The Importance of Hail Events for Landslides and Bedload Transport in Austrian Alpine Torrents

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Abstract

Landslides and bedload transport can be a threat to people, infrastructure, and vegetation. Many detailed hydrometeorological trigger mechanisms of such natural hazards are still poorly understood. This is in particular valid concerning hail as a trigger of these processes. Therefore, this study aims to determine the influence of hail on landslides and bedload transport in alpine torrents.

Based on a generated table from an event register of mountain processes maintained by the Avalanche and Torrent Control Unit (WLV) and weather data provided by the Centre for Meteorology and Geodynamics (ZAMG), 1,573 observed events between 1980 and 2019 in 79 Austrian alpine sites are analysed. Thiessen polygons are used to regionalise local weather data to adjacent regions. The spatial extend of these regions are merged with the registered torrential events. As a result of a stepwise filtering of the used data, the final inventory was created.

The results show that 95.1% of the investigated torrential processes triggered by hailstorms are debris flows or debris flow-like transports. Within the study period, a peak of hail-triggered landslides and bedload transport can be recognised in the first 10 days of August in all 39 years. Furthermore, the results suggest that hail is rather a direct than an indirect trigger for landslides and bedload transport.

Overall, we conclude that the influence of hail on landslides and bedload transport is significant. Respective hydrometeorological triggering conditions should be included in any regions. Further research for this topic is required to explore the process dynamics in greater detail.

1. Introduction

Precipitation events can trigger a wide variety of landslides and/or bedload transport, or they might facilitate the initiation of torrential processes by e.g., increasing the soil moisture content within the catchments (Abancó et al. 2021, Suribabu and Sujatha 2019, Zhao et al. 2019). The influence of hail precipitation on landslides and bedload transport has so far only been investigated rarely and has been analysed for individual events only (Alcántara-Ayala et al. 2012, D'Agostino et al. 2009, Navratil et al. 2013). For Austria, neither an individual nor a spatial attempt has yet been made to analyse the influence of hail events on landslides or bedload transport. Within this first attempt, an existing event register on torrential processes and a precipitation database with statistical means over many decades have been analysed to estimate the importance of hailstorm events for the initiation of torrential and bedload processes in high mountains.

Within the event registry provided by the Avalanche and Torrential control (WLV), a variety of natural hazards are listed. Except for bedload transport in torrents and steep river systems, all other listed mass movement processes are summarised with the term “landslides”. We follow the internationally accepted definition of landslides as a downward movement of bedrock, debris, and/or soil, within different processes, such as falling, sliding, flowing, and complex (combination of more than one process) (Cruden and Varnes 1996, Dikau et al. 1996, Hungr et al. 2014). Within these different landslide types, the following processes are referenced in the utilised event registry and examined in more detail in this study: debris flow-like transport, debris flow, earth flow, slope debris, mountain creep, rotational and translational slide, and sliding process that is not specifically defined. Furthermore, entries on bedload transport are also used.

In Austria, an average of 72 days per year with hail damage in agriculture is counted during the period between 1990 to 2000. The southern part of Styria, as well as Salzburg and Upper Austria, are most affected by hail precipitation. In Styria between 1.0 and 5.5 hail days per year are determined (Punge and Kunz 2016). Additionally, hail events show a certain seasonality in the summer months, therefore an analysis of the different months within a given year shall bring more information about the relation between the intensity of hail precipitation and the occurrence date of a torrential process.

Furthermore, lithology is a critical dispositional factor for landslide occurrence as well as bedload initiation and transport. Therefore, the distribution of these different torrential processes triggered by hail is analysed for the variety of lithological units.

Consequently, the main objective of this study is to determine if and how specific hail events can be considered as a direct (e.g., in a given storm) or indirect trigger (e.g., as antecedent conditions before the triggering event) for landslides and bedload transport in different catchments of the Austrian Alps.

2. The Current Knowledge

One important trigger for landslides is precipitation. Its total, the rain duration, and the intensity are crucial factors for the occurrence and are determining the landslide characteristics, e.g., the volume, and the runout distance. As reported for other regions, hail precipitation with a large total of water equivalent can be a direct landslide trigger (D'Agostino et al. 2009, Navratil et al. 2013).

As a result of the hail occurrence, an important process is an increased pore water pressure in the superficial soil layer resulting in a decreased frictional strength. The heavy rainfall commonly following hailstorm events weakens the soil even further and might trigger torrential processes, in particular landslides (Alcántara-Ayala et al. 2012). Hereby, hail can act as an indirect (i.e., as an antecedent condition) or direct trigger (i.e., in a given storm) of landslides and bedload transport in certain scenarios. To get more information about the potential of hail as a trigger for landslides and bedload transport, a detailed analysis of the meteorological trigger conditions has to be carried out for the predefined region (D'Agostino et al. 2009, Alcántara-Ayala et al. 2012, Navratil et al. 2013).

Hydrometeorological variables, such as precipitation, temperature, and evapotranspiration, but also soil moisture, cause a spatio-temporal susceptibility for landslides and bedload transport. High-intensity rainfalls with a short duration are the main landslide trigger in Austria, followed by low-intensity rainfalls with a land duration and snowmelt (Prenner et al. 2018, Mostbauer et al. 2018). Based on the hydrometeorological variables and trigger phenomena, Prenner et al. (2018) investigated six study regions in the Austrian Alps, with different topographical and climatic influences. By taking more areas into account, a more comprehensive assessment of the influence of precipitation on landslides can be delineated (Prenner et al. 2019).

