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Surface change modelling of small scale debris flow dynamics (Mühlsturzgraben, National Park Berchtesgaden, Germany)

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Abstract

Frequency and magnitude of debris flows are influenced by a combination of predisposition factors and variable disposition factors. Both decide whether and when extrinsic or intrinsic thresholds for the initiation of debris flows are reached. Related knowledge is of particular interest if human settlements or infrastructure are potentially affected. The small but steep catchment 'Großer Mühlsturzgraben' (GMSG) experiences frequent high-runoff events with the activity of debris flows due to both, lithologic preconditioning and location-specific high rainfall intensities at the northern fringe of the Alps. Former studies suggested a local precipitation threshold of 2 mm/10 min to induce debris flows in the area. To test the validity of this threshold the GMSG and the adjacent 'Kleiner Mühlsturzgraben' (KMSG) have been monitored using terrestrial laser scanning (TLS) since August 2015. Climate stations provided local weather data to analyse triggering thresholds of rainfall intensity.

Keywords

Debris Flow, Terrestrial Laser Scanning (TLS), Precipitation Threshold, Surface Change Modelling, Protected Areas

Introduction

Frequency and magnitude of debris flows are influenced by a combination of predisposition factors (e.g., relief, geology, tectonics, climate) and variable disposition factors (e.g., sediment availability, precipitation, snow deposits), whereas both decide whether and when extrinsic or intrinsic thresholds (e.g. slope angle, infiltration capacity, runoff) are reached and debris flows are initiated (ZIMMERMANN et al. 1997). Therefore debris flow triggers and dynamics are still not fully understood.

Debris flow events of high magnitude and frequency occurred in the small but steep GMSG catchment after massive rockfall events in 1999 (216 000 m³), which were investigated by Langenscheidt (2001b; 2002). Based on 11 events in the year 2000, this study suggests a precipitation threshold of 2 mm/ 10 min (so-called 'Rote Ampel' value) for triggering debris flows in the area, which is situated in the Klausbach valley (National Park Berchtesgaden), a popular and highly frequented tourist destination (Fig.1).

This study focusses therefore on i) the quantification of recent surface dynamics in the GMSG catchment, ii) the system parameters controlling debris flow dynamics, iii) the variability of location specific weather parameters, and iv) on the validity of the suggested threshold for triggering debris flows in recent times.

Study Area

The GMSG can be characterized as highly active alpine area due to the local

- geomorphologic characteristics ($A = 0.45\ km^2$, $\Delta h = 1250\ m$, mean slope = 33°; LVG 2009),
- climatic conditions (annual precipitation = 1500 – 2600 mm, intense precipitation events; KONNERT 2004, KRALLER et al. 2012), and
- tectonic setting (Ramsau-Dolomite and Dachstein Limestone on top of ductile Haselgebirge, high tectonic stress, high degree of fractures and faults, susceptible to weathering; LANGENSCHEIDT 1988 and 2001a, FISCHER 2005).

Since the lower Ramsau dolomite is highly susceptible to frost weathering, largest amounts of debris in the GMSG are provided from this unit - predominantly via small-scale rockfall. Intense rainstorms and/or snowmelt are responsible for the initiation of frequent debris flows flushing out the sediments (across the road) into the main Klausbach valley. In contrast, the overlaying massive Dachstein limestone tends to release larger scale rock and blockfall. If such events hit snow avalanche deposits (which often last for several months in the study area) major debris flows can be triggered spontaneously through liquefaction (LANGENSCHEIDT 2001b).

