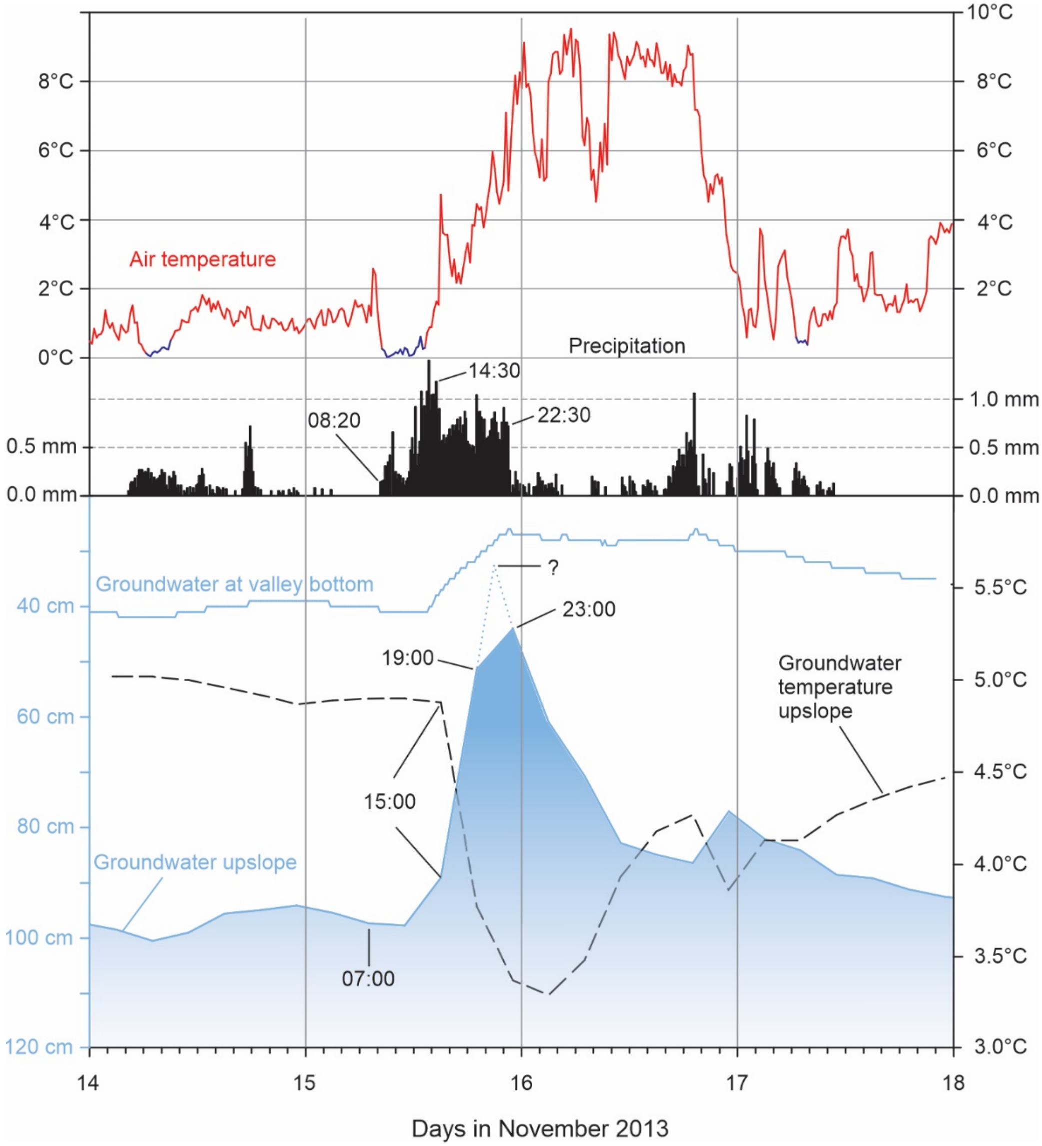


Figure 7: Groundwater fluctuations in June-December 2013. The upper curve (black) shows fluctuations at the weather station in the valley bottom. The blue curve shows the fluctuations in the borehole upslope. The minima and maxima occur at the same time (dotted lines), but the peaks upslope are sharper, last less than 4 hours, have higher amplitudes, and the individual peaks reach different levels. The ground in the valley bottom is saturated at a registered depth of around 25 cm.