Hail as a trigger mechanism over a large study region has not been examined explicitly in Austria. Based on other studies it can be assumed, however, that hail occurred also within high-intensity precipitation events (Nisi et al. 2020, Sinatra and Nugroho 2018). Therefore, within this study on different regions in the Austrian Alps, the focus is to utilize the available data on natural hazards and precipitation to approximate the effect of hail on torrential events with a focus on landslides and bedload transport.

3. Data

The event register of torrential processes was provided by the Centre for Natural Hazards Information of the WLV (Torrent and Avalanche Control). The WLV is a federal agency of the Republic of Austria and embedded within the Federal Ministry of Agriculture, Regions, and Tourism (BMLRT). As of October 2019, the event register contains 42,985 entries of natural hazards. More recent information is not available electronically yet. The event register contains eight tables, however only the two tables “event” and “event location” are relevant for this study. The archived events date back to AD 345. The older the records get, the less accurate are the respective information. In contrast, more recent entries are of higher accuracy. This trend reflects the condition of any database with historical records and is due to an increasing interest in natural events over time, a better recording of events (Glade 2001), and in particular to the damages as a result of occurring events. But indeed, also a better process understanding leads to more precise recordings and ultimately, an improved database of torrential events. It has to be stated clearly, that in this particular WLV cadastre, only damaging events have been included. Consequently, all events that did not cause damage or caused damage but have not been recorded, are not available in the database. Therefore, there exist a large number of unreported torrential events and thus, the cadastre has a large bias. Nevertheless, this is the only currently available database. Since this bias is a common problem of all historical databases (Glade 2001, Guzzetti et al. 1994, Petschko et al. 2013), this inventory is utilised within this research, besides the bias. Within the “event” table of the database, the following categories are applicable for this study: process type. location, date, duration, trigger, date of precipitation, to name the most relevant ones only. In the table “event location” coordinates are assigned to each torrential event (BMLRT 2019).

In addition to the WLV data, daily precipitation data were provided by the ZAMG (Central Institute for Meteorology and Geodynamics). Measured values are based on daily data for 79 stations for the maximum available recording length, thus from the measurement start of each station to February 14, 2020. The daily parameters precipitation total and type (ZAMG 2020) are used within this study.

4. Environmental Settings

The meteorological conditions of the different sites differ significantly throughout Austria. The mean annual precipitation and temperature depend on the elevation and the location. The precipitation ranges from 600mm in the drier eastern foothills of the Alps to 2,000mm in high elevation areas of the Central East Alps. Regarding the temperature, a similar observation can be made. In the Eastern and South-Eastern regions of Austria, in particular in the Vienna and Graz Basins, the average annual temperature is about 10-11°C. In higher and more remote areas the average annual temperature declines to 0-5°C (ZAMG 2021a).

Austria can be distinguished into the following main lithological units. The Bohemian Massif is located in the northern part of Upper Austria and the northeast part of Lower Austria. The Tertiary Basin and the Quaternary regions are mainly situated in the northern part of Vorarlberg, in the lowlands of Upper and Lower Austria, in the Austrian part of the Pannonian Basin as well as in the Graz Basin. The Penninic Nappes and the Helvetic Nappes form a line north of the Limestone Alps connecting Vienna to Salzburg and in the northern part of Vorarlberg. The Penninic Nappes are also visible in the Rechnitzer Window and the Engadinger Window of the Tauern region. Like the Penninic and the Helvetic Nappes the Northern East Alps reach from Vienna to

Vorarlberg and a small area can also be found in Carinthia. The Northern East Alps limit the Central East Alps and the Greywacke Zone in between their two sections within the Austrian border. In the very south of Austria, a small strip of the Southern East Alps is located (GBA 2015).

In the Vienna Basin the main soil type is Chernozem while in Northern Austria, brown soil and luvisol are commonly developed. Brown soil also occurs in the Greywacke zone and the Central East Alps. Along the Penninic Nappes, the Helvetic Nappes, and in the Graz Basin, especially pseudogley and gley can be observed. In the Tauern region, the main soils are podzol and slope soil. Rendzina soils can be found in the Northern East Alps. Alluvial soils are located near rivers, like Danube, Inn, and Upper Rhein (BFW 2004).

The alpine vegetation is highly influenced by the location, climate, and human impact. Within the Colline Belt predominantly dry-warm oak hornbeam forests and mixed oak forests exist. In the Montane Belt, Beech forests are at the edge of the Alps and Spruce forests dominate in the Inner Alps. Spruce-fir-beech forests or spruce-fir forests are found in higher areas of this belt. Scots pine, green alder, and hornbeam shrubland as well as larch and Swiss stone pine forests occur in the Subalpine Belt. In the Alpine Belt, no large woody plants appear anymore, but Dwarf shrub heaths characterize the land cover at this altitude (Fischer et al. 2008).

The human influence on the vegetation in the study regions should not be underestimated. Forest reduces the threat of landslides because it provides a canopy for the soil on slopes and additionally the root system increases slope stability which act against shallow landslides. The development of building ground for settlements and the tourism industry, as well as the wood production, decreases the proportion of natural forests and vegetation by clearing forest sections for buildings and cutting trees for wood production. This leads to an increased potential landslide occurrences and bedload transport in the affected areas and might also increase respective risks. As Sebald et al. 2019 has shown for the Austrian East Alps, the probability of debris flow occurrence increased from 0.03% within a 10% disturbed forest cover to 0.15% when 50% of the forest cover is disturbed. In contrast, an increase in forest cover reduces the probability of torrential hazards by roughly 9%.

