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Monitoring and modeling slope dynamics in an Alpine watershed – a combined approach of soil science, remote sensing and geomorphology

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Abstract. Steep and unvegetated slopes in mountainous areas play an important role in erosion research as they deliver large quantities of sediments to the lowlands. However, their complex hydrological process combinations are challenging for any modelling and forecasting intention. Due to its high morphodynamic activity the Lainbach valley in southern Bavaria, Germany, has repeatedly been subject to studies on erosional processes. We present a further developed approach of physically based erosion modelling on strongly inclined and heavily dissected slopes. Model parameters were spatially and temporally distributed and a statistical model was tested to compare both findings to a previous study in the same catchment on a different slope. High resolution surface models from laser scans served as validation for the modelling results and for monitoring soil loss. Especially an adjustment of hydraulic roughness values improved the results, whereas rill hydraulics demand further investigation for future model development. The study at hand focusses on the summer period and reveals adequate modelling results (98.4 % agreement in volume loss) with regard to the slope's non-stationary behaviour but leaves room for improvement for the winter period.

1 Introduction

Fluvial erosion on sparsely or unvegetated hillslopes is the major sediment source in the Lainbach valley, located in the northern Alps. Several studies have focussed on acting geomorphological processes at these slopes (Becht, 1986; Kaiser et al., 2014; Neugirg et al., 2014; Wetzel, 1992; Schindewolf et al., 2015). This study aims to improve modelled sediment yields with regard to a first attempt on a neighbouring slope and to further develop both a statistical and a physically based erosion model for their application in Alpine conditions.

Terrestrial laser scanning (TLS) also referred to as terrestrial LiDAR (**Li**ght **D**etection **A**nd **R**anging) has become a well established tool in geoscientific studies. Especially detection of surface changes in hydrological studies (Baewert and Morche, 2014; Milan et al., 2007) or volumetric changes due to mass movements, like debris flows (Bull et al., 2010; Schürch et al., 2011) and rock falls (Abellán et al., 2011; Haas et al., 2012b) can be acquired with a drastically increased spatial resolution compared to previously used geomorphological measurement tools, like erosion pins (Della Seta et al., 2009) or sediment traps (Haas, 2008). Besides the spatial resolution, the contact-less acquisition of data is another major advantage of LiDAR. In the present study we repeatedly produced LiDAR data to measure surface changes and soil losses and compare these results to our erosion model predictions for the same period.

Soil erosion models improved during the last decades and are helpful in research as well as on the administrative level. Concurrently with the increased experimental effort in erosion research (Iserloh et al., 2013; Wirtz et al., 2013; Castillo et al., 2012) a gain in computing and data acquisition capacities allowed for higher resolution terrain models produced either by TLS or by SfM procedures. In this regard, physically based erosion models might offer a powerful tool for process differentiation of steep slope dynamics. Although the physically based EROSION 3D soil loss simulation model

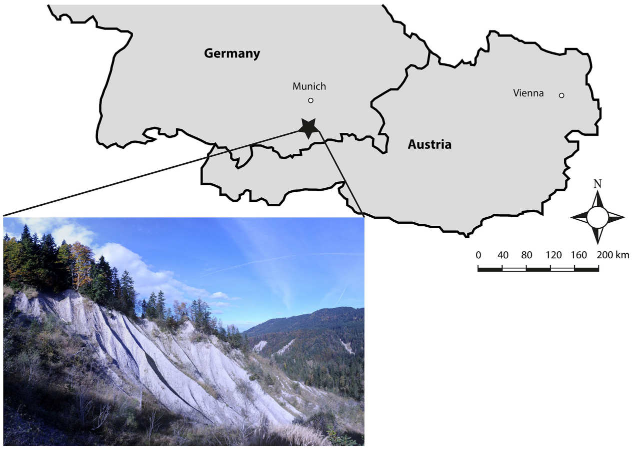

Figure 1. The study area is located in the Lainbach valley catchment in the Northern Bavarian Alps, Germany.

has been extensively validated (Starkloff and Stolte, 2014; Jetten et al., 1999, 2003; Defersha et al., 2012), applications on steep slopes go along with new challenges. The high spatial heterogeneity related with a limited accessibility of such areas is hindering parameter identification prior to model parameterization. Since first parameter identifications succeeded in 2013 including rainfall simulations (Kaiser et al., 2014) model parameterization for the Lainbach valley site became possible. Nevertheless, the natural non-stationarity of the catchment and the different processes during summer and winter were challenging for the model even though it works event based and is sensitive for heavy rainfall and discharge. Strong inclinations trigger processes like rock fall or small-scale mudflows which are not existent on agricultural land, where the model was developed. All rills on the slope are highly ephemeral with a quick response to rainfall and long inactivity during dry conditions which justifies the application of an event based soil loss model.