Air temperature
Precipitation
14:30
08:20
22:30
Groundwater at valley bottom
?
23:00
19:00
Groundwater temperature upslope
15:00
Groundwater upslope
07:00
10°C
8°C
6°C
4°C
2°C
0°C
1.0 mm
0.5 mm
0.0 mm
40 cm
60 cm
80 cm
100 cm
120 cm
5.5°C
5.0°C
4.5°C
4.0°C
3.5°C
3.0°C
14
15
16
17
18
Days in November 2013

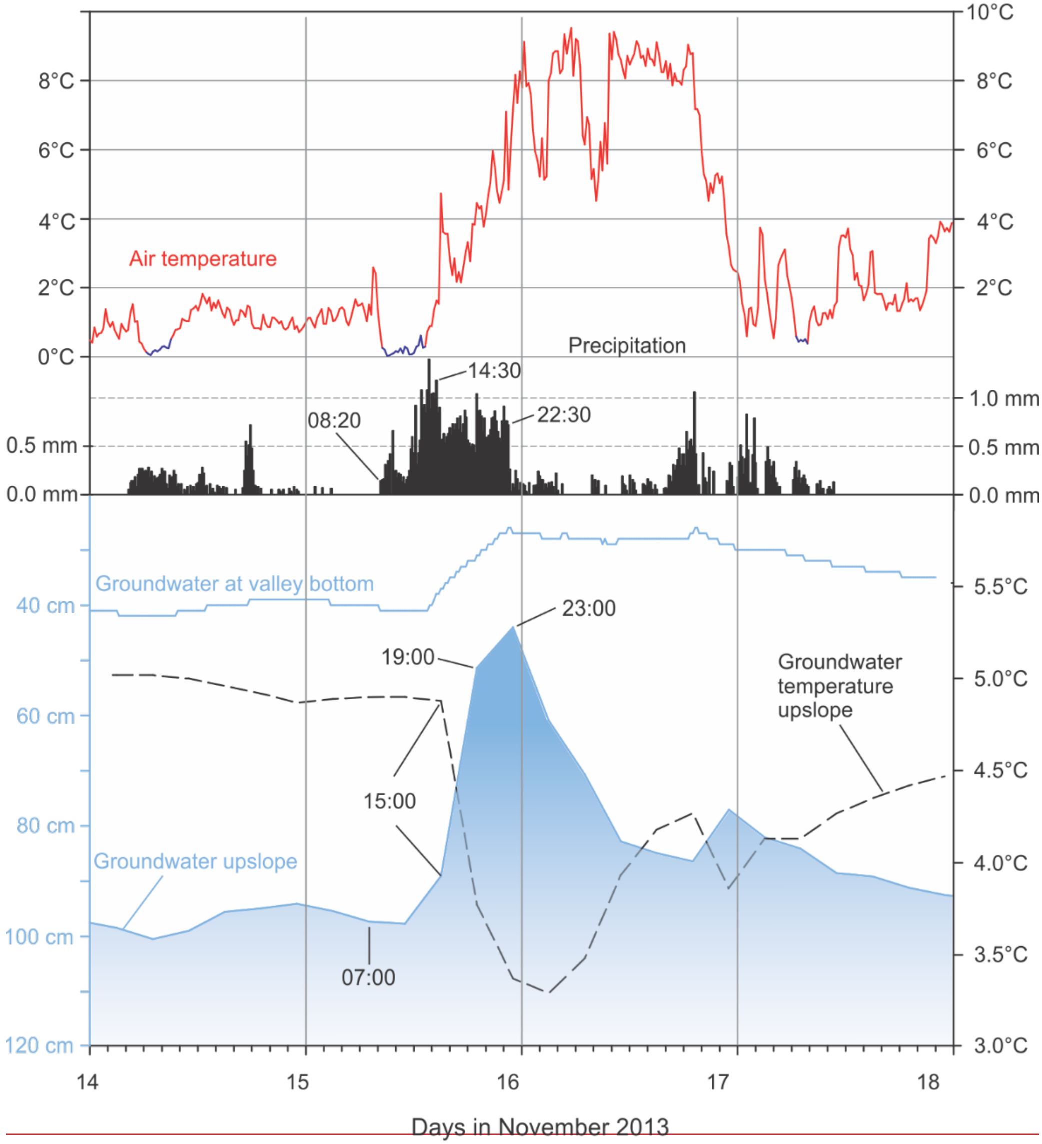


Figure 8: Air temperatures, precipitation and groundwater between 14 and 18 November 2013. The upper diagram shows air temperature (red curve) and precipitation in mm per 10 min. The lower diagram shows the groundwater level and groundwater temperature. Blue segments of the air temperature-curve show periods when the temperature is close to 0°C. Groundwater probably reached its highest level between 19:00 and 23:00, shown as a dotted line and a question mark.

