Debris-flow activity and sediment dynamics in the landslide-influenced Lattenbach catchment, Austria

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Abstract. Deep seated landslides are common phenomena in Alpine areas. In case of a direct connectivity with the channel system, the catchment's sediment yield and the probability of other forms of mass wasting processes such as debris flows may be increased significantly. Up to now, sediment dynamics related to deep-seated landslides and debris flows have not been quantified. The Lattenbach catchment (basin area 5,3 km², relief 2134 m) in Grins (Tyrol, Austria), is an example for an active DF-site, where there is geomorphological evidence of deep-seated landslide activity. In this study we shed light (1) on the location and size of active landslides in the catchment, that may deliver sediment to the channel system. Furthermore, we want to (2) quantify the contributed sediment volumes by these landslides (3) and estimate the exported sediment by debris flow. We apply an image correlation algorithm to high resolution ALS and TLS terrain models of derived over a period of 14 years to calculate surface movement rates within the catchment and locate deep seated landslide activity. We further assess the sediment yield of these landslides to the channel system and relate that with DF-volumes measured by a monitoring station at the catchment outlet. We find that there are five deep-seated landslide bodies directly connected to the channel system in the catchment. These are the largest source of sediment and significantly increases the overall sediment yield of the catchment. Our study shall contribute to the limited knowledge about the importance of deep-seated landslides for sediment dynamics and debris-flow activity, as their presence is predicted to be more frequent in the wake of global warming.

1 Introduction

Deep-seated landslides are a common phenomenon in Alpine areas [1]. Moving at speeds of less than one meter per year, these mass wasting processes can be easily overlooked and their influence on the sediment dynamics underestimated as their appearance is less obvious in nature than that of sudden, fast moving, shallow landslides. The presence of such large mass movements can significantly increase erosion rates [2] and thus the sediment yield from the catchment [3].

In case of a direct connectivity between the slow-moving material and the channel system, small shallow failures at the intersection of the large landslide body with the channel ("inner gorge") may be stochastically triggered by rainfall events to feed the channel with loose material. Subsequently, large amounts of sediment may be relocated within the channel system during periods of elevated discharge, with the potential to initiate devastating debris flows or debris floods. The volumes and timescales of these processes as well as their importance for debris-flow initiation are not well understood.

Expected changes of temperature and precipitation pattern, as well as changes in high-mountain cryosphere, deep-seated landslides are suspected to occur more frequently in the coming decades [4,5]. To assess climate change impact, it is very relevant to quantify the potential amount of sediment contribution in affected catchments.

The Lattenbach catchment in Tyrol (Austria) is an exceptionally well monitored site with a documentation of debris-flow activity dating back to 1900 and an extensive monitoring carried out since 2005. Geomorphological evidence indicates the existence of deep-seated landslides that may influence sediment dynamics and debris-flow initiation. The focus of this study is to (1) identify the location, size and speed of active landslides in the catchment, (2) assess the amount of material that is delivered to the channel system by these landslides, and (3) compare this quantity with the debris-flow exported volumes from the catchment.

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2 Study site

The Lattenbach catchment is situated on the border of the northern calcareous Alps and the crystalline Alps in Tyrol, Austria (Figure 1). The vertical relief amounts to more than 2 km over 4.5 km map distance between the Dawinkopf peak at 2,968 m and the confluence of the Lattenbach and the river Sanna in the village of Pians at 858 m elevation. The total catchment area is about 5.3km². The monthly mean temperature ranges between -1.4 C° and 17.4 C° in the valley and between -5.2 C° and 6.1 C° on the Dawinkopf peak. Due to the shading of the northern mountain range average annual precipitation is low with around 750 mm.