As a first application of the physical model presented in Schindewolf et al. (2015) showed room for improvement in terms of correct localization of dynamic rill areas and total sums of detachment, the present study successfully tackled these issues. To test the practicability of transferring the model to other areas a comparable slope in the same area with only few distinctions such as exposure and slope length was chosen.

2 The Lainbach valley catchment

The Lainbach valley catchment is an alpine mountain catchment in the northern Alps (Fig. 1), which has its highest point at 1801 m (Benediktenwand). The outlet of the catchment at ∼ 700 m is located at the town of Benediktbeuern in Upper Bavaria, about 60 km south of Munich. Although large areas of the catchment are vegetated with mixed forests (Becht and Kopp, 1988), several sparsely vegetated or completely uncovered erosional scars can be found. All of these erosional scars, according to Becht and Kopp (1988), had their maximum spatial extent on aerial photographs from 1959. The erosional scars are situated at local valley fillings that have been the result of several advances of the glacier Isar-Loisach. Becht (1992) mentions a thickness of the valley fillings of ∼ 150 m for the investigated slopes in this study. Kaiser et al. (2014) supports the assumptions of Wetzel (1992) and revealed very high bulk densities for the hillslopes. The monitored slope in this study is close located to the slope studied in Kaiser et al. (2014), Neugirg et al. (2014, 2015) and Schindewolf et al. (2015). Both slopes show nearly the same average slope gradient, the same height above sea level and the same bulk density of the substrate. Additionally, the precipitation and temperature conditions are comparable, since both slopes are located almost next to each other. The aspect of both slopes and the average slope length is entirely different (Table 1).

3 Data acquisition and model description

The results presented in this study are based on two field work campaigns that were carried out on May 2014 and October 2014. The acquisition dates have been chosen to represent the summer period in the best way and that all winterly effects (snow cover during spring, fallen leaves in the rills in autumn) could be minimized.

3.1 Data acquisition using TLS

TLS data were acquired using a Riegl LMS Z420i in combination with an on-top mounted Nikon D700 DSLR camera. The DSLR camera allows to colourize the point cloud during post processing for better orientation and filtering procedures. Two (May 2014), respectively three (October 2014) scan positions were used to minimize shadowing effects, due to heavily incised rills and gullies on the slope. The alignment of the different scan positions, as well as the alignment of the different time steps was carried out using permanently fixed tie objects, placed around the slope. For further post processing – e.g. alignment of the point clouds, colouring of the point clouds, vegetation filtering… – we used the software RiSCAN Pro v1.7.9 that comes with the TLS system. Finally processed point clouds were exported and gridded in SAGA GIS/LIS (Rieg et al., 2014) with cell sizes of 10 × 10 cm. Further details and information concerning the TLS post processing workflow are explained in much more detail in Haas et al. (2011a, 2012a).

In order to quantify and analyse surface changes, we applied a filtering method according to. Using the inaccuracy of the measuring device and a statistical t test, only significant changes were analysed. The level of detection (LoD) under a 95 % confidence interval was calculated as 5.54 cm

$$\mathrm{LoD} = t_{\mathrm{crit}}\sqrt{\delta_1^2 + \delta_2^2} \tag{1}$$

Table 1. Topographical data and relief parameter.

	Parameters for the hillslope presented in this study	Parameters for the hillslope presented in Schindewolf et al. (2015) and Neugirg et al. (2014, 2015)
height above s.l. in	~ 1000 m	~ 1000 m
aspect of the slope	East	West
average slope length	35 m	8 m
average slope gradient	50°	51°
bulk density of substrate	1930 kg m^{-3}	1930 kg m^{-3}

More detailed information on the application of the statistical *t* test are explained in Lane et al. (2003), Brasington et al. (2003), Wheaton et al. (2009), and Neugirg et al. (2015).

