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Methods for detecting channel bed surface changes in a mountain torrent – experiences from the Dorfbach torrent

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Abstract. The erosion of and depositions on channel bed surfaces are instrumental to understanding debris flow processes. We present an overview of existing field methods and highlight their respective advantages and disadvantages. Terrestrial laser scanning (TLS), airborne laser scanning (ALS), erosion sensors, cross sections (CS) and geomorphological mapping are compared. Additionally, two of these approaches (i.e. TLS and CS) are tested and applied in the channel reaches of the torrent catchments. The results of the comparison indicate that the methods are associated with variable temporal and spatial resolution as well as data quality and invested effort. TLS data were able to quantify small-scale variations of erosion and deposition volumes. While the same changes could be detected with CS and geomorphological mapping, it was only possible with lower precision and coarser spatial resolution. The study presents a range of potential methods that can be applied accordingly to address the objectives and to support the analyses of specific applications. The availability of erosion data, acquired mainly by TLS and ALS, in combination with debris-flow monitoring data, provides promising sources of information to further support torrent risk management.

1 Introduction

Debris flows and related processes are complex phenomena; thus, the occurrence and the varying characteristics of channelized debris flow events pose several challenges to both the scientific community and stakeholders of risk management. Moreover, in the last few years, an amplification of debris-flow activity in the Alps is increasingly related to climate change or to general environmental changes (Harris et al., 2009; Keiler et al., 2010; Sattler et al., 2011). Consequently, improving the physical-based understanding of debris-flow processes is needed to integrate these insights into modelling approaches and comprehensive risk management (Jakob and Hungr, 2005; van Westen et al., 2006; Deubelbeiss and Graf, 2013). Erosion and deposition of channel bed material by debris flows are important aspects of the process dynamic (Iverson, 2004). However, these processes are still poorly understood as they are rarely observed and quantified to date (Schürch et al., 2011a). Most studies focus only on the factors influencing erosion and deposition, or provide average erosion depths (e.g. Weber, 2004; Hungr, 2005; Iverson et al., 2011), rather than on compiling detailed quantitative data on erosion and accumulation within the different channel reaches. The lack of detailed observation data on channel modifications due to debris flows has been mentioned and criticized in literature (Fagents and Baloga, 2006). Nowadays, a broad range of methods supports the measurement of erosion and deposition; however, none of them was determined to be the definitive method for any particular application. This paper provides an overview of existing field methods to estimate and quantify erosion and deposition by debris flows. Their respective advantages and disadvantages are evaluated, based on the applicability of the methods on an active mountain torrent. The study focused on a comparison of five main types of surveying methods, which were evaluated to determine how to optimize their use to detect channel changes. Due to certain limitations, two of the methods – cross sections (CS) and terrestrial laser scanning (TLS) – were tested in the transport-dominated reaches of the Dorfbach torrent (Randa, Switzerland). Furthermore, this paper provides information on data collection in the field with a laser range finder (for CS) and TLS.

Review of field methods to detect erosion and deposition

Rickenmann et al. (2001) distinguished between three methodological focuses in debris-flow research: field observations, laboratory studies and numerical simulation models. Research on erosion and deposition were conducted by focusing on each of these methods. In this study, we focused on describing relevant field methods and their respective applications. During field investigations, erosion and deposition are usually detected by monitoring changes in channel morphology by observing and comparing channel conditions for a minimum of at least two different time steps. Different methods are considered with respect to the period of investigation (i.e. event, season, year) and area of interest (i.e. entire torrent, transit area, point-based sites). This paper provides an overview of currently used field methods for erosion monitoring.

Geomorphologic mapping is frequently used (e.g. Theler et al., 2010). Nowadays, various approaches including field work, aerial photo- and/or digital terrain model-based mapping are applied to acquire and present geomorphological forms and processes (Smith et al., 2011). With geomorphologic mapping, patterns of channel changes and structures (e.g. levees or debris-flow lobes) are clearly identifiable. James et al. (2012) used a different map generation approach to detect changes in fluvial systems by reconstructing and comparing digital terrain models (DTMs). However, this approach is only appropriate for the detection of large-scale changes over long time periods. After debris-flow events, pre- and post-event field photographs are compared for event documentation and analysis. Field photographs are used in the daily business of hazard and risk analysis and management (Rimböck et al., 2013).