The available weather stations of ZAMG and the finally selected study sites are shown in Figures 1a and b. Hereby, each ZAMG weather station serves as a basis for a Thiessen polygon. The assumption hereby is, that the measured precipitation at a given location is representative for the whole polygon. This is indeed a major limitation; however, no other spatial precipitation data are available for long periods. A total of 1,573 hail events can be analysed, ranging from the northernmost polygon "Rohrbach" to the southernmost "Bad Eisenkappel" and from westernmost polygon "Feldkirch" to the easternmost "Wiener Neustadt/Flugplatz" (Figure 1b). The weather stations of 66 study regions are in the Colline Belt (up to 1,050m asl), 13 weather stations are located in the Montane Belt (between 1,050m – 1,390m asl), 6 regions can be assigned to the Subalpine Belt (within 1,390m – 1,880m asl.) and 4 to the alpine belt (1,880m asl) respectively (Rubel et al. 2017, ZAMG 2020).

5. Methods

5.1. Utilizing the torrential event database

Based on internationally recognized findings of the DOMODIS (Documentation of Mountain Disasters) project of the ICSU-CDR (International Council for Science, Committee on Disaster Reduction (formerly ICSU-SC IDNDR)) and the IAG (International Association of Geomorphologists), Hübl et al. (2002) published a recommendation of documentation sheets for natural hazards in Alpine regions. Together with various expert groups (e.g., Natural Hazards Carinthia), this recommendation has been adopted in the Austrian settings and a digital event cadastre was designed and developed as a standardized tool for recording and collecting event information on torrent and avalanche processes. This cadastre is maintained by the Centre for Natural Hazards Information of the Torrent and Avalanche Control (WLV). Although it is an internal database, it has been made available for scientific research (Naturgefahren 2021).

From the 191 columns in the "event” table of the WLV event register, only the information required for this study has been selected. The identified columns include the following information for each entry: “id”, “process type id”, “process type”, “state id”, “state”, “district id”, “district”, “community id”, “community”, “event date”, “event time”, “event time maxo”, “event year”, “event month”, “event day”, “event duration”, “event duration maxo”, “trigger id”, “trigger”, “trigger phenomenon”, “precipitation date”, “precipitation time”, “precipitation begin maxo”, “precipitation duration”, “precipitation duration text”, “precipitation duration maxo”, “precipitation amount”, “precipitation amount maxo” (BMLRT 2019). Within the selected columns, some seem to be similar, e.g., the two columns “trigger” and “trigger phenomenon”. The difference is explained by the following example. A torrential event can be triggered by a thunderstorm, therefore an entry in the column “trigger” is created. But during the storm, hail was the main cause, so this information is listed in the column “trigger phenomenon” (BMLRT 2019). Thus, it is possible to differentiate the triggers in greater detail and with higher accuracy.

All data entries are provided with a quality index by the WLV, which is based on the “MAXO-code”. The variables in this code refer to the following abbreviations: m = measured value or saved value, a = assumption, x = can be determined at a later point in time and o = cannot be determined (Andrecs and Hagen 2011). This information has been used to determine if the weather information in the event register from the WLV or the weather data from ZAMG is more accurate. In the case of “m”, associated with WLV entries, the values have been used in the following analysis and the ZAMG database has been applied subject to “a”, “x” and “o” marking the values. New entries in the WLV event register contain information on precipitation and triggering (BMLRT 2019).

The selected two tables (event and event location) are linked with the help of the column “id”. This allows the exact localization of each event on a map. To avoid false interpretations, all events that are not explicitly assigned as landslides and bedload transports are excluded. As a result, only the following torrential processes are included in the subsequent analysis: “debris flow-like transport”, “debris flow”, “earth flow”, “slope debris”, “mountain creep”, “rotational slide”, “translational slide”. In addition, the data for “undefined slides” and “bedload transport” have been used. Since there were still too many entries, the different process types have been grouped in the three classes “fluvial process”, “debris flow-like process”, and “sliding process" (Rimböck et al. 2013) by applying the triangle diagram developed by Phillips and Davies (1991).

Finally, events with no entry in the “event date” column have been removed. Since the used weather data from ZAMG started in the year 1980, all data before this year have been deleted also from the torrential event database.

5.2. Utilizing the meteorological database

ZAMG's network of stations comprises approximately 260 weather stations which are listed on their website including names and coordinates. Within ArcGIS Pro (Version 2.6.2), all Austrian weather stations have been visualized. To regionalize the local weather information of the individual meteorological stations, Thiessen polygons have been applied. This is still one of the most common methods to approximate precipitation over an area, where limited weather information is available (Lü et al. 2021). Compared to the inverse distance weighting method (IDW) and the Kriging method, the Thiessen polygons focus on geometric values only and ignore topographic influence (Zhou et al. 2020). Since the available weather data does not provide any respective details, it is reasonable to apply the Thiessen polygons for first approximations, despite their limitations (Lü et al. 2021). Consequently, each weather station is assigned to one Thiessen polygon. The resulting map is shown in figure 1a (ZAMG 2021b). When two polygons meet, the edges will be a perpendicular bisector to the connecting line between two weather stations. The still open polygons along the national border of Austria are closed by using the Austrian border line. Otherwise, these polygons would extend to infinity, which has to be avoided (Yamada 2016). Since the WLV database contains the digital torrential data until October 2019 only, the additional entries of the ZAMG database are deleted (ZAMG 2020, BMLRT 2019).