3.2 Erosion 3D – physically based erosion modelling under alpine conditions

To account for the non-stationary nature of our research area a physically and event based erosion model was chosen to depict the multitude of processes adequately. All mathematical and physical equations incorporated in the soil loss model are beyond the scope of this article but are accessible in Schindewolf and Schmidt (2012). EROSION 3D requires basic parameters such as rainfall, a digital terrain model and soil structural data. Furthermore, additional inputs such as the hydraulic surface roughness and soil resistance to erosion are derived from simulated rainfall experiments. As the model was developed for and is usually applied on agricultural sites data is commonly accessible from official sources. Nevertheless, for the Lainbach valley conditions differed in various aspects from the above: smaller size of the research area, stronger inclination, higher bulk densities combined with large gravel quantities and – for the winter period – snow influences and freeze-thaw cycles. Resulting from the above and as a prerequisite for decent modelling results, adequate data needed to be generated specifically for the site. The terrain data was derived as a by-product from the TLS monitoring, data on soil behaviour to heavy rainfall was produced with an artificial rainfall simulator and on-site sampling and can be accessed in Kaiser et al. (2014). Meteorological data input was ensured by a climate station at the slope with rainfall data in 15 min steps (Fig. 2). The precipitation data was also used for extracting wet and dry soil conditions in advance to a subsequent erosive rain event. The latter were identified by filtering for events with more precipitation than 0.25 mm min^{-1} or 10 mm h^{-1}.

As shown in Schindewolf et al. (2015) the transfer of the model to alpine conditions was accompanied by various challenges which could partially be resolved in the aftermath of the initial application for the summer period. Especially the roughness values were corrected by data from rill flushing experiments along with tracer measurements. A levelling of surface irregularities in the rills by runoff was accounted for by adjusting roughness values from 0.012 for the overall slope to 0.0365 (dry) and 0.0235 (wet) for interrill areas respectively 0.0245 (dry) and 0.0095 (wet) for the rills.

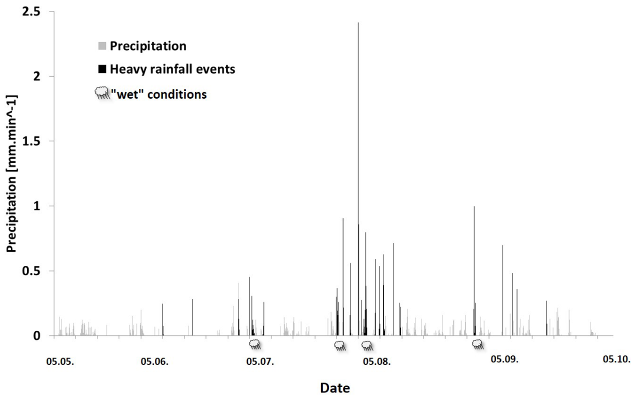

Figure 2. Precipitation for the monitored and modeled period with the filtered events and wet soil conditions for model parametrization.

3.3 Statistical-based erosion modelling using the sediment contributing area

In order to model fluvial erosion in alpine catchments, Haas (2008) and Haas et al. (2011b) developed a rule-based statistical model. Sediment delivery was measured by using erosion traps in channels. These sediment delivery rates were correlated with the size of the sediment contributing area (SCA) upstream of the related erosion trap. Both values showed positive correlations on a log-log plot. Neugirg et al. (2014) showed that an adaption from catchment to hillslope scale provides promising results. Furthermore the model was expanded with a random sampling of the chosen virtual traps in order to get a greater variance in the sizes of the SCA (Neugirg et al., 2015). For this study, measured erosion values for the five month summer period were routed downslope in SAGA GIS/LIS using the module "Catchment Area (parallel)". Since the entire slope is without hindering vegetation and it is steep enough, the rule-based approach for the

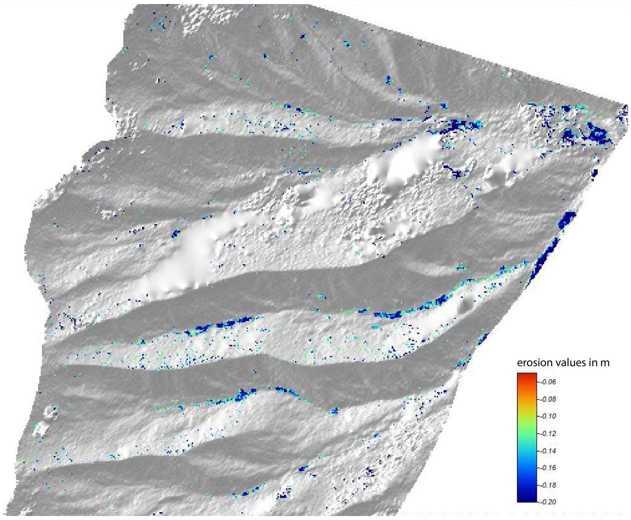

Figure 3. Surface changes from TLS data.