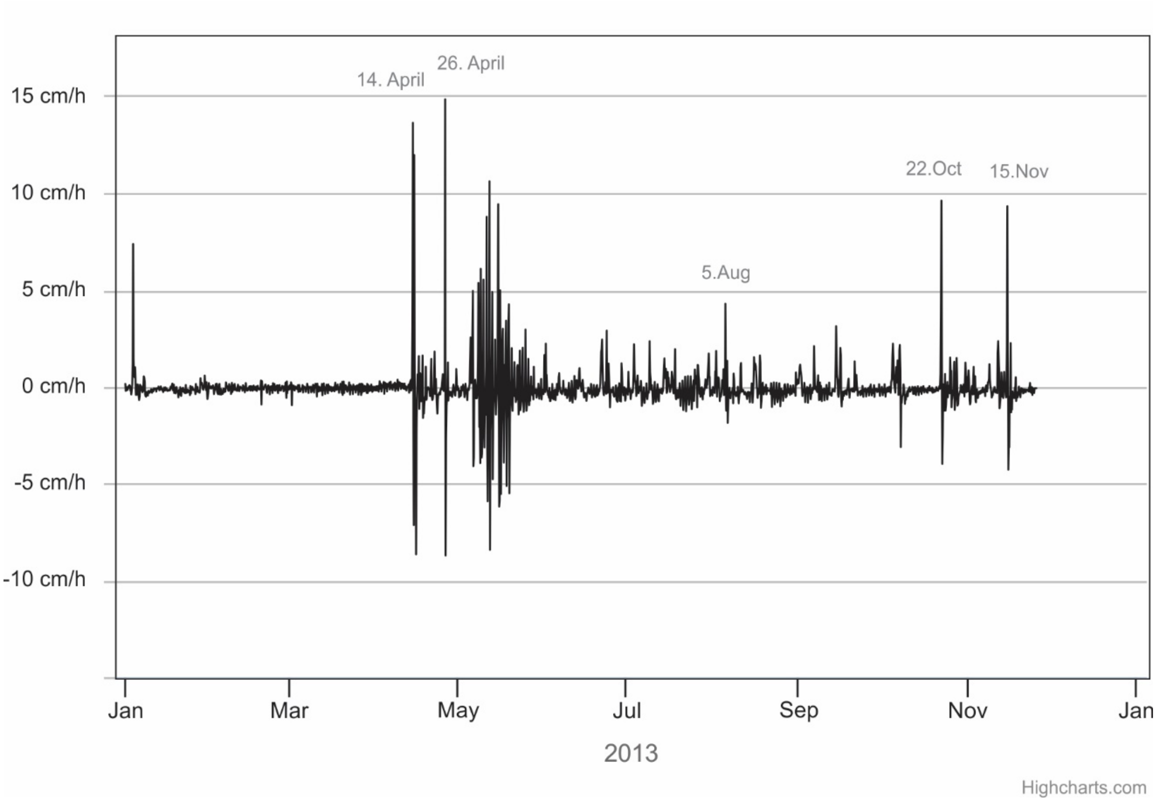


Figure 9: Rates of change of the groundwater level upslope in 2013. The highest rates are in April and May and are caused by melting of the snow cover and thawing of the ground.

5 Discussion

One weakness of this study is that the measurements on the slope are from one piezometer only. The hydrological response to the rainfall depends on antecedent moisture conditions and the porosity, hydraulic conductivity and thickness of deposits on the slope (Johnson and Sitar, 1990; Montgomery et al., 2009). The slope is covered by till and colluvium, deposits that vary widely in composition and grain size. Thus, observations from one borehole may not be representative of other areas on the same slope (Fannin and Jaakkola, 1999). The distance from the borehole to the 2013 debris flow ~~slide~~ is about 400 m (Fig. 4B). Another weakness is that the piezometer in the hillslope was set to a recording interval of 4 hours, which is too long to capture details of the most rapid changes (Fannin and Jaakkola, 1999). The strength of the study is the continuous measurements of both pore pressure and groundwater temperature in conjunction with the nearby weather station over a period of 4 years that also covers a landslide event.