Cross section (CS) analysis is one of the most frequently used quantitative methods in debris-flow and torrent research (e.g. Santi et al., 2008; Wasklewicz and Hattanji, 2009). CS supports the recording of channel geometry and its changes. Additionally, it can identify the tendencies of erosion and deposition at a specific location (Fagents and Baloga, 2006). CS are suitable for selective point-based and rough channel-wide analysis. Several types of instruments are applied to determine the cross sectional geometry, including tape measures, levelling boards and levels (Stock and Dietrich, 2006), slope profilers (Santi et al., 2008), theodolites and total stations (Theule et al., 2012) or terrestrial laser scanners (TLS) (Wasklewicz and Hattanji, 2009). In areas with deep water, echo sounding combined with a geo-referencing system are suitable. Radio detection and ranging (RADAR) systems or laser scanners mounted over the channel bed represent more elaborate systems that are usually combined with other debris-flow monitoring devices (Graf et al., 2011; McCoy et al., 2011). Breien et al. (2008) based their cross section calculations on photogrammetric and light detection and ranging (LiDAR) data. In various studies, selective cross-sectional measurements are interpolated to estimate the debris yield of a channel section or to calculate erosion volumes (Theule et al., 2012) and lag rates (Hungr et al., 2005).

The availability of new measurement devices have been linked to increased uses of DTMs (Rumsby et al., 2008) to measure pre- and post-flow topography of torrent channels. In recent studies, TLS are applied to produce DTMs and for event-based detection of channel changes. In debris-flow research, TLS is used for extensive (i.e. multiple square kilometres) and refined detection of complex channel topography (McCoy et al., 2010; Schürch et al., 2011b). Overviews and discussion on TLS data quality and measurement techniques in this context were presented by Schürch et al. (2011a). Airborne laser scanning (ALS) is suitable for the analysis of large areas such as an entire catchment, but often at low temporal resolution (Bühler et al., 2012). Scheidl et al. (2008) have used ALS data to analyse debris-flow events in Switzerland and to quantify volumetric sediment budgets and channel changes. Scheidl et al. (2008) showed that their calculations mainly correspond to the volume estimates by experts in the field and concluded that ALS is a practical, but expensive method for erosion and deposition analyses. The range imaging cameras (Nitsche et al., 2010, 2012) or photogrammetric cameras (Berger et al., 2010) were applied for small-scale analyses in easily accessible areas. Their application in debris-flow studies is very limited to date. Photogrammetric analysis of orthophotos enables variable large-scale analysis to be conducted (Breien et al., 2008). While range imaging cameras are mainly applied for event analysis, orthophotos also support retrospective analysis if different data sets are available. A recent, affordable and user-friendly alternative is close-range photogrammetry (field photographs) with structure from motion (SFM), which is used to obtain high-resolution spatial data that is suitable for modelling meso-and micro-scale landforms and generating DTMs. The approach requires multiple overlapping photographs, camera parameters as well as its orientation and the image-matching algorithm. However, the necessary equipment is easy to handle in steep terrain due to low bulk volume (cf. James and Robson, 2012; Westoby et al., 2012).

In situ methods directly detect channel changes during an event and were developed as an alternative to the comparative approach described above. Measurements are conducted using scoured sensors to identify maximum erosion changes. Tracer stones consisting of radioactive, magnetic, fluorescent tracers or colours were tested in various studies (McCoy et al., 2011). The radio frequency identification (RFID) technology was developed to monitor fluvial debris transport in mountain torrents (Schneider et al., 2010). Berger et al. (2010) designed and applied erosion sensors made from individually erodible aluminium elements in the Illgraben torrent (Switzerland). This technique enables selective point-

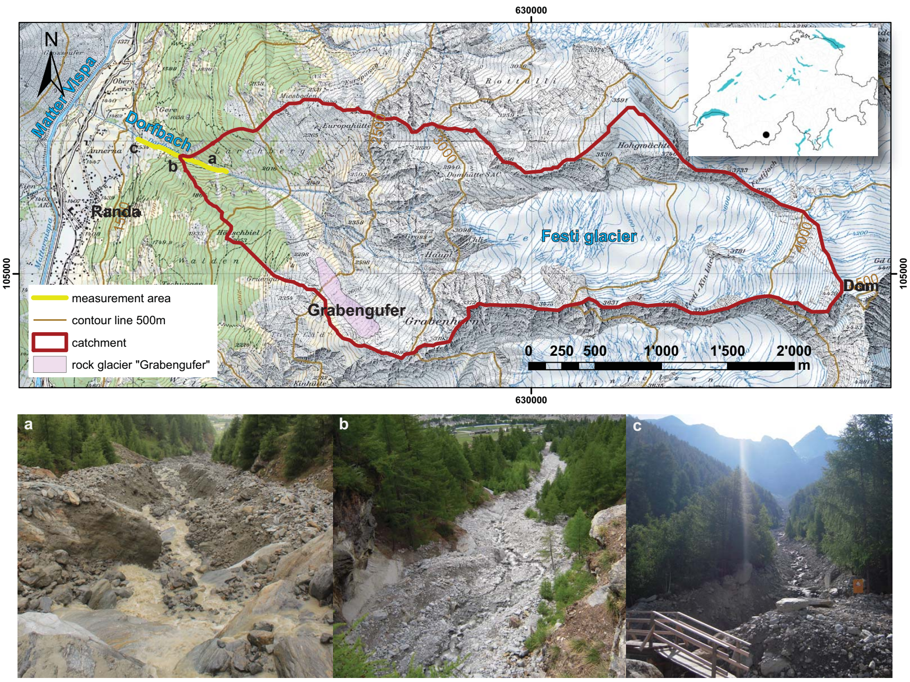

Figure 1. Map and photos of the study area Dorfbach torrent (Randa) in the Zermatt Valley, Switzerland (pixmaps© 2015 swisstopo (5704 000 000)). Photos **(a)–(c)** showing different sections of the measurement area (© Ch. Graf, WSL).