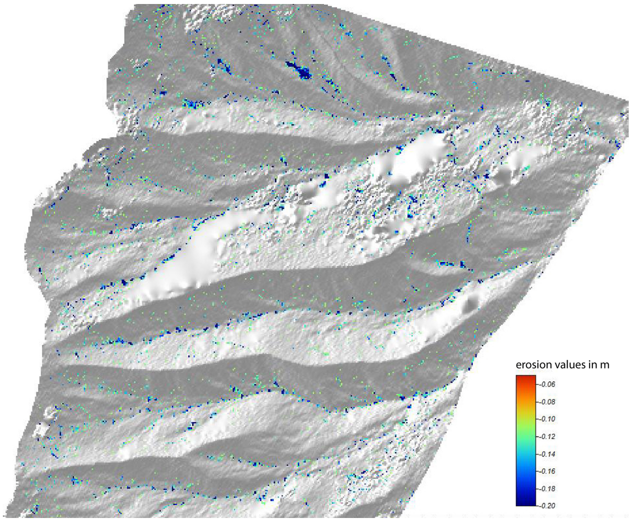

Figure 4. Modelling results from E3d.

extraction of the SCA could be ignored. Instead the normal hydrological catchments were used. In order to expand the statistical analysis from Neugirg et al. (2014) we allowed the sampling algorithm to pick any grid cell within a rill/channel. We used a random sampling to pick one grid cell for each rill/channel. In terms of statistical independence it is important to only pick one cell per rill. Otherwise lower lying cells in a rill are autocorrelated with the other cells as they are directly independent from the upwards lying cells (downslope routing of the surface changes). Therefore we correlated the sediment yield and the size of the hydrological catchment for 14 values and applied a linear equation according to the sampled values. The sampling was repeated 100 times, which leads to 100 different linear equations. The linear equations are based on the Eq. (2):

$$\text{log. sediment yield} = \text{intercept} + \text{slope} \cdot \text{SCA} \qquad (2)$$

4 Results

4.1 Measured surface changes using TLS

The erosion of all grid cells with significant erosion values has a mean of 21 cm and a standard deviation of 18 cm. Erosion is mainly focussed within the rills and at the bottom of the channels (Fig. 3). These areas show consistent and coherent greater erosional areas. Some smaller singular erosion patches are also at the slopes and channel walls. Furthermore almost no erosion can be detected at the channel heads. The main erosion hot spots are from about 1/3 of the channel length down to the slope foot.

4.2 E3d Model results

For the summer period a maximum surface lowering of 51 cm at a mean value of 15 cm at a standard deviation of 4.77 cm. Negligible deposition occurred in a few cells on the slope bottom whilst the larger quantity of soil is transported beyond the area of the investigated slope (Fig. 4). With regard to a pattern in the modelled soil loss the rills show concentrations of higher erosion value. Nevertheless, areas on the sidewalls of the incisions also show contributing rilling forms. Compared to the TLS results the proportion of the sidewall effects is higher, while rill incision in the large rills is underestimated. Furthermore, a tendency of higher changes towards to upper (western) part of the slope in the model contradicts the TLS data, which reveals major incisions in the lower (eastern) areas.

4.3 Statistical-based erosion model results

The model results show a positive correlation between sediment contributing area and the sediment yield (Fig. 5, left side). The goodness of the correlation is expressed as R^2 for each of the 100 linear equations (Table 3). R^2 values are distributed from 0.26 to 0.63 with a median of 0.48. In order to achieve a better comparability, intercept and slope of the linear equations was averaged for one month. Intercept values show a range from 0.336–0.531 with a median of 0.432. Slope values vary between 0.068 and 0.191 with a median of 0.132.

5 Discussion

Considering the results presented in Schindewolf et al. (2015) the spatial and temporal distribution of manning's n roughness values showed an improved reproducibility of the summerly slope processes. Furthermore, it was mandatory to also apply the significant changes (LoD) of the TLS scans of the modelling results from EROSION 3D. As erosion induced surface changes are frequently scaled in a mil-

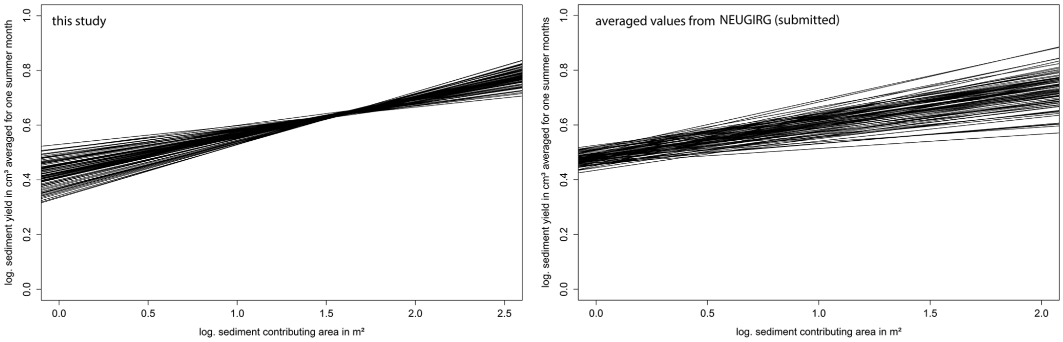

Figure 5. Model results of the statistical-based erosion model. Averaged values for one month for this study (left) and for the study by Neugirg et al. (2015) (right).