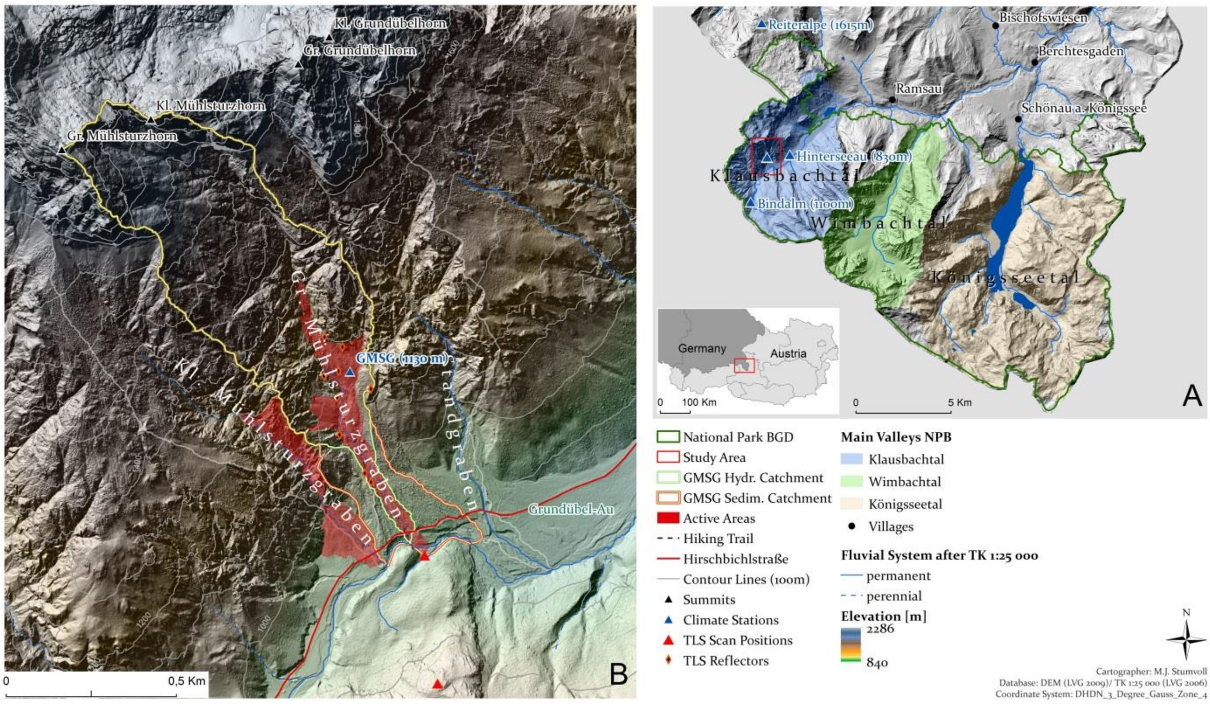

Figure 1: A: Study area in the National Park Berchtesgaden (Database: DEM LVG 2009/ LVG 2006). B: the GMSG (~ 0.055 km²) is situated west of the KMSG (~ 0.042 km²). Active areas (red) correspond to the area surveyed via TLS. Both scan positions, nine reflectors and the weather stations are indicated (STUMVOLL 2016).

Methods

To investigate recent sediment dynamics in the GMSG and the KMSG, surface models were generated using terrestrial laser scanning (TLS) (Riegl LMS Z620i) and compared with each other as well as with a digital elevation model from 2009, based on airborne laser scanning (ALS) (LVG 2009). Five TLS campaigns took place since August 2015, each with two scan positions (Fig.1B). These were registered using both reflectors and an iterative closest point (ICP-) algorithm called Multi Station Adjustment (MSA) (RiSCAN Pro). To compare TLS and ALS data, the project was transferred into a global coordinate system and (fine) registered via a second MSA. After filtering and triangulation of the data, mesh-based surface change volumes were calculated for different time slices (Fig.3; Tab.1). Resulting surface changes are interpreted with respect to external and internal triggering factors such as precipitation events or internal system dynamics. To investigate local precipitation variability, a weather station was installed within the GMSG and the data compared with two nearby climate stations operated by the National Park Berchtesgaden (Fig. 1, Fig. 2).

Results and Discussion

Weather data show a high local variability during the course of the day and year with respect to both magnitude and timing of precipitation as well as temperature range. During summer 2015 high-magnitude precipitation events predominated, reaching the GMSG up to one hour after the surrounding weather stations ('Hinterseeau' and 'Bindalm' located 1.2 and 2.5 km apart; Fig.1A) but always with the highest magnitude. Precipitation events of lower magnitude were registered in autumn 2015, which overall was unusually dry (Fig.2A). The highest mean daily temperature of all weather stations was reached in the GMSG, reflecting the south-eastern exposition of the catchment. This relation and the deviation from the other stations successively increased towards the end of the year.