based measurements of time, duration and erosion depth as a result of debris flows or fluvial processes. The sensors measure up to 1 m of erosion at a resolution of 0.05 m. However, it is not designed to measure deposition.

2 Research area

Inhabitants and visitors in the Matter Valley (Switzerland, Valais) are threatened by various natural hazard processes; moreover, an observed change in the frequency of debris-flow events enhances this peril (Graf and McArdell, 2005; Stoffel et al., 2011; Graf, 2013). The Dorfbach torrent case study is based on the assessment of one of these hazardous torrents in the Matter Valley (Fig. 1). The steep and sustained catchment of the Dorfbach torrent covers an area of 5.8 km^2, ranging from the Dom (4545 m a.s.l.) to the confluence with the Matter Vispa (1440 m a.s.l.). The Festi glacier in the upper part of the catchment contributes to a perennial discharge in the Dorfbach torrent channel (GHO, 2004). The catchment is dominated by debris material from weathered bedrock and rock fall events. Additionally, permafrost soils above 2500 m a.s.l. and the rock glacier Grabengufer supply debris material and additional water to the Dorfbach torrent. Thus, the dynamics of the rock glacier affects the amount of material and water supply that is available, which are – apart from topographical features and climatic factors – preconditions for the initiation of debris flows. In recent years, increasing flow velocities at the Grabengufer rock glacier have been observed (Delaloye et al., 2013). During spring and summer, small debris flows develop in the steep (mean slope angle 33°, maximum slope angle 39°) talus below the rock glacier (Graf et al., 2013). Very large debris-flow events have also been recorded in this area in the past (Graf and McArdell, 2005). The Dorfbach torrent channel is characterized by an average bed slope of 26° (GHO, 2004) and surface roughness by grain sizes between 0.5 and 1 m. Thus, occurring debris flows are mainly granular with a small amount of cohesive material (Graf and McArdell, 2005). In the transit area, erosion, as well as deposition, occurs during a single event (Graf et al., 2013).

The focus of this study is on processes within the transit zone that is characterized at the beginning of the study (June 2011) by a 2–4 m deep eroded channel in loose material and a clearly detectable generation of levees (see photos Fig. 1). Recent events occurred after a longer period of inactivity (Fig. 2), whereby three larger debris flows reached the deposition area situated on the distinctive debris cone of the Dorfbach (Graf et al., 2013). Many other subsequently smaller debris flows terminated and deposited material in the transit zone. Part of these depositions were remobilized by larger events, resulting in highly variable and changing channel bed topography.

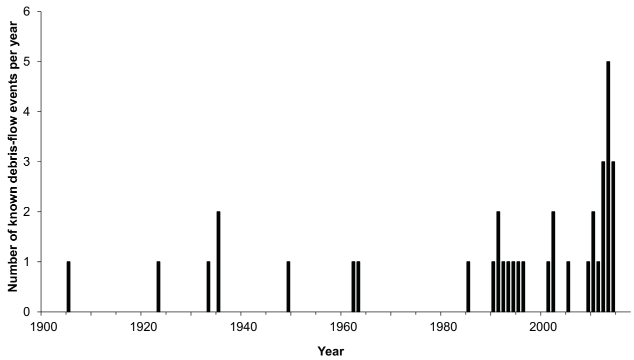

Figure 2. Recorded debris-flow events in the Dorfbach torrent channel since 1900 based on Graf and McArdell (2005) and Graf et al. (2013). Most recent events from 2010 to 2014, which reached the deposition area (fan apex or fan or receiving river), are added.

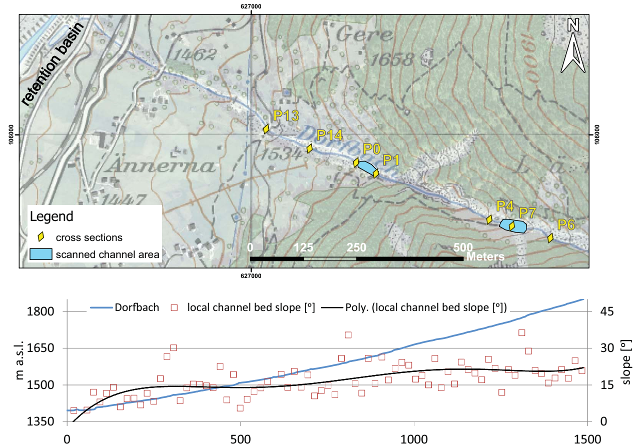

Figure 3. Overview of measurement locations (CS and TLS scanned channel area) in the study area of the Dorfbach torrent. A longitudinal profile of the channel is added, showing slopes for channel sections overlaid a polynomial (swissimage and pixmaps© 2015 swisstopo (5704 000 000)).