Table 2. Surface changes acquired with TLS (left) and E3D (right).

TLS			E3D		
no. of cells with significant surface change	mean of change	Volume (m^3)	no. of cells with significant surface change	mean of change	Volume (m^3)
3785	−0.22 m	8.523	5537	−0.15 m	8.665

Table 3. Results from the statistical based erosion model for one month.

SCA this study	Intercept	Slope	R^2	SCA (Neugirg et al., 2015)	Intercept	Slope	R^2
min	0.336	0.068	0.26	min	0.448	0.052	0.12
median	0.432	0.132	0.48	median	0.482	0.116	0.48
max.	0.531	0.191	0.63	max	0.519	0.183	0.89

limetre range, TLS results are questionable at the lower end of the scale. Thus, the modelling could be adduced to adequately complement the laserscan in a way that also microtopographical changes are included in the overall erosion budget. However, for reason of comparability between TLS and EROSION 3D a LoD of 5.54 cm was applied on both methodologies.

Analysing the spatial distribution of the soil loss illustrates differences between both applications especially in the rills. The adjusted roughness values for dry and wet conditions interacting with a fitted spatial differentiation of rill and interrill areas improved the pattern but also leaves potential for further advancement. As the initial model application was limited to agricultural sites during model parametrisation, sheet flow played an important role. This could be a reason for more detachment on the rather even sidewall parts of the rills and less erosion in the rill's depression lines when compared to the TLS data. As rill hydraulics are not yet implemented in the model the active parts on the laser scans, which are more or less limited to the lower regions of the rills, are less active in the EROSION 3D results. This is due to the flow reaching transport capacity which hinders further detachment while accumulated runoff, undercuttings and turbulent flow might further boost erosion inside the rills.

The model results of the statistical-based erosion model show medium to good correlations for 50 % of the samplings. Half of the models show higher R^2 values than 0.48. This is exactly the same median R^2 value Neugirg et al. (2015) showed for another smaller slope in the same catchment area (Table 3, Fig. 5). However, the range of R^2 is much smaller than the values for the previous study. In contrast, intercept and slope values are in very good agreement with the values from Neugirg et al. (2015). This agreement is very promising as it implies the applicability of the model from one slope to another under same conditions (similar substrate, precipitation) in one catchment area. Resulting differences between this (2014) and the previous study (2009) might be due to different precipitation data, contrary aspect of the slope and differences in the length of the slope. But these differences show much less discrepancies than the comparison of this method for study areas with different substrate and climatic settings (Neugirg et al., 2015).

6 Conclusions

The presented results (Table 2) do show progress in soil loss modelling for the research area for fluvial erosion during the summer, but also leave room for improvement in spatial distribution. By ignoring the winter period we avoided the phase of highest activity in the catchment and thus excluded several variables that favour non-stationarity. This was a result of limitations in modelling that became evident when comparing TLS-measured erosion rates to modelled ones for the winter period analysed in Schindewolf et al. (2015). Future research will tackle the winter period including freeze-thaw cycles, solifluction and snow-triggered processes.

Rill processes are not yet implemented in the model and need to be tackled for a suitable reproduction from the spatial distribution point of view. Nevertheless, an adjustment of roughness values led to better results in comparison to the TLS data. While the grid resolution increased rapidly from $20 \times 20\,\mathrm{m}^2$ to now $10 \times 10\,\mathrm{cm}^2$ the model parameters do not yet meet the demands of the new high resolution environment. Individual processes need to be measured and analysed more precisely after the change in scale with rill behaviour and hydraulics being of major importance. Regarding the fact that the modelling approach was implemented to reproduce and thus forecast soil losses for comparable slopes, the significant agreement between total soil losses from both methods is a step forward.

Predictions for future erosion volumes can not be made yet. A first step towards a prediction is the analysis and quantification of each single geomorphological process and its contribution to the annual sediment budget. First promising results and a clear differentiation between winter and summer processes show the studies of Schindewolf et al. (2015) and Neugirg et al. (2015). Nevertheless, a separation of all processes is necessary. Therefore, for future studies a decrease of the level of detection is absolutely crucial. Especially very small processes and minor surface changes that often occur, even during lower intensity rain falls, cannot be detected with the present LoD calculations.

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