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Event documentation and analysis of mass wasting processes in the Gastein valley (Salzburg/Austria) in November 2019

Master's Thesis

For the fulfillment of the requirements for the degree of

Diplom-Ingenieur

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Vienna, February 21

Author's Declaration

Unless otherwise indicated in the text or references, or acknowledged above, this thesis is entirely the product of my own scholarly work. Any inaccuracies of fact or faults in reasoning are my own and accordingly I take full responsibility. This thesis has not been submitted in whole or part, for a degree at this or any other university or similar institution. This is to certify that the printed version is equivalent to the submitted electronic one.

Date Signature

Gratitude

First, I want to thank Prof. Roland Kaitna, for his great support as my supervisor. He supported my work with interest and great commitment. He was a reliable supervisor and communication and time management worked out well.

Second, I want to thank Markus Keuschnig and the GeoResearch team for their support. Thanks to Markus Keuschnig for the input in defining the topic and realizing the field work. Thanks to the GeoResearch team, which were great office colleagues during the time working on this thesis.

Then I want to thank Severin for his support during the first field trip, who supported me as driver, cook and friend.

At this point I want to thank also my study colleagues, who accompanied me through my studies at the University for Life Sciences and made them a great time.

Last, but not least I want to thank my parent for their support during the whole time and giving me this great opportunity for studying in this way.

Kurzfassung

Starke Unwetter mit massiven Niederschlägen führten im November 2019 zu zahlreichen Massenbewegungen, wie Murgängen und Hangrutschungen im östlichen Alpenraum. Unter anderem war auch das Gasteinertal schwer davon betroffen. Massenbewegungen sind im alpinen Raum keine Seltenheit und stellen seit jeher eine Gefahr für dortige Siedlungsgebiete und Infrastrukturen dar. Auch, oder gerade deshalb, ist es wichtig den Umgang mit solchen Gefahren ständig zu verbessern, um Risiko und Schäden zu minimieren. Um eine möglichst effiziente Gefahrenreduktion zu erreichen ist ein gutes Prozessverständnis und speziell der Auslösemechanismen notwendig. In dieser Masterarbeit werden wichtige Aspekte und Einflussgrößen, die für die Auslösung von Lockergesteinsrutschungen und Hangmuren eine Rolle spielen, identifiziert und quantifiziert. Die Analyse erfolgte anhand der Ereignisse vom November 2019 im Gasteinertal.Hierfür wurde zu Beginn eine detaillierte Ereignisdokumentation, basierend auf den zwei Ansätzen der Feldkartierung und Methoden der Fernerkundung, durchgeführt. Aufbauend auf dieser umfangreichen Datenbasis wurde eine quantitative Analyse der Massenbewegungen sowie deren Ursachen durchgeführt. In der Datenbeschaffung wurden neben Fernerkundungsdaten auch Ereignischroniken und unterschiedliche thematische Karten (geographische,- Landnutzung, etc.) miteinbezogen. Bei der Feldkartierung wurden dann detaillierte Informationen zu den einzelnen Anrissgebieten, wie die Beschaffenheit der Gleitfläche, Breiten- und Mächtigkeiten der Anrisse, genaue geografische Koordinaten sowie weitere Auffälligkeiten in der Umgebung aufgenommen. Somit konnten in der Analyse schließlich Häufigkeitsverteilungen und Instabilitätsindizes für unterschiedliche Parameter berechnet werden. Geotechnische Erklärungen sollten die statistischen Ergebnisse unterstützen. Starke Hangneigungen, Existenz geologisch vorhandener Gleitflächen und Material Verfügbarkeit konnten als natürliche Faktoren, Dispositionserhöhende Faktoren, identifiziert werden. Neben diesen, konnten jedoch auch ein anthropogener Einfluss auf Hangversagen festgestellt werden. Dieser zeichnete sich besonders im Einflussbereich von Forststraßen und Wanderwegen ab. Hangeinschnitte, die mit der Konstruktion von Forststraßen einhergehen zeigten eine deutliche Häufung von Lockergesteinsrutschungen. Bei einer detaillierteren Analyse konnte festgestellt werden, dass einerseits ungünstig angelegte Hangneigung der Böschungen und künstlich geschaffene Geländekanten ein Problem darstellen. Andererseits zeigten Forststraßen und Wanderwege auch einen starken Einfluss auf die Hanghydrologie. Mithilfe dieser Erkenntnisse konnten am Ende Anregungen zur Verbesserung in Forststraßenbau und – Erhaltung abgegeben werden.

Abstract

Heavy storm events in November 2019 led to numerous landslides and hillslope debris flows in within wide areas of the eastern alps, including areas like the Gastein Valley which has also been hit dramatically. Settlements in alpine areas have always been endangered by such mass movements and had to deal with its consequences. Making targeted risk reduction strategies and mitigation measures requires detailed knowledge about the processes themselves. By a deepening of the information on the release mechanism of the hillside debris flows and landslides, this study is expected to contribute to the reaction triggered by intense rainfalls, as it was the case in November 2019. The aim is therefore to provide identification and quantification of the critical parameters which increase the slopes' susceptibility towards such mass movements. Subsequently detailed event documentation is needed, followed by a quantitative analysis performance. For the event documentation, a combined approach both of a desk study and field mapping is applied, in order to overcome the respective disadvantages of both methods, and thus deliver the best possible data base. Within the desk study remote sensing data, landslide inventories and various thematic maps (geographical, land-use, etc.) are examined. The field mapping aims to collect detailed information about the release areas and their circumstances including sliding plane characteristics, size, coordinates, special artifacts in their environment and type of mass movement. For the quantitative analysis the frequency distribution and instability index for different parameters are calculated. To support the findings geotechnical explanations and detailed qualitative analysis of some examples are elaborated. Finally, within this thesis, not only the natural disposition-favouring parameters as high slope inclination, material availability and layered soil structure can be identified, but also a significant impact of artificially excavated slopes due to forest roads and hiking trails could be identified. Crucial factors linked with forest roads are inclination and condition of their cut- and fill slopes, as is their impact on water channelling and runoff. These findings enable recommendations for forest road construction and maintenance measures to reduce landslide risk within this context.

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1. Introduction

In November 2019 heavy rain- and snowfall events dominated wide parts in the southern regions of Austria and led to a series of damaging mass movements such as shallow landslides hillslope debris flows and debris flows. Amongst others also the Gastein valley was hit dramatically by this special weather conditions, leading to numerous mass wasting processes that covered large parts of the valley floor with mud and debris. During the event several houses were evacuated, roads and railway tracks were closed and in the community of Bad Gastein two houses were destroyed by a landslide (ZAMG, 2020). Figure 1 gives some impressions of the consequences and damages that occurred in the Gastein valley in November 2019. Picture (b) and (c) show the devastating landslide in Bad Gastein. Picture (a) and (b) give an impression on the numerous hillslope debris flows being released along the hiking trail “Gasteiner Höhenweg”. Picture (d) shows the largest slides in the Anger valley and (f) a house in Bad Hofgastein which was close to being hit by the mud and debris.

Figure 1: Impression of the events in the Gastein valley - (a) Faschingberg, (b) Bad Bruck, (c) Bad Bruck, (d) Angertal, (e) Faschingberg, (f) Bad Hofgastein (photo: Robert Delleske, Markus Keuschnig, Forest Engineering Service of the Torrent and Avalanche Control (WLV), regional office Salzburg)

The event in November 2019 does not describe an isolated problem in alpine areas. Due to their geomorphic and topographic setting alpine areas have always been prone to various natural hazards including hillslope and torrent processes. In recent years, extreme weather situations led to damaging mass wasting processes with increasing impact on residential areas (Fuchs, Röthlisberger, Thaler, Zischg, & Keiler, 2017).

This increased risk towards mass movements may have several reasons. On the one hand global warming may enhance extreme weather events and thus, increase the magnitude and frequency of such mass movements (Gariano & Guzzetti, 2016; Huggel, Clague, & Korup, 2012). Several studies tried to quantify the effects of climate change and landslide abundance and magnitude (Gariano & Guzzetti, 2016). On the other hand, human land-use is changing. More and more residential and industrial infrastructure has been built in high-risk areas. Hence humans have to deal with an increasing vulnerability towards such mass movements (Fuchs et al., 2017).

Consequently, it became more and more important to deal with such processes and reduce damage. Many efforts were taken in improving mitigation and risk reduction towards natural hazards by implementing different measures (Bründl, 2009; FOEN, 2016). For a targeted risk reduction strategy and the design of optimal mitigation measures not only event documentation itself but also further process understanding plays an important role. Several studies tried to examine the influence of different parameters on mass movement processes. Moser (1971) examined the influence of different lithological circumstances on the release and development of mass movement processes in Carinthia. More recent studies dealt with the potential impact of different parameters such as forest, vegetation, slope inclinations and height above sea level (Rickli, Zimmerli, & Züricher Kaspar, 2000; Tilch, Haberler, & Kociu, 2017a; Tilch, Haberler, & Kociu, 2017b). For all parameters, some correlation with the release of parameters could be stated, even though they differ in significance. Fan et al. (2016) examined the influence of soil spatial variability and spatial organization of initial water content on the susceptibility towards landslides and found out that both have an impact on initiation time and volume of landslides. In literature also the anthropogenic impact is mentioned as influencing parameter, as change of land-use and infrastructural constructions may have a destabilizing impact on slopes (Prinz & Strauß, 2011; Schwarz, Tilch, & Kociu, 2007; Wemple, Swanson, & Jones, 2001) . This study is supposed to contribute to further understanding of process and release mechanism with its potential impact factors. Therefore, release areas of the landslides in the Gastein valley, triggered by the heavy rainfall events in November 2019 are analysed and key factors for slope destabilization are identified.

2. Aim and scope of the study

The study aims to systematically document the landslide events that occurred between November 12th and November 17th in the Gastein valley, Austria. Besides reconstruction of meteorological conditions, special focus is given to the impact of anthropogenic structures, especially forest roads and hiking trails on the release of mass movements. Further it is supposed to analyse the geotechnical aspects of road impact on hillslope stability and to formulate recommendations for future road construction and maintenance.

The specific research questions are be listed as follows:

1. What meteorological conditions led to the landslide events? Which are the dominating geomorphologic processes during the event?
2. Is there a spatial pattern of release areas? Are their distinct topographic characteristics defining the locations of mass movements initiation?
3. Is it possible to quantify the impact of anthropogenic infrastructure on slope stability? What parameters play a key role?
4. What engineering improvements can be recommended to increase the resilience for society to deal with and reduce the risk in future?

For the elaboration of these questions, the Gastein valley offers a useful study site, as there were many landslides and debris flows triggered by the same meteorological event. This delivers a representative sample of events showing the same circumstances and thus facilitates quantitative analysis.

3. Process classification

In nature, there exists a wide variation of mass movement processes in mountain regions. For classification, processes can be distinguished by a set of criteria as velocity and mechanism of movement, material involved, mode of deformation, geometry of the moving mass and water content. Internationally, several authors have suggested different classification schemes (Hungr, Evans, Bovis, & Hutchinson, 2001; Selby, 1993). The current study refers to the Austrian Standards ONR, 24800. Here, mass movement processes in mountain regions are classified into:

Fluvial processes, which describe mass movement under the influence of water and are either bounded on the depth contour of a stream channel or its flooding areas. These processes also include all torrential processes. Within this study all processes bounded on a stream channel or torrent will be summarised under the term *debris flow*. There will be no differentiation by the proportion of water to soil involved in the process.

Gravitational processes, which describe mass movement or mass wasting soil processes, that in general can be defined as the downslope movement of soil and rocks under the influence of gravity on a sliding surface including some kind of shear deformations. There are basically no other transport media needed, even though they often may be involved and play a supportive role, as does water by reducing shear strength. All hillslope processes without any binding to a depth contour are included here (Bründl, 2009; FOEN, 2016; Prinz & Strauß, 2011; Selby, 1993).

This study focuses on hillslope processes. Often the terms *soil/debris slides, landslides and shallow landslides* are used synonymously (in German referred to as "*Oberflächennahe Rutschung, Lockergesteinsrutschung*"). Here, the general term landslide is used. The process is characterised by slope stability failure due to an abrupt loss of shear strength, as will be described in more detail in the chapter 4.1. Landslides cover a wide range of size and volume. Their sliding plane can show different characteristics, i.e. it may be shallow or deep, show a planar or a rotational form and be formed of granular soil or bedrock. After initiation, slides may also travel with different velocities (Glade, Tilch, & Kociu, 2020b). The mass and material moved consists of loose rock and granular soil.

Prinz & Strauß (2011) describe five possible mechanism of movement:

Fall: describes an abrupt detachment of rocks or boulders from the potential release area, mostly steep walls or clips leading to free falling, bouncing or rolling of the material. There is almost no shearing involved. (see Figure 2/1)

Topple: describes a rotational movement of boulders out of steep walls, depending on the joints and discontinuities. (see Figure 2/2)

Slide: is the downward movement of rocks or soil on sliding plans. Sliding includes a distinct sheer zone. (see Figure 2/3)

Spread (drift): describes an extension of cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads may result from liquefication or flow of the softer material. (see Figure 2/4)

Flow: describes a spatially continuous movement. Thereby shear surfaces are short lived and usually not preserved after the event. Its velocity distribution is similar to the one of a viscous fluid. (see Figure 2/5)

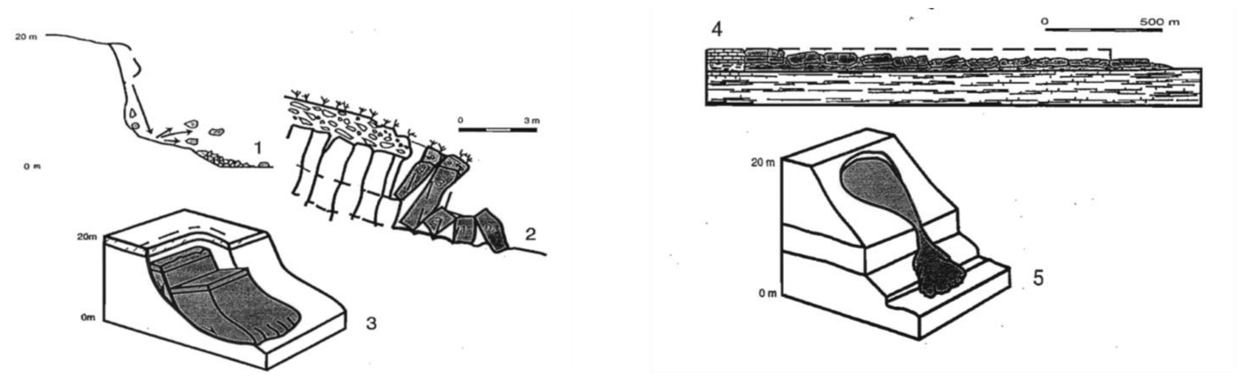


Figure 2: Types of mass wasting soil -process mechanism (1) fall, (2) topple, (3) slide, (4) spread (drift) (5) flow (The Canadian geotechnical Society, 1993)

The flowing process hereinafter is referred to as *hillslope debris flow* (German term used is “Hangmure”) and describes a second phase in process development (see also chapter 4.1*)* (Glade et al., 2020b). Hillslope debris flow describes the flow of loose rock and soil under the influence of water. They develop on rather steep slopes with soils of low permeability (i.e. quaternary formations (*Quartärbildungen*), slope wash (*Gehängelehm*), clayey moraines (*tonige Moränen*)). The development of hillslope debris flows is often associated with high water-content, i.e. after intense rainfall or snow melting. They reach rather high velocities, i.e. 10m/s (Bründl, 2009; FOEN, 2016). Increased water content and velocity in general leads to an increased length of the displaced mass (Bollinger, Kreusen, Rovina, Wildberger, & Wyss, 2004). In this study the events reported are denoted landslide or hillslope debris flow dependent on their transit length. Figure 3 shows some examples from the Gastein valley for the relevant processes.

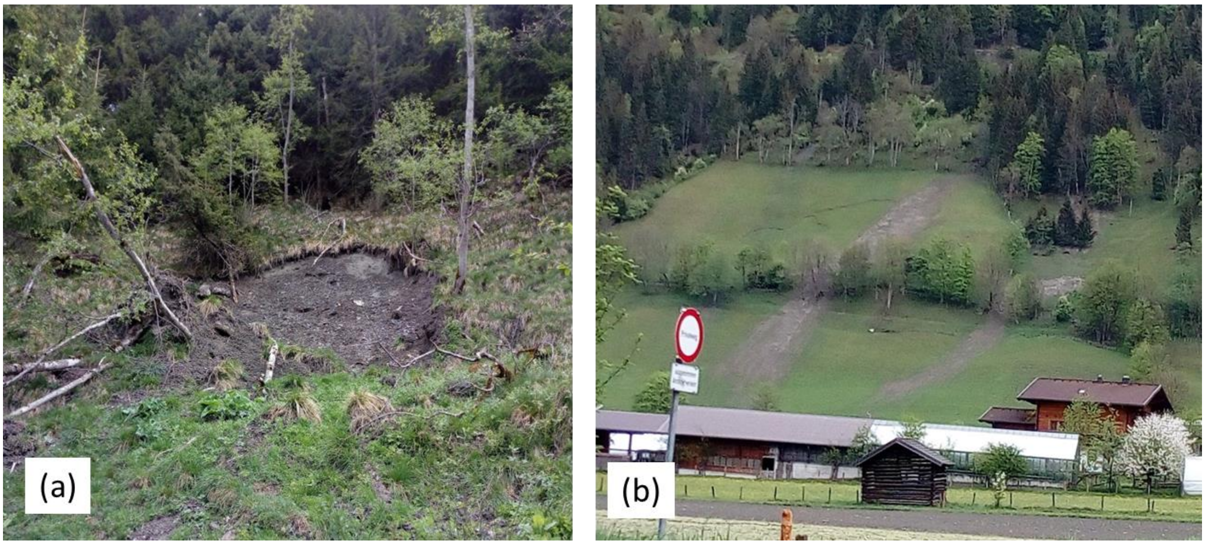


Figure 3: Examples from the Gastein valley for (a) landslide (left hand-side) and (b) a hillslope debris flow (right hand-side) - photo: Magdalena Pescoller

4. Geotechnical basics for slope stability and impact factors

4.1. Model for the release mechanism of translational landslides

Slope stability is based on the force equilibrium between the sum of resisting forces and the sum of driving forces. In literature known as Factor of safety F (see Eq. 1).

$$F = \frac{sum\ of\ resisting\ forces}{sum\ of\ driving\ forces} = \frac{\tau_f}{\tau} \qquad (1)$$

Is F < 1, the slope is in a condition of failure. Both, the resisting forces and the driving forces are dependent on various factors. For translational landslides a two-dimensional model is used to calculate forces and the critical state. A mobile slice rests on a slope with constant angle. The forces acting on a point on the shear plane are illustrated in Figure 4 (Prinz & Strauß, 2011; Selby, 1993).

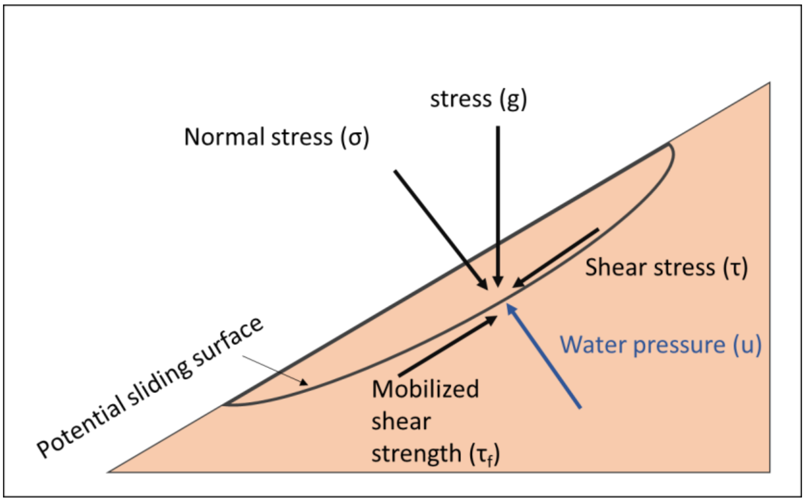


Figure 4: Hillslope stability analysis - Forces acting at a point on a potential failure plane adapted from (Selby, 1993)

The shear stress acts down the slope and is resisted by the mobilized effective shear strength of the soil. The threshold to slope failure is given by the Coulomb criterion (Eq. 2):

$$\tau_f = (\sigma_n - u) * tan\varphi' + c' \qquad (2)$$

τ_f … shear strength at any point in the soil, determined by:

σ_n …the normal stress imposed by the weight of solids and water above the point of soil

u…the pore water pressure derived from the unit weight of water and the piezometric head

φ'…the angle of friction with respect to effective stresses and

c'…the effective cohesion

The slope reaches critical state as soon as the shear stress overwhelms the critical shear strength (Iverson, 1997; Selby, 1993). Once triggered, the debris landslide may develop in different ways depending on given circumstances. Abundant water content enforces transformation in a more widespread deformation, that can be defined as a hillslope debris flow, as mentioned earlier. Indeed, slope failures as explained, accounts for one of the most important release mechanism of hillslope debris flow (Iverson, 1997; Rickli et al., 2000).

4.2. Impact factors and the concept of disposition

Both, driving and resisting forces are influenced by several factors. They either increase shear stress or have a decreasing impact on shear strength (Selby, 1993). Impact factors differ in their time scale, i.e. they may decrease shear strength for decades by changing for example soil structure or they may only lead to a short term increase in shear stress by high water infiltration and thus reduction in cohesion (Selby, 1993). According to the time scale Zimmermann et al. (1997) gives the following definition of terms:

Basic Disposition: describes the general susceptibility towards mass movements on a long-time scale, i.e. years, decades, etc. Factors characterizing the disposition of an area, are recognized as stable for a long period of time. The main factors are the geology/ lithology and the material availability, the hydrogeology and the topography describing slope inclination, morphology etc. (see also Figure 5).

Variable disposition: describes a more short-term variation in the susceptibility towards mass movements and depends mostly on hydrometeorological variables which change within days to weeks and influence stability of granular soil and rocks. Those variables define the so called “pre-event conditions”. Some also show cyclical or seasonal variations (examples are displayed in Figure 5).

Trigger: is the short-term sudden stress on a system which finally triggers the mass movement. In the Austrian alps mostly meteorological and hydrological events induce mass movements. Such events can be either short convective precipitation and thunderstorms with high intensity or longer lasting precipitation periods. Intense Snow- and ice melting may also act as trigger.

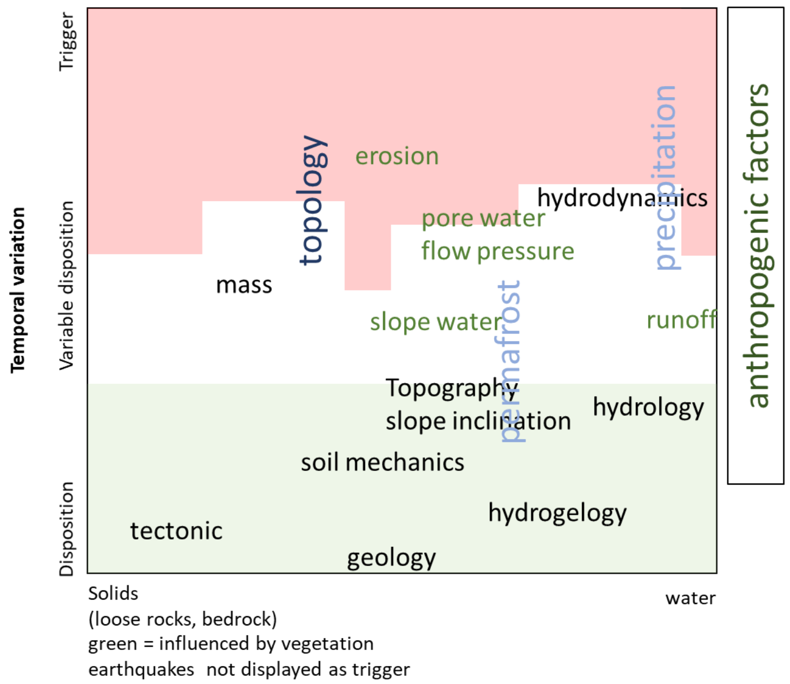


Figure 5: Factors influencing mass mobilization/ landslides → modified after (Bollinger et al., 2004)

The shallower the landslide, the more the upper impact factors in Figure 5 function as trigger. Changes in slope water, runoff or flow pressure have a more distinct impact on the near-surface stability of slopes than on deeper layers (Bollinger et al., 2004). An introduction to the main factors, being concerned when analysing landslide releases is given below:

Terrain and topography: basic disposition

This intends basically the slope inclination, exposition and the morphology (Rickli, 2001). For the most critical slope inclinations concerning landslides the literature presents values ranging from 30°-40°. Under 20° and above 50° landslides are very rare. Hence, above 50° it is assumed that material availability is not given due to constant denudation (Moser, 1997). Morphologically past studies show that especially slightly concave slopes (zero order basins), slope terraces and natural or artificial breaks in slopes show a higher possibility of slope failure (Aleotti, Baldelli, & Polloni G., 1996; Hübl, 2000; Moser, 1997). All of those terrain factors are rather stable and long lasting and thus define the basic disposition. Nevertheless, changes in slope steepness or height may occur. They are caused by different sources such as water erosion at the toe slope or human activity, which then may change the susceptibility towards landslides significantly (Prinz & Strauß, 2011). No significant difference can be reported considering slope exposition, even though a slightly higher landslide activity on south faced slopes is mentioned. This is the case when the slope consists of mostly loose material where freeze-thaw processes have an important impact (Prinz & Strauß, 2011; Ruff, Kühn, & Czurda, 2009).

Soil/Geology: basic disposition

Another long -term factor is the geology and soil conditions in the region. Hereby the important parameters are the resistance of soil, influenced by cohesion and angle of friction, the permeability and the weathering. Generally, grain size and distribution are the main characteristics defining cohesion, angle of friction and also permeability and weathering. Soil permeability is of special interest for the development of sliding planes, which often follow the boundary from a permeable layer to a non-permeable layer (Moser, 1997; Rickli, 2001). Geologically disposition varies depending on the lithological composition, but especially on the structural geology i.e. the dipping of joints, faults and geological layers in relation to the falling of the slope.

Vegetation: basic disposition - variable disposition

Another important impact factor on susceptibility of slopes towards land sliding is the vegetation. In comparison to the factors mentioned before, vegetation has a more differentiated impact which may also vary on a shorter timescale, thus not only affecting ground disposition but also variable disposition. Depending on the type of vegetation, its structure and condition, it may have positive or negative impact on slope stability. Vegetation influences soil structure and as consequence water infiltration. It may either reduce water infiltration through interception and thus stabilize, or enhance water infiltration through building cracks by death roots, which decreases stability. Another important effect of vegetation is reinforcement by the roots. This reinforcement is further dependent on the structure of forest, the depth of roots and the soil conditions (Moos et al., 2016; Rickli et al., 2000; Rickli, 2001). The impact of vegetation often shows seasonality depending on the biological cycle and thus influences variable disposition (Prinz & Strauß, 2011).

Water impact: variable disposition – trigger

Water plays a key role not only as trigger but also when it comes to increasing variable disposition. Depending on water input through meteorological and hydrological circumstances it may increase weight on a given point through water saturation. Furthermore, it may reduce shear strength by increasing pore water pressure (Rickli, 2001). This as a consequence enables slope failure already at a smaller external load (Prinz & Strauß, 2011). The runoff on saturated soil and given flow paths on non-permeable layers enhance mass movements further by acting as downward moving force (Lehmann & Or, 2012).

Meteorology and hydrology: variable disposition – trigger

As already mentioned, water impact is driven by meteorological and hydrological aspects, as they define water availability to a certain extend. In meteorological terms precipitation rate, intensity, duration but also the form of precipitation, i.e. if it falls in form of rain or snow, plays an important role as it affects water availability, rain erosion, soil saturation, etc. On the other hand, hydrology determines runoff rates and paths. Meteorological events in the European Alps account for the most important trigger when it comes to landslides and flows as several studies of such events show (Aleotti et al., 1996; Moser, 1971; Rickli, 2001; Schwarz et al., 2007; Tilch et al., 2017a; Wemple et al., 2001). Indeed intense and prolonged rainfall lead to a rapid increase in soil water content and trigger abrupt movement of soil (Lehmann & Or, 2012).

Anthropogenic impact: basic disposition – variable disposition – trigger

On most of the above described factors, human being can have an impact due to artificial modifications of the environment, as described in literature (Bollinger et al., 2004). According to Prinz & Strauß (2011) the two main factors – slope inclination and water impact – are modified by human activity, i.e. infrastructural constructions within hillslopes, soil sealing in general, etc. The general impact on landcover and land-use by humans influences water paths and disposition towards mass movements by changing vegetation and soil structure (ex. Meadows, managed forests, etc.). Moreover, soil sealing in general affects disposition as it modifies the water impact by preventing natural infiltration. Case studies show that especially road networks may affect hillslope stability since they trigger shallow landslides (Schwarz et al., 2007; Tilch et al., 2017a). The geotechnical impact of roads on hillslopes is discussed in more detail in the following chapter.