5.3. Merging the torrential event database, the meteorological database and the lithological database

In the next step, the torrential event and meteorological databases have been merged. As mentioned, the WLV table does not provide information on the precipitation date for all entries. To be able to carry out an analysis and to connect the precipitation value and type of precipitation with the ZAMG data, the following rules are applied:

For events with no event time available, the precipitation date of each entry has been checked. If no precipitation date is given, the WLV event date is used, otherwise, the ZAMG precipitation date is considered more accurate than the event date of the ELV database. For the values where only the WLV date of the event is known, the ZAMG daily precipitation value is used, as it is not known when the event happened throughout the day. If an event has a known event time it can be connected to the period it best represents.

WLV events with entries in the column “event time” can be similarly merged with the ZAMG data. No precipitation data or time means that only the event time can be used. If there is a ZAMG precipitation date, but no WLV precipitation time available, then the precipitation date is still considered to be more correct than the event time. That rule must be applied if the precipitation date is different from the event date and therefore the daily precipitation or daily precipitation type is applied. If the ZAMG precipitation date and the WLV event date are the same, then the event time is used since the time value is considered to be more accurate. If an event has a known precipitation time, it can be linked to the best fitting ZAMG value.

Now the WLV-ZAMG database can be merged on the base of the polygons and utilised within a GIS system. Only 79 weather stations in Austria can distinguish between different precipitation types, so for this analysis, these weather stations are used as shown in figure 1b (ZAMG 2020).

Since the lithology (figure 2) provides some basic information on the near-surface and thus, it is important on the effects of hail on torrential processes. This information has also been imported into ArcGIS Pro and adapted based on the UBA template (UBA 2004). The available information has been grouped into the following main lithologies: Bohemian Massif, Tertiary Basin, Quaternary, Penninic Nappes, Helvetic Nappes, Northern East Alps, Greywacke Zone, Central East Alps, and Southern East Alps (GBA 2015).

To evaluate whether there was any precipitation in the 5 days before an event and to verify if hail can be seen as a direct or indirect trigger for landslides and/or bedload transport, an analysis of the antecedent precipitation is carried out. In many regions, antecedent precipitation is an important aspect in the triggering of landslides, e.g., by increasing the soil moisture and therefore, reducing soil strength. Since no detailed information on antecedent periods for landslide-triggering events in Austria are available, a common length for an antecedent period for Central European regions has been applied from literature (Jemec and Komac 2012, Rahardjo et al. 2019, Kuradusenge et al. 2020). Based on these studies, a threshold of 5 days has been defined and implemented in this analysis (BMLRT 2019).

To add the missing precipitation duration and precipitation amount values in the WLV database, ZAMG precipitation values are used. It has to be noted, however, that due to the selection process of the meteorological ZAMG data, some ZAMG data do not increase the accuracy of the database. The limitation of the ZAMG data does not always allow a proper merging, 24-hour values cannot be divided into 1-hour values, because it is not clear when the precipitation in question occurred in the 24 hours. There would be misjudgements in this investigation and consequently, the analysis of the precipitation duration and the precipitation amount have not been further processed in this study (ZAMG 2020, BMLRT 2019).

If snowmelt was given as a trigger phenomenon, the entry was deleted. The assumption herein is, that the temperature increase - and not the precipitation on the date of occurrence - is the real reason for this event. If rain within the column “trigger” and snowmelt within “trigger phenomenon” was given, this dataset was not deleted. It can be assumed that the rain has influenced the melt and not only the temperature rise is the cause of this torrential event. If flooding was entered within “trigger”, the respective entries were deleted.

To avoid double entries, the ID is checked for every entry in the two tables and compared if there are any clones unintended created through the various work steps. Since entries with time information for precipitation are more accurate, they are superimposed over those without time information, if the rest of the data has the same information.

If heavy precipitation triggers many torrential processes in the same catchment, they are individually recorded in the WLV database. This might influence the significance and introduce a bias in the results of this study. To reduce the influence of major event entries within the same catchment these have to be compared with each other and merged into one event.

The finally resulting database was used for the respective analysis.

6. Results

As shown in figure 3a, 465 rainfall-triggered landslides are associated with the following landslide types: 39.8% debris flow-like transport, 37.2% debris flow, 7.7% translational slide, 7.1% rotational slide, 4.3% slide (not defined), 3.4% slope debris and 0.4% earth flow. The total of 142 hail-triggered landslides contains the following process types: 47.2% debris flow-like transport, 47.9% debris flow, 4.2% slide (not defined) and 0.7% rotational slide (figure 3b).

If the two percentage distributions between landslides triggered by rain and those triggered by hail are compared, it can be concluded from the available data that about three-quarters (even higher for hail) of the triggered landslides were debris flow-like processes (debris flow and debris flow-like transport). About one-quarter of the events are rainfall-triggered slides, and while only approximately 5% of slides were triggered by hail. Therefore, hailstorms seem to initiate debris flows or debris flow-like transports more frequently than slides.

Bedload transport has been triggered in 81.6% by rain, 18.2% by hail, and 0.2% by snow (figure 3c). The percentage distribution of precipitation types that triggered bedload transport clearly shows that about four-fifths of the events were caused by rain and one-fifth by hail only. This analysis suggests that rain has a far greater influence on bedload transport than hail.

A total of 185 bedload transport events are located on the described lithologies and are distributed in 40.0% in the Central East Alps, 22.7% in the Greywacke Zone, 17.8% in the Quaternary, 11.4% in the Tertiary Basin, 2.7% in the Bohemian Massif, 2.7% in the Penninic Nappes, 1.6% in the Northern East Alps and 1.1% in the Southern East Alps respectively (figure 4a). The same analysis was carried out for the 135 debris flow-like relocation processes, thus including debris flow-like transports and debris flows. The distribution in the different lithologies (figure 4b) refer to: 43.0% Central East Alps, 16.3% Greywacke Zone, 21.5% Quaternary, 0.7% Tertiary Basin, 6.7% Penninic Nappes, 11.1% Northern East Alps, and 0,7% Southern East Alps.