5.1 The storm Hilde landslide event, 15–16 November 2013

The groundwater level in the piezometer on the slope peaked between 19:00 and 23:00, and this is probably the time window when the debris flow was triggered. We measured the peak at 23:00 at 44 cm below surface, but because the piezometer only took measurements every 4 hours, and the rise of the groundwater declined between 19:00 and 23:00 without any change in precipitation or air temperature, it is likely that the actual peak was reached earlier than 23:00 and was higher than 44 cm (see Fig. 8~~6~~). Extrapolations of the groundwater level curve from 19:00 and 23:00 indicates that the peak might well have been at a depth of 30 cm and sometime around 20:30-21.30 (Fig. 8, stippled line). From a study in Oregon, USA, Montgomery et al. (2009) concluded that most of their piezometers recorded that groundwater was still rising at the time of a debris flow failure, and this suggests that the debris flow at Anestølen occurred earlier than 23:00.

The substantial drop in groundwater temperature suggests that part of the infiltration was from snowmelt. There was already some snow on the ground on 15 November (Fig. 6~~S9~~), and the precipitation in the morning and until about 15:00 fell as snow because of the low air temperature (Fig. 8). During this time there was no response in the groundwater level or temperature. However, after 15:00, when the warm, moist air of the storm reached Anestølen, the groundwater rose by 9.5 cm/h and at the same time, the temperature of the groundwater dropped by 0.2 °C/h. The rapid snowmelt added extra water to the slope and augmented the infiltration rate and groundwater rise, as seen from rainfall on snow on slopes in Alaska (Sidle, 1984) .

The groundwater level in the hillslope continued to rise as long as the infiltration rate was higher than the downslope discharge of groundwater (Fig. 10, middle panel). The heavy rain ceased at 22:30, and after 23:00 the groundwater level fell by 3 cm/h (Fig. 10, lower panel). The groundwater level was still rising just after 19:00, so the peak, when groundwater was less than 50 cm from the surface, itself must have been shorter than 4 hours. Such a short peak suggests that very little groundwater from higher up the slope or from bedrock fractures (Johnson and Sitar, 1990) could have contributed to the rise in groundwater level. The entire groundwater rise can be explained by vertical infiltration through the surface. The full amplitude of the groundwater peak was 54 cm during storm Hilde (Fig. 8), and this is an order of magnitude larger than the total amount of rainfall and snow (53 mm). A similar relationship has been found in other studies (e.g. Sidle, 1984).

5.2 Other groundwater episodes

Melting of the snow cover in combination with rain on the slope leads to high groundwater levels. In 2013 we recorded the year's highest peaks in April and May (Fig. 6), when the ground was partly frozen and still covered by substantial amounts of snow (Fig. 6S9). The high peaks correspond to lows in the groundwater temperature curve, reflecting the infiltration of cold meltwater. The small wiggles in the temperature curve end on 26 May – the same day the snow pillow at the weather station was free of snow (Fig. S9). The highest peaks were on 15 April and 16 May, 33 cm and 28 cm below the ground respectively, and coincided with rain (Fig. 6), and high air temperatures (> 8°C) (Fig. S1) and thawing of the frozen soil. This high ground water level pore pressure did not cause any sliding, perhaps because parts of the soil on the slope re were as still frozenconsiderable snow cover, estimated at around 1 m (Fig. S9).

The fluctuations that occurred during storm Dagmar on 26–27 December 2011 were exceptional and similar to those during storm Hilde event. During storm Dagmar, groundwater rose to 28 cm below the surface, and the groundwater temperature dropped by 1.8°C (Fig. S87). The groundwater rose by 13.5 cm/h between 19:00 and 23:00 on 26 December (Fig. S11). A major cause was a considerable increase in air temperature that melted a lot of snow, in combination with some precipitation (37.5 mm; Fig. S87). In spite of this, there were no observations of any sliding on this particular slope.