4.3. Road network and its interaction with mass movements

A road network includes different types of roads – from highways to forest roads and hiking trails. In this thesis the focus will be set on forest roads and hiking trails, as they show great interaction with mass movements and are prominent on steeper slopes in the investigation area.

4.3.1. Forest roads

Figure 6 shows a typical cross section of a forest road for sloping sites. It gives an overview on the components involved.

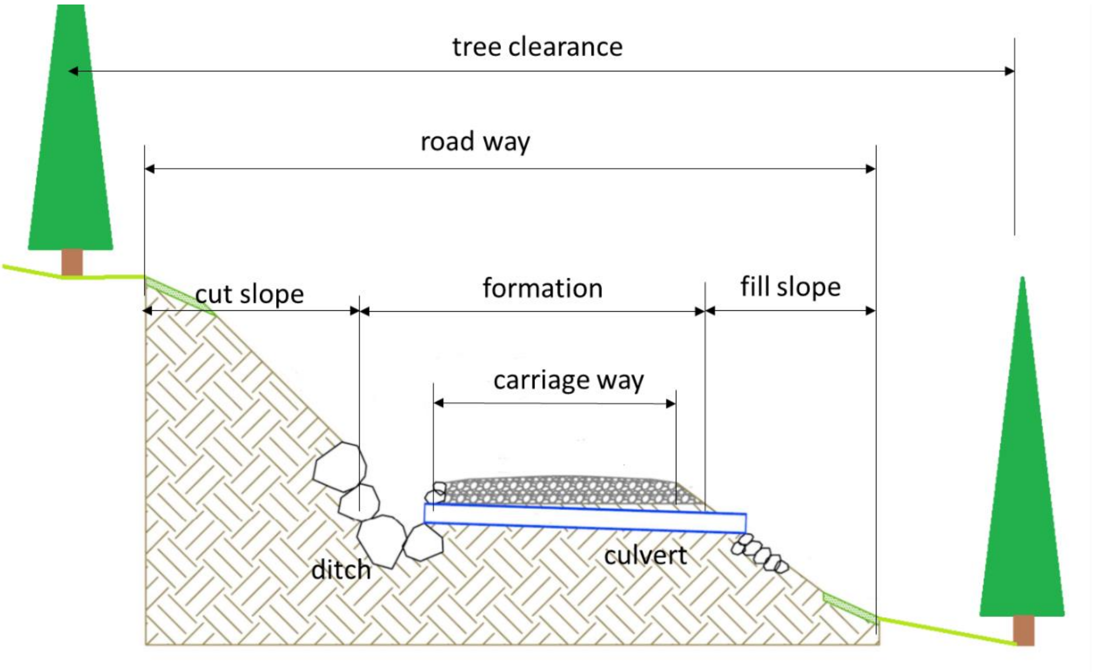


Figure 6: Typical cross section of a forest road adapted from (Ryan, Phillips, Ramsay, & Dempsey, 2004)

The following items will be of deeper interest when it comes to interaction with mass movements, and will hence be described in detail according to Ryan et al. (2004):

Tree Clearance

Tree clearance defines the distance at which trees have to be cut for forest road construction. In the Forest road Manual by Ryan et al. (2004) a minimum of 15m is given.

Road way

The road way includes the area between the extreme limits of earthwork, i.e. in a side hill construction reaching from the edge of the excavated section to the toe of the fill section, thus including the cut slope, the formation and the fill slope.

Formation

The formation includes the area between the usable limits of earthwork, i.e. in a side hill construction reaching from the toe of the excavated section to the top of the edge of a fill section, thus including the road surface and any roadside drains.

Carriage way (road surface)

The carriage way includes the area of formation, strengthened for the passage of vehicles. The carriage way is supposed to be curved in its cross-sectional profile (camber) to aid water runoff.

Water management elements

Surface runoff has a major impact on soil erosion and thus weaking of forest road structure. Hence several features for effective water drainage are necessary. Channels for removal of excess water have to be provided longitudinal (parallel to forest road) and horizontal.

For longitudinal water removal roadside drains (ditches) are implemented. Roadside drains basically describe the angle between the toe of the slope cutting and the edge of the cambered formation. Depending on water availability they may vary in depth.

Horizontal water drainage systems can either be above ground or underground. Examples for above ground constructions are simple earth hollows/gullys (in German: "*Erdmulden*") or transversal ruts (in German: "*Querrinnen*") (Kuonen, 1983). Underground culverts of different sizes enable drainage of run-off from uplands and the periodic removal of run-off from the formation itself.

4.3.2. Geotechnical aspects considering roads and slope stability

According to the different elements described, a road network can have various impacts on the stability (Figure 7). A landslide may either be triggered within the road way or be intersected and reinforced by the road way through different elements. A special role may be taken by the water management elements (Wemple et al., 2001).

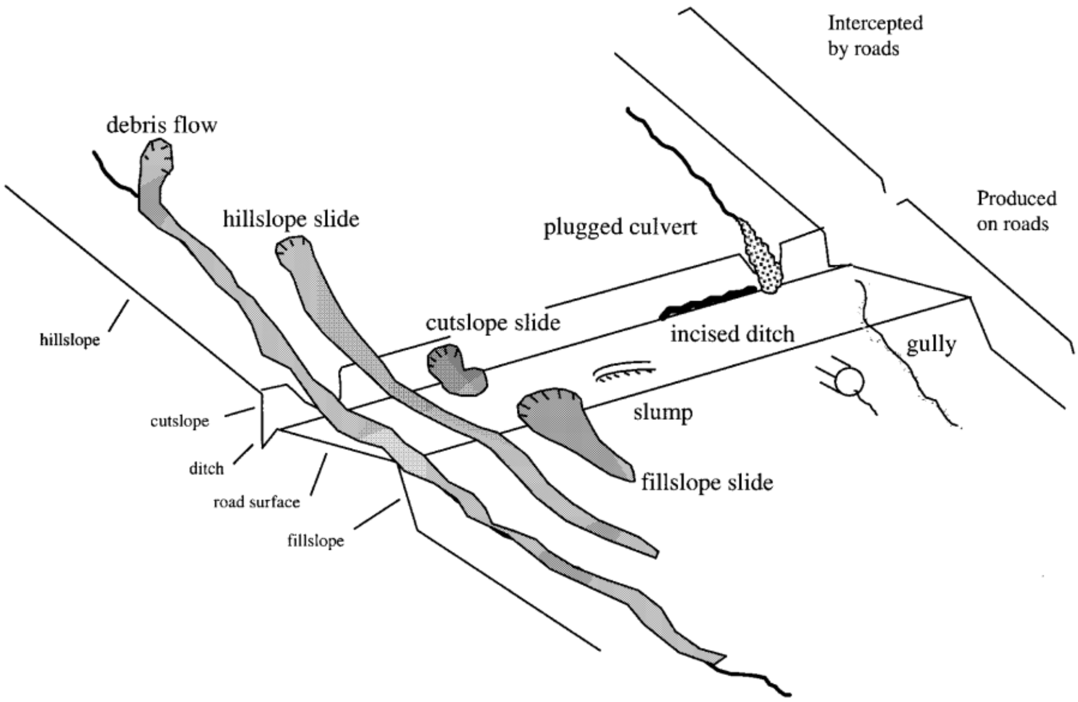


Figure 7: Typology of erosional and depositional features produced by mass-wasting and fluvial processes and associated with forest roads adapted by (Wemple et al., 2001)

Roads cutting a hillslope can lead to problems increasing the disposition towards mass movements:

Change of slope inclination - Prinz & Strauß (2011) identify the change of slope inclination as one of the most critical aspects for increasing disposition towards shallow landslides. Slope inclination may be increased as soon as hillsides are cut by roads. Furthermore, such cuts often mean a removal of toe slope and thus reducing lateral support which consequently increases shear stress (Selby, 1993). In Figure 7 this type of failure is sketched as cut slope or fill slope slide.

Routing of sediments – A forest road may either act as sediment storage for material transported down the slope or as sediment production and even increase the mobilised soil. Sediment production is mainly caused by water erosion. In their study Wemple et.al (2001) found out, that erosion and thus sediment production on roads in general exceeds sediment deposition. The sediment routing effect of forest roads is no triggering aspect but may become important for entrainment and thus size development of landslides.

Routing of water – Concerning the road network plugged culverts, incised ditches and gullies from roads change water paths distinctively (Wemple et al., 2001). Concentrated water inflow may than trigger slope failure. The process of water routing by road drainage and the following impact on slope stability is also described by Montgomery (1994). To mention an example of negative effects, road surfaces enforce hortonian overland flow, which for soil mantled hillslopes in humid regions is generally untypical. Consequently, overland flow increases erosion and thus enables triggering of shallow landslides. For more detail see also the extract on *Water impact* in chapter 4.2.

Generally, the explained problems also account for hiking trails cutting slopes. Hence, within this thesis hiking trails are dealt with, in the same way as forest roads.

5. Study site

5.1. Gastein valley

The study site covers most of the Gastein Valley, which is situated in the western part of Austria in the county Salzburg. Aiming a good representativity of the study (Rickli et al., 2000), events throughout the whole valley beginning from Dorfgastein and reaching into the Kötschach valley are included. In total this led to an initial investigation area of 330 km², which finally was reduced to 173m³ in further analysis, as large areas lie in highly alpine zones not relevant for the research questions. Figure 8 shows the extensions of the investigation area with the relevant sections and gives an overview on its location.

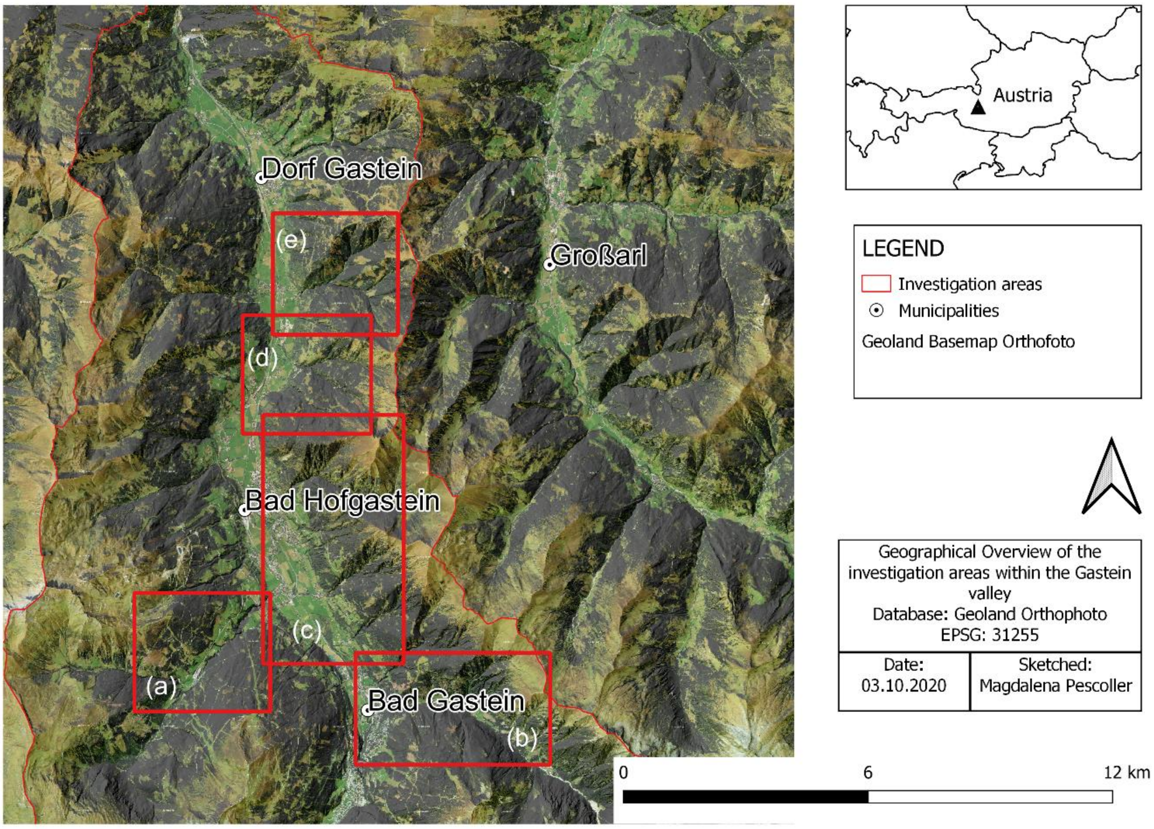


Figure 8: Geographical overview of the investigation area and geographical sections relevant for this thesis, (a) Angertal, (b) Bad Bruck and Kötschach valley, (c) Faschingberg and Bad Hofgastein – Gasteiner Höhenweg, (d) Laderding, (e) Harbach valley and Dorf Gastein (QGIS)

5.1.1. Geography and Geomorphology

The Gastein Valley is part of the district St.Johann im Pongau and from northern side reachable via the Klammtunnel near Lend. The valley then stretches north- to south for around 40km until it ends in the Hohen Tauern, bordering Carinthia. In the end the valley splits up in the Kötschach valley (west) and from Böckstein (east) in the Anlauf valley and the Naßfelder valley (Bergfex GmbH, 2020; Bundesamt für Eich- und Vermessungswesen) . The valley floor lies at around 800m a.sl. in Dorfgastein and reaches 1500m a.sl. in Sportgastein (Nassfelder Hochebene) (Lafenthaler, 2007) .

On the west side the Gastein valley is separated from the Rauris valley by the Goldberg group, a mountain chain reaching heights over 3000m. On the east side the Ankogel group is separating the Gastein valley from the Großarl valley, including mountains reaching altitudes over 3000 m.a.sl especially towards the valley head also on this side.

As most alpine valleys, the Gastein valley was covered by ice in the last glacial period (Würm 115.000-11.700 b.p. (Geolgische Bundesanstalt)). Until 14.500 b.p. the ice shield reached the valley floor in Bad Gastein (Land Salzburg, 2020). Moraines from this time still can be found and were mapped by Exner (1956b). He indicates moraine material widely spread over the lower parts of the valley slopes (see also Figure 9). This results in the existence of loose material and rock debris. A distinct identification of the source of material was partly difficult due to intense vegetation covering the slopes. Additionally, in the course of time many large block- and rockslides covered the valley floor and make differentiation between rock slide material and moraine material even more complex (Exner, 1956a). After the retreat of the ice, the valley floor was covered by 100 meters of debris, granular soil and sand by the river systems. Nowadays, many settlements are situated on alluvial fans (Lafenthaler, 2007). Independent from its origin, the slopes around the Gastein valley offer abundant coarse material for mass waste processes.

The valley floor can be described as a flat plane. Slopes of different inclinations form the surrounding mountainous chains. The orographic right-hand side is steeper with inclinations up to 45°, while inclinations on the western valley side are mostly under 30°, as shown in Figure 18 in chapter 7.4*.*

This can be partly explained by the structural geology as there is a general NE dipping throughout the valley (Exner, 1956b). This results in an “in-dipping” on the west-facing slopes and an “out-dipping” on the east-facing slopes.

Inclinations are a first order control for the disposition towards mass movements as discussed in chapter 4.2. Hence, one may expect an increased susceptibility towards mass movements on the right hand-side of the valley.

5.1.2. Geology and Hydrogeology

Geologically the Gastein valley is dominated by the so called Tauern- Window. The Tauern-Window is located between the Brenner and the Katschberg and has a length of 160km (W-E extension). In North- South direction its extension reaches 30-60km. It includes the mountain groups of the Zillertaler Alps, the Tuxer Alps and the Hohe Tauern (Nationalpark Hohe Tauern; Pestal, 2009).

Geologically the Tauern – Window exposes the underlying penninic system with its nappe subsystems. Geologists further differentiate between the subpenninic system, where the Venediger nappe system and the Eklogit zone belong to, and the penninic system which contains the Glockner- nappe system and the Matreier Schuppenzone- Nordrahmenzone. While the Venediger nappes system is based on highly metamorphic central gneiss, the penninic nappe systems are characterized by mica slate and calcareous phyllites (known as "*Bündnerschiefer*") (Pestal, 2009).

The valley itself in the southern part is situated between the Hochalm-Ankogel group and the Sonnblick-core. Both, being part of the Venediger-nappe system and thus being based on granite gneiss. These two gneiss massifs are separated by the Mallnitzer Mulde belonging to the pennincum and lithologically being built up of mostly slate and phyllite. In addition to the Mallnitzer Mulde some other cross depressions are characterising the geology of the Gastein valley. Another important depression is the Gasteiner Mulde, which is separating the Hochalm-Ankogel massif in the Stiglitzlappen and the Hölltorkern. The northern part of the valley is completely dominated by the slate cover (Penninicum) of the Hohe Tauern window, thus lithologically characterised by slates and phyllites (Exner, 1956a). Figure 9 shows an extract of the geological map, including the most interesting part of the investigation area, i.e. the region between Bad Hofgastein and Bad Gastein.

Generally, the rocks are intensively faulted, show several shear zones and fractures and tectonic mixed zones. Hence groundwater flows through pores, joints and karst. Permeability may differ throughout the valley (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2003; Land Salzburg, 2020). From a hydrogeological point of view the thermal springs at the end of the valley in Bad Gastein may be mentioned as interesting point, as also their origin is still not completely known (Lafenthaler, 2007).

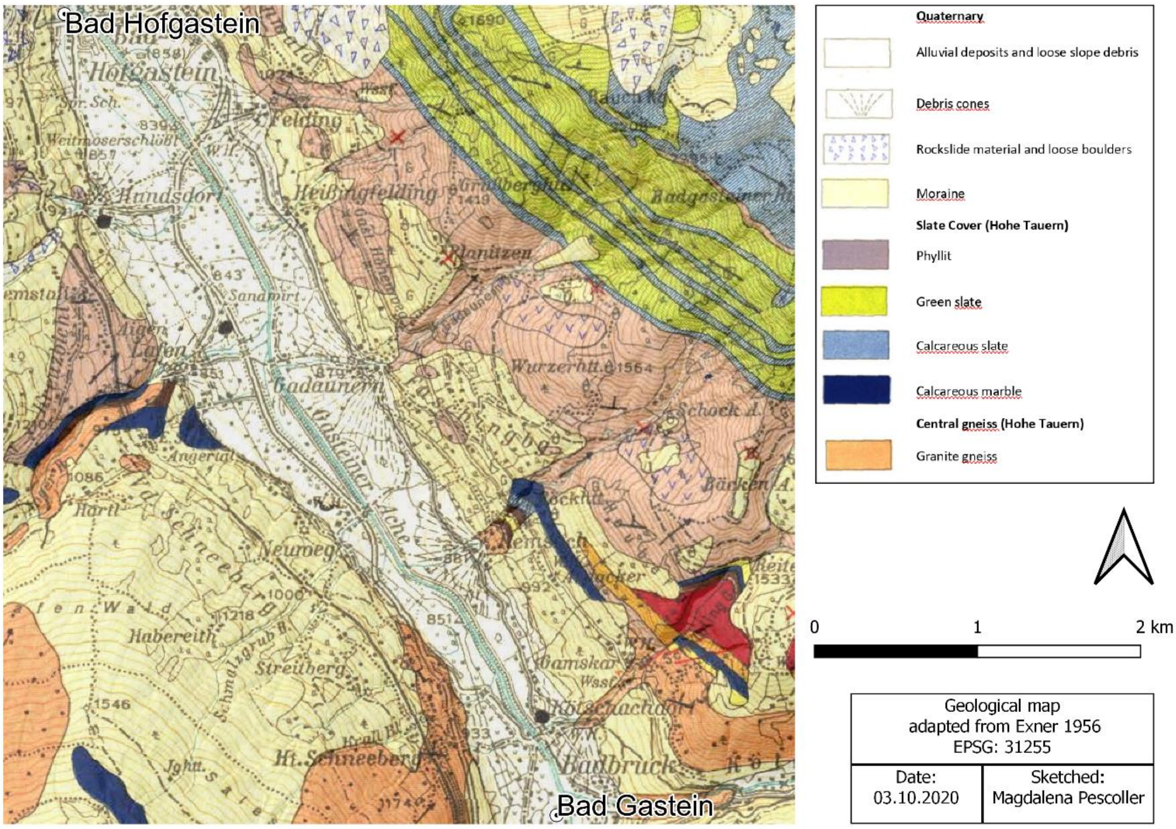


Figure 9: Extract of the Geological map, sketched by Exner (1956)

5.1.3. Vegetation and land use

The Gastein valley includes different climatic and thus different vegetational zones. The timber-line is between 1700-1900. The valley floor is strongly dominated by human land-use, i.e. residential and industrial area. Large regions are also used as meadows and farmland (Lafenthaler, 2007).

Moving upwards the slopes, meadows and farmland are replaced by forests. The forests are strongly dominated by spruces. With increasing altitude, pines and larches become more frequent (Lafenthaler, 2007). Large parts of the forests are managed forest land and thus also rather densely developed by forest roads. The Gastein valley has a forest-road network of 330km. Several parts of the forest are denominated as protection forest, especially in higher regions (Land Salzburg, 2020). Parts of the forest areas show severe problems with bark beetles, weakening the forests and reducing its protective force (Fanninger, 2020, personal communication). Above the timber-line characteristic alpine and high alpine vegetation dominates, i.e. grass and scrub until it continues with rocks only. As mountain tourism destination, the Gastein valley is also characterised by many skiing areas and several hiking trails (Lafenthaler, 2007).

The lower slope parts are mostly covered with a rather deep layer of brown earth. The valley floor is characterised by intensive grassland (in German: “*intensives Grünland*”) based on rather deep layers of pseudogley and fluvial sediment (in German: “*Ausedimente*”). At higher altitudes extensive grassland (in German: “*extensives Grünland*”) dominates, also based on a layer of pseudogley (alpine pseudogley) and colluvial sediment (in German: “*Lockersediment*”) (Land Salzburg, 2020).

These layers of loose sediment show a good water permeability. Waterlogging can be observed in several areas as reported in the inventory of soil condition by the province of Salzburg (See Appendix 6 - Pt. 503154).

5.1.4. Natural hazards

As an alpine valley, the Gastein valley is prone towards several types of mass movements. The events analysed within this thesis do not represent the first time that the civilisation in the Gastein valley experiences damages, as data from hazard inventories and witness reports confirms (Bundesministerium Landwirtschaft, Regionen und Tourismus, 2021; Land Salzburg, 2020). Examples of long-lasting mass movements are the deep-seated landslide of the Graukogel (Ebner, Oktober, 2013) and the rockfall activity of the Ingelsberg (Lafenthaler, 2007). The most recent bigger debris-flow event was triggered by heavy storms in July 2016. A huge amount of glacial sediments was transported from the Tischlerkar into the valley and caused damage to settlements (ZAMG, 2016).

But not only such large hazards endanger settlements and infrastructure in the Gastein valley. There are also many smaller landslides and hillslope debris flows periodically endangering areas in the Gastein valley (Land Salzburg, 2020). Thus, besides historical documentation a hazard zone plan for the valley exists. A comparison of past hillslope slides and the events from November, 2019 shows that similar sections were endangered (for the map and detailed interpretation see Figure 39 in chapter 8).

6. Methodology

The approach in this study is based on a broad data acquisition to enable quantitative analysis. The events and release areas are partly detected in field research, partly in a detailed "desk study" taking into account several types of data sources.

6.1. Data sources

For preparation of the field trip and the analysis afterwards, several sources were available. A summarizing list of the data sources used follows:

<u>Sources used for mass movement detection within the desk study:</u>

Satellite Imagery:

- Plante Scope (18/11/19 and 10/04/20)
  - Further processed into:
    - Orthophoto and Hillshade (PlanetScope 18/11/19)
    - Calculation of NDVI for all images
- Sentinel 2 (26/10/19)

UAS-data (Georesearch Forschungsgesellschaft mbH – Robert Delleske):

- Orthophotos with a resolution of 5x5cm

Witness reports/Landslide inventory:

- Forest authority Salzburg – damages on forest roads reported (W. Fanninger)
- Forest engineering service of the Torrent and Avalanche Control (WLV), regional office Salzburg:
  - field documentation in April (Bad Hofgastein)
  - SAGIS – landslide inventory
- Interview with local residents (A. Winkler)

Sources used for describing the investigation area and parameter analysis:

Webmaps:

- Geological map (GEOFAST)
- SentinelHub (false colour, NDVI)
- Geoland map layers (open street, …)
- Bergfex OSM
- Quick OSM (QGIS -Plugin)
    - Landuse Dorfgastein, Bad Hofgastein, Bad Gastein
    - Road network Dorfgastein, Bad Hofgastein, Bad Gastein

Landslide inventory:

- WLV – Wildbach und Lawinenverbauung
    - SAGIS – Hazard zonation plan

UAS-data (Georesearch Forschungsgesellschaft mbH – Robert Delleske):

- DGM (5x5m) of defined areas
    - Further processed into:
        - Contour lines
        - Inclination map

Sources used for meteorological event reconstruction:

Meteorological data– 01.10.2019-30.11.2019:

- ZAMG: daily perception rates (Bad Gastein, Rauris, St. Johann)
- ZAMG: perception rates in minutes (Bad Gastein, Rauris, St. Johann)
- ZAMG: Amount of fresh snow for the above-mentioned stations
- ZAMG: Temperature measurements for the given period

6.2. Regional assessment – preparation work for the field trip

The initial screening of the region was done by using the orthophoto from the 11/08/19 as shown in Figure 10. Additionally, the UAS data available for defined regions was considered to get an even better impression of the events (see Figure 10). The aim was to predefine areas where landslides occurred so as to serve as an orientational support in organising the field mapping.

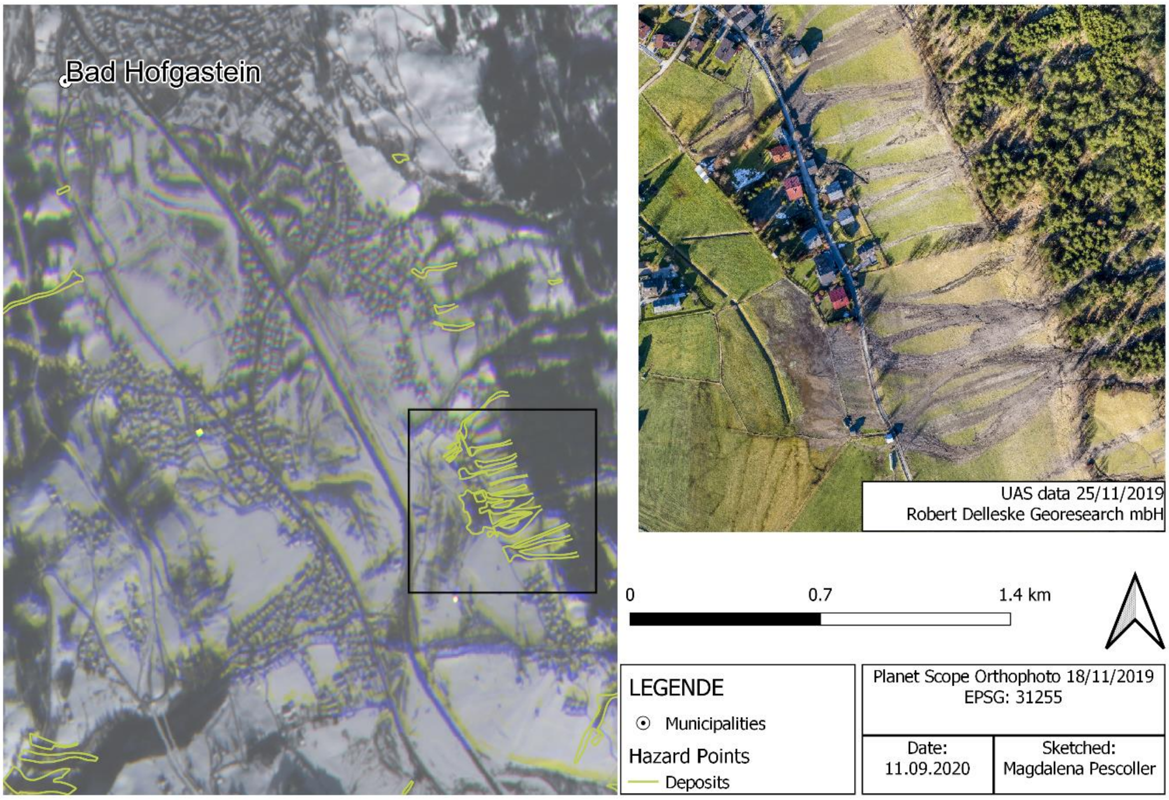


Figure 10: Database for the initial screening

For an effective orthophoto screening, parameters for landslide identification were defined. As the ground was snow covered, the deposits were distinguishable easily by their colour and shape. Table 1, in chapter 6.4 shows the parameters defined. Additionally, to the hazard point identification the outline boundaries for the study site were set. As for quantitative analysis, representativity increases with the increasing number of data (Rickli et al., 2000) the whole Gastein valley from Dorfgastein into the Kötschach valley was included.

For the field trip a framework sheet was prepared defining the attributes for documentation (see Figure 11). The field notes can be found in the Appendix 1-2.

Data-form: Field mapping Gastein Date:

ID	Coordinates	Rupture width	Rupture depth	Sliding plane	Notes

Figure 11: Guidelines for the field trip

6.3. Field Work

To obtain more detailed information on the type of mass movement and visual characteristics of the events, field work is necessary (CNR, 2014). During field work, the hazard points identified during preparation work were reached on foot. As the key interest of the study are release areas, the aim during field mapping was to localize release areas rather than transit or deposit areas.