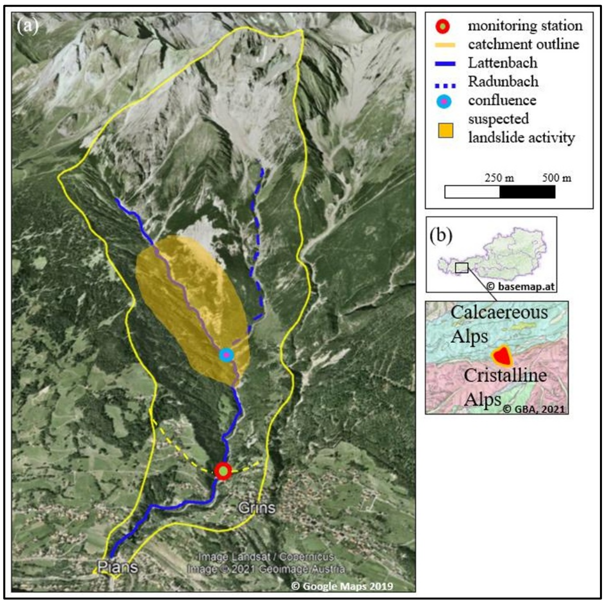

Fig. 1. a) Overview and b) geographic and geologic setting of the Lattenbach catchment. Why use this yellow cyrcle when we know where the landslides are (use maybe map from Leo Schranz).

There are two main channels in the upper part of the catchment, the main stem of Lattenbach on the western side and the Radunbach on the eastern side. Both streams merge at an altitude of 1,160 m around 1.7 km from the catchment outlet. The Lattenbach channel runs along a fault zone that has developed between the northern calcareous Alps and the crystalline Alps in the south. This caused a sequence of weak rocks and stronger formations in the areas near the channel. There are large post glacial deposits (moraines) and scree slopes in the sub-catchment of the Radunbach tributary. In the Lattenbach tributary on the other hand only minor amounts can be identified at first sight. Downstream of the confluence, public mitigation works started in the 1930ies. Since then, a series of check dams over a stretch of about one kilometre were built and are currently replaced. A monitoring station of the BOKU's Institute of Mountain Risk Engineering, measuring timing, speed and flow depth of passing debris flows, has been installed at the lower end of this reach in 2005, about one kilometre from the confluence with the receiving river Sanna. For the scope of this research, we will consider this monitoring station as the catchment outlet, as the area upstream covers the all relevant sediment sources and is the location of debris-flow initiation.

3 Methods

3.1 Identification of active landslides

Since 2006 the Federal Government of Tyrol (Amt für Geoinformation) repeatedly organizes airborne lidar (ALS) campaigns of the whole state area. The Lattenbach study catchment is covered in the surveys of August 16, 2006, September 15, 2016 and September 21, 2019. Lower parts of the catchment have also been covered in a 2012 survey, which we do not include in this analysis. We carried out an additional survey of the identified landslides using a Riegl VZ-4000 long-range terrestrial laser scanner (TLS). To cover the whole area of interest, we scanned from a total of 16 scan positions within and outside the catchment. These different scans were later put together to form a continuous point cloud and registered on the ALS point cloud of 2019, which we considered to be the ground truth. These tasks were performed in the software package RIEGL RiSCAN Pro [6].

The surface displacement was determined using the image correlation algorithm implemented in the open-source software SAGA GIS [7] following procedures described by Bremer [8] and Fey et al. [9]. In general, the image correlation algorithm finds corresponding features in two compared images. Through the application of this method a raster with the three-dimensional displacement vectors in each of the evaluated pixels was calculated for each timestep between 2006 and 2020. From this layer the active landslide areas were delineated visually.

3.2 Sediment import

The downslope flux of sediment in the deep-seated landslide bodies was estimated using average velocities across the delineated landslide bodies. The near channel areas with very large calculated velocities have been excluded due to the lack of visual features present in compared points in time. Without knowing the detailed geometry of the landslide body, we defined the depth of the incised gully at the landslide toe as the representative depth of the landslide. Multiplying this average depth with the average flow velocity and integrating along the affected channel length provided volume estimates for every timestep between the lidar surveys.