Another episode when there was a very rapid rise in groundwater level occurred on 18–19 August in 2012. Here, the groundwater rose from below the sensor and up to 97 cm below the surface (Fig. S76) at a rate of more than 15.7 cm per hour (Fig. S10). This was the highest rate measured during the four years of recordings (Figs. 910, S10–S12). Nevertheless, no landslide was observed, probably because the groundwater level was too low when the rain started, and so the peak did not reach higher than 97 cm below the surface. This shows that it is not the rise itself, but the level that the groundwater reaches, that is important.

When the groundwater level in the piezometer rises above 50 cm below the surface, the slope reaches a critical condition. Such a high groundwater level was only recorded three times during the four years of observations (2010-2013): during snow melting in mid-April and early May 2013 and during the storms Hilde in 2013 and Dagmar in 2011. This corresponds to only 0.13 % of the four years of data. On these occasions parts of the slope might have been fully saturated, or artesian conditions might exist, especially in depressions or areas where conductive layers are thinning out or are blocked by less permeable deposits (Johnson and Sitar, 1990; Sidle, 1984). In order for the pore pressure to reach such a high level during a rainstorm, the groundwater level before the onset of the storm has to be sufficiently high, not much deeper than 1 m below the ground. In addition, our data indicate that the groundwater level will only be above 50 cm for a very short time, probably less than 5–6 hours, and that these conditions only persist as long as infiltration is higher than the downslope discharge of groundwater. This pattern is in contrast to groundwater measurements from the nearby weather station in the valley bottom, which show much broader peaks.

We thus think that a network of instrumented piezometers in some selected slopes susceptible to debris flows and debris slides could improve the Norwegian warning system. The Norwegian forecasting and warning service for rainfall and snowmelt induced landslides is based on weather forecast of precipitation and air temperature and hydrological models (Krøgli et al., 2018). The models are checked with real-time data of precipitation, air temperature, water discharge and groundwater levels. However, the groundwater data are from piezometers installed in rather flat terrain and not from slopes susceptible to landslides. Our study shows a large difference in duration and amplitudes between the simultaneous groundwater fluctuations in the valley bottom and the groundwater fluctuations up on the slope. To also include groundwater data from piezometers in slopes susceptible to debris flows could increase the accuracy of the warning system.

5.3 Future changes in precipitation and snowmelt?

Many of the landslides triggered during storm Hilde were caused by simultaneous heavy rainfall and strong snowmelt. Such rain-on-snow events in Western Norway may become more frequent in the future. Storm Hilde was a typical atmospheric river storm, a type that has caused 57 of 60 extreme daily precipitation events in Western Norway since 1900. Of these, 62 % occurred in the months November, December and January – while none occurred in April, May, June and July (Azad and Sorteberg, 2017). The frequency of extreme precipitation events over Norway has increased by 25–35 % over the last 120 years (Sorteberg et al., 2018) and modelling indicates that it will increase further in the future (Hanssen-Bauer et al., 2017). Since most of these events occur in the winter months, it is very likely that we will see more rain-on-snow events in Western Norway in the near future that could increase the risk of debris flows~~slide events~~ and floods.