Event documentation increases in complexity with time after the event due to vegetation growth and human reparation work (Tilch, 2019). Therefore, field visits in general should be performed the soonest possible date after an events occurrence.

For this study the first field trip could only take place between the 04^{th} of May and the 08^{th} of May:

For systematic investigation of the release areas, the Gastein valley was split into geographical sections, which were observed according to the following timeline (for an overview on the investigation sections see Figure 8 in chapter 5.1:

04/05/2020 Investigation of the “Gasteiner Höhenweg”, starting from the “Faschingberg” out towards Bad Hofgastein, the “Faschingberg” itself and the “Gasteiner Höhenweg” in the other direction – until Ramsach

05/05/2020 Investigation of the events in the Anger valley, the big event in Bad Bruck and the events above Laderding

06/05/2020 Investigation around Dorf Gastein and the Harbach valley

08/05/2020 Investigation of the Kötschach valley

The mapping was conducted analogically, based on the prepared framework (see Figure 11 in chapter 6.1). The geographical coordinates were taken with a Garmin GPS handheld device. For the other parameters the following instruments were used: Markierstock, TruePulse 360 – for measuring distances and a mobile phone (Huawaii) to take pictures.

The target of the visits was to fill the gaps within the framework as completely as possible with proper information. Under the point “Notes”, especially information on water conditions and neighbouring infrastructure was noted. Additionally, there were taken at least 4 pictures each, for documentation. They include an overview of the release area (a), a detailed shot of the sliding plane (b), a shot in downwards direction to document the transit area (c) and a picture documenting the surrounding area (d). Figure 12 shows an example of 4 pictures taken for a specified release area:

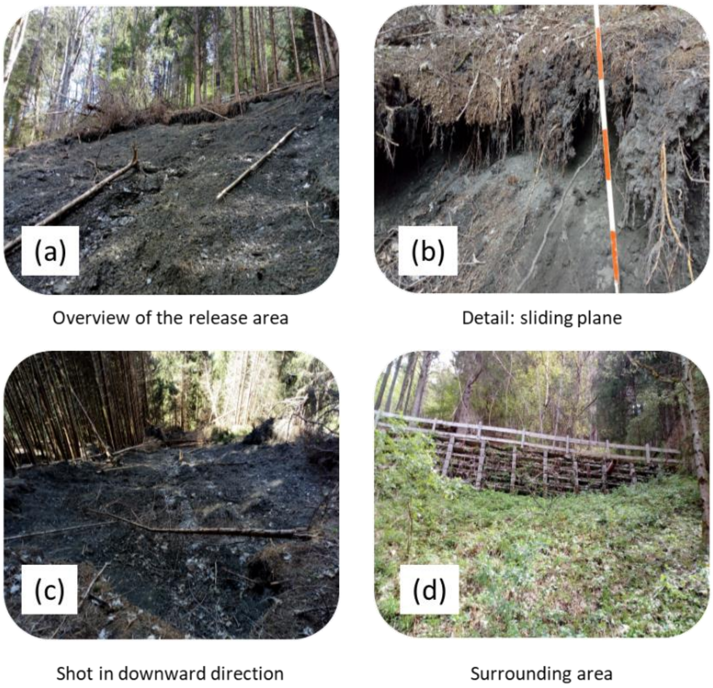


Figure 12: Field work - Example for pictures taken (photo: Magdalena Pescoller)

A second field trip was organised between the 10th and the 11th of June. In preparation for this field trip a more intense desk study (described in chapter 6.4) preceded. Within the second field trip the focus was set on information from local experts and verification of hazard point information received from landslide inventories and witness reports by the WLV Salzburg and the Forest authority St. Johann i. Pongau. Therefore, a meeting with W. Fanninger (responsible forest inspector for the district) was organised on June, 10th. The meeting consisted of an inspection of spots where damage on forest streets has been reported. General information about forest street construction and problems in maintenance were discussed.

On June 11th another field work day followed for gathering some more detailed information about selected spots. For documentation the software Qfield (tablet) was used.

6.4. Post processing and data analysis

After the field trip data post processing and analysis followed. Beforehand the data collected in the field was merged with data from landslide inventories provided by the WLV, Salzburg and the forest authorities St. Johann i. Pongau. In addition to this data collection another more detailed visual interpretation of the aerial photography data was conducted. Basically “fresh” landslides are easily distinguishable from their surroundings as they show characteristic patterns and distinct boundaries towards unaffected areas (CNR, 2014). On the one hand the data from landslide inventories was verified and specified (information on location and surroundings), on the other hand additional spots were identified. Table 1 gives an overview on the parameters used in landslide identification.

As landslide areas are usually bare or covered by disturbed material, the NDVI (normalized difference vegetation index) was calculated based on the available orthophotos, to support photo interpretation (Liu, Wong, Huang, & Yang, 2002). The NDVI is usually used for quantifying green vegetation and based on the different absorption of Near-Infrared and Red wavelengths by chlorophylls (Sentinel-Hub). For landslide areas a NDVI-value between 0 and -0,3 is given (Liu et al., 2002).

In this study it was useful, as sections affected by landslides and hillslope debris flows show significantly less vegetation as their surroundings in the begin of April (See Figure 13)

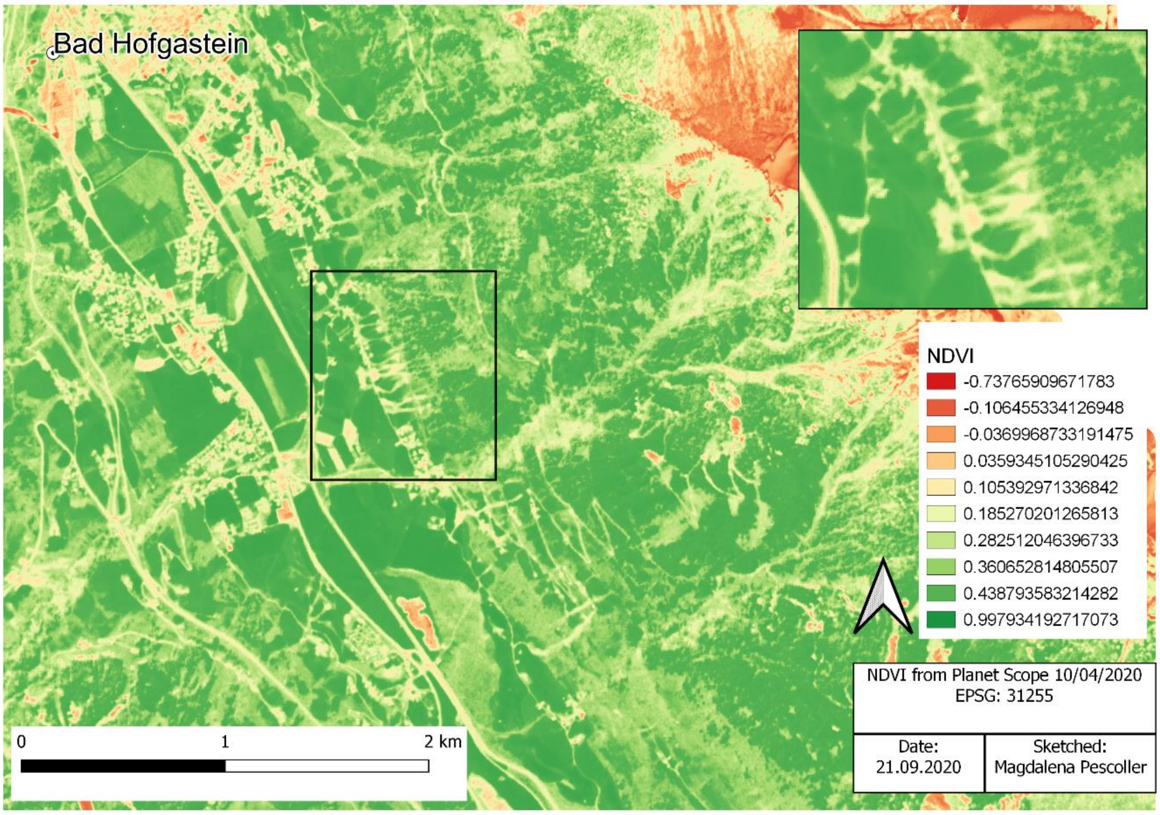


Figure 13: NDVI Calculation for mass movement detection (Planet Scope 10/04/20)

Comparing the NDVI calculation from April 2020 with one from October 2019 (pre- event) shows an even more distinct image of sections being affected by debris flows.

Table 1: parameters for photo interpretation adapted from (Liu et al., 2002)

Orthophoto	
Parameter	*Likely characteristics*
Colour	Black on white font
Shape	Lenticular, spoon-like, tree-like pattern
Shadow	
Position	
Direction	Long axis along direction of gravity
NDVI	
Parameter	*Likely characteristics*
Colour	Yellow, brownish, red -orange
Shape	Lenticular, spoon-like, tree-like pattern
Shadow	
Position	
Direction	Long axis along direction of gravity

According to the information available for each event, they were classified by different attributes. For classification the software QGIS and Excel were used.

Depending on the source of information of release areas, data depth varied, which reduced statistical population for some attributes.

First, the data was classified by attributes relevant to process identification. Hence it has been distinguished by hillslope processes (no interaction with stream channel) and torrent processes (bounded on torrent stream channel). Further the sliding plane and the size of the release areas were classified. Table 2 shows the classes used for each attribute, characterising the process itself.

Table 2: Characteristics of release areas

Type	Sliding plane	Width of rupture	Depth of rupture
1…hillslope process	1…Loose material	1...< 5m	1...turf (<20cm)
2…torrent process	2…Bed rock	2...5m - 15m	2... 20cm – 60cm
		3...15m - 25m	3… 60cm – 100cm
		4…25m - 35m	4… 100cm – 140cm
		5…> 35m	5… 140cm – 180cm
			6…> 180cm

Secondly, natural attributes relevant for disposition (basic – and variable) were classified and analysed. The geological classes were defined according to Exner (1956b). Elevation and Inclination classes were adapted to the topography of the Gastein valley. The classes defined are listed in Table 3.

Table 3: Natural attributes relevant for the disposition towards mass movement

Elevation	Inclination	Geology
< 900 m.a.sl.	< 20°	Phyllit
900 – 1000 m.a.sl	20°-25°	Moraine
1000 – 1100 m.a.sl.	25°-30°	Slate cover
1100 – 1200 m.a.sl.	30°-35°	Granite gneiss
200 – 1300 m.a.sl.	35°-40°	Rockslide material and boulders
1300 – 1400 m.a.sl.	40°-45°	Calcareous slate
> 1400 m.a.sl	>45°	

To analyse the anthropogenic impact on release areas, the land-use and road network in the Gastein valley were analysed. Based on the field mapping, information about the influence of land-use on release areas has been available. General land-use information on the Gastein valley was retrieved from Quick OSM (QGIS – Plugin). To merge information, a classification system fitting both input data sets was necessary.

For classification the six major classes used for land-use from LISA (Land Information System Austria) served as basis. They include: residential area (in German. "*Siedlung*"), traffic/Road System (in German. "*Verkehr*"), agricultural areas (in German: "*Landwirtschaft*"), forest (in German: "*Forst*", whereas within this class also natural woods are included), natural and semi-natural areas (in German: “*Natürliche/naturnahe Flächen*”) and waterbodies (“Wasser”) (Banko, Grillmayer, Ortner, & Perger, 2010). Out of these six classes, four relevant classes for this thesis were defined:

- Residential area + Traffic/Road System
- Agricultural area
- Forest
- Natural and semi-natural areas

For simplification, in a first step classes including only proportionally irrelevant area size (< 0,5km²) were excluded from the Quick OSM data base. The remaining classes were summarized and assigned to one of the four predefined classes as shown in Table 4.This enabled area calculation for land-use analysis.

Based on the notes from field mapping, also each release area could be assigned to one of the four classes.

Table 4: Land-use classification

Land-use classes from Quick OSM		**Land-use classes (adapted from LISA)**
Commercial Industrial Residential Railway	→	Residential and Infrastructure
Farmyard Meadow	→	Agricultural areas
Forest	→	Forest
Scrub Grass grassland	→	Near-natural areas

In a second step a more specified analysis with a focus on the road network only was conducted by introducing the attribute “road impact – yes/no”, similar to studies by Tilch (2013) and Schwarz et al. (2007). This allowed then further statistical analysis of the release areas documented during field mapping.

Regarding the road network an additional layer from Quick OSM was integrated in the QGIS Project. The layer included the road network as line segments, also with information on the type of road (i.e. forest road, hiking trail, highway, etc.). To consider the fact, that the extend of the impact area of roads exceeds the road itself (see Figure 7), buffering was applied. Buffering implies a tool in GIS applications to create polygons surrounding other polygons, lines or points. The so called “Buffer zone” can vary in size and is defined by the buffering distance.

By buffering, a realistic impact area for the road network could be calculated. To find the best fitting buffer size 3 option have been tested:

- Buffer 10m
- Buffer 25m
- Buffer 50m

(Calculations with QGIS)

Each buffer was compared with the located release areas of mass movements, where information about road impact was available. This comparison shows that for a buffer of 25m, 93,2% of the located release areas for which the road network was identified as impact factor lied within the buffer. For a buffer of 10m the percentage fitting is already reduced to 80%. While inclusion within the buffer of hazard points, which during field mapping were identified as independent from road network, remains the same for these two buffers, but increases significantly with a buffer of 50m. Hence a buffer of 25m is used for further calculations. Table 5 gives an overview on the absolute numbers of fit.

Table 5: Absolut numbers of fit between field mapping and buffering (QGIS) regarding the attribute: road impact

	Field mapping	**Buffer 10m**	**Buffer 25m**	**Buffer 50m**
Road impact	n= 44	missing n= 10	missing n= 3	missing n= 0
No road impact	n= 35 + 15	wrongly within the buffer n=7	wrongly within the buffer n=7	wrongly within the buffer n=18

The numbers in the column “Field mapping” here include hillslope (n =35) and torrent processes (n =15), whereas those events with road impact can be defined as hillslope processes only. For further statistical analysis hillslope processes only are seen as relevant, as for debris flows the trigger impact of forest roads is negligible.

For analysis a frequency distribution based on the absolute numbers from field mapping and the classifications according to above listed parameters, was calculated. Regarding land-use, additionally to frequency distribution of the four classes listed in Table 4, the “road impact” was considered separately.

To relate the frequency distribution of hazard points to the general distribution of respective classes within the investigation area the instability index I as described by Schwarz et al. (2007) was calculated with:

$$I = GR\ (\%)/GS\ (\%) \qquad (3)$$

with

GR…being the proportion of mass movements with a specific parameter (for ex. neighbouring forest road) in relation to the total amount of mass movements documented, for ex. the sum of all mass movements being triggered under the influence of forest roads in relation to the sum of all mass movements in general.

GS…being the proportion of area of respective parameter in relation to the area of the whole investigation area, for ex. the sum of the area taken by forest roads in relation to the total investigation area.

An instability index > 1 indicates that the defined parameter (for ex. neighbouring forest road) is found above average within the documented mass movements. This indicates that the parameter may favour the release of mass movements. An instability index < 1 indicates that the parameter has no impact on triggering mass movements.

An example is given for explanation:

An investigation area has 100km². Thereof 60km² are used as meadows. This gives a GS of 60/100 → 0.60. Within this investigation area 100 landslides were counted. Thereof 70 landslides were released within meadows. This gives a GR of 70/100 → 0.70.

Finally, an Instability Index of 0.70/0.60 → 1.67 is calculated. As 1.67 > 1 it may be assumed that meadows enforce the release of landslides.

In this thesis the instability index was calculated for all of the land-use classes defined above as well as for the road network, where the GS was defined based on the area covered by the 25m buffer.

After quantitative analysis, failure mechanism and road interaction were analysed in more detail. Due to varying information depth of identified release areas not for all a qualitative analysis of failure mechanism was possible. According to the problems described in chapter 4.3.2 the possible impact of forest roads on landslides can be summarized as displayed in Table 6.

Table 6: Forest road impact on the initiation and development of landslides (Montgomery, 1994; Wemple et al., 2001)

Impact	**Cause - process**	**Effects**
Increased disposition	by changing slope inclination and formation of artificial terrain edges through excavation	➔ Cut slope slide ➔ Fill slope slide
Trigger factors	Water routing through malfunctioning of water management elements and changed slope morphology	➔ Plugged culverts ➔ Overland flow ➔ Gullies/ earth hollows ➔ Incised ditches
Impact on entrainment and development	Sediment routing – through missing vegetation, availability of loose material	➔ Sediment production/ erosion ➔ Sediment deposition

This table serves as guideline for single event analysis and final identification of critical aspects in the case of the Gastein valley. This finally enables the discussion of possible mitigation measures and improvement possibilities concerning forest road construction.

7. Results

In total for this thesis 125 release areas of landslides and hillslope debris flows were documented within the Gastein valley. Note that, this means no claim on completeness regarding all events that may be occurred during the storm events. Out of the 125 events, 67 events were documented within the field work. 15 release areas were identified within the desk study. The remaining events were partly reported by the WLV, Salzburg (14) and partly by the forest authority of St.Johann im Pongau (29). These different sources led to different populations depending on the parameter examined. For 97 events a detailed parameter analysis could be carried out.

7.1. Meteorological circumstances and variable disposition

The mass movements in the Gastein valley were triggered by the heavy precipitation. Between November, 12th and November, 17th a series of three heavy rainfall events took place. For this study the precipitation data from the ZAMG precipitation station in Bad Gastein (1.092 m.a.sl.) on a daily resolution was analysed and combined with data about snow height and temperature measured at the same station.

In detail we speak about three events following each other within five days (Figure 14). The first rainfall event occurred on November, 12th, with a daily precipitation amount of 52,5 mm. As snow height measured at the station Bad Gastein increased (Figure 15), most of the precipitation must have been fallen as snow. Temperature close to zero supports the notion of a mixture between snow and rainfall. On November, 15th the second heavy rainfall event followed with 71,9 mm. A small increase in recorded snow height (marked in dark blue in Figure 15) indicates again a mixture between rain and snow. The temperatures by that date confirm the assumption. The third intense rainfall event followed two days later on November 17th, with 74,7 mm. As there is no raise of snow height it can be assumed that it mostly fell as rain. Concerning the chronic for storms from the ZAMG Webpage the snow line between the 12th and the 18th of November varies between 750 m.a.sl. and 1100 m.a.sl. As for November 12th, heavy snow fall even for Zell am See (750m.a.sl) was reported and for the 17th up to Bad Gastein heavy rainfall was documented. In total between November 11th and November 17th, 253,7 mm of precipitation were documented.

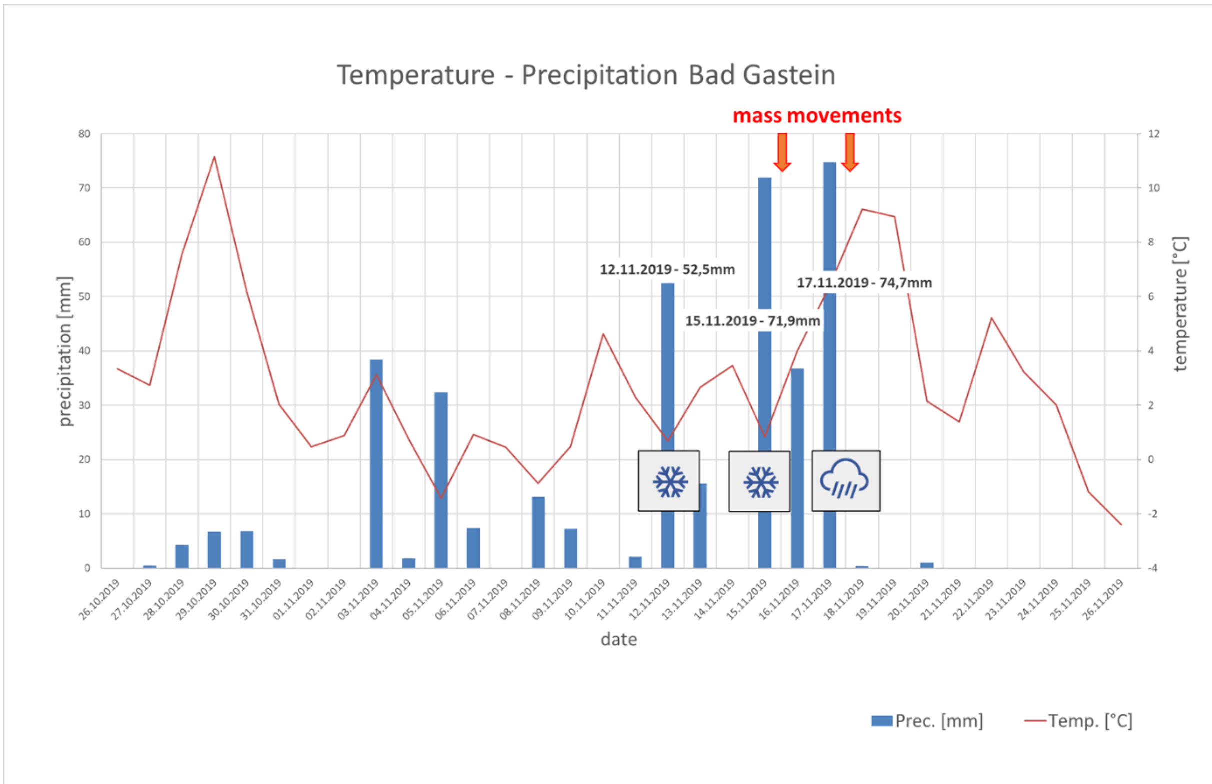


Figure 14: temperature and precipitation measured at the Station in Bad Gastein (1029m.a.sl.) (ZAMG, 2019-2019; ZAMG, 2020)

This series of precipitation events led to numerous landslides and hillslope debris flows causing severe damage within communities in the valley. Red arrows in Figure 14 mark the time sections where mass movements occurred according to the chronic of mass movements provided by the ZAMG (2020).

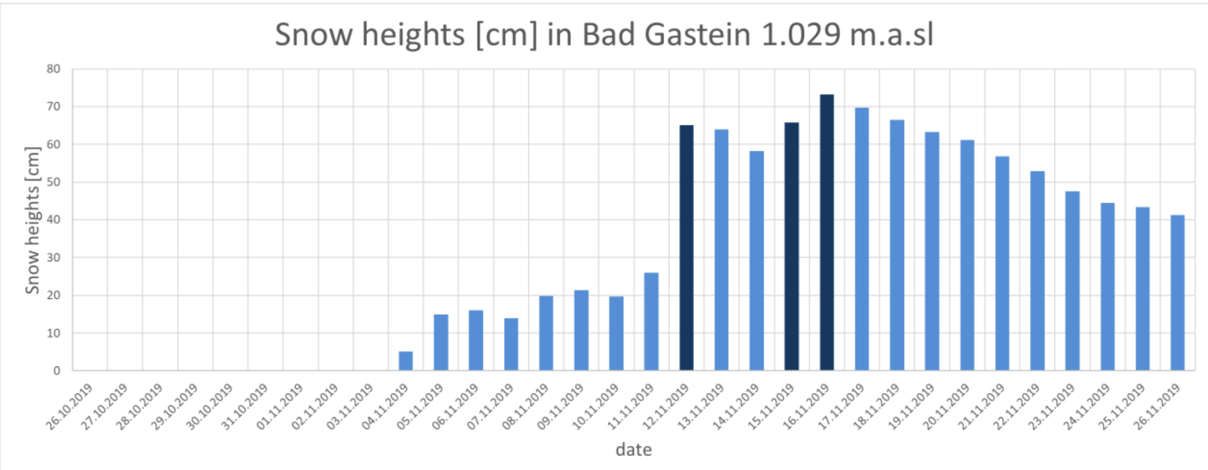


Figure 15: Development of snow heights during the weather event in November 2019, at the station Bad Gastein – 1029 m.a.sl. (ZAMG, 2019-2019)

7.2. Geographical distribution of release areas

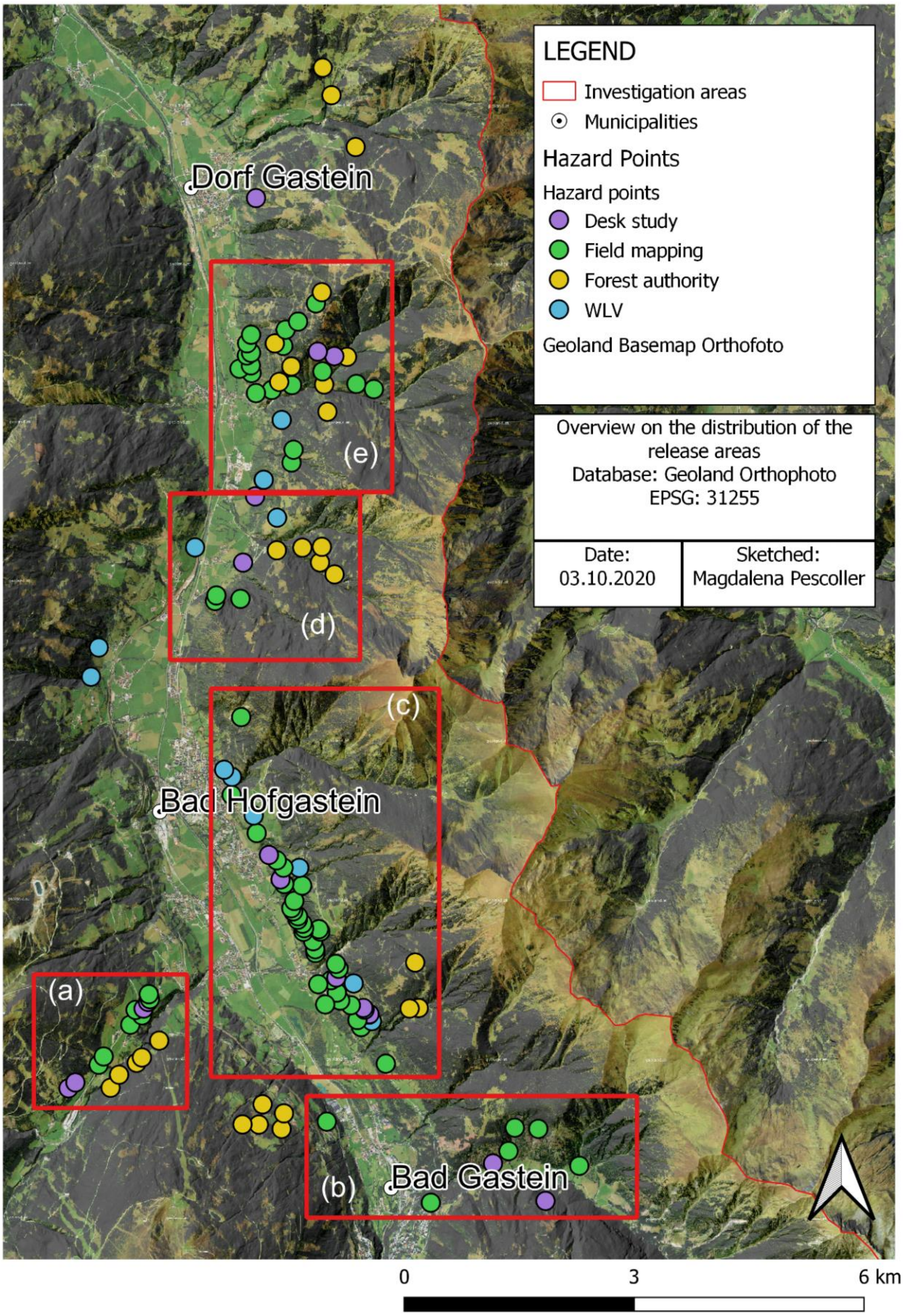


Figure 16: Geographical distribution of release areas, including information about data source and investigation areas, (a) Angertal, (b) Kötschach valley and Bad Bruck, (c) Bad Hofgastein and Faschingberg including the "Gasteiner Höhenweg", (d) Laderding and (e) Harbach valley and Dorf Gastein

Figure 16 gives an overview on the spatial distribution of documented release areas in this study. As already mentioned above, data has been aggregated within different sources – i.e. partly from desk study, partly from inventories (forestry authority and WLV) and partly from field mapping. It can be observed that release areas seem somehow to be collected around certain areas. A very distinct line seems to be within investigation area (c) – where all spots follow a line which correlates with the “Gasteiner Höhenweg”.