According to the TLS data no debris flow events occurred in the active area (0.05 km² of 0.45 km²) of the GMSG between August 2015 and June 2016, although 10 heavy precipitation events exceeded the 'Rote Ampel' threshold suggested by LANGENSCHEIDT (2001b; 2002) (all between 15 August and 11 September 2015). The maximum recorded 10-minutes precipitation sum amounts to 5.2 mm (3 September 2015); the maximum hourly total reached 11.9 mm (21 August 2015), whereas in this hour the 'Rote Ampel' threshold was exceeded five times in a row (Fig.2B).

Although no debris flows occurred, sediment dynamics could be detected via surface comparison (Fig.3; Tab. 1). A volumetric error of ±0.25 m ('no change') was taken into account for each time period, considering inaccuracies arising from TLS data acquisition and post processing.

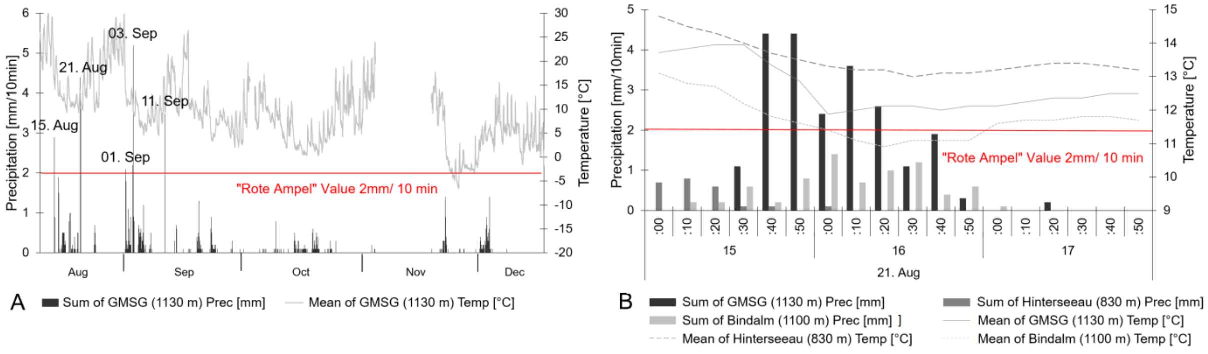

Figure 2: Precipitation and temperature in the GMSG. A: 10 min values between 11 August and 15 December 2015. B: 10 min values on 21 August 2015 between 3 and 5 pm (all three climate stations) (STUMVOLL 2016).

Sediment redistribution occurred with specific patterns in the debris flow channel of the GMSG, which can be identified clearly, and on the debris cone at the foot of the KMSG. Between 2009 and 2015 (ALS I) erosion overbalanced deposition in the GMSG (net loss of ~ 5 000 m³), whereas a net gain of ~ 13 000 m³ was observed in the KMSG (Fig.3A; Tab. 1). The 6 year sediment transfer patterns and the respective areas affected which are visible in the long-term comparison using ALS data are also visible using recent TLS data (Fig.3B, D-G), especially in the more active KMSG. On the debris cone of the KMSG different events of erosion and deposition can be distinguished (Tab. 1). The GMSG on the contrary experiences mainly internal sediment redistribution, with the areas mostly affected today being situated at the transition zone between rock face and debris covered area (rockfall/ avalanche deposits) as well as on a debris cone at the orographically right side of the debris flow channel, which repeatedly gets undercut in the case of debris flow events (sediment supply). Specific events are visible looking at details. Between October and December 2015 (TLS III) rockfall deposits can be detected in the GMSG, accounting for ~ 2 000 m³ (Fig.3F). Snow deposits of ~ 8 000 m³ are visible in the same area considering the time slice between December 2015 and June 2016 (TLS IV) (Fig.3G).