It can be concluded that lithology has some influence on the locations of torrential events triggered by hail. Two-third of the bedload transport events occur in the Central East Alps and the Greywacke Zone. While in the Quaternary and Tertiary Basins approximately one-third of the events are initiated, the remaining lithologies seem not to be important. In contrast, the percentage of landslide distribution is different. The percentage of the events occurring in the Quaternary is larger than in the Greywacke Zone. The two lithologies Northern East Alps and Penninic Nappes have a larger percentage share than in bedload transport. The occurrences in the Tertiary Basin can be neglected.

Figure 5 lists the events caused by hail and classifies them into specific monthly segments for the whole investigation period. Approaching the high point in August the events in the previous monthly segments increase slowly before they rise significantly. It is evident, that most events were triggered in the first days of August and right after this peak the events in the following monthly segments decline sharply.

The percental distribution of the precipitation types that indirectly triggered a bedload transport (179 events) can be determined as follows (figure 6a); 87.8% rain, 0.5% snow, 1.0% hail, 2.5% rain and snow, 7.6% rain and hail, and 0.5% rain, sleet, and hail. In the case of precipitation types that directly triggered a bedload transport (142 events) rain accounts for 59.2% and hail for the remaining 40.8% (figure 6b). The distribution of the precipitation types that indirectly triggered a landslide (133 events) refers to 77.4% rain, 1.5% hail, 6.0% rain and snow, 14.3% rain and hail, and 0.8% rain, snow, and sleet (figure 6d). In the case of direct precipitation events (54 events), a distinction can again only be made between 42.6% rain and hail 57.4% (figure 6e).

When differentiating between the direct and indirect influence of precipitation types on landslides and bedload transport, a trend can be identified. Only rain influences about three-quarters (even more for landslides) of all indirectly triggered events. The remaining percentages of indirectly triggered events are very low, only the category “rain and hail” accounts for about 7% for bedload transport and double that for landslides, i.e., about 14%. In the case of the direct triggering of landslides and bedload transport, a distinction can only be made between the two types of precipitation. Rain is responsible for about 60% of all directly triggered bedload transport events and hail for 40%. In contrast, the ratio for landslides is exactly the opposite, i.e., 40% rain and 60% hail.

If only the events are considered that were triggered by hail and compare the percentual distribution of direct and indirect hail impact, the following results for bedload transport can be obtained: 77.3% direct hail influence and 22.7% indirect hail influence (figure 6c). In figure 6f the percentage the relation of the 52 landslide events is 59.6% by direct hail influence and 40.4% by indirect hail influence. The proportion of landslides or bedload transport that were triggered directly or indirectly by hail events indicates that for both process types, hail has rather be a direct influence. This is truer for bedload transport (77.3%) than for landslides (59.6%), but both process types suggest that the majority of hail events can be considered direct triggers.

7. Discussion

The analysed data regarding the trigger precipitation of landslides and bedload transport indicate that hail primarily causes debris flows and debris flow-like transports. The percental distribution of events, which were triggered by rain, also shows that debris flows and debris flow-like transports are the majority of events. Both results confirm that water is of major importance in these two landslide types, which are mainly triggered by precipitation. Nevertheless, the high percentage of hail-caused events indicates that hail is more likely to trigger debris flows and debris flow-like transports. Hail rarely triggers other landslide types compared to rain. Bedload transport is more prone to rain than to hail. This is related to the higher water content required for this process which can be more easily achieved by rainfall than by hail precipitation. The frozen water in hail has to be melted first before the liquid water is available to contribute to bedload transport. Based on the available data, hail itself seem not to have a direct impact on bedload transport. It should be mentioned, however, that in these analysis steps only direct and no indirect factors, such as soil moisture, vegetation, or human influence, were considered. Since hail events are always associated with rain, some events may have been mistakenly assumed to be caused by hail, even though rain was the actual trigger.

Regarding the impact that lithology has on hail triggering debris flows, debris flow-like transport, and bedload transport, it can be stated that the Central East Alps, followed by the Greywacke Zone and the Quaternary are the lithologies which are most affected by respective events. It can be concluded that these lithologies are more susceptible to the impact of hail events than other lithologies. However, the study of the influence of lithology can be biased also with respect to the topography. More hail falls in certain regions of Austria than in others and certain lithologies may not have the assumed effect on hail-triggered processes because these lithologies just happen to be in the area where hail occurs more often. Due to the generalization of the lithologic map, some events may have been assigned to the wrong lithology, thus affecting the results.

Comparing the monthly segments of events triggered by hail, a maximum of the events can be asserted in the first 10 days of August in the observation period 1980-2019. Reasons for this increase and then immediate decrease can be the higher number of precipitations with hail in this monthly section. Or the previous precipitations might have weakened the soil strength and events occurring at the beginning of August leads to the initiation of torrential processes. After the peak in August, the number of events triggered by hail decreases because less hail events occur. In addition, the required removal material was already involved in the previous processes and is less available for subsequent ones. As the year progresses until the following spring, transportable material has now been again available in the areas of torrential processes. Unfortunately, no detailed information was available neither for the changes of the material availability in the catchments nor on the intensity and duration of precipitation. Thus, at the current state of knowledge it seems that the first 10 days of August have had more intense or long-lasting hail precipitation than in other periods, leading to an increased triggering of torrential events.