7.3. Distribution of release areas in respect to elevation

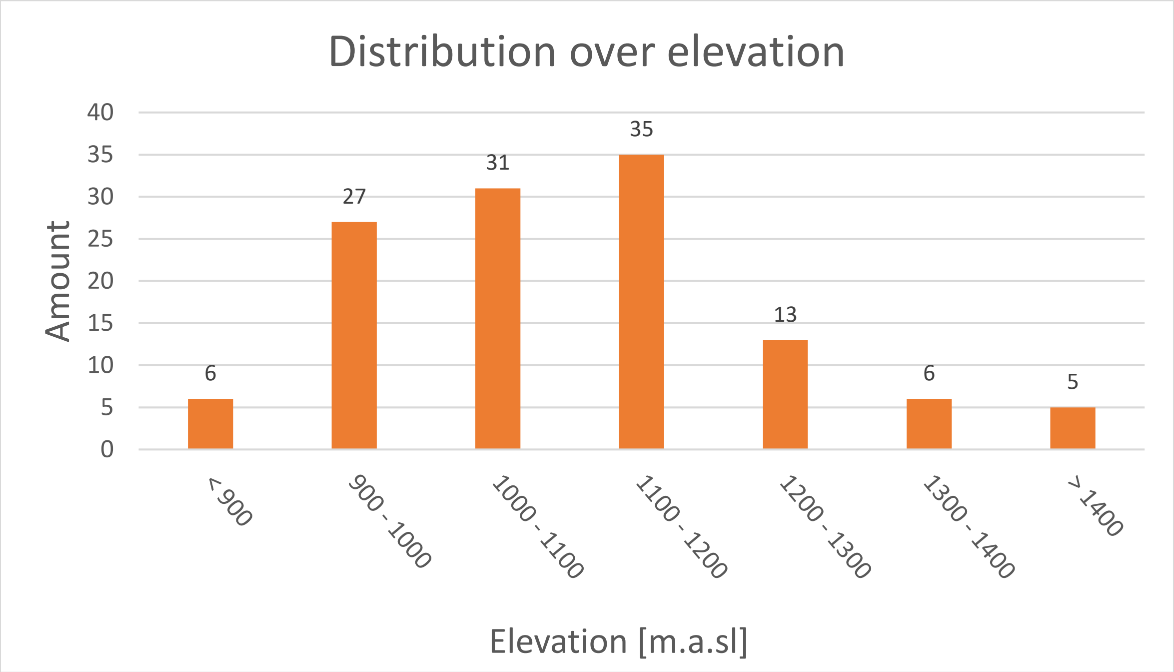


Figure 17: Height distribution of release areas (population n = 125)

Regarding the distribution of release areas in respect to altitude, a distinct threshold can be noticed at 1400 m.a.sl. Only 5 landslides were reported over a height of 1400 m.a.sl. (Figure 17). Most of the release areas were reported between 900 and 1200 m.a.sl. The highest release area was documented at an altitude of 1560 m.a.sl. The lowest at 855 m.a.sl.

7.4. Distribution of release areas in respect to slope inclination

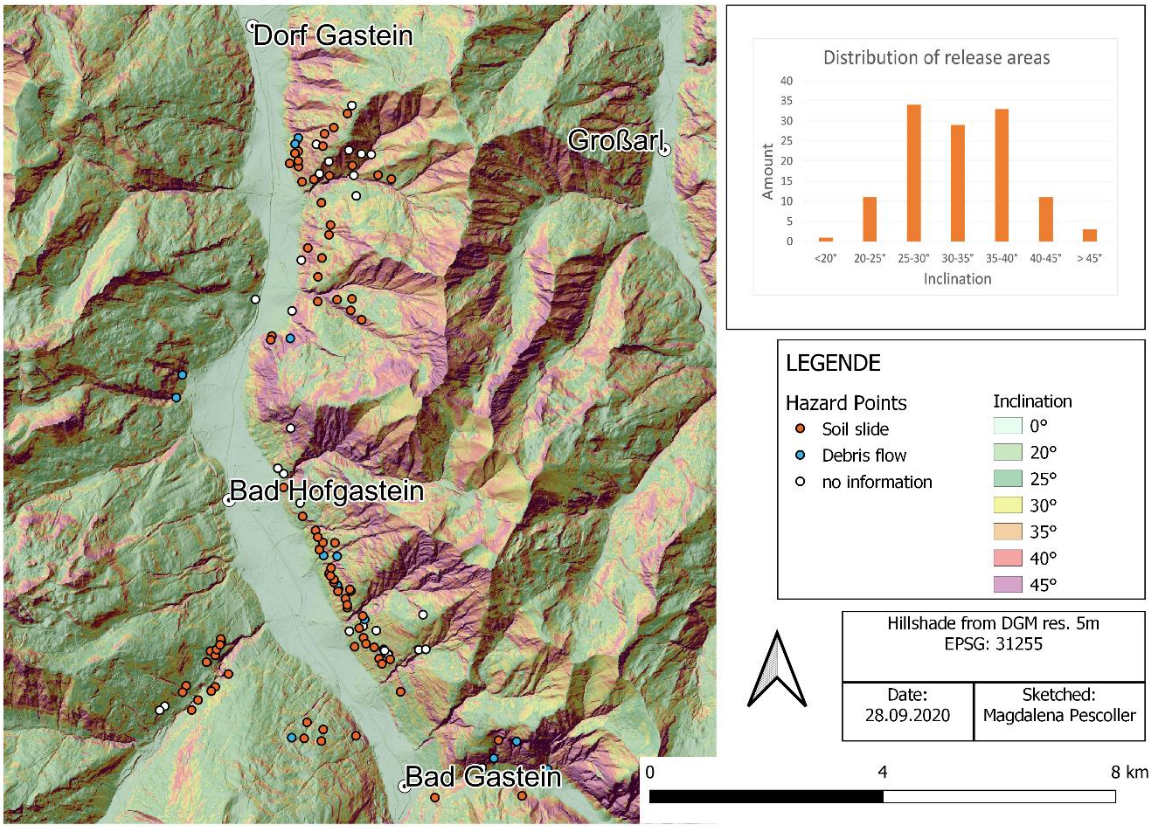


Figure 18: Inclination map (QGIS calculation from a DGM res. 5m) including the release areas and a graph showing the distribution of release areas in respect to slope inclination (population n = 125)

Figure 18 shows a map of the spatial distribution of local inclination within the study area. The dots indicate the release areas of the landslides and debris flows. As already mentioned in the description of the study site the valley shows a distinct asymmetry regarding slope inclination. While the orographic right-hand side (west-facing) is characterized by slope inclinations ranging from 35-45°, the orographic left-hand side (east-facing) is dominated by less steep slopes mostly around 25°. The quantitative analysis of the distribution of landslides according to slope inclination shows clear peaks between 25° and 40°. The landslides triggered within this range of slope inclination account for 79% of total.

7.5. Characteristics of release areas

Each mass movement, for which enough information was available, was analysed and classified by the characteristics pointed out in chapter 6.4Post processing and data analysis, i.e. type, rupture width and depth and sliding plane.

In total 84% of the events reported were classified as hillslope processes (landslide and hillslope debris flows), the remaining events could be assigned to torrent processes (intensive sediment transport and debris flows) (population n= 97).

The analysis of the sliding plane shows that for 72% of cases only loose soil and rocks were involved. 22% of the landslides and debris flows happened directly on a bedrock layer (population n =79). For 6% the sliding plane could not be assigned to one of the two classes distinctively. Figure 19 gives an overview on the type and sliding plane classification.

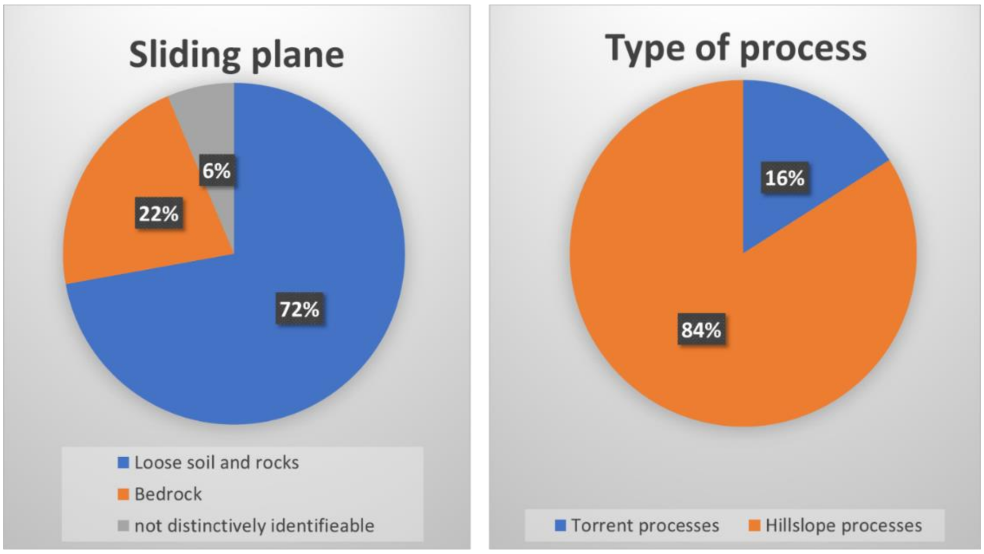


Figure 19: Sliding plane characteristics (right hand side – population n = 97) and type of mass movement (left hand side – population n = 79)

Data on event magnitude (width and depth of rupture) is only available for the cases being reported within the field mapping. Concerning the rupture width and depth the following pattern can be drawn:

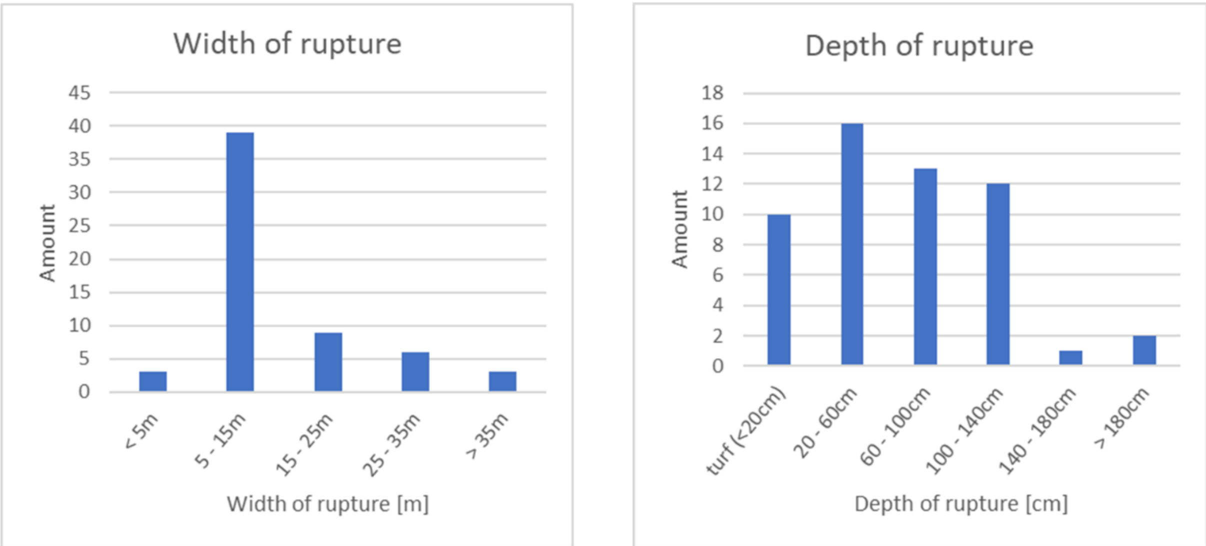


Figure 20: Width of rupture (population n=60) and depth of rupture (population n =54)

Most of the landslides have a crack width of 5-15m, only very few show a rupture width of more than 35m (Figure 20). Concerning crack depth, a relatively even distribution between only turf sliding and 140cm can be reported.

7.6. Vegetation and anthropogenic impact on release areas

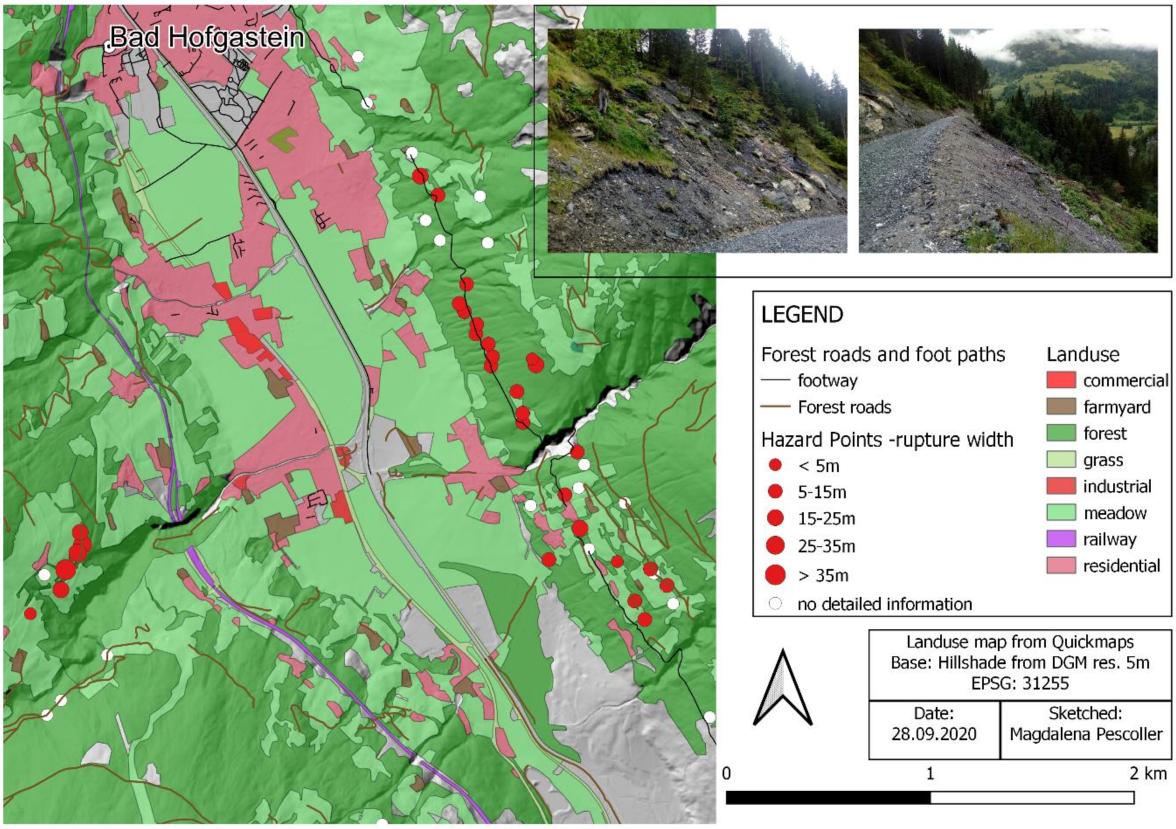


Figure 21: Land-use in the Gastein valley including forest roads and foot paths (Quickmap) - Sample Image of a forest road affected by a landslide (right upper corner)

Figure 21 gives an impression on the land-use distribution in the Gastein valley. As a sample the area surrounding Bad Hofgastein is demonstrated. Further, it can be seen that the documented hazard points seem to be somehow collected around the forest roads and/or hiking trails. Again, the collection of landslides around the “Gasteiner Höhenweg” can be seen clearly.

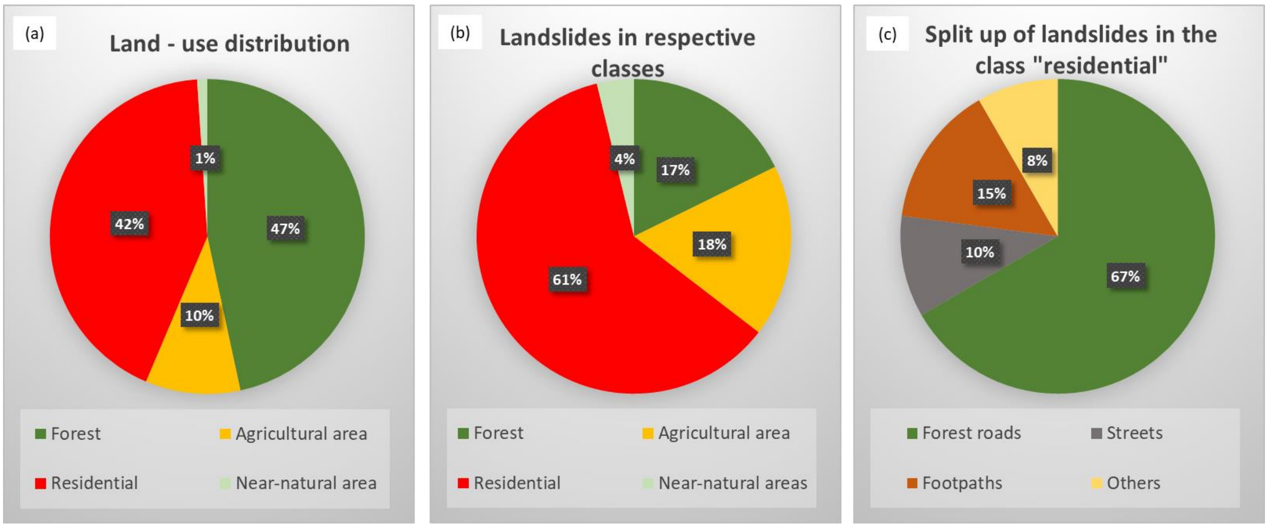


Figure 22: (a) general land-use distribution of the investigation area, based on a total area of 173km², (b) landslides in respective classes, based on a population of n=79, (c) more detailed separation of landslides assigned to the class "residential" into type of roads (n =48)

As seen in Figure 22, 61% of the events happened are related to residential area, whereas only 42% of the investigation area is assigned to residential area. Looking more into detail the pie chart in picture (c) shows that within the impact of residential area, the road network dominates by far, i.e. 92%, when summing up streets, footpaths and forest roads.

The results of the statistical analysis regarding the parameter "road impact" are shown in Figure 23 and Figure 24.

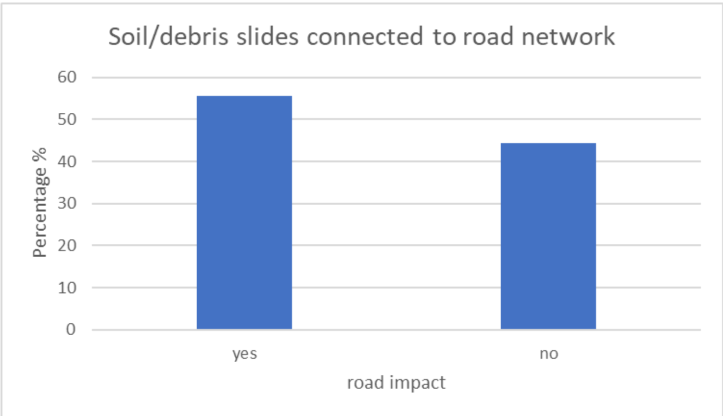
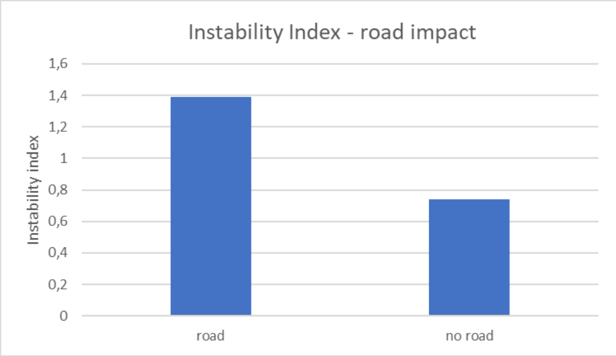


Figure 23: Hillslope processes connected to the road network - database: field mapping (population n =79)



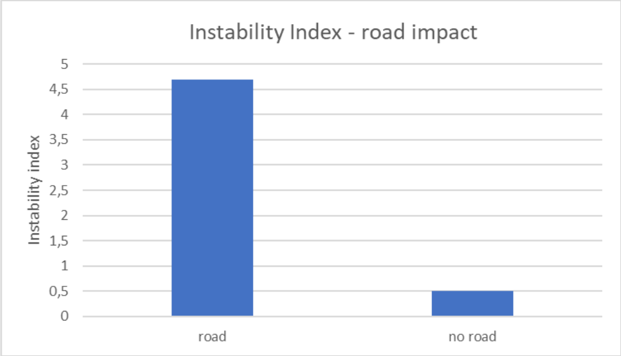
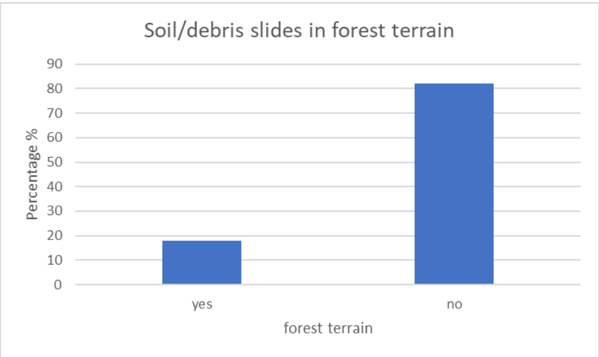


Figure 24: Instability Index - left hand-side - calculated on the bases of the complete road network in Gastein with a buffer of 50m; right hand-side - calculated on the bases of only forest roads and footpaths with a buffer of 25m (population events n =79)

Figure 23 shows that over 50% of landslides show a distinct link to road impact. The instability index, which relates to the proportion of respective land-use classes in general, shows an even higher correlation. The graph on the left hand-side in Figure 24 gives an instability index of 1.31 for the class “road impact”, which is around twice the instability index for no road impact (0.77). As the instability index 1.31 > 1, a favouring impact of roads on the release of landslides can be assumed. Given the fact, that no landslide occurred in the valley floor, where most of the road network is situated even increases significance of the graph. Hence the graph on the right hand-side in Figure 24 is calculated only including forest roads and footpaths, which are supposed to be situated on hillslopes. The result is even more significant, as the instability index for road impact is 9 times (4.74) the index for no road impact (0.50).

Additionally, the impact of water in combination with the road network is documented. For 51% of landslides, which are affected by roads and paths, water plays an essential role, mostly through concentrated runoff from forest roads. Concentrated runoff can either be caused by drainage systems or through ruts and bad surface quality of the road.

In addition to the road impact analysis, also the portion of landslides triggered in forest terrain and agricultural areas is calculated. The results can be seen in Figure 25 and Figure 26.



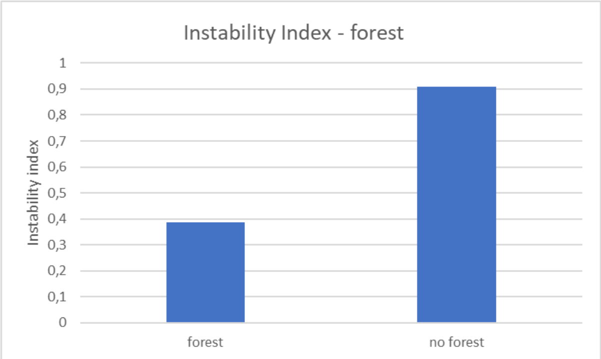


Figure 25: Frequency distribution of landslides in forest terrain (left hand-side, population n=79) and instability index for forest (right hand-side)

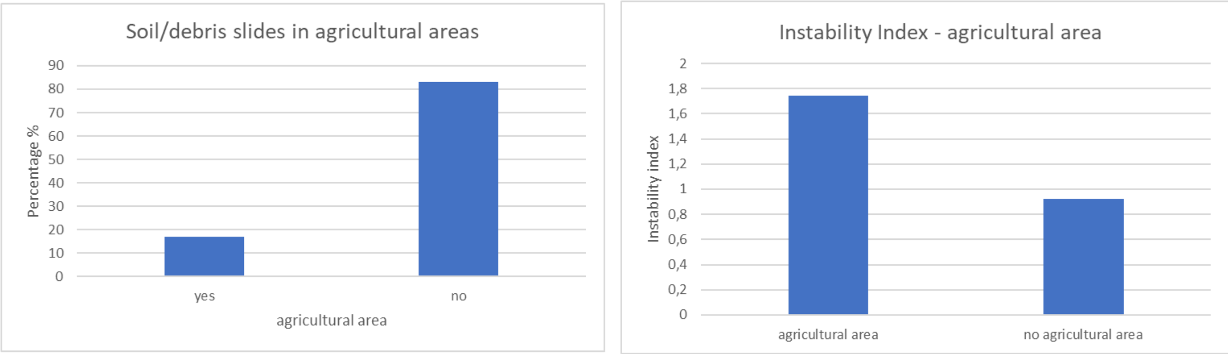


Figure 26: Frequency distribution of landslides in agricultural areas (left hand-side, population n = 79) and instability index for agricultural areas (right hand-side)

Figure 25 shows the frequency distribution (left hand-side) and the instability index for forest terrain. The frequency distribution draws a clear image. 82% of landslide release areas are situated outside forest terrain. The instability index confirms this result, as for “no forest” it is approximately three times the instability index for “forest” (0.91 – no forest vs. 0.39 – forest).

A less clear result can be seen in Figure 26 concerning agricultural areas. Looking at the frequency distribution (left hand-side) with 83% far more landslides are released outside agricultural areas. Whereas the instability index draws a controverse image. The index for “agricultural area” stands at 1.74, which is almost double the index for “no agricultural area”, standing at 0.92.

In addition, to the distribution of landslides within land-use classes, size of the release areas was considered to assess the risk potential. Figure 27 shows the distribution of rupture width (right hand-side) and rupture depth (left hand-side) separated for different land-use classes.

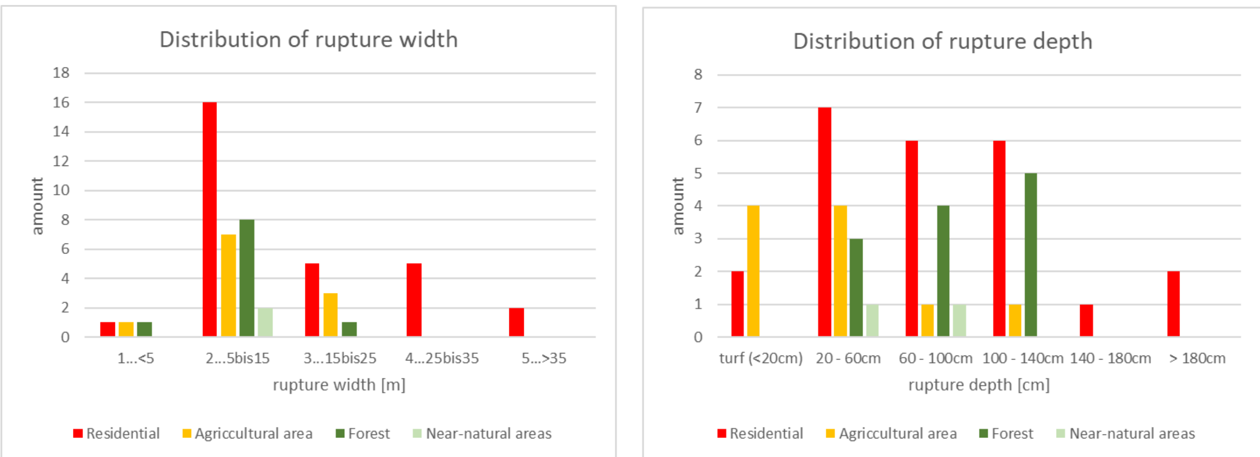


Figure 27: Distribution of rupture width (right hand-side) and rupture depth (left hand-side) over land-use classes (population n=67, only out of field mapping)

Both graphs show that, the largest release areas are situated within residential areas. This can also be confirmed by the impressions during field mapping. Two of the most devastating examples are shown in Figure 28.