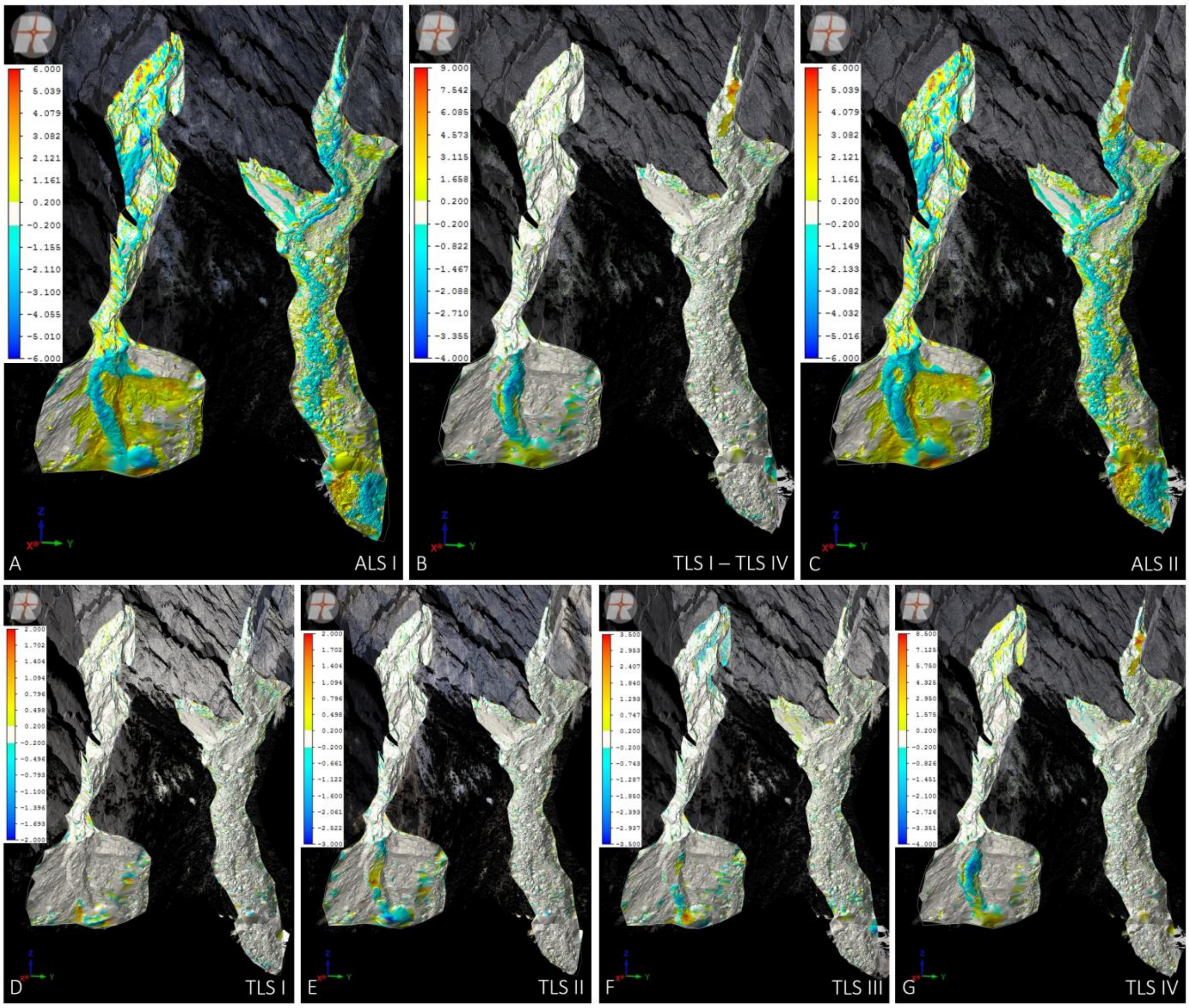

Figure 3: Volumetric surface comparison of ALS and TLS data for different time periods. The KMSG is situated on the left, the GMSG on the right side of the figures. Note the different colour scales. For time periods and surface change volumes see Tab. 1 (STUMVOLL 2016).