3 Methods and comparison approach

An overview of field methods for quantifying erosion and deposition by debris flows are based on two (pre- and post-event topography) approaches, which were tested in the field (Fig. 3). Furthermore, geomorphological mapping based on an orthophoto-map was conducted to provide a comprehensive overview of the change processes in the transit area and to relate this with the results generated by cross section measurements and TLS. In addition to these approaches, two further methods presented in the literature were considered in the overall comparison (Sect. 3.3).

3.1 Cross sections

Cross sections (CS) (see Px Fig. 3) were measured for key sites, representative locations within homogeneous channel areas. At least one CS per homogeneous channel area is needed to interpolate information between the sampled locations. A further criterion for the selection of CS sample locations is to find stable position where the instrument will be installed on both channel banks. While these locations are proximal to the channel, there is a high probability that they are unaffected by the in-channel processes. In this study, geomorphological mapping, aerial photos and details about previous events provided information to select for representative CS locations in the transit zone of interest. Seven CSs were measured once a month from June to September 2011.

Cross-sectional measurements were conducted by combining the TruPulse 360B Laser Rangefinder from Laser Technology, Inc. (LTI, 2009) on a tripod with a differential GPS (dGPS) GeoXH6000 from Trimble (Trimble, 2011). The measurement accuracy of the TruPulse is ± 0.3 m in distance, $\pm 0.25°$ in inclination and $\pm 1°$ in azimuth to high quality targets (LTI, 2009). The Trimble dGPS measurements have a root mean square error of 0.1 m + 1 ppm after post-processing. Further information about the measurement principles can be found in Oguchi et al. (2011). Measurement positions on both sides of the channel are geo-referenced by dGPS and highlighted with coloured markers and spikes to ensure experimental repeatability. The dGPS measurements were repeated during every field session because of low dGPS data quality, especially for the first measurement. Only high quality measurements were retained for further calculations. A straight line between two corresponding positions is scanned with a minimum of 60 single distance measurements. Data on inclination and distance are directly transmitted to the dGPS to be recorded and to calculate the coordinates of each point measurement within the CS. Additionally, for each measurement, the height of the above ground laser rangefinder is registered to enable the comparison of repeated measurements to be undertaken. Two measurement procedures were tested (Fig. 4): (a) measurements were taken from both side of the channel to minimize shading effects and (b) hidden parts are indirectly measured with a prism on a levelling pole, so that measurements could be recorded from just one side of the channel. A clearly detectable and systematic misalignment due to high inclination inaccuracy (precision of 1°) and azimuth measurement (precision of 0.25°) by the rangefinder required data correction, illustrated in Fig. 5. This error favours measurement procedure (b). After data correction, two and more data sets from the same CS were gathered in different time slots. These were plotted together to visualize, localize and quantify changes in channel geometry. The maximum width, bed width, maximum height and the CS area are quantified and compared with results of the other applied methods.

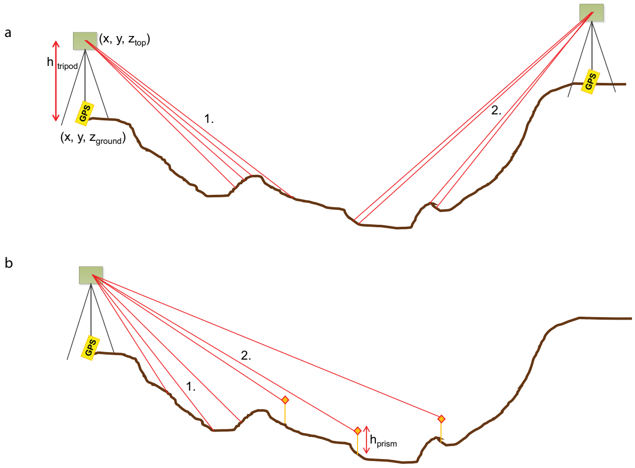

Figure 4. Schematic illustration of the two measurement principles with laser range finder and dGPS for cross sections. Numbers describe the measurement steps. **(a)** Direct measurement from two sites. **(b)** Direct measurement from one site with indirect measurement of the hidden parts of the cross section with a prism on a levelling pole.