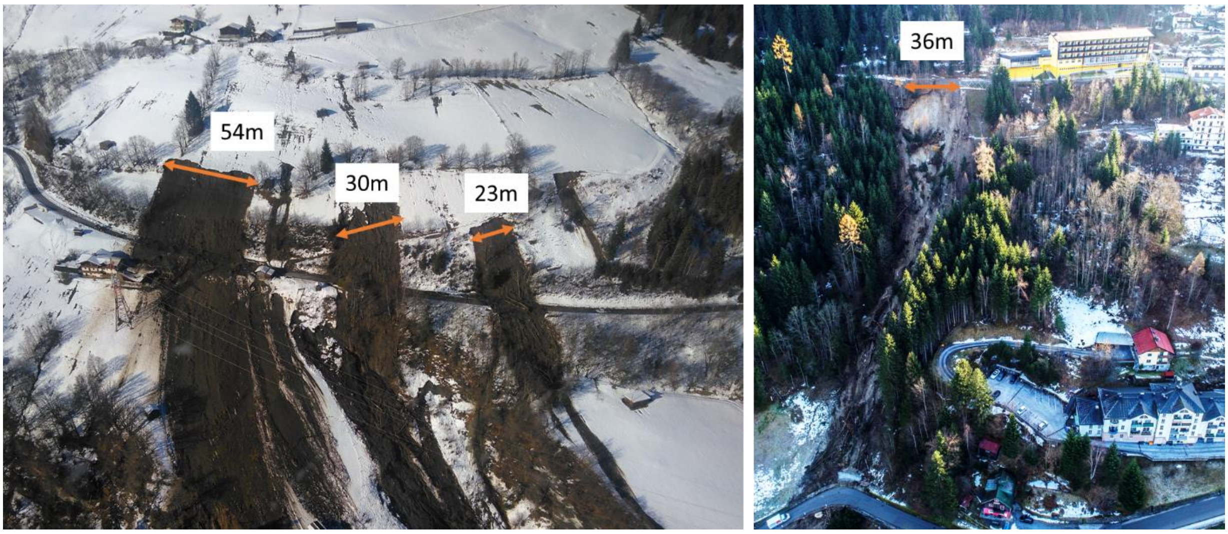


Figure 28: Selection of some of the largest hillslope slides – left hand-side: Angertal – complete destruction of a stable, right – hand-side: Bad Bruck, covering and destroying houses with its residents (photo: WLV- left hand-side, Robert Delleske - right hand-side)

7.7. Event analysis and failure mechanism

Finally, 38 events were analysed in more detail on their failure mechanism and the impact of forest roads and foot paths. Some representative examples thereof will be presented within this chapter, whereas the others can be found in the Appendix 7. (Named by their number given during documentation and the prefix "FID" for consistency with the QGIS-project)

FID 55

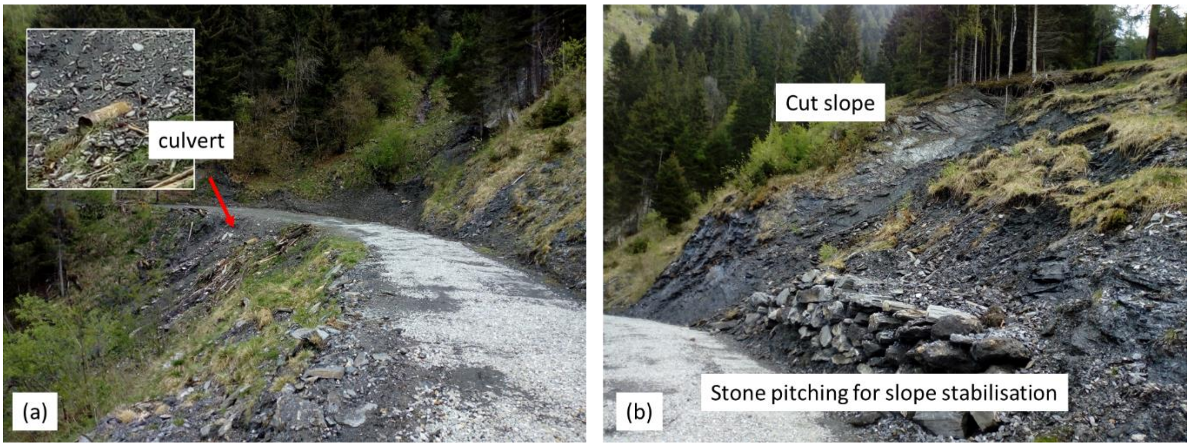


Figure 29: photo documentation Harbach valley - FID 55 (photo: Pescoller Magdalena)

The event, numbered “FID 55” is an example from the investigation area Harbach valley, in Figure 16 (e). As shown in Figure 29 there is a slope failure adjacent to forest road, with a soil slide above and underneath the forest road. A more detailed view on the sliding plane itself is displayed in Figure 30. We find a mixture between bed rock on the left side, and loose material, on the right-hand side.

Figure 30: sliding plane characteristics (photo: Magdalena Pescoller)

In Figure 29 also a stone pitching can be seen. It might have been constructed after the event to stabilize the now even more weakened cut slope. Since November 2019, the forest road was reconstructed which leads to the assumption that surface material was eroded during the event. On the fill slope side, a continuation of the debris movement can be observed (see picture (a)). In addition, a culvert for water runoff regulation can be noticed.

FID 15

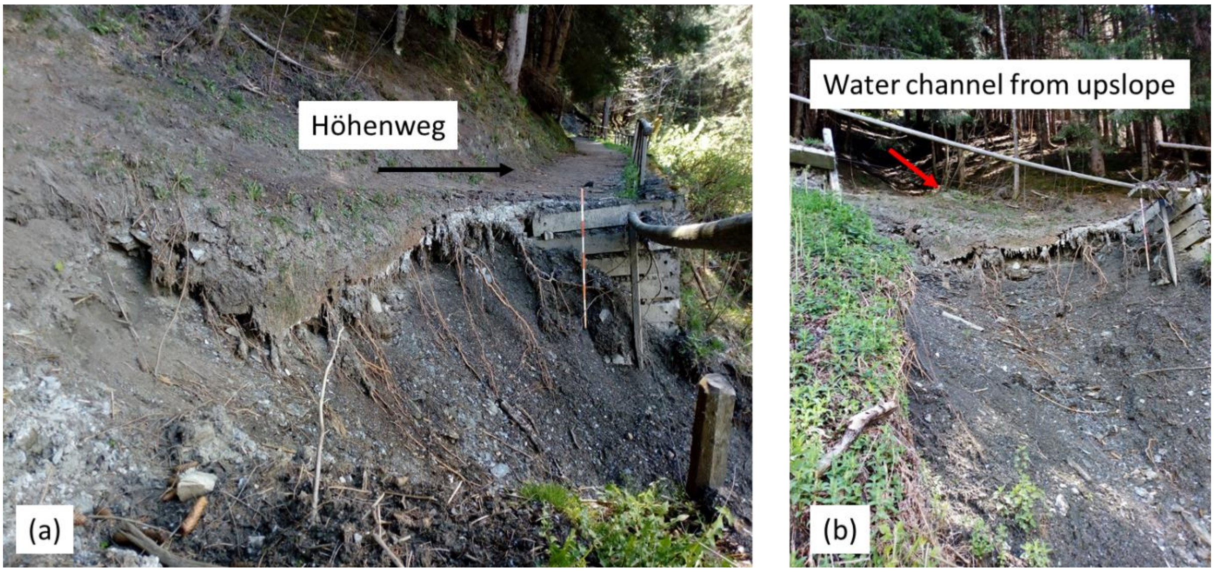


Figure 31: Photo documentation "Gasteiner Höhenweg" – FID 15 (photo: Magdalena Pescoller)

Event “FID 15” is an example from the “Gasteiner Höhenweg” where many landslides were triggered. We find that the landslide was initiated on the transition between path surface and fill slope. One can also see the stabilization structures on the right hand-side which may suggest stabilization problems in history or at least high inclinations which made such structures necessary. FID 15 is also an example for overland flow as on the upper side of the path (see Figure 31 (b)) a distinct water channel can be identified.

The slide here was released in soil only. No bedrock layer can be made out within the sliding plane.

FID 74

Figure 32: Photo documentation Angertal – FID 74 (photo: (a) WLV, (b)-(c) Robert Delleske)

The next example explained here is event “FID 74” located in the investigation area Anger valley (Figure 16 (a)). It is a very large, destructive landslide that was triggered on the cut slope of a terrace track/forest road. Probably also here the cut slope inclination may have been causative for the failure. The release area on the cut slope is shown in Figure 32 (b). Figure 32 (a) gives an overview on the extensions of the hillslope debris flow. It also shows the surrounding environment consisting mainly of meadows and agricultural areas. Slope inclination in this area in general is rather high. In Figure 32 (c) the effects of the landslide are demonstrated as the destroyed stable can be seen.

The sliding plane in this case seems to mainly consist of loose material and soil. No influence of water management elements can be seen.

FID 16

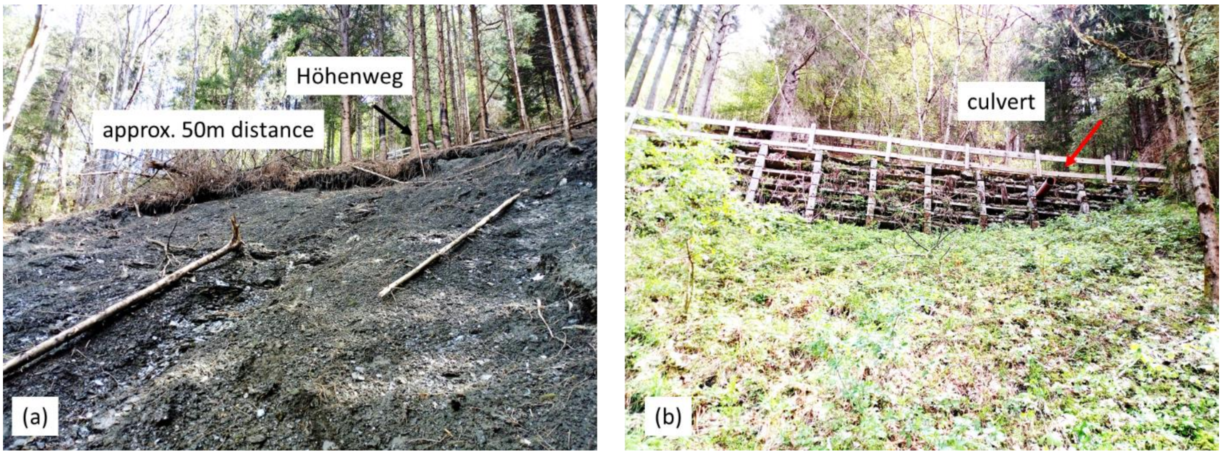


Figure 33: Photo documentation "Gasteiner Höhenweg" - FID 16 (photo: Magdalena Pescoller)

Event “FID 16” shows an example for malfunctioning of a water management measure. It is situated also on the “Gasteiner Höhenweg” (in Figure 16 (c)). Figure 33 shows the release area of a landslide which is situated approximately 50m downslope the “Gasteiner Höhenweg”. The sliding plane is made of loose material and soil only. Enforced soil erosion due to concentrated water infiltration with high pressure by the drainage culvert from the “Gasteiner Höhenweg” may have affected the slopes failure (see Figure 33 (b)).

FID 65

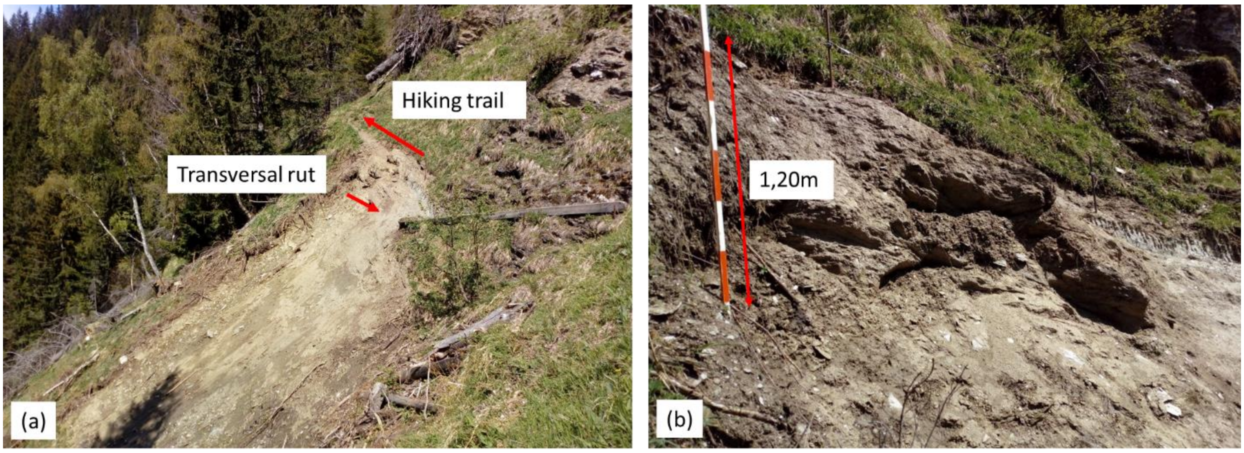


Figure 34: Photo documentation - Kötschach valley - FID 65 (photo: Magdalena Pescoller)

Event “FID 65” shows another example for malfunctioning of water management elements. In Figure 34 (a) the hiking trail from the Kötschach valley up to the pasture and restaurant Poserhöhe is shown. A transversal rut was supposed to manage water runoff. At the outflow point of the transversal rut a landslide has been triggered as can be seen in the image. The sliding plane shows partly bed rock, the soil cover was removed during the event.

Figure 34 (b) gives an impression on the rupture size of the landslide. As can be seen the rupture depth was 1,20m. The deposit of this landslide is found in the valley floor. I.e. it had a transit length of approx. 400m of height difference.

FID 43

Figure 35: Bad Bruck – Overview FID 43 (UAS photo: Robert Delleske)

Event "FID 43" finally shows the most devastating landslide which occurred during the storm events. It is located in the investigation area (b) in Figure 16, relatively central in the village of Bad Gastein, severely affecting a part of the locality Bad Bruck. The effects are displayed in Figure 36 (d), which shows one of the destroyed houses during the event. In Figure 35 an overview on the extensions of the landslide is shown. The release area shows a rupture width of 11m in the upper part (path edge) and a rupture width of 36m little more downslope. The travel length was approx. 250m and overcame a height difference of 100m. Within the sliding plan loose material and soil dominates, hence the process can be assigned to be a shallow landslide in its beginning that transformed into a hillslope debris flow.

More details about the release area can be seen in Figure 36 (a) to (c). We find that the landslide is triggered on the fill slope of a foot path. The fill slope failed exactly after the end of the protective structure (see Figure 36 (c)). The whole downward slope shows very steep inclinations thus landslide process development was easy. Water drainage elements as also seen in Figure 36 (c) support the suggestion of water impact on such processes.

Figure 36: Release area (a)- (c) of the landslide destroying settlement within Bad Bruck (d) (photo: Markus Keuschnig (d), Magdalena Pescoller (a)-(c))

An interesting fact in this case, is, that the whole sliding plane before the event was covered by forest. Figure 37 (a) shows an Orthophoto from the 09.09.2019 where the whole area is covered by forest, whereas Figure 37 (b) shows the same section just after the events on November 25th, 2019.

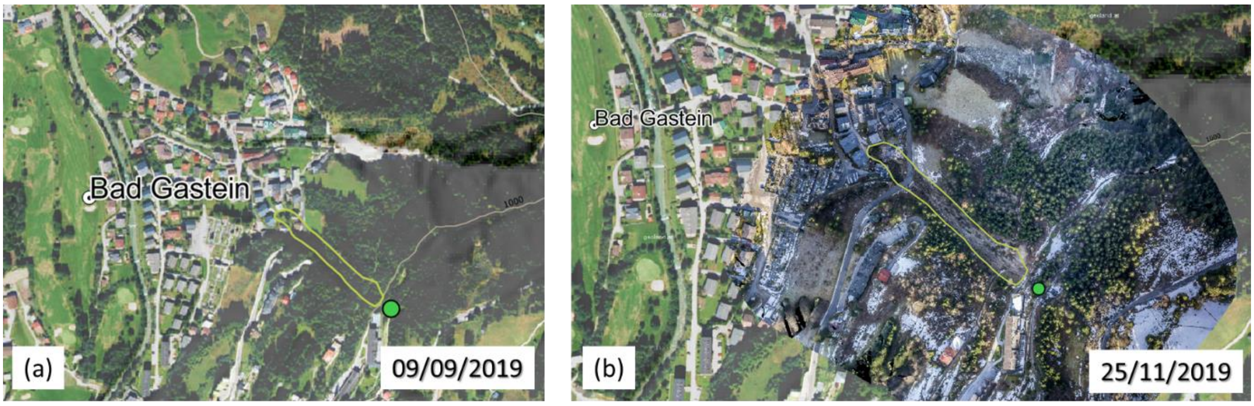


Figure 37: Comparison of relevant area, (a) Geoland orthophoto (last actualisation 09/09/2019) and UAS orthophoto from 25/11/2019 (Robert Delleske)

While Figure 38 (a) shows the release area right after the event, i.e. November 25th, the image (b) was taken in May 2020. It can be seen that such events may have longer lasting destabilising effects on slopes. The crack in image (a) seems to have been released in (b).

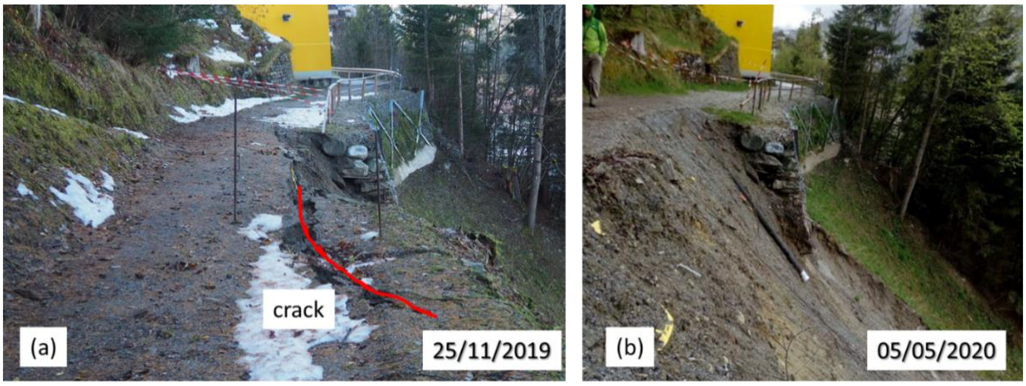


Figure 38: Comparison, release area on the 25/11/2019 (a) and the release area on the 05/05/2020 (b) (photo: (a) Robert Delleske, (b) Magdalena Pescoller)

8. Discussion

The storm in November 2019 had devastating consequences for the Gastein valley. As the main following mass wasting processes, shallow landslides and hillslope debris flows could be identified. To prevent such processes in the future a more detailed process understanding is important. Prevention starts at the release area of such mass movements, which is the focus in this study. For the release of landslides, the slopes basic disposition, the variable disposition and the trigger factors are relevant (Kienholz, 1995). Within this thesis the Gastein valley was investigated concerning its natural disposition and variable disposition. The storm event of November 2019, being defined as trigger event was reconstructed. Additionally, the human impact on the susceptibility towards mass movements is analysed.

Trigger – Analysis and interpretation of the weather storm and its impact

Reconstruction of the rainfall event in November 2019 draws a clear picture on the trigger for mass movements. As described in the chapter 7.1 water availability for slope destabilization was definitely given.

In the context of historical data, the precipitation amount of these days in November 2019 reaches the level of extreme events. As extreme precipitation an amount over 3 days for the region of the Gastein valley 150-200mm are stated (return period 30 a -as the value is the maximum based on the 30 years reference period 1961-90) (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, 2003). The total precipitation between November 15th and November 17th was 182,8mm. Also, the one-day precipitation amount reaches the median of annual maximum-daily precipitation within the reference period (1961-90), which lies at 52,8mm. Considering the fact that precipitation partly fell in form of snow on November 15th, surface runoff increased due to increasing temperatures causing snowmelt and additional rainfall on November 17th. Such weather patterns are not uncommon to precede landslides and hillslope debris flows as observed in the Gastein valley. Similar precipitation sequences were observed in other cases around the Alps (Moser, 1971; Petrascheck, Berwert-Lopes, Mani, & Zarn, 1998).

In fact, antecedent rainfall increases the variable disposition towards mass movements (Gariano & Guzzetti, 2016; Glade & Crozier, M. & P, S., 2000). For the triggering of landslides, two metrics describing the precipitation event are often considered, namely intensity and duration. Efforts have been made to find threshold values for this parameters by several authors (Guzzetti, Peruccacci, Rossi, & Stark, 2008; Moser, Janu, & Mehlhorn, 2016). For this study the amount, but especially the duration of precipitation led to prewetting conditions for the moment of slope failure. High water saturation increases pore pressure and thus leads to reduced shear strengths (Selby, 1993). Such longer lasting wet periods are not unusual for triggering shallow landslides (Schwarz et al., 2007). As already mentioned, in this case also the form of precipitation was important. The fact that precipitation in the first phase fell in form of snow that later melted, affected variable disposition. Snowfall in the first phase works as a water storage and thus leading to a runoff delay, which then ended up to become runoff effective with the last rainfall on November, 17th. As a consequence, runoff on November, 17th supposedly was higher than the rain fallen on that day, due to a combination of high antecedent moisture (limiting infiltration) and additional snowmelt. This supports the assumption that the history of meteorological events is crucial in triggering the mass movements, which answers the first research question about meteorological circumstances leading to the event.

Disposition of the slopes in the Gastein valley towards shallow landslides

Analysis of the disposition in general concerns the second research question as it is closely linked to the spatial distribution of release areas. In other words, the spatial distribution of landslides gives interesting hints on disposition distribution within the investigation area. This study delivers some distinct results regarding certain parameters characterising hillslope sections and areas being prone towards slope failure.

The result show, that the slopes, especially ones situated on the orographic right-hand side have a natural disposition towards landslides as these slopes are steeper than the ones on the orographic left-hand side. The analysis of slope inclination draws a typical image for landslide releases. Most slope instabilities have been documented at an inclination range of 25° to 40°. This is in accordance with other studies. For the event analysis of shallow landslides in Switzerland Rickli et al. (2000) reported inclinations from 28°-45° that showed the greatest disposition. Also Schwarz et al. (2007) came to similar results in their investigations of landslide events in Styria with a maximum slope for the release of shallow landslides of 35°.

Even though it has to be mentioned that for this case, slope inclination may not be the only reason for landslide concentration on the orographic right hand-side of the valley. Other conditions as, vegetation, forestry, land-use and soil structure may play a role. Some of them were analysed but an all-encompassing analysis would go beyond the scope of this thesis.

Another interesting aspect is the upper threshold of slope inclination around 45°-50°, where no more landslides are documented. A fact, that does not only come out in this thesis but also in several others. As reasons therefore missing material availability (Moser, 1997) and the domination of other processes, i.e. falling are given (Ruff et al., 2009).

A more difficult link is the one between altitude and disposition. Although the results displayed in Figure 17 would suggest a clear link between altitude and landslide release areas, as they all seem to be concentrated between 900 -1200 m.a.sl. Whereas almost no slides were triggered above 1400 m.a.sl. Other studies even come up with similar heights to show a greater disposition towards shallow landslides. Schwarz et al. (2007) count most processes being released under 1300 m.a.sl. in their study about shallow landslides triggered in Styria by a storm in August 2005. This positive correlation may result from other conditions bound to sea level, as climatic and weather conditions, soil depths, varying land-use and forest density (Schwarz et al., 2007). In this thesis weather conditions were considered in more detail, as the varying form of precipitation within the event seemed to play a key role in triggering the events. Especially the snow-line during the storm has been of interest. Based on a lapse rate of 0.6°C on 100m of height difference, for November 16th rainfall up to 1600m.a.sl and for November 17th rainfall up to 2000 m.a.sl. can be assumed (based on values Figure 14) (ZAMG, 2021). Therefore, up to 1400 m.a.sl. a mixture of rain and snow, enforcing landslide release, can be assumed.

Due to a limited database, this study does not include a detailed geologically and geotechnical assessment. However, the analysis of sliding planes confirms the presence of rather deep layers of loose material, i.e. moraine material, rock debris from historical mass movements. Indeed, 72% of mass movements are triggered in loose material. With caution it can be stated that in the lower slope parts of the Gastein valley sediment for mobilisation is abundant, hence enforcing disposition for landslide occurrence. To affirm this statement a more detailed investigation of soil, in form of profiles would be necessary.

Generally, the spatial variability of shallow landslides within this storm event is in line with past event documentations. Historical events from the SAGIS inventory are compared with the ones from November 2019 (Figure 39). It can be seen that some areas showed a clear susceptibility towards landslides in the past. As an example, the region of Bad Gastein/Bad Bruck, where in November 2019 one of the most devastating landslides occurred (see Figure 28 – right hand-side) is demonstrated. The event inventory lists two past events – one in 2009 and another one in 2018. Both have been defined as hillslope debris flows (Land Salzburg, 2020). Also, the protection structure (see chapter 7.7 for detailed analysis of the event itself) suggests that the slope has already shown some instability before November 2019.

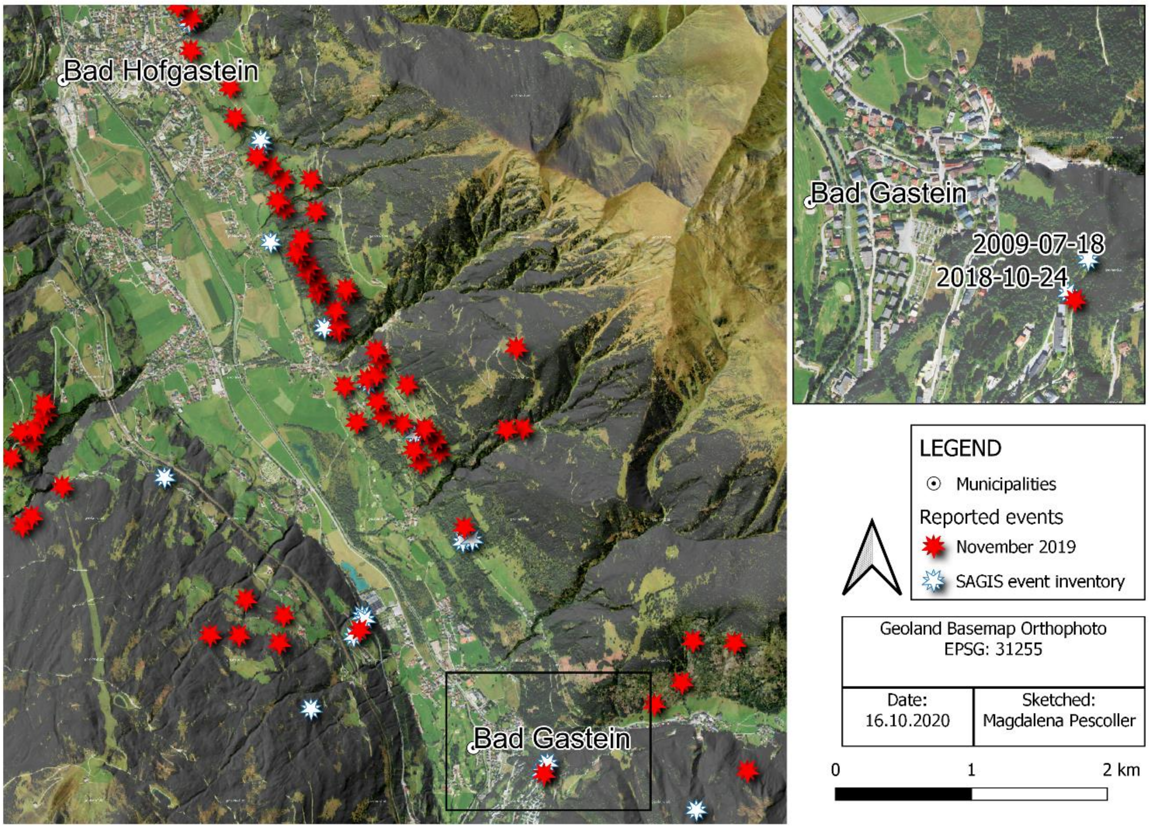


Figure 39: Map including events from November 2019 and events from the SAGIS - event inventory (Land Salzburg, 2020)

Variable disposition of the slopes in the Gastein valley towards shallow landslides

Vegetation accounts for an important factor affecting slope stability. Therefore, also within this thesis the correlation between the release of shallow landslides and forest terrain was tested.

It can be confirmed that in Gastein valley there were more slides released in regions without forest compared to regions with forest. This is in agreement with the outcome of other studies (Rickli et al., 2000; Schwarz et al., 2007). Hence, a stabilizing effect by forests can be assumed.

The analysis of forest and vegetational impact is not performed in further detail as the focus of this study is rather on anthropogenic infrastructure. Other studies proofed the vegetational impact in more detail also considering additional impact factors at the same time, i.e. slope inclination and forest, in order to point out the forests relevance for protective purposes (Rickli, 2001). The variable stabilizing component of vegetation, especially forests derives from its strong dependence on condition and age as Ruff et al. (2009) and Rickli et al. (2000) investigated in their studies.

The second vegetational aspect analysed within this thesis is agricultural used land. The results in this case are less clear, but still indicate an increased exposure towards landslides within agricultural used areas. For agricultural used areas, the frequency distribution and the instability index in Figure 26 may lead to different conclusions on its impact. Regarding the frequency distribution in Figure 26, landslides being released within agricultural areas seem to be far less (by number) than those being released in areas without agricultural impact. This result is based on the fact, that within the Gastein valley “agricultural used area” takes only a little part (10% - see Figure 22 (a)) compared to other land-use classes. This fact, is considered in the calculation of the instability index. Therefore, looking at the instability index for “agricultural used area” one can see that there is a destabilizing impact on slopes by agricultural usage. From a geotechnical point of view, increased disposition towards land sliding in agricultural areas can be explained based on disturbed vegetation and cattle trails (Prinz & Strauß, 2011). Nevertheless, in the case of the Gastein valley it is not the most dominating factor as can be seen by absolute numbers (see Figure 22 (b)).

Anthropogenic impact on slope stability in the case of the Gastein valley

The third research-question deals with the impact of residential areas and anthropogenic structures on landslides. The focus to answer this question is on forest roads and hiking trails.

In Figure 22 it can be seen that a great portion, i.e. 61% of release areas are found within residential area, including the road network. Splitting up, 67% thereof, are released within the impact area of forest roads. The frequency distribution and instability index for the attribute “road impact” draws a clear image. A road network seems to significantly reduce slope stability. This result is also confirmed by other studies, in which a destabilizing effect of road construction on hillslopes is mentioned, as by Wemple et al. (2001) or Schwarz et al. (2007).

Within this thesis, efforts were taken to explain the statistical correlation between road network and slope failure. Table 6 (see chapter 4) gives an overview on the main processes linked to a road network. In the Gastein valley almost half of the landslides were triggered by malfunctioning of water management elements. The other half has been enforced by unnatural steepness of excavated slopes and artificially created terrain edges. In many cases a mixture of both effects has been responsible.

Relating to the formulas in chapter 4 slope inclination changes the ratio between driving and resisting forces significantly. Increasing inclination angle leads to a shift towards driving forces. The related consequences with changed slope inclination are named with cut slope slide and fill slope slide in Figure 7. Examples for a cut slope slide are the event numbered “FID 55” and “FID 74”.