Rainfall is the most important indirect trigger for both landslides and bedload transports. However, when analysing the direct triggers, a larger difference between debris flows and bedload transport can be identified. Hail, as a direct trigger, is responsible for about 40% of bedload transport and 60% of landslides in the Austrian East Alps. According to these values, hail does not play a major role in indirectly triggering natural hazards, but as a direct causative agent, it has a significant share. This finding is indeed biased by uncertainties - since other indirect factors were not considered and thus the real influence of precipitation on the process cannot be fully inferred. In addition, the influence of the indirect and direct triggers cannot be measured, i.e., how much the precipitation contributed to the occurrence of the event.

To gain a better understanding of the indirect and direct influence of hail on landslides and bedload transports these need to be specifically differentiated and, in both cases, hail can be considered a direct rather than an indirect trigger. Here, the same uncertainties as in the previous argument should be highlighted.

In summary, it can be mentioned that the discussed research questions provide new insights into the influence of hail on landslides and bedload transports in the Austrian Alps, however, the uncertainty of the used data has to be considered. The fact that only damage-causing events were analysed, and many database entries had to be removed due to missing information, many other events have not been considered appropriately in the analysis. The generalisation, concerning lithology and Thiessen polygons, creates the possibility that wrong data was linked to the events which might have caused incorrect information as well. The attempt to gain information about the intensity and duration of the triggering events with the help of the weather data failed because the weather data was too inaccurate for this analysis step.

8. Perspectives

This study attempts to approximate the influence of hail precipitation on landslides and bedload transport and provides an overall picture by analysing various research questions. Though some open questions remain.

Eyewitness reports play a particularly important role for future recordings, as hail is a very local phenomenon and weather station data is therefore often too imprecise for analysis. We see great potential in radar data and POH data (probability of hail) to get more detailed precipitation information about hail. With such detailed precipitation data, the uncertainties described would be minimised and further analysis could be carried out.

In addition, previous events could be reprocessed in a structured manner so that they provide more information for future analyses and new events could meet requirements through standardised and more detailed forms. To provide more data for further research in the future also non-damage-causing events should be included in the WLV database.

In some watersheds, devices measuring soil moisture could be installed on some slopes where landslides have already been observed to gain information about soil water content. This would allow additional influencing factors to be considered in the analysis. This research could also be intensified, thus creating a possible early warning system. In such an early warning system, in addition to weather data, information on soil, lithology, and vegetation would have to be available in a common database to generate simulations for the specific areas.

In times of climate change, focusing on the impact it will have on precipitation in the East Alpine region and estimating what changes will occur in the near future and how the rest of the factors will be affected by them. Main questions include if there will be a shift in precipitation amount, intensity, or frequency in the observed areas, and whether this will cause a change in triggering landslides and bedload transport. These research questions could be investigated if more detailed data and information would be available.

A general improvement of such analysis would be if every occurring natural event is recorded, categorised, localised, and stored in a database linked to the most accurate weather, soil, and lithology data possible. This will allow further analysis of the influence of hailstorms on torrential processes. Consequently, this would immensely contribute to the understanding of natural hazards in Austria in the future.

Declarations

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The authors have no relevant financial or non-financial interests to disclose.

Author Contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mario Schritter and Thomas Glade. The first draft of the manuscript was written by Mario Schritter and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Disclosure of potential conflicts of interest:

1. Not applicable, the authors have no relevant financial or non-financial interests to disclose.
2. Research involving human participants and/or animals:

Not applicable, no human participants and/or animals are examined

Informed consent:

Not applicable, as no human subjects were used for this study.

Credit author statement:

Mario Schritter: Conceptualisation, Methodology, Software, Data Curation, Writing - Original Draft

Thomas Glade: Validation, Resources, Supervision

References

1. Abancó C., Bennett G. L., Matthews A. J., Matera M. A. M. and Tan F. J. (2021): The role of geomorphology, rainfall and soil moisture in the occurrence of landslides triggered by 2018 Typhoon Mangkhut in the Philippines – Natural Hazards and Earth System Sciences 21 (5), 1531-1550.
2. Alcántara-Ayala I., López-García J. and Garnica R. J. (2012): On the landslide event in 2010 in the Monarch Butterfly Biosphere Reserve, Angangueo, Michoacán, Mexico. – Landslides 9, 263-273.
3. Andrecs p. and Hagen K. (2011): Dokumentation von Lockersedimentrutschungen – Voraussetzungen, Nutzen und praktische Erfahrungen – In: Skolaut C. (Ed.): Wildbach und Lawinenverbau - Zeitschrift für Wildbach-, Lawinen-, Erosion- und Steinschlagschutz 166, 226-237.