3.2 Terrestrial laser scanning

Terrestrial laser scanning (TLS) is a method that enables the efficient acquisition of a large quantity of 3-D information of a surface. The channel is surveyed using Leica ScanStation C10 with five Leica High-Definition Surveying (HDS) 6″ targets, which ensures a horizontal and vertical precision of 0.1 m in 100 m (Leica, 2012). Measurement planning and data acquisition were conducted according to Schürch et al. (2011b). Two channel areas that were ∼ 70 m in length in the upper and lower transit zone are surveyed on three occasions between June and September 2011 (see details Table 1, Fig. 3 and Fig. 6). Each survey was conducted with three to five scan stations. Scan stations were positioned to minimize shadows in the scanned area and the scan grid spacing was 0.1 m for a range of 100 m from the scanner. Target positions were measured with dGPS to georeference and register the point clouds in the post-processing procedure.

All point clouds from one scan area and different epochs are registered together to ensure relative comparability (cf. Schürch et al., 2011a). Data filtering was conducted manually, whereby point clouds were visualized, and dispensable or erroneous points (either due to vegetation, people, instruments, artefacts) were excluded. Raster data with a grid width of 0.1 m were calculated from the filtered point clouds for each scan area and epoch by applying inverse distance weighting (IDW) for DTM interpolation. The three DTMs corresponding to the epoch of each scan area were analysed to visualize height differences between two raster data sets/epochs. Mean vertical changes, maximum erosion and deposition heights, as well as the affected area were calculated and relocated sediment volumes were then estimated.

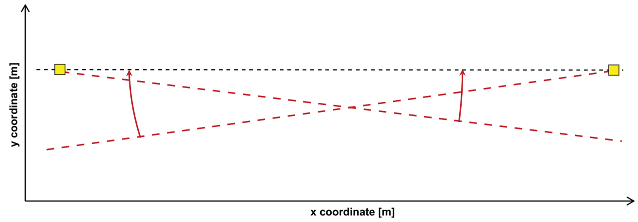

Figure 5. Principle of data correction (bird view): inaccurate data points are projected by rotation (red arrow) to their actual position. Yellow rectangles: measurement sites; red line: measured data points; black line: projected data points.

Figure 6. TLS measurement in Dorfbach torrent (Foto© Ch. Willi, WSL/GIUB, 9 September 2011).

3.3 Comparison of different methods

The comparison of different, key methods focuses on information about the usability, advantages and disadvantages with respect to channel change detection. CS, TLS, geomorphological mapping, erosion sensors and ALS were considered for this comparison. The main requirements by which each of these five methods for localizing and quantifying changes in the channel were assessed against, were formulated based on the overall research interest and customized to the specific characteristics of the Dorfbach torrent transit zone. Considering the following requirements, methods were compared with respect to location and process-related aspects, data accuracy and quality and/or organizational issues based on multiple criteria. The collected data corresponded to experience gained during fieldwork at the Dorfbach torrent, were extracted from relevant literature (derived primarily from Scheidl et al., 2008; Berger et al., 2010, 2011) and from personal communications with B. McArdell and C. Scheidl (cf. categories and sub-categories in the supplement).

Table 1. General information about the extent and quality the two TLS scan regions as well as the calculated difference models.

	Lower scan region	Upper scan region
Altitude	1600–1630 m a.s.l.	1730–1760 m a.s.l.
Total 2-D area	1072 m^2	1388 m^2
Length	~ 70 m	~ 63 m
Width	12–17 m	19–27 m
Interpolated area (due to	104–231 m^2	189–204 m^2
missing data points)	10–22 %	12–14 %
Calculated difference models	10.06.2011–04.08.2011	12.07.2011–04.08.2011
	04.08.2011–16.09.2011	04.08.2011–16.09.2011
	10.06.2011–16.09.2011	12.07.2011–16.09.2011

Table 2. Results of the cross sectional measurements before and after flooding of 23 August 2011 (CS = cross section, * = data of the eroded channel inside CS P6).

CS	Altitude (lowest point) (m a.s.l.)	Local channel bed slope (°)	Approx. CS width (m)	Approx. bed width (m)	Max. height before event (m)	Approx. CS area before event (m^2)	Tendency of changes within meas. period	Max. channel change Δh (m)
P6	1782	40	17*/ 34	4	4*/6.3	44*/124	No change	0
P7	1743	24	21	15	2	28	No change	0
P4	1724	24	28	9	3.8	60	Channel erosion	−1.6
P1	1615	15	12	2	3.8	25	Deposition	1.4
P0	1598	16	20	10	3.4	33	Channel erosion	−0.5
P14	1571	15	17	6	5	47	Channel erosion	−1.0
P13	1531	14	11	5	5.5	44	Deposition	0.7

4 Results

In June 2011, shortly before field investigation started, a small debris flow (< 1000 m^3) reached the debris retention basin in the upper deposition area. However, no debris flow was monitored during the field investigation between June and November 2011. Consequently, channel changes detected during this period corresponded to continuous changes, or to changes attributed to a small flood on 23 August 2011.