Regarding fill slope slides, the examples in this case (“FID 74”, “FID 43”) suggest that besides inclination also other factors may play a role. It is noticeable that the transition edge between road surface and fill slope seems to be a predetermined breaking point. Terrain edges also in other studies are mentioned to enforce land sliding (Hübl, 2000; Moser, 1997). According to Aleotti et al. (1996) such morphological formations favour the development of a wetting front, leading to a faster saturation of soil. This effect is be nicely visualized in the example "FID 15" (Figure 31).

Another problem may occur due to missing vegetation surrounding forest roads, as seen in Figure 6. Ryan et al. (2004) give a minimum tree clearance for forest roads of 15m. Here also the effect of sediment entrainment, enforced by road surfaces can be mentioned, as soil is more exposed to water overflow (Wemple et al., 2001). A fact that makes it even more important to concern water impact when planning forest roads and hiking trails. Water infiltration may especially be important regarding the fill slope, as seen in the examples above, where mostly fill slope failure is the reaction on malfunctioning of water management elements and unfavourable water discharge.

These failure effects have been observed to be the same for forest roads and hiking trails, as the largest landslide (see event "FID 74") has been triggered in connection with a hiking trail. One may assume greater destabilizing impact on slopes due to higher transitory stresses by heavy machinery passing on forest roads (Selby, 1993). On the other hand-side hiking trails may be located in even steeper environments, showing a higher natural disposition towards mass wasting processes. This study suggests that if certain conditions are changed in an unfavourable way for slope stability, mechanical stresses afterwards play a minor role for final failure.

Both, forest roads and hiking trails have an influence on a slope's hydrology, which could be observed within this study (examples are "FID 16", "FID 55", "FID 65", etc.) and is also confirmed by other studies (Montgomery, 1994). Referring to Table 6, all of the listed failure mechanism could be observed in the events in the Gastein valley. The dominant problem with water management elements was the collection of water and subsequent concentrated discharge. This problem was not only limited to the direct surrounding (i.e. failure of fill slope and transition edges between road surface and fill slope) of roads and trails but had also an impact on slopes at a certain distance, as can be seen with "FID 16". It may be assumed that in this case high pressure of water infiltration facilitated soil erosion and triggered sliding. Speaking in terms of malfunctioning water management measures plugged culverts and plugged transversal ruts caused problems by inducing water overland flow and thus enforcing sediment erosion on road surface and fill slopes (see "FID 65").

To meet those problems associated with forest roads and hiking trails several aspects in construction should be concerned.

- When forest roads or hiking trails are constructed by excavating slopes a focus should be set on the cut- and the fill slope. First their inclination should be moderate. Guidelines for road construction suggest inclinations of 1:1,5 (Prinz & Strauß, 2011). If higher inclinations are needed stabilization structures should be considered.
- Secondly also vegetation within these slopes should be considered as vegetation may play a key role in sliding plane formation (Hübl, 2000). Hence it is advised to emphasize on the right seed mix for stabilization. The right seed mix may stabilize the slope by anchoring and connecting layers of soil. With sliding planes formed due to bed rock layers, stabilization with biological measures will not be effective anyway. There rather technical measures may be necessary.
- The third aspect which during constructions should be considered are water management elements. The selection of an inadequate drainage system may have disastrous effects in case of extreme rainfall events. Forest roads and hiking trails consist usually of an unpaved surface, i.e. sediment erosion during rainfall has to be considered for surface runoff routing. Water management elements have to be dimensioned also for larger amounts of sediments being transported within the runoff. Otherwise, the probability of plugging as can be seen in the cases examined within this study, is high. Fords should be considered in several cases. Inappropriate elements, observed within this investigation, as culverts with too small diameters (see Figure 41) or drainage gullies with too tiny grid spacing enforce mass movements. In general, grided gullies for unpaved roads are critical as they are easily plugged (W. Fanninger, 2020 personal communication).
- Further maintenance plays a key role as also mentioned by W. Fanninger (2020). Especially after such events proper restoring and maintenance work would be necessary. Figure 40 (a) and (b) gives two examples where restauration after the events in November 2019 still is missing. Figure 40 (a) shows the cut slope, where the top layer slipped. As the slope shows a rather steep gradient clearance of sediment would be useful. In addition, the overhanging grass should be eliminated for optimization of water runoff and hence reduction of water pressure for road surface overflow and soil erosion (W. Fanninger, 2020, personal communication). Figure 40 (b) shows an example where road surface could be improved. As the surface consists of very soft, silty soil it can be seen that distinct wheel ruts are formed. Those may affect

water runoff in an unfavourable way. Such wheel ruts should be prevented by regular restoring work of road surfaces.

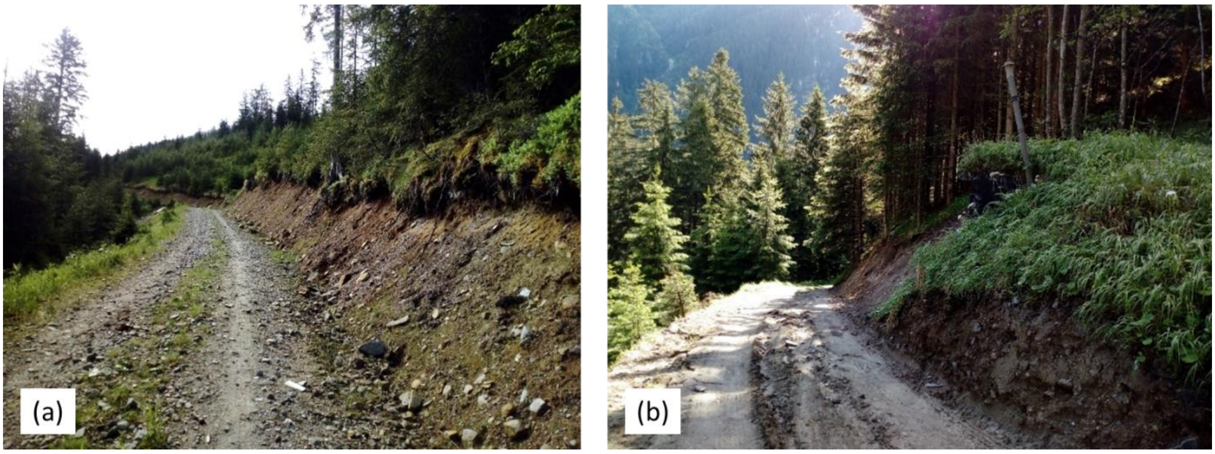


Figure 40: (a) cut-slope sliding Kötschach valley and (b) Road surface Kötschach valley (photo: Magdalena Pescoller)

Figure 41: Culvert after reparation work - "Gasteiner Höhenweg" (photo: Magdalena Pescoller)

Uncertainties and limits of the study

As research work in general, also this study has its limits and uncertainties. The aspect of representativity may obviously be discussed. Due to limited data depth for several release areas, parameter analysis may be based on a rather small population. This is a typical problem with natural hazards (Glade, Mergili, & Sattler, 2020a) as data collection often is challenging. Data usually is already limited based on the number of events occurred, which may be rather small for statistical analysis. In addition, accessibility of the release areas may not always be possible due to topographic circumstances. The results hence, may be biased by the fact, that event detection is easier along forest roads and hiking trails than somewhere else within the forest. Also, time may be a limiting factor in data collection. As it was for example the case in this thesis, the access to the investigation area was only possible five months after the event itself. As a consequence, many release areas were not in their original shape anymore, due to reconstruction work and vegetation processes. Through the combination with data from the analysis of remote sensing data, release areas could partly be reconstructed such as the population finally has been big enough to justify statistical analysis. Nevertheless, one should be aware of this aspect when deriving conclusions out of this study.

Available data also decides on simplifications to be made within analysis, which always includes further loss of detail. For this study, especially in the case of land-use, some simplifications had to be made. Uncertainties may especially arise from the buffer line of 25m for forest roads and hiking trails. As per definition this includes a strong simplification of their impact area. Also, the calculation of the respective same buffer for forest roads and hiking trails may be restricting. Especially on a small regional scale, including the buffer, changes the portion of “forest” and “no forest” area. Regarding the fact, that this buffer line is adapted according to landslides where forest roads enforced slope failure significantly (see also Table 5 in chapter 6.4), the assumption is valid as the attribute “forest” – “no forest” is not expected to be the dominant in this case. The impact of forest roads in this case seems to be higher than the protection achieved by forest. It has to be taken into consideration that tree clearance is always part of a forest road, creating a “no forest” area by definition. Disturbing the vegetation in the tree clearance area makes this area different from a standard forest anyway.

9. Conclusion and Outlook

This thesis provides a quantitative analysis of the influence of different topographic and land use parameters on slope stability in a mountain environment. The focus hereby is on the impact of anthropogenic infrastructure. Evaluation of the impact of different parameters is conducted throughout a detailed event documentation and analysis of landslide events in the Gastein valley in November 2019. The main outcome of the study can be summarized by answering the research questions as follows:

1. *What meteorological conditions lead to the landslide events? Which are the dominating processes during the event?*

The precipitation events from November 12th to November 17th can be clearly identified as landslide trigger. Crucial for triggering was an increase of temperature, which raised the snow line. Further precipitation led to a rain-on-snow situation up to altitudes above 1400 m.a.sl. Even though torrent and hillslope processes are triggered, the dominating ones were clearly hillslope processes with 84%.

2. *What is spatial variability of release areas? Are their clear characteristics defining the spots where hillslope mass movements were triggered?*

In total 125 events are documented, showing a distinct distribution over the investigation area. Almost all of the events were recorded on the orographic right-hand side below 1400 m.a.sl. This distribution is based on the natural disposition within the investigation area. The orographic right-hand side is steeper, i.e. release areas are mainly found within inclinations from 35°-45°. Out of natural characteristics, slope inclination was the most dominant factor for defining release areas. Abundancy of moraine and other loose material is related to slope inclination and probably also altitude.

3. *Can the impact of anthropogenic infrastructure on slope stability be quantified? What parameters play a key role?*

The impact of anthropogenic infrastructure was found to be significant for slope stability. With 61% landslide events being related to human infrastructure an impact thereof can be assumed. The largest impact on slope stability is shown by the road and hiking trail network. As critical parameters, inclination change and artificial terrain edges due to slope excavation, and water routing through malfunctioning water management elements can be identified.

4. *Are there improvement possibilities for society to deal with and reduce the risk in future? If so, what kind of?*

For future risk reduction a special focus should be set on forest road construction and maintenance. Maintenance measures may concern all forest road elements, from cut-slope and road surface to water management elements. They also vary in type as they may be of technical (e.g. stone pitching), biological (e.g. support of vegetation growth) or organisational (e.g. clearance of transversal ruts and culvert, land management and hazard zonation plans) nature.

Outlook and future work

This thesis adds to the understanding of shallow landslides triggered by extreme storm events in an alpine environment. Some parameters were analysed with respect to their importance for slope failure. Follow-up work may focus on a more detailed analysis of soil parameters for modelling the influence of road construction on slope stability. Landslide modelling is already used by different authorities as helpful tool in hazard zone planning (F. Goldschmidt – Geologist Carinthia, personal communication 2020).

Besides the geotechnical impact of roads , the hydrological impact of the road network on a regional scale should be further investigated. This could be done by distributed hydrologic modelling, but probably also in form of laboratory experiments.

The data base collected within this study would also suggest the generation of a disposition map for the Gastein valley, similar as proposed by Tilch & Schwarz (2010) for other regions. For that, a more detailed analysis of soil and geology would be needed.

The results of this study, together with similar events reported by other authors (e.g. (Rickli et al., 2000; Tilch, 2019) shall represent the basis for improved engineering measures to reduce negative impacts of road and train constructions.

10. List of figures

11. List of tables

12. List of equations

13. Reference List

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14. APPENDIX

APPENDIX_1: Field notes 2: Excel Table where field notes have been digitalised

Table 7: digitalised field notes (Excel)

Datum	Gebiet	ID	Anrissbreite [m]	Anriss-mächtigkeit [cm]	Gleitfläche	Anmerkungen
04. Mai	Höhenweg Bad Hofgastein	1	21	80-100	Lockermaterial	tw. Fels, Abbruchkante entspricht Wegkante
04. Mai	Höhenweg Bad Hofgastein	2	10	Grasnarbe	Lockermaterial	
04. Mai	Höhenweg Bad Hofgastein	3	Gerinne -> Mure	um Gerinne Abbruch Grasnarbe	in Gerinne Bedrock, außerhalb Lockermaterial	Entfernung Wegkante 25-30m, alles wieder hergerichtet
04. Mai	Höhenweg Bad Hofgastein	4	10	50-80 eher 50	Bedrock	
04. Mai	Höhenweg Bad Hofgastein	5	6,1	50-80	Lockermaterial	Höhenweg - Wegkante gerutscht, Rinne
04. Mai	Höhenweg Bad Hofgastein	6	10	80	Lockermaterial -> Auslauf Rinne	Anbruch bei Trampelpfad

04. Mai	Höhenweg Bad Hofgastein	7	5	20-30	Bedrock, 5cm Auflage Erde in Rutschmasse	keine Infrastruktur, Anbruch im Wald
04. Mai	Höhenweg Bad Hofgastein	8	21	100-120	Bedrock	ca 100m unter Straße PLanitzen, rechts 2te kleinere Rutschung (10m Anrissbreite)
04. Mai	Höhenweg Bad Hofgastein	9	4	100	Bedrock	oberhalb Rinnsal, Wasser in Rutschfläche
04. Mai	Höhenweg Bad Hofgastein	10	9	100	Lockermaterial, in Rinne Bedrock	Abbruch an Wegkante Höhenweg
04. Mai	Höhenweg Bad Hofgastein	11	5	80	Bedrock	Einleitung Rinnsal oberhalb, Al: ca. 10m
04. Mai	Höhenweg Bad Hofgastein	12	5	10 bis 20	Bedrock	Gerinne -> baldiger Übergang zur Mure
04. Mai	Höhenweg Bad Hofgastein	13	5,7	30 bzw. Wegstütze	Bedrock	Anrisskante = Kante Weg
04. Mai	Höhenweg Bad Hofgastein	14	6,1	100-120	Lockermaterial	Anrisskante = Kante Weg

04. Mai	Höhenweg Bad Hofgastein	15	6,1	40 bzw. Wegstütze	Bedrock	Anrisskante = Kante Weg, von oben eindeutig Wassereintrag
04. Mai	Höhenweg Bad Hofgastein	16	9	80	Lockermaterial	Entfernung Weg, inklusive Drainage - 15m
04. Mai	Höhenweg Bad Hofgastein	17	11	80-100	Lockermaterial	Wegkante gebrochen
04. Mai	Höhenweg Bad Hofgastein	18	Gerinne -> Mure			unten alles hergerichtet, evtl. Zufahrt von oben Straße Planitzen
04. Mai	Höhenweg Bad Hofgastein	19	Gerinne -> Mure			Wegkantenabbruch
04. Mai	Höhenweg Bad Hofgastein	20	5 bis 10	20	Lockermaterial	Anriss 50m unter HW; Seitenrutsche Rinne; Punkt auf Weg gesetzt
04. Mai	Bad Hofgastein	21	15 bis 20	Wegkante		? Neulich bearbeitet
04. Mai	Bad Hofgastein	22	6	20-30	Bedrock	8 bis 10m über Straße

04. Mai	Bad Hofgastein	23				Rutschung Inglsberg -> keine flachgründige Rutschung, große Blöcke in Bewegung
04. Mai	Faschingberg	24	3	120	Lockermaterial	Bruch unter Straße, Drainage Wasserlauf in Rutschmasse, Anriss = Straßenkante
04. Mai	Faschingberg	25	5 bis 10			alles wieder gerichten, Anrissmächtigkeit nicht mehr erkennbar
04. Mai	Faschingberg	26	14 bis 16	20-30	Lockermaterial	stark hergerichtet, Durchlass wo HW, Gerinne
04. Mai	Faschingberg	27	6	50-80	Bedrock	10-15m bis Weg bzw.Straße
04. Mai	Faschingberg	28	6 bis 8	20-40	Lockermaterial	40-50m Wegentfernung
04. Mai	Faschingberg	29				kein Anriss mehr erkennbar, hergerichtet/planiert

04. Mai	Faschingberg	30			Lockermaterial	Anrisskante nicht sichtbar, muss weiter oben sein, alles gerichtet, mehrere Wege kreuzen den Transitbereich
04. Mai	Faschingberg	31	14,1	120-140	Lockermaterial	2m oberhalb Zaun, tw. wieder hergerichtet
05. Mai	Angertal	1	30	Grasnarbe	Lockermaterial	hergerichtet, Anrisskante schlecht sichtbar, Abbruchb bei Weg
05. Mai	Angertal	2	25/ 18 aus QGIS?	Grasnarbe	Lockermaterial	Anrisskante nicht mehr sichtbar, Abbruch bei Weg
05. Mai	Angertal	3	4 bis 5	10 bis 20	Lockermaterial	Rinne, Abflussrohr sichtbar
05. Mai	Angertal	04 =0 5	15 bis 20	30 bis 40, 2x nebeneinan der	Lockermaterial	Anriss an Hangkante, Punkt zu hoch aufgenommen
05. Mai	Angertal	6	in Rohr, 2m	40 bis 60	Lockermaterial	Abflussrohr, 10m unter Straße - Fotos verloren ?

05. Mai	Angertal	0,005	15 bis 20	nicht mehr sichtbar - Grasnarbe	Lockermaterial	Weg = Anriss
05. Mai	Angertal	7	20	120-140	Lockermaterial	dicht an Weg, Zaun abgerissen
05. Mai	Angertal	8	50-60 ? 18m (aus QGIS gemessen!)	nicht mehr sichtbar - Grasnarbe	Lockermaterial	Straße oberhalb (1-50m)
05. Mai	Laderding	9				Murgang in Gerinne, oberhalb Felswand -> Wasserfall
05. Mai	Laderding	10	10	100-120	tw. Bedrock	
05. Mai	Laderding	11	8 bis 10	40	Lockermaterial	Eintritt Wasser - siehe Foto
05. Mai	BadBruck	12	oben 15m, mitte 36m	50-200	Lockermaterial	bis Straßenkante, nben Verbauung
06. Mai	Dorf Gastein	13	5 bis 8m Seitenanrisse	20-80 entlang Gerinne	Bedrock	murfähiges Gerinne

06. Mai	Dorf Gastein	14			Bedrock	Seitenabrüche, Erosion -> murfähiges Gerinne
06. Mai	Dorf Gastein	15	19,2 breit St.; oben 9,4 -> IR: 10x10m	Hauptrutschung: 60; Initialrutschung: 60	Hauptruschung: Lockermaterial Initialrutschung: Bedrock	oberhalb kleinere Initialrutschung; Wasseraustritt in Rutschmasse; 50m drüber Wegkante
06. Mai	Dorf Gastein	16	12x12m	40-60	tw. Bedrock	Anbruch mitten im Wald
06. Mai	Dorf Gastein	17	1) 10 bis 15 2) 10	60 40 bis 50	beide Lockermaterial	2 Rutschungen: 1) Anrisskante=Wegkante; 2) Anrisskante oberhalb Weg
06. Mai	Dorf Gastein	18	2m; 10m; 15m x19m	100	Lockermaterial	Rotationsrutschung; 8 bis 10m unter Wegkante
06. Mai	Dorf Gastein	19	6,4	60	Lockermaterial, mittig Ausbildung Rinne -> Bedrock	Direkte Einleitung Wasserabfluss Weg
06. Mai	Harbach	20	29,3	nicht mehr sichtbar	Bedrock oberhalb Straße, darunter nicht mehr sichtbar - planiert	
06. Mai	Harbach	21	30	180-200	tw. Bedrock (größtenteils)	ca. 16m über Forststraße abgebrochen

06. Mai	Harbach	22	15m am Weg		Lockermaterial	Rinne, Wasserabfluss - Wegdrainage von oben
06. Mai	Harbach	23	8 bis 10	180-200	Lockermaterial	16m über Weg
06. Mai	Harbach	24	10 bis 15	30 bis 50	Bedrock, oberhalb Straße	unter Wegkante, daneben gleich Gerinne
06. Mai	Harbach	25	6 bis 8	100-120	tw. Bedrock	oberhalb Forstweg
06. Mai	Harbach	26	8 bis 10	80 bis 120	Lockermaterial	Abbruchkane = Wegkante, Drainagerohre
06. Mai	Harbach	27	10	nicht mehr sichtbar -> Wegkante, neue Verbauung	Lockermaterial	Fotos verloren?
06. Mai	Harbach	28	63 an Wegkante	schon hergerichtet , nicht mehr wirklich sichtbar	Lockermaterial	kreuzt die Straße 3x; oberste Anrisskante = Wegkante - bischen drüber (15m breite?)
06. Mai	Harbach	29	11	120	Lockermaterial	Drainagerohr, Weg in Flucht

06. Mai	Harbach	32	10 bis 15	30 bis 50	Lockermaterial	10m über Weg
06. Mai	Harbach	33	10 bis 50	60 bis 80	Lockermaterial	viele Rutschungen über gesamten Hang, 2 Forstwege/Traktor zufahrten im Hang, tw. Anbrücke direkt an Wegkante - Wiesenversatz; gesamte Bewegung November 2019 (grundsätzlich anfälliges Gebiet - Moränengebiet)
08. Mai	Kötschachtal	34	9x9	30-40	Bedrock	steiler Abfall in Gerinne/ Seitenariss
08. Mai	Kötschachtal	35	2-10m Seitenanrisse neben Gerinne	Grasnarbe	Bedrock	oberhalb WeißeWand -> Wasser
08. Mai	Kötschachtal	36	8	120-160	Bedrock	selber Gerinneauslauf wie 34, Anbrauch an Wegkante Wanderweg Poserhöhe
08. Mai	Kötschachtal	37	5bis10m um Abflussrinne, Ausbildung Rinne durch Ereignis ? Oder schon vorhanden ?	Grasnarbe	Bedrock	Seitlicher Einfluss in Bach; Punktaufnahme Einfluss Rutschung in Bach
08. Mai	Kötschachtal	38	20-30			Foto von gegenüberliegend em Hang, Anbruch direkt bei Forstweg…

10. Jun	Lenzbaueralmweg	95	120		Lockermaterial	Steinschlichtung aus dem Jahr 2017 wurde weggerissen, eindeutiger Abfluss Gerinne
10. Jun	Ober Laderding	104		Grasnarbe	Lockermaterial	Wasserableitung der Forstwege nicht funktionsfähig - Wasser rinnt zusammmen und dann gesammelt ab; Vielfach einfacher Abbruch der Grasnarben wo die Einleitung durch Drainagerohre erfolgt;sehr steile Böschungswinkel; Am Rand verstopfte Drainagekanaldeckel - Wartung regelmäßig notwending, diese Bauart eher für asphaltierte Straßen geeignet, da dort weniger Geschiebe - für geschotterte Forststraßen wäre besser offene Berggräben
		105			Lockermaterial	
		106			Lockermaterial	
		107			Lockermaterial	
		108			Lockermaterial	Große Rutschung: Fotos 13:42 - Rutschung zwischen Kehre - Straße passiert oberhalb und unterhalb der Anbruchstelle; zu steile Böschungswinkel - außerdem nicht einheitlich geböscht - Grasüberhang schlecht für Wasserableitung an Böschung - unterspülen und schießen --> fördert

						die Erosion durch Wasseraufprall
10. Jun	Privatweg Laderding	kein punkt			Lockermaterial	
10. Jun	Angertal	84			Lockermaterial	Steinverschlag wurde nach hinten versetzt - Straße talseitig gesessen
		85			Lockermaterial	Bild_143310 - Felsblöcke, konnten auch vom Bagger nicht entfernt werden - möglicherweise Festgestein nicht weit?
		86			Lockermaterial	
		87			Lockermaterial	Wald?
		88			Lockermaterial	
10. Jun	Streitberg	89			Lockermaterial	Weg - Wasserableitung über Spurrinnen, fließt dann gesammelt irgendwo unkontrolliert ab
	Oberreitweg	90			Lockermaterial	
		91			Lockermaterial	
		92			Lockermaterial	

		93			Lockermaterial	Gerinne - Wald abgeholzt zur Entlastung - besondere Belastung auch durch Laubwald bei größeren Schneefällen, Ausperrung von Vieh, Gerinne spült auch unterhalb des Weges

APPENDIX_2: Interview Material – Wolfgang Fannigner damage maps

Figure 42: Documented damage on forest roads section 1 (source: W. Fanninger)

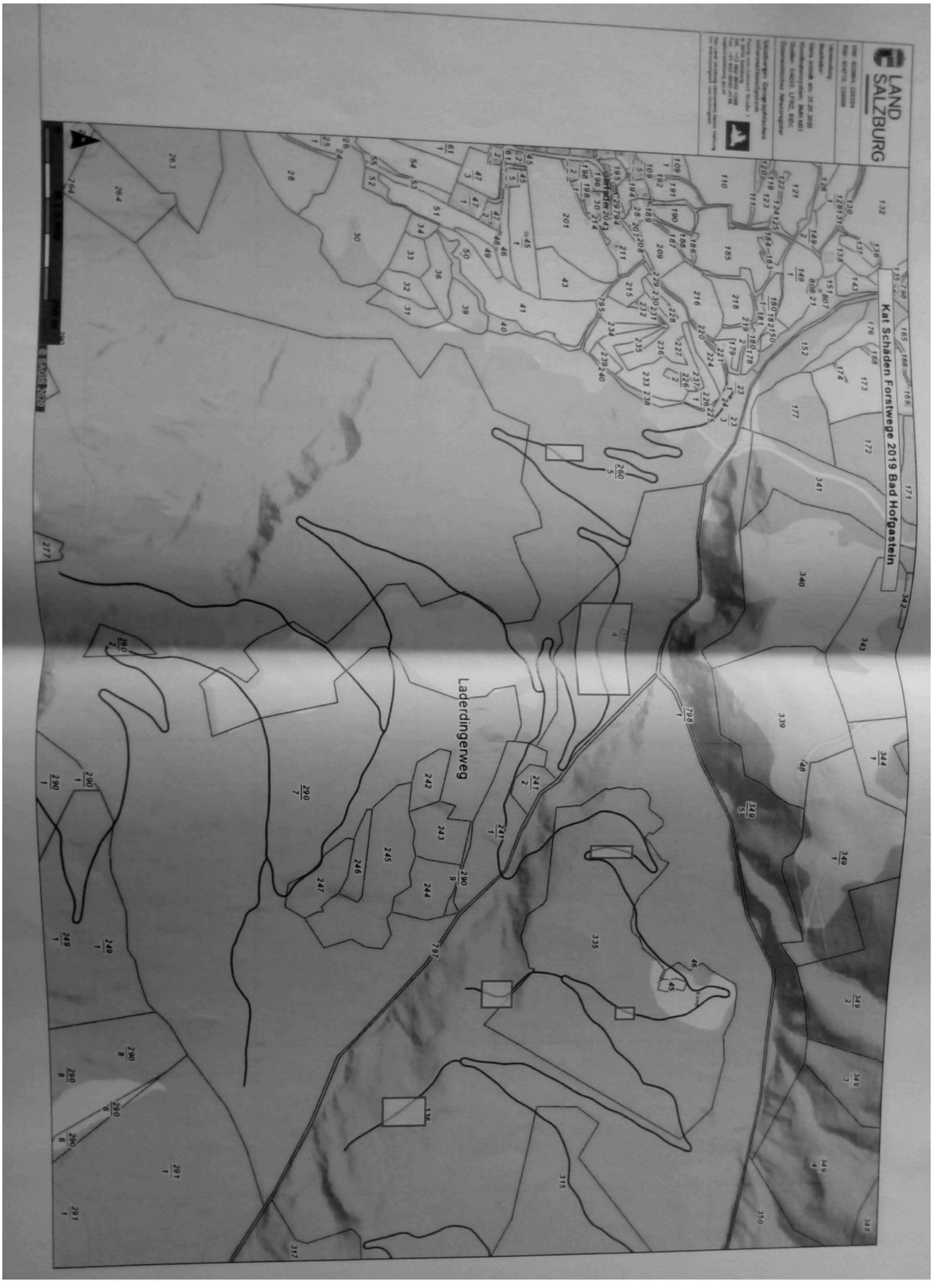


Figure 43: Documented damage on forest roads section 2 (source: W. Fanninger)

Figure 44: Documented damage on forest roads section 3 (source: W. Fanninger)