4. BFW (Austrian Research Centre for Forests) (Ed.) (2004): eBOD. Digitale Bodenkarte, online: https://bodenkarte.at/#/center/13.3458,47.7132 (accessed 26.10.2021).
5. BMLRT (Federal Ministry of Austria for Agriculture, Regions and Tourism) (Ed.) (2019): WLK.digital. Eventkataster. – Vienna.
6. Cruden D. M. and Varnes D. J. (1996): Landslide Types and Processes Landslides. – In: Cruden D. M. and Varnes D. J. (Eds.): Landslides: Investigation and Mitigation. – Special Report – Transportation Research Board 247, 36–75.
7. D'Agostino V., Cesca M. and Marchi L. (2009): Field and laboratory investigations of runout distances of debris flows in the Dolomites (Eastern Italian Alps). – Geomorphology 115 (3-4), 294-304.
8. Dikau R., Cavallin A. and Jäger S. (1996): Database and GIS for landslide research in Europe. – Geomorphology 15 (3-4), 227-239.
9. Fischer M. A., Oswald K. and Adler W. (2008): Exkursionsflora für Österreich, Liechtenstein und Südtirol. – Linz.
10. GBA (Geological Survey of Austria) (Ed.) (2015): Catalogue Geology of Austria 1: 500,000, online: https://www.data.gv.at/katalog/dataset/d31cf1a1-011e-44a6-9588-cc29126b3573 (accessed 26.10.2021).
11. Glade T. (2001): Landslide hazard assessment and historical landslide data - an inseparable couple? – In: Glade T., Albini P. and Frances F. (Eds.): The use of historical data in natural hazard assessments.- Advances of Technological and Natural Hazard Research – Kluwer, 153-168.
12. Guzzetti F., Cardinali M. and Reichenbach P. (1994): The AVI project: A bibliographical and archive inventory of landslides and floods in Italy – In: Environmental Management 18, 623–633.
13. Hübl J., Kienholz H. and Loipersberger A. (Ed.) (2002): DOMODIS - Documentation of mountain disasters. Schriftenreihe 1. Klagenfurt. (With contributions from: Balteanu D., Corominas J., Egli T., Glade T., Hegg C., Schrott L. and Sperling M.) – Klagenfurt.
14. Hungr O., Leroueil S. and Picarelli L. (2014): The Varnes classification of landslide types, an update. – Landslides 11, 167–194.
15. Jemec M. and Komac M. (2012): Impact of antecedent rainfall on shallow landslides. – In: Koboltschnig G., Hübl J. and Braun J. (Eds.): Interpraevent Conference Proceedings, International Research Society INTERPRAEVENT – Grenoble, 194-195.
16. Kuradusenge M., Kumaran S. and Zennaro M. (2020): Rainfall-Induced Landslide Prediction Using Machine Learning Models. The Case of Ngororero District, Rwanda. – International Journal of Environmental Research and Public Health 17 (11), 4147.
17. Mostbauer K., Kaitna R., Prenner D. and Hrachowitz M. (2018): The temporally varying roles of rainfall, snowmelt and soil moisture for debris flow initiation in a snow-dominated system. – Hydrology and Earth System Sciences 22, 3493-3513.
18. Naturgefahren (Leben mit Naturgefahren) (2021): Das Ereignisportal des digitalen Wildbach- und Lawinenkatasters, online: https://www.naturgefahren.at/karten/chronik/ereignisdoku/Ereignisportal.html (accessed 26.10.2021).

19. Navratil O., Liébault F., Bellot H., Travaglini E., Theule J., Chambon G. and Laigle D. (2013): High- frequency monitoring of debris-flow propagation along the Réal Torrent, Southern French Prealps. – Geomorphology 201, 157-171.
20. Nisi L., Hering A., Germann U., Schroeer K., Barras H., Kunz M. and Martius O. (2020): Hailstorms in the Alpine region: Diurnal cycle, 4D-characteristics, and the nowcasting potential of lightning properties. - Quarterly Journal of the Royal Meteorological Society 146 (733), 4170-4194.
21. Petschko H., Brenning A., Bell R., Goetz J. and Glade T. (2013): Assessing the quality of landslide susceptibility maps – case study Lower Austria. – In: Natural Hazards and Earth System Sciences 14 (1), 95-118.
22. Prenner D., Kaitna R., Mostbauer K. and Hrachowitz M. (2018): The Value of Using Multiple Hydrometeorological Variables to Predict Temporal Debris Flow Susceptibility in an Alpine Environment. – Water Resources Research 54, 6822-6843.
23. Prenner D., Hrachowitz M and Kaitna R. (2019): Trigger characteristics of torrential flows from high to low alpine regions in Austria. – Science of the Total Environment 658, 958-972.
24. Punge H.J., and Kunz M. (2016): Hail observations and hailstorm characteristics in Europe: A review. – Atmospheric Research 176-177, 159-184.
25. Rahardjo H., Nistor M.-M., Gofar N., Satyanaga A., Xiaosheng Q. and Yee S. I. C. (2019): Spatial distribution, variation and trend of five-day antecedent rainfall in Singapore. – Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 14 (3), 177-191.
26. Rimböck A., Barben M., Gruber H., Hübl J., Moser M., Rickenmann D., Schober S. and Schwaller G. (2013): OptiMeth - Beitrag zur optimalen Anwendung von Methoden zur Beschreibung von Wildbachprozessen. – In: International Research Society INTERPRAEVENT (Ed.): Schlussbericht 1 (3), 1-35.
27. Rubel F., Brugger K., Haslinger K. and Auer I. (2017): The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. – Meteorologische Zeitschrift 26 (2), 115-125.
28. Sebald J., Senf C., Heiser M., Scheidl C., Pflugmacher D. and Seidl R. (2019): The effects of forest cover and disturbance on torrential hazards: large-scale evidence from the Eastern Alps. – Environmental Research Letters 14 (11), 114032.
29. Sinatra T. and Nugroho G. A. (2018): Analysis of Heavy Rainfall with Hail using Reflectivity and Radial Velocity Derived from X-Band Radar in Bandung (Study Case: March 17, 2017). - IOP Conference Series: Earth and Environmental Science 166, 012039.
30. Suribabu C. R. and Sujatha E. R. (2019): Evaluation of Moisture Level Using Precipitation Indices as a Landslide Triggering Factor – A Study of Coonoor Hill Station. – Climate 7 (9), 111.
31. UBA (Federal Environment Agency Austria) (Ed.) (2004): Map 6: Location of the layers in the geological units, online: https://www.umweltbundesamt.at/fileadmin/site/themen/boden/boris/geologische_einheiten_referenzwerteband.pdf (accessed 26.10.2021).
32. Yamada I. (2016): Thiessen polygons. – International Encyclopedia of Geography: People, the Earth, Environment and Technology, 1-6.
33. ZAMG (Central Institute for Meteorology and Geodynamics) (Ed.) (2020): Measured values based on daily data from the 79 selected stations for the period from the start of each station until 02/14/2020 for the