3.3 Sediment export

Sediment export was determined from data of a debris-flow monitoring station, which has been in operation since summer 2005. Here, the flow stage during debris-flow events is measured by two radar sensors located above well-defined cross sections. Using a rating curve yields respective cross-section areas. The flow velocity is estimated by measuring the time difference in the flow stage hydrographs and then dividing the sensor distance by this time interval. In 2014 a Doppler radar system was installed, which measures the surface velocity over the whole duration of the debris [10]. A volume estimate is then calculated by multiplying the velocities with the respective wetted perimeter and then integrating over the whole duration of the passing debris flow (see [11] for details).

3.4 Initiation zone

We performed UAV surveys after each debris flow in the 2020 and 2021 season to locate the respective initiation zones. These were carried out with a DJI MAVIC 2 PRO and a DJI PHANTOM 4 RTK using the UAV mission planning software UGCS and AGISOFT METASHAPE PRO to produce digital surface models. We applied a coalignment-of-surveys approach described in Cook et al. [12] and Nota et al. [13] and then calculated and analysed differences between surveys in QGIS 3.22.

4 Results

We find a total of four active landslide bodies in the main stem of Lattenbach creek as well as one at the confluence with the tributary Radunbach (Figure 2). Landslide 1, the largest of the mass movements had a variable depth of 35 m to 50 m, the smaller landslides 2-5 depths between 10 m and 25 m. The average movement rates show a fairly constant movement for landslide 1 and 2, whereas the smaller 3-5 behaved more variable.

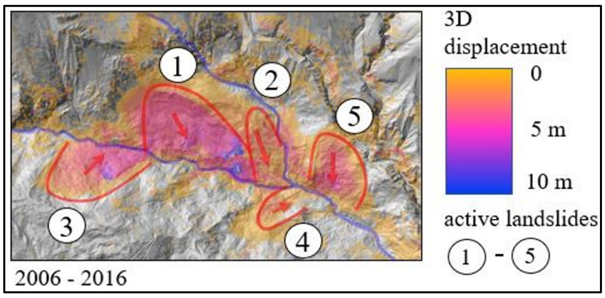

Fig. 2. Displacement of the 5 landslides between 2006 and 2016

Sediment volumes delivered to the channel ("contributed volume") on an annual basis varied between 1,230 m³ for landslide 4 and 18,834 m³ for landslide 1 (Table 1). We calculated a total annual sediment yield of 18,122 m³ between 2006 and 2016. After an acceleration of landslides 3-5, the amount of sediment delivered rose to 29,022 m³ per year between 2016 and 2019. Starting in 2019, the largest landslide – no. 1 – accelerated and contributed 18,834m³ alone, landslide 3 slightly slowed down and delivered 4,788m³. The other three landslides could not be evaluated in the last study period as vegetation cover made processing of the respective parts in the TLS data impossible.

Table 1. Annual contributed volumes by landslides

Lanslide No.	Annual contributed volume 2006-2016	Annual contributed volume 2016-2019	Annual contributed volume 2019-2020
1	11,610	12,900	18,834
2	1,425	3,225	no data
3	2,520	6,384	4,788
4	1,230	3,444	no data
5	1,337	3,069	no data
Total	**18,122**	**29,022**	**23,622**

Between 2005 and 2020, the monitoring station registered 16 debris flows, i.e. an average of one event per year (Table 2). Between 2011 and 2014, no debris flows have been registered, which also fits to the unusually low storm frequency during this time. The largest event happened in 2016 with a total volume of 46,080 m³. Over the whole study period we estimate a total debris-flow volume of 225,683 m³, with an average of 15,712 m³ per year.

Table 2. Annual cumulative debris-flow volumes

Year	**Volume** [m³]
2005	14,568
2007	22,266
2008	14,039
2010	10,000
2015	35,154
2016	46,080
2017	55,268
2018	16,308
2019	8,000
2020	14,000
Total	**235,683**
Annual average	**15,712**

A first analysis of the erosion and deposition patterns in the catchment showed a clear connection between the presence of deep-seated landslides and increased material relocation (Fig. 3). Especially in the parts of the channel along landslides 1 and 2, significant erosion was observed.