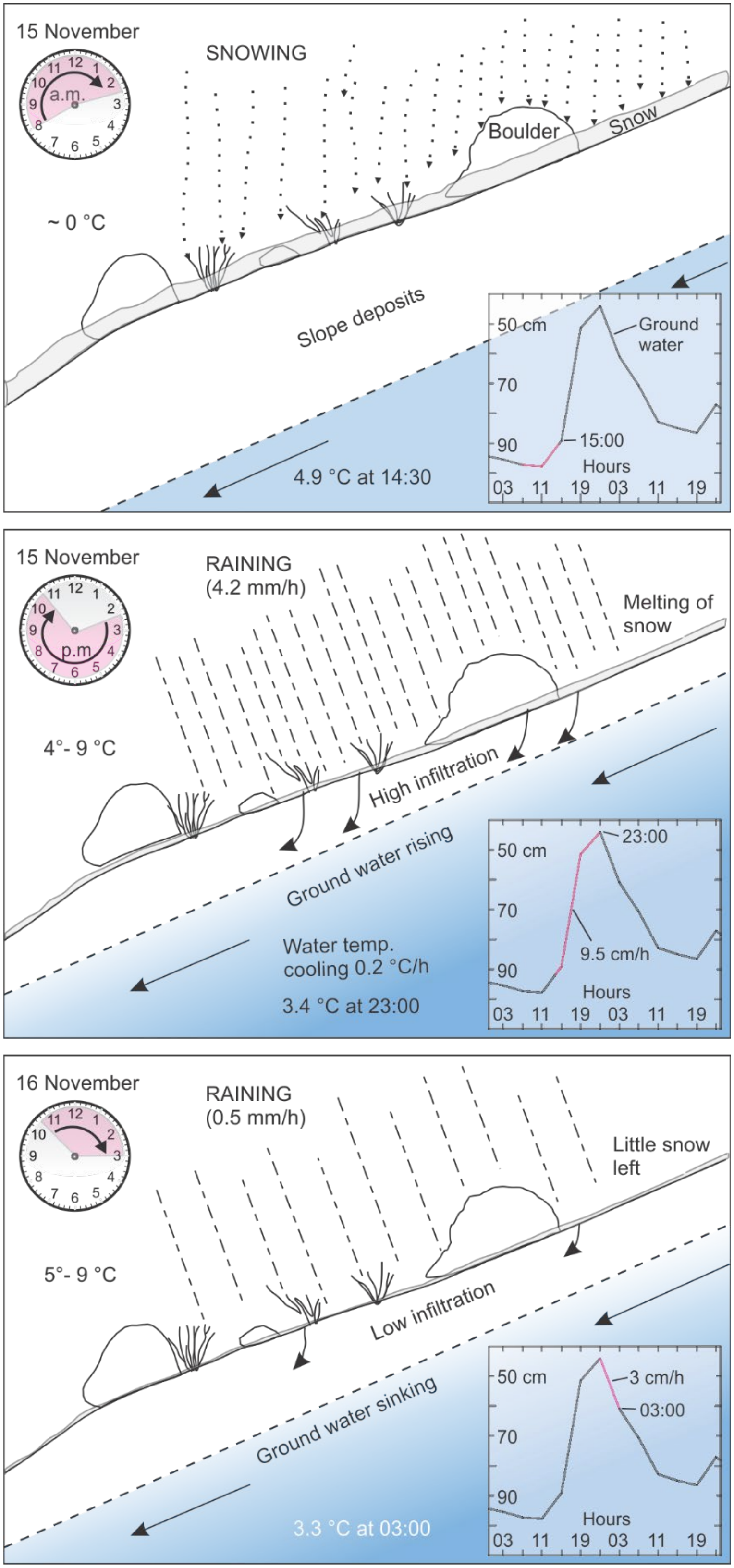

15 November
SNOWING
a.m.
~ 0 °C
Boulder
Snow
Slope deposits
4.9 °C at 14:30
50 cm
70
90
Ground water
15:00
Hours
03 11 19 03 11 19
15 November
RAINING
(4.2 mm/h)
p.m
Melting of snow
4°- 9 °C
High infiltration
Ground water rising
Water temp. cooling 0.2 °C/h
3.4 °C at 23:00
50 cm
70
90
23:00
9.5 cm/h
Hours
03 11 19 03 11 19
16 November
RAINING
(0.5 mm/h)
Little snow left
5°- 9 °C
Low infiltration
Ground water sinking
3.3 °C at 03:00
50 cm
70
90
3 cm/h
03:00
Hours
03 11 19 03 11 19

Figure 10: Diagrams to explain the situation on the hillslope during storm Hilde on 15–16 November 2013. The purple section of the clock and purple segment of the groundwater curve in the graph in the lower right corner show the time. Upper panel: Between 08:00 and 14:30, air temperatures were close to 0° C and the precipitation fell as snow. Groundwater level was stable (graph in lower right corner). Middle panel: Between 14:30 and 22:30, the air temperature rose to 9 ° C, it rained 4.2 mm/h, groundwater level rose by 9.5 cm/h and groundwater temperatures dropped by 1.6 ° C. Lower panel: After 22:30, the heavy rain ceased and the groundwater dropped by 3 cm/h.