parameter's precipitation amount – Vienna.
34. ZAMG (Central Institute for Meteorology and Geodynamics) (Ed.) (2021a): Yearbook, onlin https://www.zamg.ac.at/cms/de/klima/klimauebersichten/jahrbuch (accessed 26.10.2021).
35. ZAMG (Central Institute for Meteorology and Geodynamics) (Ed.) (2021b): Meteorological Network, online: https://www.zamg.ac.at/cms/de/klima/messnetze/wetterstationen (accessed 26.10.2021).
36. Zhao B., Dai Q., Han D., Dai H., Mao J. and Zhuo L. (2019): Probabilistic thresholds for landslides warning by integrating soil moisture conditions with rainfall thresholds. – Journal of Hydrology 574, 276-287.

Figures

Figure 1

Maps showing (a) Position of the ZAMG stations with Thiessen polygons in Austria. (b) 79 Thiessen polygons with ZAMG precipitation data.

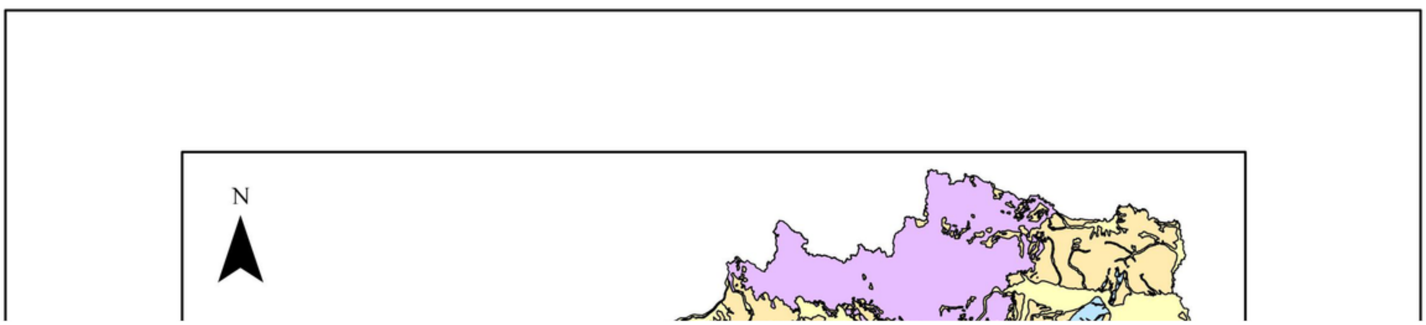

Figure 2

Map of the grouped lithological units in Austria.

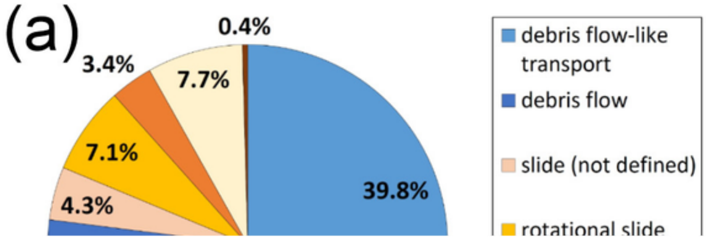

Figure 3

Pie charts showing (a) Landslides triggered by rain (n=465). (b) Landslides triggered by hail (n=142). (c) Bedload transport triggering precipitation types (n=974).

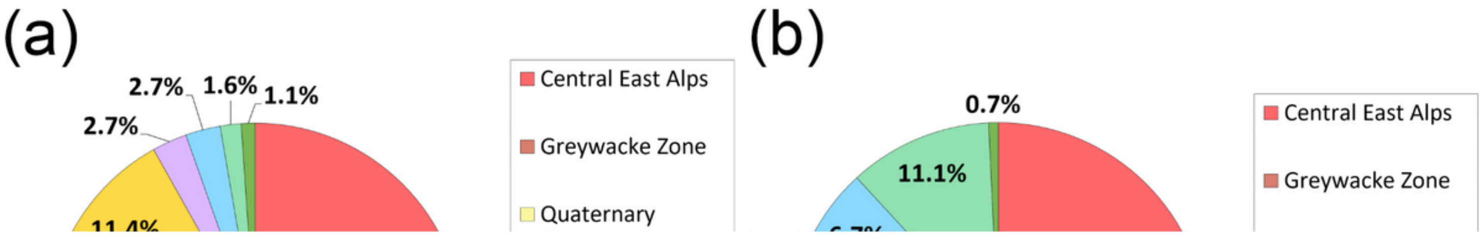

Figure 4

Pie charts showing (a) Bedload transports triggered by hail on predefined lithologies (n=185). (b) Debris flow-like relocation processes triggered by hail on predefined lithologies (n=135).

Figure 5

Line chart showing hail events that triggered bedload transport (n=185) and debris flow-like relocation processes (n=135) over predefined periods

Figure 6

Pie charts showing (a) precipitation types that indirectly triggered a bedload transport (n=179), (b) precipitation types that directly triggered a bedload transport (n=142), (c) percentage of bedload transports that were triggered directly or indirectly by hail events (n=75), (d) precipitation types that indirectly triggered a landslide (n=133), (e) precipitation types that directly triggered a landslide (n=54), and (f) percentage of landslides that were triggered directly or indirectly by hail events (n=52).