4.1 Cross sections

The main information and overview of results derived from the seven representative CSs are presented in Table 2. During the observation period, erosion and/or accumulation within the channel of five CSs could be detected. In one CS, no change was detected (P6 in Fig. 3, Table 2), whereas in another CS, a strong misalignment prevented reliable results from being obtained (P7 in Fig. 3, Table 2). Thus, detailed results are only presented for two examples. Figures 7 and 8 each present a CS with data collected data from all three epochs. Two epochs (B, 14 July 2011 and C, 4 August 2011) present results of the situation before the flood that occurred during the last epoch (D, 21 September 2011) and afterwards.

CS P1 (Fig. 7) is located in the lower transit area below a narrow gorge section (cf. Fig. 3). The u-shaped cross section has a small bed of about 2 m deep, a maximum width of 12 m and is limited to the right side by two levees (Fig. 7). The cross sectional area amounts to circa 25 m^2 with a maximum height of 3.8 m. The local channel bed slope is 15°. Only small height differences of 0.1–0.2 m were detected between the two epochs (B and C) before the flood event. These differences correspond to measurement-based uncertainties that are mainly due to the low quality of the dGPS data. Consequently, it was not possible to provide any definitive remarks about continuous changes. Figure 7 clearly shows that in this part of the channel, deposition occurred due to the small flood event. Maximum deposition amounts were 1 m deep and the flow path was elevated by 0.5 m. Furthermore, erosion occurred on the knickpoint between the channel bed and the slopes. Consequently, channel changes in this CS were the most distinctive.

CS P4 (Fig. 8) is located up-stream of the gorge section in the upper transit area (cf. Fig. 3). This CS is more than twice as wide (upper profile width 28 m, channel bed width 9 m) as the gorge located downstream (cf. P1). In addition, its runoff capacity is higher with an area of approximately 60 m^2. The local channel bed slope is 24°. Based on the channel geometry of this location, erosion by flooding is expected. The mismatched data collected from the left and right slopes complicated data interpretation. The horizontal and vertical offsets amount to more than 1.5 m. Continuous changes were undetectable. The roughly estimated channel changes due to the flood amounted from several to 0.1 m of erosion along the whole channel bed. The right slope remained stable. An estimation of changes could not be provided for the left slope due to missing data.

Table 3 provides information on possible sources of error associated with the acquisition of cross sectional data with the applied methods. dGPS measurements were accurate to 0.1–0.2 m. In more narrow parts of the torrent channel, accuracy is low (0.5–0.8 m), mainly due to a lack of reception of satellite signals. When considering the TruPulse measurements, considerable errors were caused by the measurement device itself because of the low azimuth and inclination precision of 1 and 0.25°. While the horizontal error was corrected (Sect. 3.1), neither quantification nor correction is possible for the inclination error due to the lack of a height reference. In the data, the effect of the distance measurement precision (0.3 m) and other effects (see Table 3) were not clearly detectable. Only single outliers were easily identifiable but these were rare.

4.2 Terrestrial laser scanning

Table 4 presents the results of the TLS measurements of the two scan regions. For each scan region, channel parameters and changes for three time steps (difference models) are presented. Each scan consists of 10–17 billion measurement points. Scans are registered with a maximum deviation of 0.02 m. Errors due to artefacts, objects, or vegetation are not quantified. In the lower scan region, 10–20 % of the area was interpolated due to missing data points. The root mean square error (RMSE) of all interpolated raster data amounted to 0.08 m (Table 3). The estimated precision in the vertical difference in the difference model amounted to ±0.25 m. Consequently, the resolution was defined accordingly.

Figure 9 is an example of the difference model that shows channel changes due to the occurrence of a small flood between 4 August 2011 and 16 September 2011. Erosion is marked in red and deposition in blue. In the parts marked in light ochre, no significant changes (exceeding ±0.25 m based on the estimated vertical precision of the model) could be detected. Roughly, 50 % of the scanned area was affected by changes. Erosion width amounted to between −0.5 and −3 m, and a maximum erosion height of up to −2 m was measured. Erosion occurred mainly on the right side of the inner levee and partly at the bottom of the left bank. In a downstream section, in-channel deposition was predominant. In the upper part, more than 2 m of deposition was measured. The deposition height continuously decreased towards the lower part of the section, however strong local variations are also observed. Mean height change amounted to 0.6 m (Table 4). In the lowest part of the section, erosion and deposition varied locally. In total, over 290 m^3 of material was deposited in and 160 m^3 was eroded from the channel section.

4.3 Comparison of methods

Detailed results of the comparison are presented in the Supplement with respect to the main requirements. The main results were described in the following section; for information on erosion sensors, refer to Berger et al. (2011, 2010) and on ALS, refer to Scheidl et al. (2008).