6 Conclusions

1. The storm Hilde, 15–16 November 2013, ~~event~~ in western Norway generated ~~produced~~ relatively large amounts of precipitation near the coast on the western slopes of the mountain range ~~near the coast~~(90–120 mm pr. 24 hours). Farther inland, precipitation was lower (30–90 mm) but fell first as snow on higher ground. ~~was high but not extreme.~~ The strong warm front in the storm gave rise to a rapid temperature increase of 8–9 °C, initiating snowmelt that supplemented the rainfall and le~~a~~d to a rapid rise in groundwater. This situation triggered over hundred landslides in western Norway.

2. We measured groundwater levels in a hillslope that failed in this~~e~~ storm, at Anestølen in western Norway. The groundwater responded rapidly to the rainfall and increase in air temperature during the storm and rose by 9.5 cm/h, simultaneously with a pronounced drop in groundwater temperature of 0.2°C/h. The groundwater peak reached at least 44 cm below the surface and the groundwater temperature had dropped by 1.6 °C when the debris flow was triggered.

3. During the storm t~~T~~he slope remained saturated or near saturated for a short time, and the ~~.~~ c~~C~~ritical conditions of the slope lasted only for 4–5 hours ~~during the Hilde storm~~.

4. Two episodes stand out from the data collected over four years (2010, 2011, 2012 and 2013) in the hillslope piezometer; – the groundwater peaks during storm Hilde in 2013 and storm Dagmar in 2011, both storms had ground water levels that reached higher than 50 cm below the surface.

~~4.~~5. Normally the groundwater level in the hillslope piezometer fluctuated between 150 cm and 75 cm below the surface. The groundwater level ~~in the hillslope piezometer~~ was below 50 cm for 99.87 % of the four years of data.

~~5.~~6. The infiltration of surface water is clearly recorded in the groundwater temperature curve as a short-lived anomaly. The anomaly depends on the amount of infiltration and on the temperature difference between the ground and the air. The largest negative anomalies (up to 1.5–1.8 °C) are related to episodes of rain on snow ~~snowmelt~~ in the fall~~, 1.5–1.8 °C~~. Infiltration of s~~S~~ummer rain caused at most a 1 °C positive temperature anomaly~~rise~~.

Author contribution

SB conceived the project, did the fieldwork, collected the data and wrote the first draft. AS described the weather situation during the storm (Fig. 3), was responsible for the precipitation map in Fig. 12 and wrote the first draft of chapter 5.3 “Future changes in precipitation and snowmelt.”

Declaration of competing interest

The authors declare that they have no conflict of interest.

Acknowledgments

Ola Olsen, Kevin Saurin and Sondre Wenaas mapped the 2013 debris flow ~~event~~ at Anestølen and collected information about the ~~slide~~ event. Geir Magne Tyssebotn and Julia Heggdal Velle drilled the borehole on the hillslope and installed the piezometer with the first mini-diver. Knut Møen (Norwegian Water Resources and Energy Directorate) answered questions about data from the weather station. Ottar Husum provided local information. Jan Helge Aalbu allowed us to use his photos in Fig. 2A and 2C. We inspected and plotted the data using the program Highcharts (https://www.highcharts.com/). Denise Christina Rüther and Helge Henriksen gave ~~provided~~ critical comments that improved the paper, and the two referees, Ivan Vergara and anonymous, suggested changes that developed the paper further. We are grateful for the time and constructive comments they all shared. Alison Coulthard provided assistance with language editing.

Supplementary material

Fig. S1: Air temperatures recorded at the weather station at Anestølen in 2013

Figs. S2-S5: Photos of the debris flow in 2013 at Anestølen

Fig. S6: Groundwater and groundwater temperatures at the weather station in 2013

Fig. S7~~6~~: Groundwater fluctuations and ~~,~~ groundwater temperatures in borehole upslope, and precipitation in 2012

Fig. S8~~7~~: Groundwater fluctuations and~~,~~ groundwater temperatures in borehole upslope, and precipitation in 2011

Fig. S9~~8~~: Groundwater fluctuations and~~,~~ groundwater temperatures in borehole upslope, and precipitation in 2010

~~Fig. S9: Snow at the weather station at Anestølen in 2013~~

Fig. S10: Rates of change of groundwater level in borehole upslope in 2012

Fig. S11: Rates of change of groundwater level in borehole upslope in 2011

Fig. S12: Rates of change of groundwater level in borehole upslope in 2010

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