Reference to Fig.3	**A**	**D**	**E**	**F**	**G**	***B***	***B***	**C**
	ALS I	TLS I	TLS II	TLS III	TLS IV	TLS I - TLS IV	TLS I - TLS IV	ALS II
time period	ALS 2009 - TLS 21.08.2015	TLS 21.08.2015 - TLS 29.08.2015	TLS 29.08.2015 - TLS 12.10.2015	TLS 12.10.2015 - TLS 15.12.2015	TLS 15.12.2015 - TLS 28.06.2016	TLS 21.08.2015 - TLS 28.06.2016	TLS 21.08.2015 - TLS 28.06.2016	ALS 2009 - TLS 28.06.2016
						add up	calculation	
	approx. 6 years	8 days	44 days	64 days	196 days	312 days	312 days	approx. 7 years
Precipitation		*33mm; 5 RA*	*160mm; 3 RA*	*125mm; 0 RA*				
GMSG Fill [m^3]	14 643	1 448	1 128	2 803	11 150	16 529	11 884	21 969
GMSG Cut [m^3]	19 529	1 666	1 087	1 381	1 768	5 902	1 470	16 476
Difference	*-4 886*	*-218*	*41*	*1 422*	*9 382*	*10 627*	*10 414*	*5 493*
KMSG Fill [m^3]	26 370	1 153	1 174	1 212	2 853	6 393	1 799	29 189
KMSG Cut [m^3]	13 354	1 175	1 950	1 958	2 696	7 779	3 195	14 290
Difference	*13 016*	*-22*	*-776*	*-746*	*157*	*-1 386*	*-1 396*	*14 899*
KMSG DC Fill [m^3]	*7 831*	*564*	*656*	*493*	*1 671*	3 384	*1 156*	*7 457*
KMSG DC Cut [m^3]	*4 061*	*554*	*1 319*	*750*	*1 805*	4 428	*2 235*	*4 832*
Difference	*3 770*	*10*	*-663*	*-257*	*-134*	-1 044	*-1 079*	*2 625*

Tab. 1: Volumetric surface comparison of ALS and TLS data for different time periods, see Fig. 3. RA means ‘Rote Ampel’ threshold; DC means debris cone (calculated separately for the KMSG) (STUMVOLL 2016).

Comparing the surface change models calculated for the time slices ALS I, ALS II and TLS I – TLS IV (Fig.3A-C; Tab. 1) underlines the importance of short-term measurement intervals: Although the overall sums remain the same the composition of the resulting values strongly varies. This was most pronounced regarding the avalanche deposits within the GMSG, lasting there up to six months of the year (~ 8 000 m³ in June 2016) and distorting the results when measuring only once a year. Even considering only the TLS measurements, the calculation of TLS I – TLS IV gives the same final totals but the fill and cut values are assembled differently once the individual TLS time slices are considered and added up (see Tab. 1B: add up/ calculation).

Conclusion and Outlook

The study highlights the temporal variability of precipitation thresholds for triggering debris flows. After the disturbing rockfall events in 1999 the GMSG responded with a high frequency debris flow activity. With decreasing sediment availability as a variable disposition factor, triggering precipitation values have increased between 2000 and 2016 and the GMSG system might have reached a new form of steady state.

Long lasting avalanche deposits are supposed to strongly control debris flow dynamics in the GMSG. However, their influence concerning runoff intensification and sudden liquefaction through heavy rockfall are so far barely investigated. Future measurements will help to better understand these links. The interaction of thermal stress and rockfall activity has been also just barely investigated but may play an important role in this area (e.g. COLLINS & STOCK 2016).

The combination of high resolution digital terrain models (TLS/ALS) and weather data proved to be a suitable monitoring design for analysing debris flow triggers and dynamics in alpine catchments. However, the spatial and temporal variability of both, precipitation (events) and sediment availability are major challenges demanding for short TLS measurement intervals.

To investigate future dynamics in this highly active system, the so far relatively short time series (one year) will be continued. Furthermore, photogrammetric analysis of historic air photos will help to reconstruct past sediment dynamics for several decades.

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