4.3.1 Location and process

Erosion sensors cannot be applied to torrents with high surface roughness, such as the Dorfbach channel. If the bed or banks are unstable, measurements taken with a TLS or laser range finder are hindered. ALS flight are not affected by channel conditions, however the channel must be open and visible from above. If erosion exceeds 1 to 2 m in depth, erosion sensors are systematically destroyed by the erosion process. CS, as well as TLS, are also limited when depths have a difference of around 10 m, due to restricted visibility, unstable banks or channel inaccessibility. Only airborne ALS and geomorphological mapping remain applicable after large events; however, these methods are constrained by steepened banks and slope. In general, greater efforts are required as accessibility becomes more difficult, especially for sites characterized by uneven topography.

4.3.2 Quality criteria

The applicability of the methods described differs significantly. CSs and erosion sensors provide selective point-based data, TLS enables measurements to be made within confined areas and ALS and geomorphological mapping are suited for investigations over entire torrent channels. TLS and erosion sensors measure with precision in the 0.01 m range, while laser range finders, dGPS and ALS take measurements with 0.1 m of precision. Depending on the mapping basis position, the accuracy of geomorphological mappings is a few metres. The spatial sampling resolution of erosion sensors is very low (i.e. with five measurement sites over 20 m^2). The cross sectional sampling resolution is 0.1 m, but decreases to 50–150 m for interpolated data between two CSs. If there is good areal coverage of the location of interest and there are few shadows, the TLS raster resolution is 0.1 m or lower. The raster resolution of ALS data is 0.5–5 m. The mapping resolution is estimated to several metres. Height differences can only be estimated. The results of the TLS survey showed that the temporal resolution may be relatively low, as continuous changes are negligible in comparison to event based changes. Only erosion sensors are capable of making continuous measurements, if the erosion depth of the sensors is not exceeded and data logging starts with the onset of an event. For frequent and short-term measurements, field methods are more suitable compared to the more cost-intensive ALS approach.

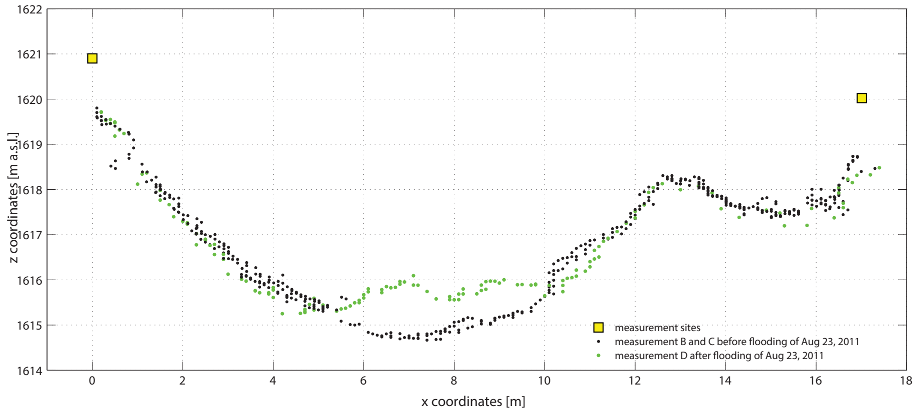

Figure 7. Cross section P1 (view in flow direction): channel changes after flooding of 23 August 2011.

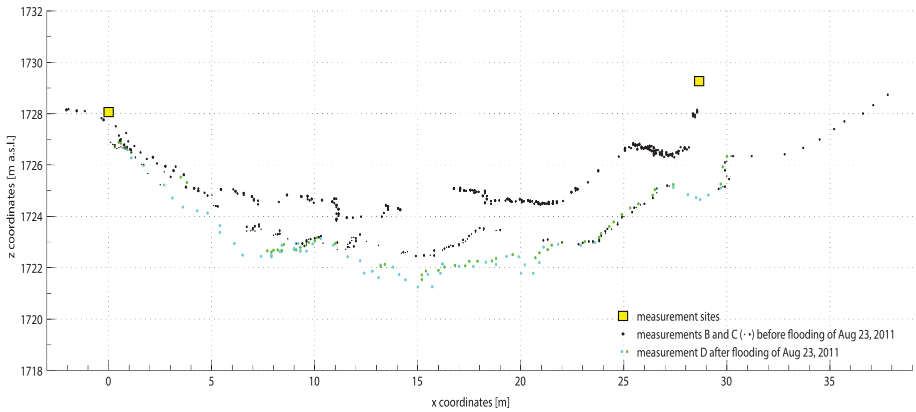

Figure 8. Cross section P4 (view in flow direction): channel changes after flooding of 23 August 2011. Measurements B (14 July 2011) and C (4 August 2011) show results of the situation before the flood and D (21 September 2011) the cross section afterwards.