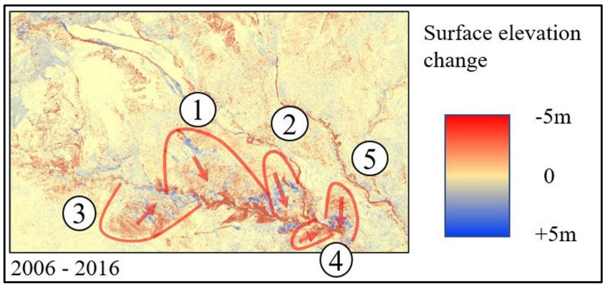

Fig. 3. Erosion and Deposition between 2006 and 2016

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5 Discussion and conclusion

Our results indicate that debris-flow activity is strongly connected to deep-seated landslides located in the Lattenbach catchment. This is in contrast to other well-monitored sites [14-16], where material for debris-flow initiation is mainly derived from channel refill by weathering and hillslope processes.

A first assessment of erosion and deposition at the intersection between the deep-seated landslides and the channel (“inner gorge”) derived from the UAV surveys indicates a rapid channel refill at the time scale of a debris-flow event.

For a detailed sediment budgeting at the catchment scale, there are two main challenges at the current stage of the study. First, we did not assess the amount of suspended sediment and bedload that is exported out of the catchment, when no debris flows are occurring. Furthermore, there are substantial uncertainties about the actual depth of the deep-seated landslides. Despite these limitations, we conclude that the five deep seated landslides within the Lattenbach catchment deliver sediment volumes to the channel system in the order of magnitude of material exported by debris flows. Thus, landslide activity is the most important source of sediment in the catchment and significantly increases the overall sediment yield.

References

1. C. Prager, C. Zangerl, G. Patzelt, R. Brandner, Natural Hazards and Earth System Sciences **8**, 2 (2008)
2. J. J. Roering., L. Stimely, B. Mackey, J. Schmidt, Geophys. Res. Lett. **36** (2009)
3. M. Schwab, D. Rieke-Zapp, H. Schneider, M. Liniger, F. Schlunegger, Geomorphology **97**, 3-4 (2008)
4. A. I. Patton, S. L. Rathburn, D. M. Capps, Geomorphology **340** (2019)
5. M. Jakob, In *Hazards and Disasters Series, Landslide Hazards, Risks, and Disasters (Second Edition),* Elsevier, 505-579 (2022)
6. Riegl Laser Measurement Systems, http://www.riegl.com/products/software-packages/riscan-pro/
7. T. A. Scambos, M. J. Dutkiewicz, J. C. Wilson, Robert A. Bindschadler, Remote Sensing of Environment **42**, 3 (1992)
8. M. Bremer, O. Sass, Geomorphology **138**, 1 (2012)
9. C. Fey, M. Rutzinger, V. Wichmann, C. Prager, M. Bremer, C. Zangerl, GIScience & Remote Sensing 437-461 (2015)
10. R. Koschuch, P. Jocham, J. Huebl, *One Year Use of High-Frequency RADAR Technology* in Alpine Mass Movement Monitoring: Principles and Performance for Torrential Activities, Engineering Geology for Society and Territory - Volume 3. Springer, Cham (2015)
11. J. Huebl, R. Kaitna, Environmental and Engineering Geoscience **27**, 2 (2021)
12. K.L. Cook, M. Dietze, Earth Surf. Dynam. **7** (2019)
13. E.W. Nota, W. Nijland, T. de Haas, International Journal of Applied Earth Observation and Geoinformation **109** (2022)
14. J.A. Coe, D.A. Kinner, J.W. Godt, Geomorphology **96**, 3 (2008)
15. G.L. Bennett, P. Molnar, B.W. McArdell, P. Burlando, Water Resources Research **50**, 2 (2014)
16. F. Comiti, L. Marchi, P. Macconi ,M. Arattano, G. Bertoldi, M. Borga, Natural Hazards **73**, 3 (2014)