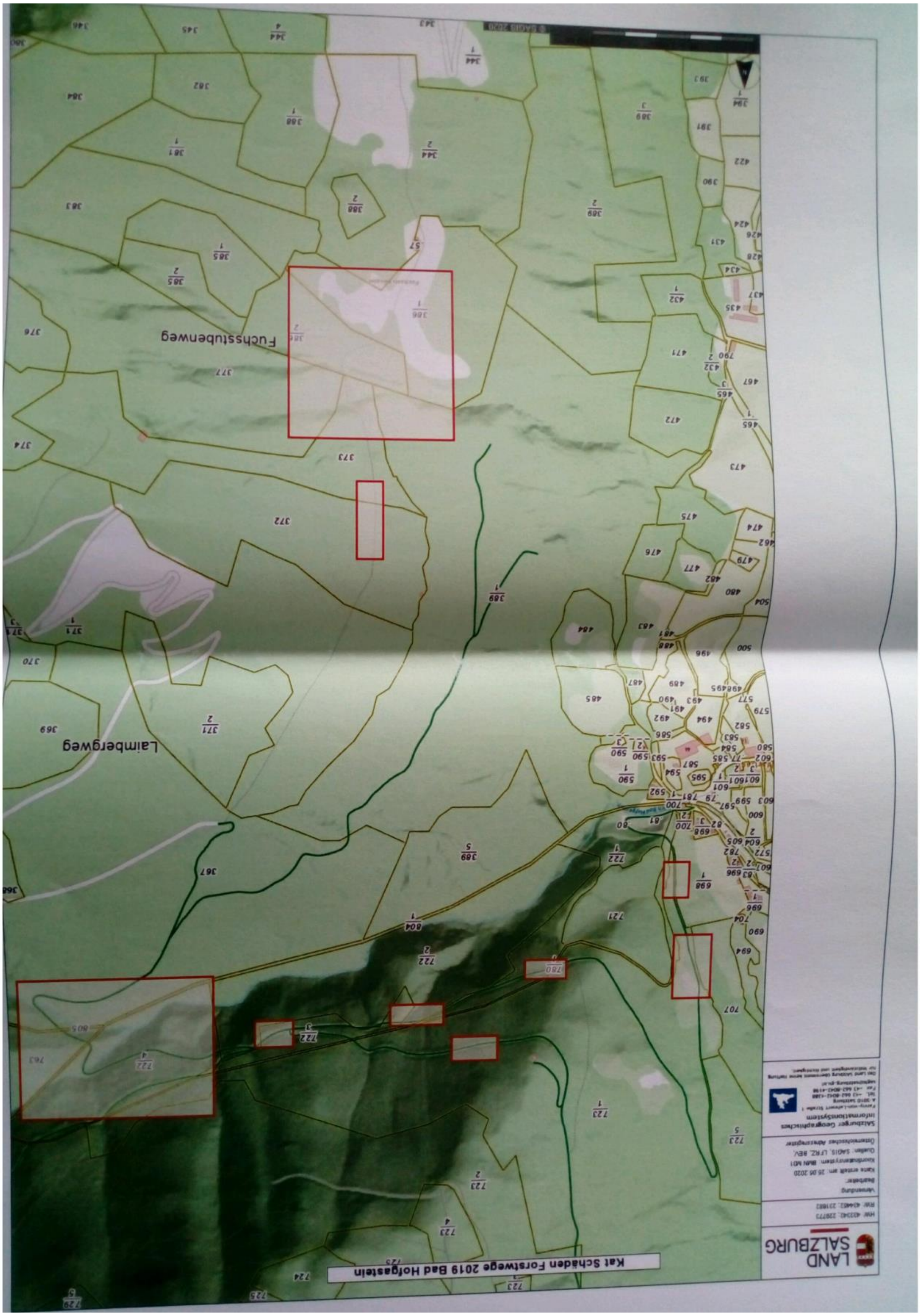


Figure 45: Documented damage on forest roads section 4 (source: W. Fanninger)

Figure 46: Documented damage on forest roads section 5 (source: W. Fanninger)

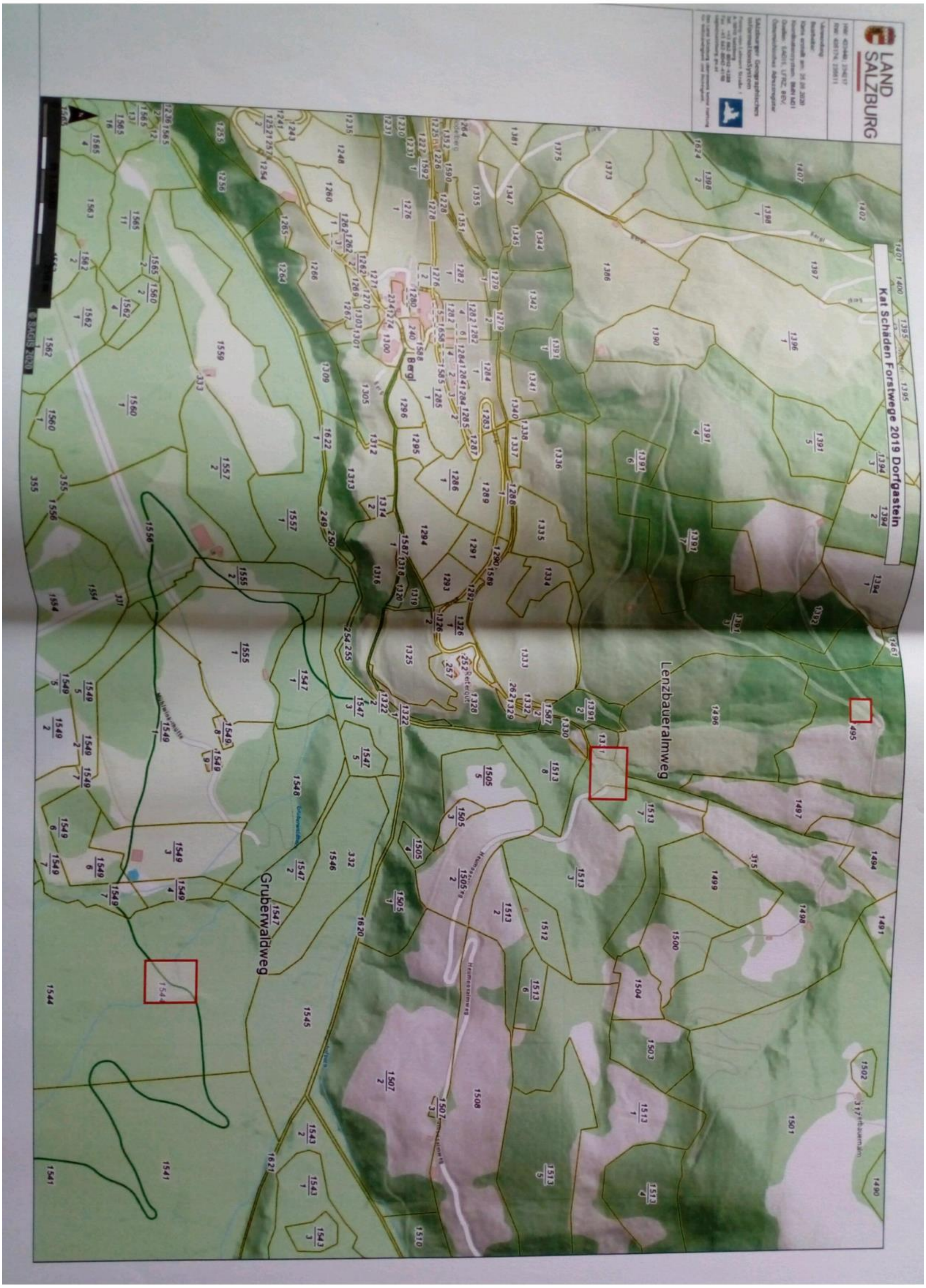


Figure 47: Documented damage on forest roads section 6 (source: W. Fanninger)

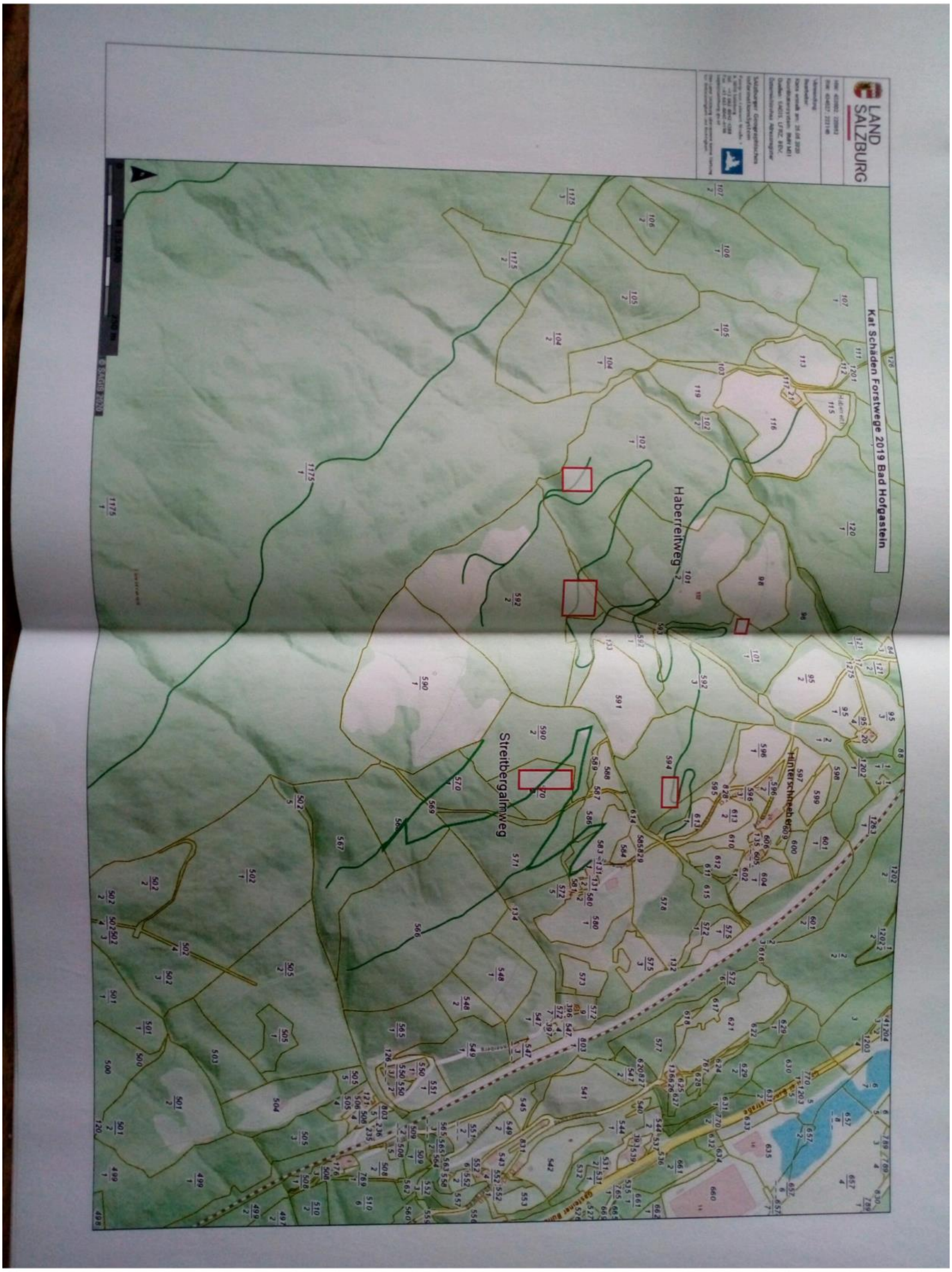


Figure 48: Documented damage on forest roads section 7 (source: W. Fanninger)

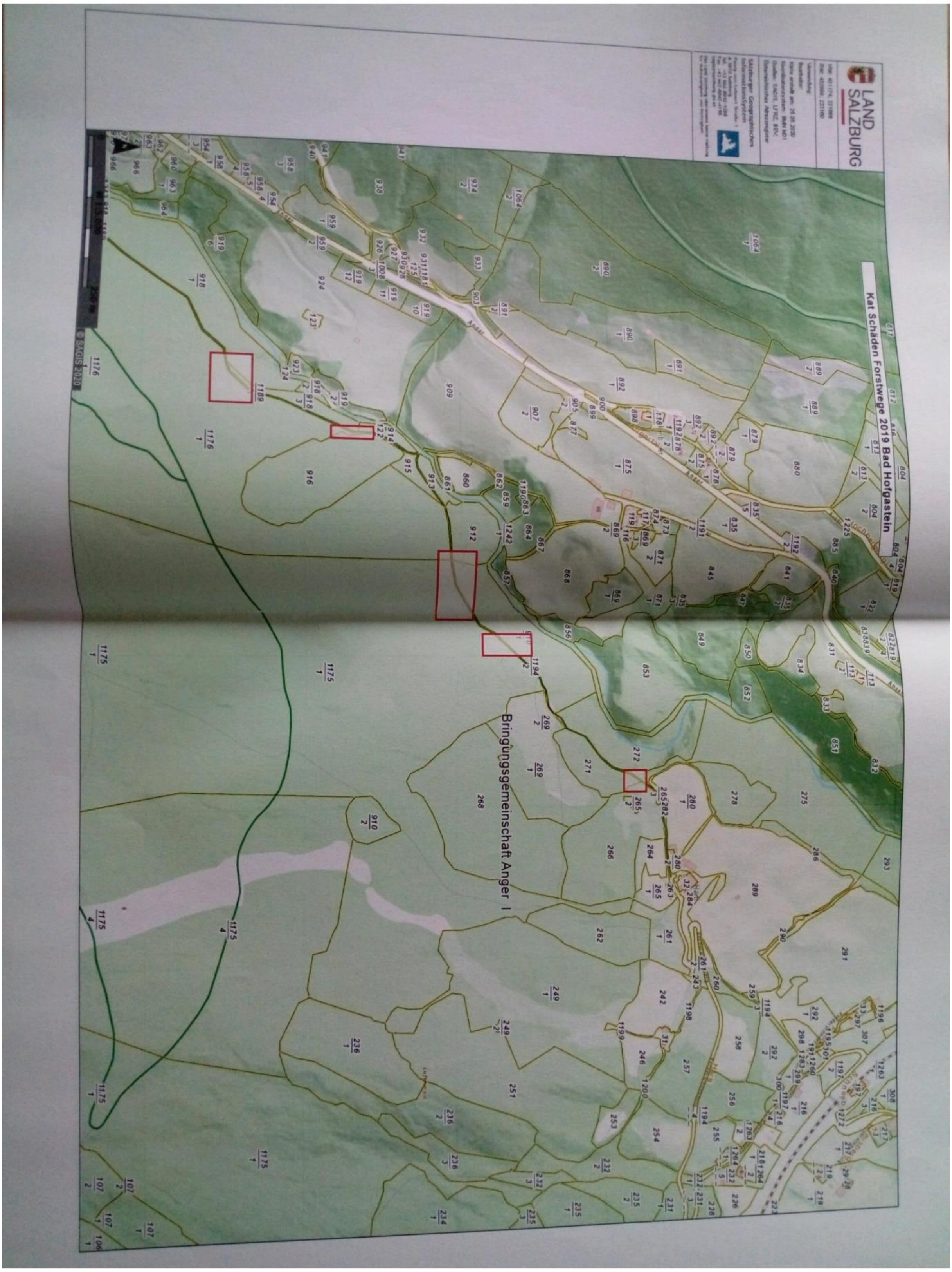


Figure 49: Documented damage on forest roads section 8 (source: W. Fanninger)

APPENDIX_3: Overview on documented events (QGIS)

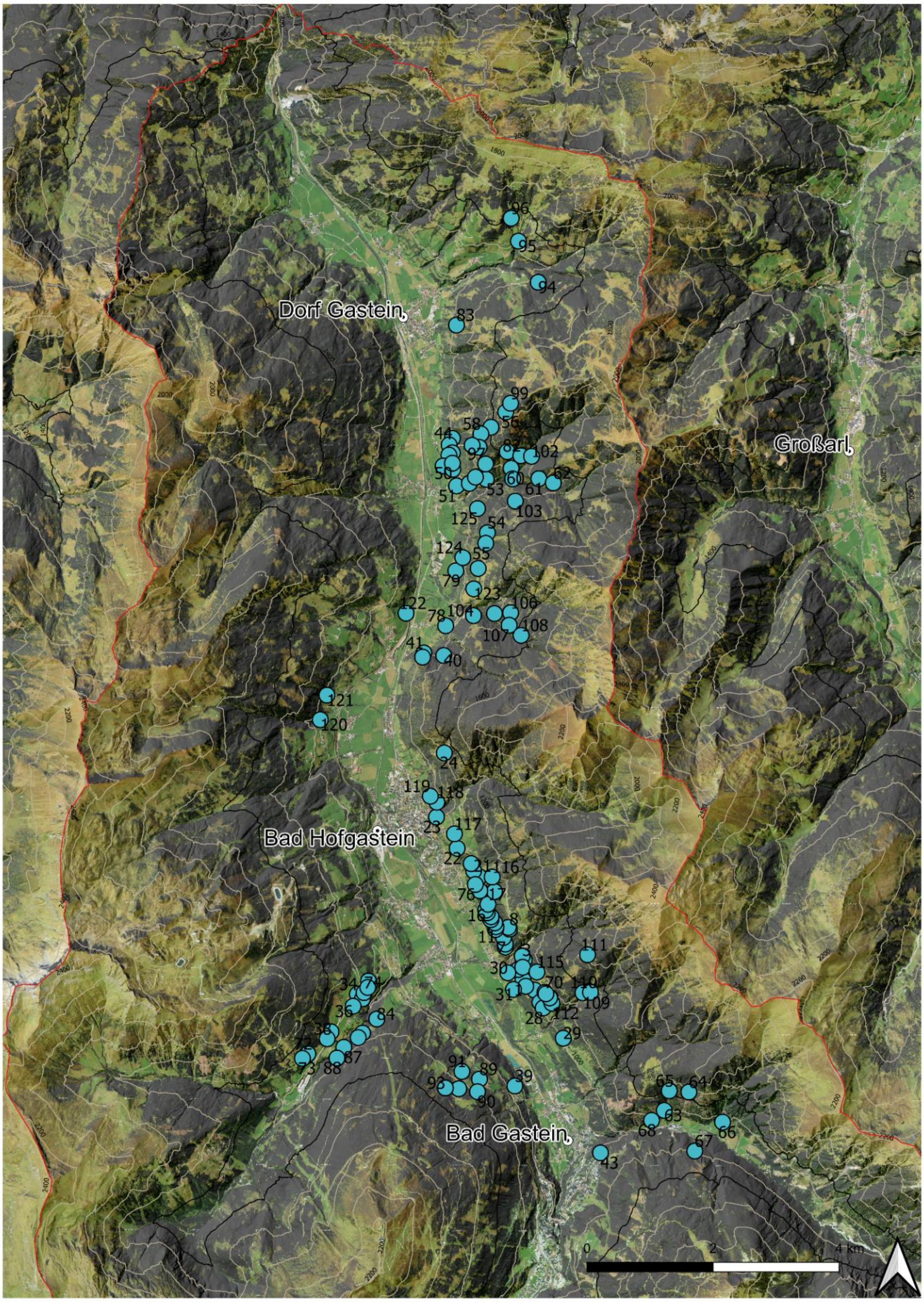


Figure 50: Overview on documented events with numbered FID

APPENDIX_4: Calculation: Excel Table of different Calculations

Calculations – Frequency distribution/ Instability Index - Excel

1. Extraction Areas according to defined land-use classes from Qgis (Quick OSM – landuse)

				proz.Fläche	
Forest	134,85	km²	Wald	78,30	%
Meadow	28,01	km²			
farmyard	0,52	km²	Landwirtschaft	16,56	%
Industrial	0,32	km²			
residential	4,73	km²			
commercial	0,04	km²	Siedlung/Verkehr	3,70	%
grass	0,51	km²			
Scrub	1,77	km²			
grassland	0,20	km²	naturnahe Fl	1,45	%

2. Berechnung relevante Fläche für Straßennetz

Berechnungsannahmen ohne Puffer:				
Breite FS: b	3,5	m	0,0035	km
Länge FS Netz: l	330	km		
Fläche FS		b*l	1,155	km²
Breite WW: b	1,5	m	0,0015	km
Länge WW Netz: l	52	km		
Fläche WW		b*l	0,078	km²

Berechnungsannahmen Puffer 25m:				
Breite FS: b	53,5	m	0,0535	km
Länge FS Netz: l	330	km		
Fläche FS		b*l	17,655	km²
Breite WW: b	51,5	m	0,0515	km
Länge WW Netz: l	52	km		
Fläche WW		b*l	2,678	km²

Längenberechnung QGIS – Datensatz QuickOSM

Fläche ohne Puffer:			Fläche mit Puffer 25m:		
Fläche Forststraßen:	1,150	km²	Fläche Forststraßen:	17,655	km²
Fläche Wanderwege:	0,078	km²	Fläche Wanderwege:	2,678	km²

Summe	1,228	km²	Summe	20,333	km²
proz.Anteil Wege:	0,718	%	proz.Anteil Wege:	11,891	%
proz.Anteil kein Weg:	99,282	%	proz.Anteil kein Weg:	88,109	%

Bezogen auf Gesamtfläche Untersuchungsgebiet 173km².

Fläche gesamtes Straßennetz			Fläche gesamtes Straßennetz_Puffer25m		
Fläche	4,801	km²	Fläche	73,392	km²
proz.Anteil Straße	2,808	%	Proz. Anteil Straße	42,920	%
Proz. Anteil keine Straße	97,192	%	Proz Anteil keine Straße	57,080	%

3. Flächenanteilsberechnung Klassen, inklusive Straßennetz GS

	ohne Wege	mit Wege	mit Wege gepuffert 25m	Proz. Anteil
Forest	134,855 km²	133,885 km²	77,391 km²	44,56 %
Agricultural area	28,527 km²	28,318 km²	16,373 km²	9,43 %
Residential	5,088 km²	6,316 km²	78,480 km²	45,19 %
Near-natural area	2,488 km²	2,476 km²	1,426 km²	0,82 %
Gesamtfläche:			173,670 km²	

4. Extraktion Anteilsmäßige Verteilung Massenbewegungsprozesse GR

Datengrundlage: Field mapping

proz.Anteil Hangmuren mit Wegeinfluss	yes	55,70	%
proz.Anteil Hangmuren ohne Wegeinfluss	no	44,30	%
proz.Anteil Hangmuren im Wald		18	%
proz.Anteil Hangmuren nicht im Wald		82	%
proz.Anteil Hangmuren Siedlung/Verkehr		61	%
proz.Anteil Hangmuren nicht Siedlung/Verkehr		39	%
proz.Anteil Hangmuren Landwirtschaftlicher FL		17	%
proz.Anteil Hangmuren nicht Landwirtschaftlicher FL		83	%

5. Berechnung Instabilitätsindex

Puffer25m für Wege

Instabilitätsindex Wald	forest	0,22989323	0,38606027
Instabilitätsindex kein Wald	no forest	3,77831734	0,90857476
Instabilitätsindex Verkehr/Siedlung	residential area	16,5137364	1,43243828
Instabilitätsindex nicht Verkehr/Siedlung	no residential area	0,40495875	0,67926183
Instabilitätsindex Landwirtschaftliche FL	agricultural area	1,02650984	1,74381171
Instablititätsindex keine Landwirtschaftliche FL	no agricultural area	0,99473833	0,91965494

Ohne Puffer		
Instabilitätsindex Weg		77,555419
Instabilitätsindex kein Weg		0,44624265
Mit Puffer 25m nur Forststraßen und Wanderwege		
Instabilitätsindex Weg		4,68391554
Instabilitätsindex kein Weg		0,50282913
Gesamtes Straßennetz mit Puffer 25m		
Instabilitätsindex Weg	road	1,29767
Instabilitätsindex kein Weg	no road	0,77617

APPENDIX_5: Soil profiles SAGIS

STANDORTSBESCHREIBUNG

Kennzahl:	**503154**	***Erhebungsdatum:***	**25.09.90**
Nutzungsform:	**extensives Grünland**		Grundrasterpunkt
Lagedaten:	Heißingfelding, BAD HOFGASTEIN GB: Gastein		
ÖK-Nr:	155	***BMN-Koordinaten:***	

Seehöhe:	1750 m	***Exposition:***	SW	***Hangneigung:***	69 %
Geländeform:	Unterhang	***Kleinrelief:***	unruhig		

Grundgestein:	Glimmerschiefer, Phyllit, basenreich (z.B. Kalkglimmerschiefer, Kalkphyllit
Bodentyp/Norm:	Pseudogley auf Lockersedimenten; tiefgründig
Bodentyp:	Alpin pseudovergleyter Farbortsboden
Bodenhydrologische Verhältnisse:	Oberflächenabfluß
Wasserhaushalt:	gut versorgt
Nutzung:	Almen und Bergmähder; geringe Intensität
Bewirtschaftung:	
GVE/ha:	0

Anmerkung:

Lage/Vorkommen:	Steilhang, Schuttkegel, südwestschauend. Hangunterteil
Muttergestein:	Schuttmaterial aus Kalkglimmerschiefer. Dunkelgraue Schiefer, teilweise Grünschiefer und vereinzelt Quarze.
Bodentyp:	Alpin pseudovergleyter Farbortsboden
Humus:	Ao moderartiger Auflagehumus
Kalkgehalt:	Tief entkalkt, Gestein oft kalkhaltig.
Wasserhaushalt:	Gut versorgt oder wechselfeucht mit überwiegender Feuchtphase (Schneelage, hohe Taubildung) aber hohe Durchlässigkeit und geringe Speicherkraft.
Erosion:	Mäßig rutsch- und abschwemmgefährdet, durch Vegetation geschützt, mäßig lawinengefährdet
Lagerung:	Locker - lose Lagerung
Bewirtschaftbarkeit:	Alm buckelig, einige Viehgangeln
Schwankung:	tiefgründig, in Umgebung Hangvernässungen
Nutzung:	Alm
Sonstiges:	
Pflanzenbestand:	Bürstling, Eisenhut, Zittergras, Rispe, Thymian, Fingerkraut, Frauenmantel, Nelkwurz, Almrosenbüsche, vereinzelt Wacholder, kleiner lockerer Lärchen- und Fichtenbestand.

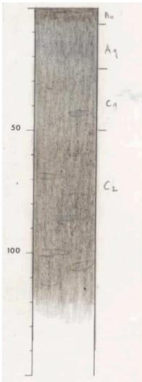
Land Salzburg
Für unser Land!

Datenquelle: Salzburger Bodenzustandsinventur
Amt der Salzburger Landesregierung
Abteilung Land- und Forstwirtschaft
Referat Agrarwirtschaft, Bioenergie und Bodenschutz

Profilbeschreibung Kennzahl: 503154

Bodentyp: Alpin pseudovergleyter Farbortsboden

Nutzung: extensives Grünland



Ao 0-6 cm
Bodenart: uS; stark humos; Moder
Bodenfeuchte: erdfrisch; geringer Anteil Grus und Steine; Farbe: 10YR3/1; einzelne deutliche mittlere Bleichflecken
einzelne deutliche kleine Rostflecken;
kalkfrei;
zerfallend; keine Regenwurmtätigkeit; Wurzelfilz; allmählich übergehend

Ag 6-25 cm
Bodenart: sU; Humusflecken
Bodenfeuchte: erdfrisch; mäßiger Anteil Grus und Steine; Farbe: 5Y3/1; viele deutliche mittlere Bleichflecken
einzelne deutliche kleine Rostflecken;
kalkfrei; undeutlich Struktur feinkrümelig;
zerfallend; geringe Regenwurmtätigkeit; stark durchwurzelt; allmählich übergehend

C1 25-50 cm
Bodenart: sU;
Bodenfeuchte: erdfrisch; mäßiger Anteil Grus und Steine; Farbe: 10YR4/1;
kalkfrei; undeutlich Struktur feinkrümelig;
zerfallend; viele Grobporen; geringe Regenwurmtätigkeit; mittel durchwurzelt; allmählich übergehend

C2 > 50 cm
Bodenart: sU;
Bodenfeuchte: erdfrisch; hoher Anteil Grus und Steine; Farbe: 2`5Y4/2;
kalkfrei;
zerfallend; geringe Regenwurmtätigkeit; schwach durchwurzelt;

Kennzahl: 503154 Nutzung: extensives Grünland

Tiefenstufe	pH-Wert	Karbonate (%)	Gesamt-N (%)	C/N-Verhältnis	Org-C (%)	Gesamt-S
0-10 cm	4,3	0	0,28	10,79	3,02	0,02
10-20 cm	5,3	0	0,25	8,32	2,08	0
20-30 cm	5,6	0	0,19	6,95	1,32	0,01
30-50 cm	5,9	0	0,16	7,94	1,27	0
50-70 cm	5,9	0	0,12	7,75	0,93	0

Austauschbare Kationen in mval/kg:

Tiefenstufe	Kalzium	Magnesium	Kalium	Natrium	Aluminium	Eisen	Mangan	H+	KAK	V (%)
0-10 cm	57,65	3,46	1,38	0,3	0,78	0,21	3,05	5,5	72,33	87
10-20 cm	40,59	1,48	0,36	0,26	0,22	0,05	0,91	5,9	49,77	86
20-30 cm	32,25	1,15	0,56	0,17	1,23	0	0,33	7,6	43,29	79
30-50 cm	29,51	1,15	0,36	0,35	0,11	0	0,22	2,3	34	92
50-70 cm	18,73	0,74	0,46	0,35	0,22	0	0,18	14,9	35,58	57

Gesamtgehalt (Königswasserauszug) in ppm:

Tiefenstufe	Kalzium	Magnesium	Kalium	Natrium	Aluminium	Eisen	Mangan	Phosphor	Arsen	Bor
0-10 cm	1660	5890	440	50	10730	34980	800	390	25,1	5
10-20 cm	1040	6850	580	70	12200	39410	850	380	37,3	16
20-30 cm	5340	19110	2750	260	22000	35960	430	580	10,1	22
30-50 cm	740	6450	480	60	11330	39810	1340	420	12	21
50-70 cm	470	6260	320	30	10570	38200	1330	370	8,8	8

Tiefenstufe	Cadmium	Kobalt	Chrom	Kupfer	Quecksilber	Nickel	Molybdän	Blei	Vanadium	Zink
0-10 cm	0,88	12	18	33	0,08	33	2	46	20	77
10-20 cm	0,94	12	22	31	0,08	32	2	50	24	101
20-30 cm	0,94	20	63	20	0,01	31	1	25	111	48
30-50 cm	0,94	14	21	35	0,11	36	2	36	21	82
50-70 cm	0,95	15	19	35	0,1	37	2	30	19	85

Fraktionsanteil der Korngröße in %:

Tiefenstufe	630 - 2000 µm	200 - 630 µm	63 - 200 µm	40 - 63 µm	20 - 40µm	10 - 20 µm	6,3 - 10 µm	2 - 6,3 µm	1 - 2 µm	0 - 1 µm
0-10 cm	17,6	14,3	33,7	0,2	1,6	3,9	2,6	6,6	3,4	16,1
10-20 cm	15,6	14,4	26,2	0,1	2,1	3,7	2,7	8,7	3,9	22,7
20-30 cm	17,4	15,6	26,8	0,6	3	4,1	2,2	5,7	3,3	21,2
30-50 cm	18	16,9	28,7	0,7	3,4	4,3	2,6	6,2	2,5	16,6
50-70 cm	26,4	17,1	24,8	0,2	2	3,2	2,1	5,5	2,6	16,1

APPENDIX_6: Event analysis

FID: 1	
Location:	Höhenweg Bad Hofgastein

Figure 51: Photo documentation FID 1 (photo: Magdalena Pescoller)

Type of mass movement:	Debris/soil slide – fill slope slide
Type of road:	track/ terrace ("befahrene Geländekante")
Impact of forest road:	Fill slope inclination/ soil structure

FID: 4	
Location:	Höhenweg Bad Hofgastein

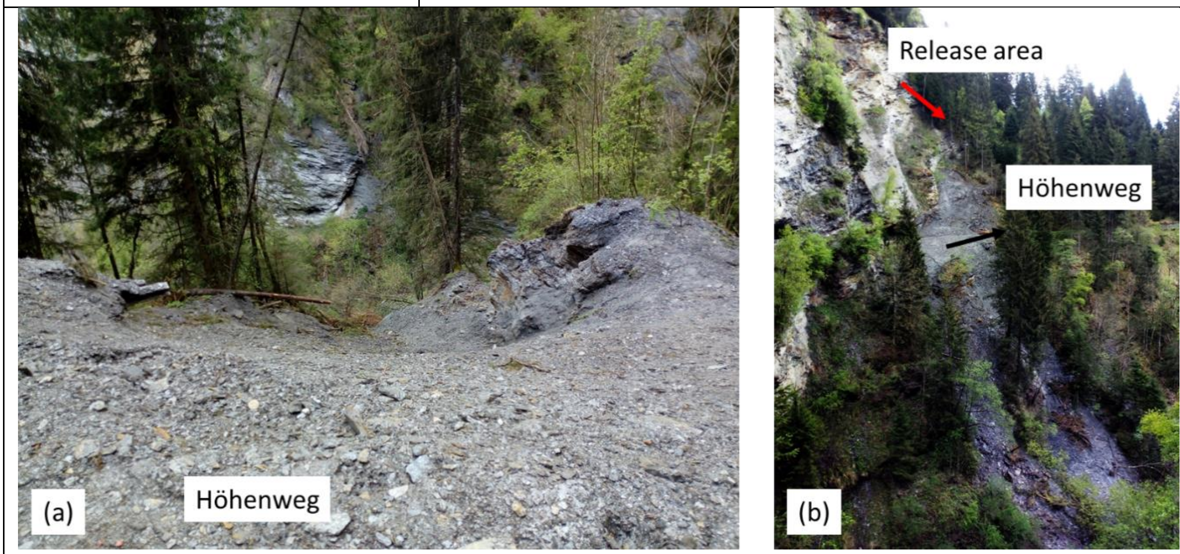


Figure 52: Photo documentation FID 4 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide - cut slope slide
Type of road:	Foot path
Impact of forest road:	Sediment production/ erosion – cut slope inclination?

FID: 5	
Location:	Höhenweg Bad Hofgastein

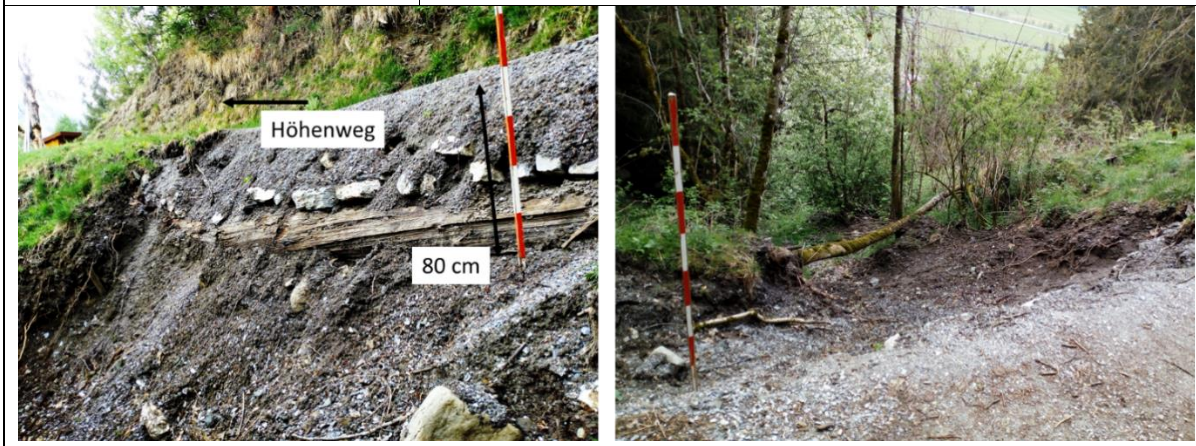


Figure 53: Photo documentation FID 5 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide – fill slope slide
Type of road:	Foot path
Impact of forest road:	Fill slope inclination and overland flow

FID: 6	
Location:	Höhenweg Bad Hofgastein

Figure 54: Photo documentation FID 6 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide – fill slope slide
Type of road:	Terrace, also used as track
Impact of forest road:	Concentrated surface runoff by the drainage system; culvert downslope → high water table/soil water saturation?

FID: 8	
Location:	Höhenweg Bad Hofgastein

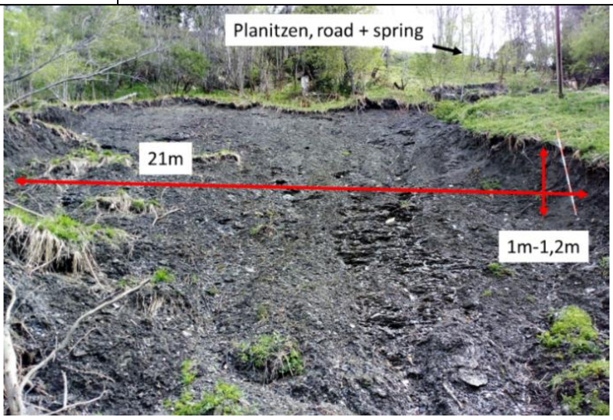


Figure 55: Photo documentation FID 8 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide
Type of road:	street
Impact of forest road:	surface runoff + spring – Winkler, bestätigung Sagis (Abholzung 2005/6 – Winkler), no direct road connection…

FID: 10	
Location:	Höhenweg Bad Hofgastein


Figure 56: Photo documentation FID 10 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide – fill slope slide
Type of road:	Foot path
Impact of forest road:	Fill slope inclination and overland flow

FID: 13	
Location:	Höhenweg Bad Hofgastein

Figure 57: Photo documentation FID 13 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide – fill slope slide
Type of road:	Foot path
Impact of forest road:	Fill slope inclination and overland flow

FID: 14	
Location:	Höhenweg Bad Hofgastein

Figure 58: Photo documentation FID 14 (photo: Magdalena Pescoller)

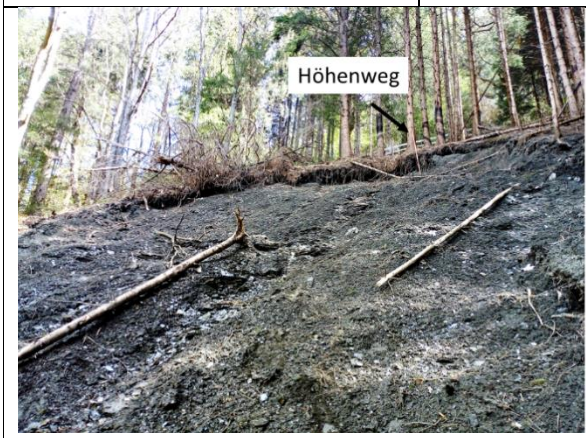
Type of mass movement:	debris slide – fill slope slide
Type of road:	Foot path
Impact of forest road:	Fill slope inclination – sudden change of inclination, terrain pointed edge/ transition carriage way-fill slope

FID: 15	
Location:	Höhenweg Bad Hofgastein

Figure 59: Photo documentation FID 15 (photo: Magdalena Pescoller)

Type of mass movement:	hillslope debris flow
Type of road:	Foot path
Impact of forest road:	Overland flow, transition carriage way- fill slope

FID: 16	
Location:	Höhenweg Bad Hofgastein



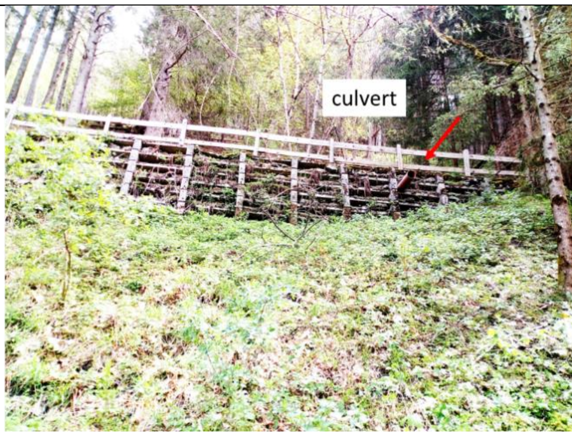


Figure 60: Photo documentation FID 16 (photo: Magdalena Pescoller)

Type of mass movement:	debris slide
Type of road:	Foot path
Impact of forest road:	Water routing, drainage – soil erosion

FID: 17	
Location:	Höhenweg Bad Hofgastein

Figure 61: Photo documentation FID 17 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide – fill slope slide
Type of road:	Foot path
Impact of forest road:	Overland flow, fill slope inclination

FID: 18	
Location:	Höhenweg Bad Hofgastein

Figure 62: Photo documentation FID 18 (photo: Magdalena Pescoller)

Type of mass movement:	Debris flow
Type of road:	Foot path
Impact of forest road:	Sediment production

FID: 19	
Location:	Höhenweg Bad Hofgastein

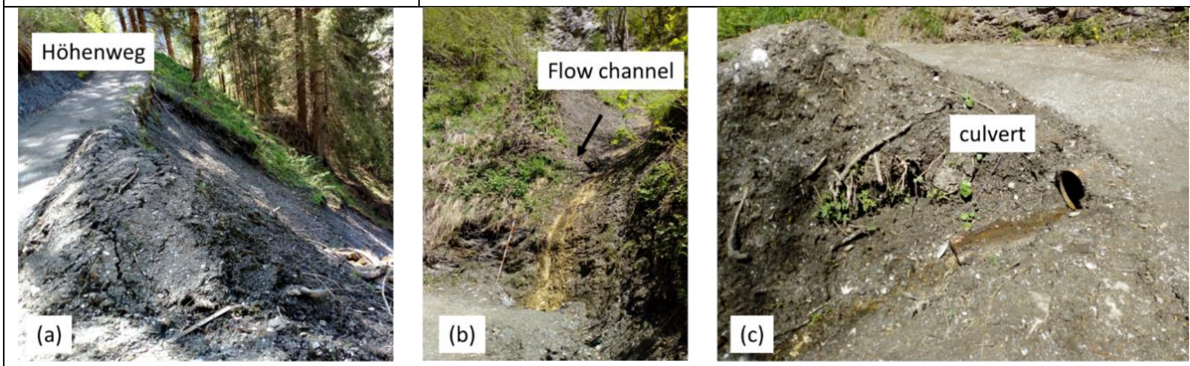


Figure 63: Photo documentation FID 19 (photo: Magdalena Pescoller)

Type of mass movement:	Debris flow
Type of road:	Foot path
Impact of forest road:	Plugged culvert

FID: 25	
Location:	Faschingberg

Figure 64: Photo documentation FID 25 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide -fill slope slide
Type of road:	Foot path
Impact of forest road:	Concentrated surface runoff, drainage system → high water table, soil water saturation

FID: 28	
Location:	Faschingberg

Figure 65: Photo documentation FID 28 (photo: Magdalena Pescoller)

Type of mass movement:	Debris flow/ Hillslope debris flow?
Type of road:	Foot path
Impact of forest road:	Plugged culvert

FID: 31	
Location:	Faschingberg

Figure 66: Photo documentation FID 31 (photo: Magdalena Pescoller)

Type of mass movement:	Debris/soil slide
Type of road:	terrace
Impact of forest road:	Overland flow, change of inclination terrace – slope?

FID: 32	
Location:	Angertal

Figure 67: Photo documentation FID 32 (photo: left hand-side – WLV Salzburg, middle and right hand-side – Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow – fill slope slide
Type of road:	Forest road
Impact of forest road:	Fill slope inclination – soil erosion, overland flow

FID: 37	
Location:	Angertal

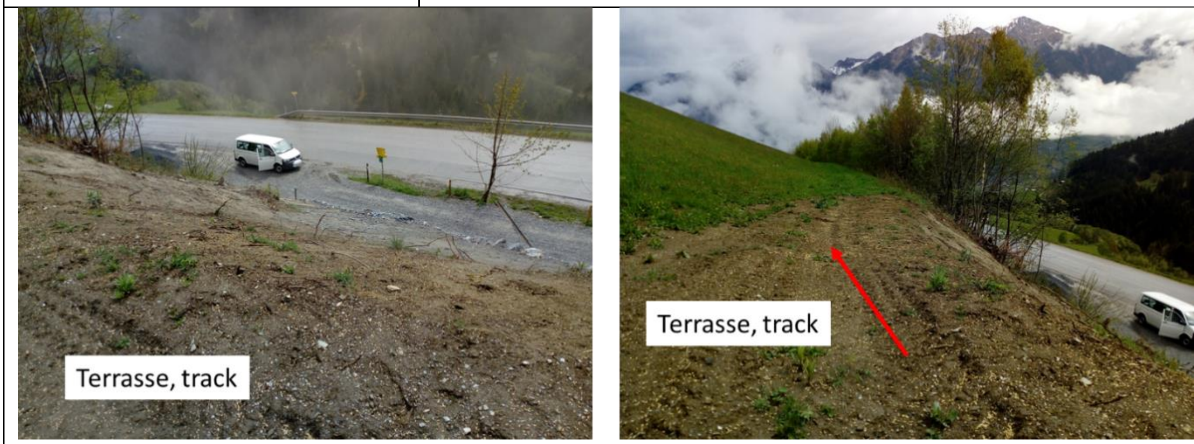


Figure 68: Photo documentation FID 37 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide -fill slope slide
Type of road:	Terrace, track
Impact of forest road:	Transition edge terrace/ artificial break in slope – fill slope, overland flow

FID: 38	
Location:	Angertal

Figure 69: Photo documentation FID 38 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide -fill slope slide
Type of road:	Forest road
Impact of forest road:	Water routing – concentrated surface runoff through a transversal rut

FID: 39	
Location:	Angertal

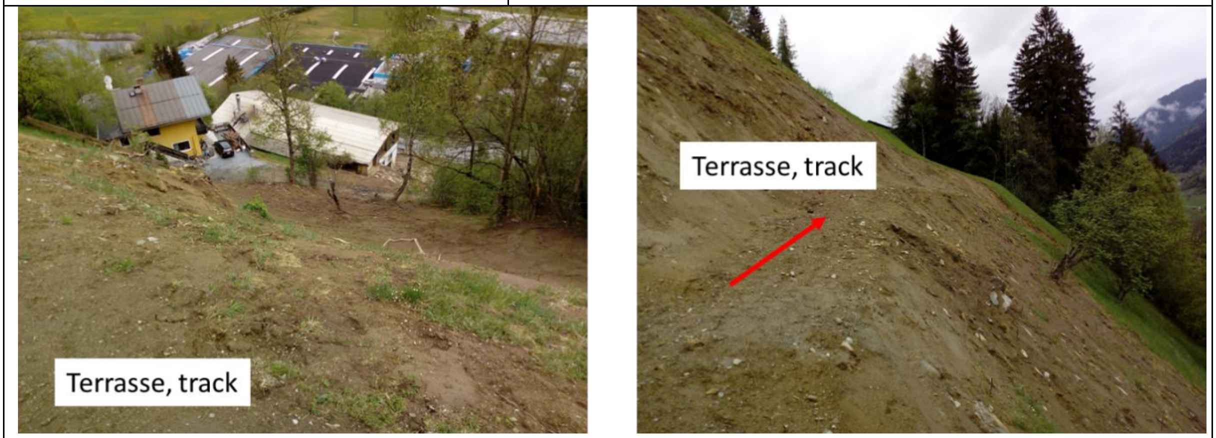


Figure 70: Photo documentation FID 39 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow -cut slope slide
Type of road:	Terrace, track – artificial break in slope
Impact of forest road:	Sediment production

FID: 43	
Location:	Bad Bruck

Figure 71: Photo documentation FID 43 (photo: (a) - Robert Delleske, (b)-(d) - Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow -fill slope slide
Type of road:	Foot path
Impact of forest road:	Slope inclination and overland flow

FID: 48	
Location:	Dorf Gastein

Figure 72: Photo documentation FID 48 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide – cut slope slide
Type of road:	Terrace, track – artificial break in slope
Impact of forest road:	Slope inclination and overland flow

FID: 49	
Location:	Dorf Gastein

Figure 73: Photo documentation FID 49 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow
Type of road:	Forest road
Impact of forest road:	Concentrated road surface runoff through transversal rut

FID: 50	
Location:	Dorfgastein

Figure 74: Photo documentation FID 50 (photo: Magdalena Pescoller)

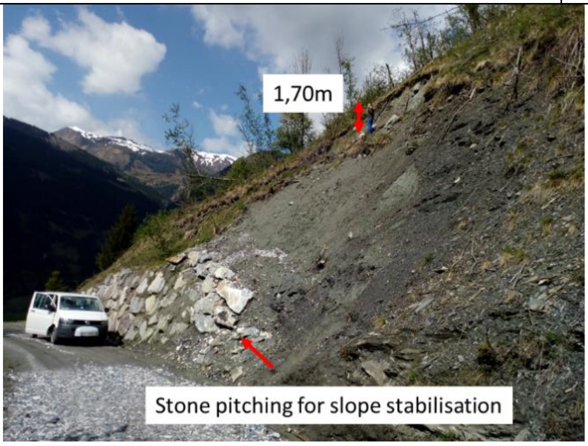
Type of mass movement:	Hillslope debris flow
Type of road:	Forest road
Impact of forest road:	Concentrated road surface runoff through an earth hollow

FID: 51	
Location:	Harbach valley

Figure 75: Photo documentation FID 51 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow – cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope – and fill slope inclination

FID: 52	
Location:	Harbach valley



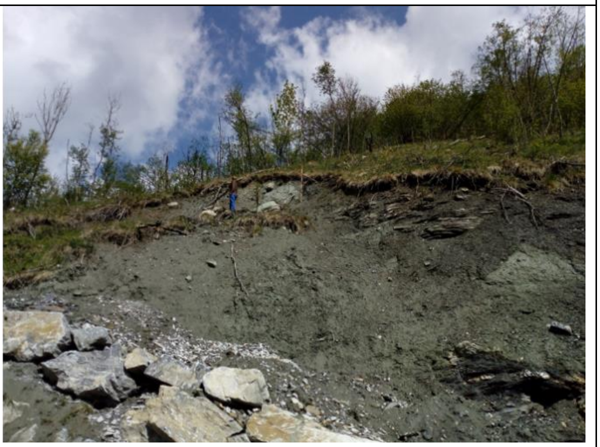


Figure 76: Photo documentation FID 52 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide – cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope inclination

FID: 53	
Location:	Harbach valley

Figure 77: Photo documentation FID 53 (photo: Magdalena Pescoller)

Type of mass movement:	Debris flow
Type of road:	Forest road
Impact of forest road:	Plugged culvert – cut slope inclination

FID: 54	
Location:	Harbach valley

Figure 78: Photo documentation FID 54 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide – cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope inclination, slope toe weakened through hillside ditch

FID: 55	
Location:	Harbach valley

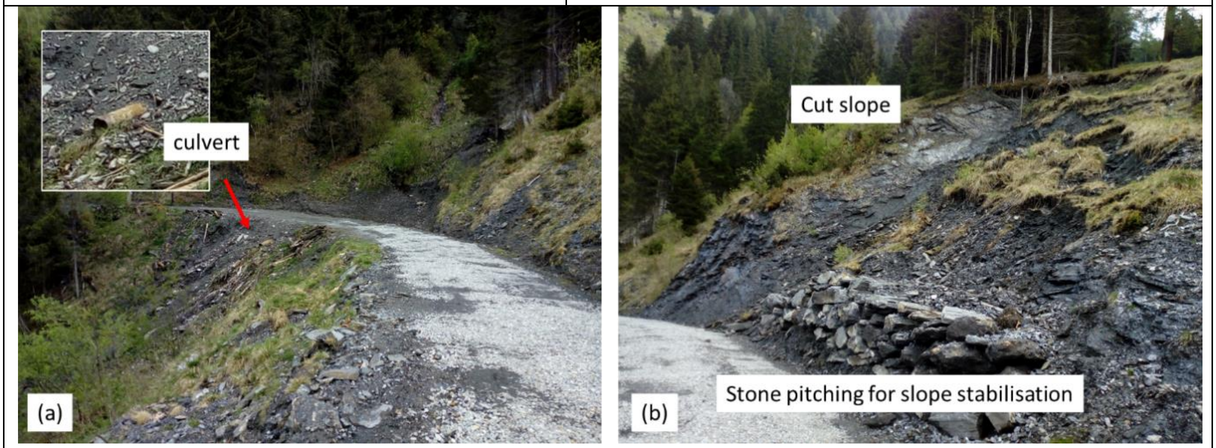


Figure 79: Photo documentation FID 55 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow - cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope inclination + plugged culvert

FID: 57	
Location:	Harbach valley

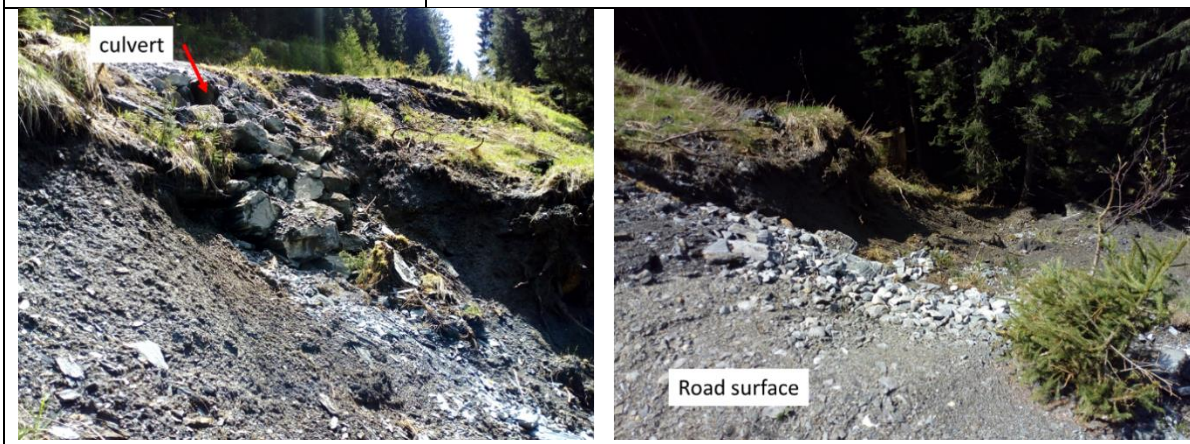


Figure 80: Photo documentation FID 57 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow – fill slope slide
Type of road:	Forest road
Impact of forest road:	Plugged culvert – sudden concentrated road runoff

FID: 59	
Location:	Harbach valley

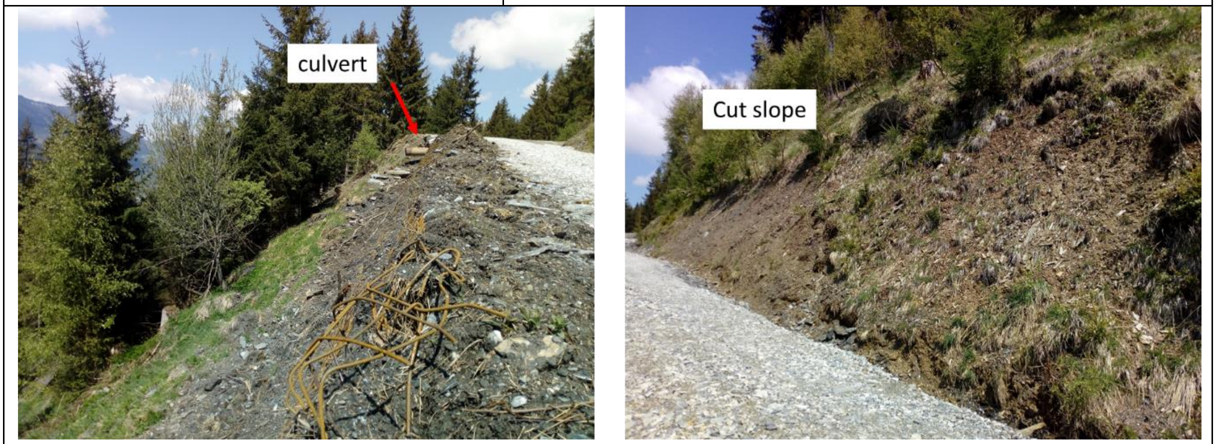


Figure 81: Photo documentation FID 59 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide – cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope inclination + plugged culvert – continuation on fill slope

FID: 62	
Location:	Harbach valley

Figure 82: Photo documentation FID 62 (photo: Magdalena Pescoller)

Type of mass movement:	Debris/soil slide
Type of road:	Forest roads
Impact of forest road:	Soil slides and slumps over the whole hill – high water table? Soil water saturation?

FID: 65	
Location:	Kötschach valley

Figure 83: Photo documentation FID 65 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow -fill slope slide
Type of road:	Foot path
Impact of forest road:	Concentrated road surface runoff through transversal rut, fill slope inclination

FID: 67	
Location:	Kötschach valley

Figure 84: Photo documentation FID 67 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow – cut slope slide
Type of road:	Forest roads
Impact of forest road:	Inclination of cut slope, high water table/ high water availability – see water reservoir?

FID: 74	
Location:	Angertal

Figure 85: Photo documentation FID 74 (photo: (a) - WLV Salzburg, (b) and (c) - Robert Delleske)

Type of mass movement:	Hillslope debris flow - cut slope slide
Type of road:	Forest road
Impact of forest road:	Cut slope inclination

FID: 85	
Location:	Angertal

Figure 86: Photo documentation FID 85 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow - cut slope slide
Type of road:	Forest road
Impact of forest road:	Inclination of cut slope + plugged culverts – fill slope sliding, sediment production

FID: 105	
Location:	Above Laderding

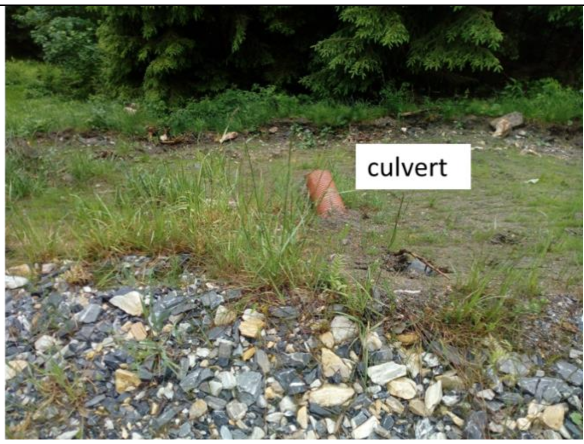


Figure 87: Photo documentation FID 105 (photo: Magdalena Pescoller)

Type of mass movement:	Debris slide -cut slope slide
Type of road:	Forest roads
Impact of forest road:	Cut slope inclination in combination with plugged culverts – continuation fill slope slide, sediment production

FID: 126	
Location:	Above Laderding

Figure 88: Photo documentation FID 126 (photo: Magdalena Pescoller)

Type of mass movement:	Hillslope debris flow
Type of road:	None
Impact of forest road:	Drainage system behind stable/shed – concentrated water inflow – anthropogenic water routing