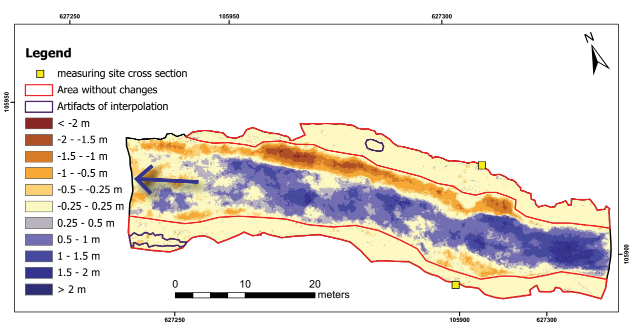

Figure 9. Channel changes after flooding of 23 August 2011 in the lower scan region. With the two yellow rectangles measurement sites of the cross section P1 are marked. Blue colours indicate deposition, red colours indicate erosion. No changes are detected in the light ochre areas.

4.3.3 Organizational aspects

The suitability of the chosen measurement device significantly influences the amount of time and effort that is required to conduct field work. Instruments for mapping and cross sectional measurements are easily to manage by a single person, compared to multiple pieces of TLS equipment that has to be carried by at least three people. Erosion sensors are uniquely installed with a digger. Based on the findings of this case study, the total amount of time and effort to acquire data from one single event differs significantly. In particular, 2–3 days are required for geomorphological mapping, 8–9 days for CS measurements to be made (post-processing is relatively intensive, requiring an additional 3–4 days) and 9–10 days for the acquisition of ALS data if a professional conducts the work. In general, the overall amount of resources that need to be invested decreases with each subsequent measurement with respect to or with greater levels of experience or expertise. Initial costs associated with the installation of erosion sensors is very high. These costs include the development, construction and installation of the sensors. Yet, almost no post-processing is required and sensors can be used for multiple events. With 14–15 person-days, TLS measurements require the greatest amount of resources, particular with respect to the conditions of our case study. Field

Table 3. Possible sources of errors applying CS and TLS measurements (including further data processing).

Method	Data	Error source	Error amount
CS	Laser rangefinder raw data	Distance accuracy	±0.3 m
		Inclination accuracy	±0.25°
		Azimuth accuracy	±1°
	dGPS data after post-processing	Root mean square error	0.1 m + 1 ppm
	P1 post-processed and data	Horizontal and vertical offset	< ±0.1 m
	P4 post-processed and data	Horizontal and vertical offset	> ±1.5 m
TLS	TLS raw data	Position accuracy	0.06 m
		Distance accuracy	0.04 m
		Inclination accuracy	60 µrad
		Modelled surface accuracy	0.02 m
		Target registration accuracy	0.02 m
	dGPS data after post-processing	Root mean square error	0.1 m + 1 ppm
	TLS point cloud	Registration accuracy	< 0.2 m
	Raster data	Raster resolution	0.1 m
	Interpolation raster	Root mean square error	0.08 m
	Difference model	Vertical error	±0.25 m

Table 4. Erosion and deposition parameters for three time steps (difference models) for the lower and upper TLS scan region. Erosion is indicated with negative numbers. *Italic* marked data describe continuous changes, the others describe changes due to the flooding of 23 August 2011 (Ø = mean; SD = standard deviation).

Difference models	Ø vertical change (m)	SD of Ø vertical change (m)	Max. deposition height (m)	Max. erosion height (m)	Deposition volume (m^3)	Erosion volume (m^3)	Absolute volume change (m^3)	Area with deposition (m^2)	Area with erosion (m^2)	Area without any changes (±0.25 m) (m^2)	(%)
Lower scan region											
04.08.11–10.06.11	*−0.02*	*0.14*	*1.37*	*−1.5*	*30*	*60*	*−30*	*25*	*51*	*996*	*93*
16.09.11–04.08.11	0.15	0.59	2.14	−2.19	300	140	160	354	167	551	51
16.09.11–10.06.11	0.12	0.59	2.13	−2.24	290	160	130	352	190	529	49
Upper scan region											
04.08.11–12.07.11	*−0.03*	*0.09*	*2.24*	*−2.26*	*20*	*60*	*−40*	*11*	*20*	*1357*	*98*
16.09.11–04.08.11	0.01	0.87	2.87	−3.79	430	420	10	422	391	574	41
16.09.11–12.07.11	−0.02	0.86	2.84	−3.81	410	430	−20	407	401	579	42

work requires a least two people and post-processing is time intensive (i.e. an additional 5–7 days). Furthermore, financial expenses differ between the different methods. While mapping is very inexpensive, the assessment of a single high-alpine catchment such as the Grabengufer/Dorfbach (approx. 2.5 km^2) costs around CHF 15 000 and includes approx. 2.5 h of helicopter flight time, as well as an entire day dedicated to processing the acquired data, based on estimates provided by Bühler and Graf (2013). Erosion sensors, described by Berger et al. (2010), are an exclusive version that can be constructed with more affordable materials (cf. McCoy et al., 2012).

5 Discussion

New measurement devices and further development onto lighter, faster, and more inexpensive laser scanners has led to an increase in the application of relevant methods in geoscience (cf. James and Robson, 2012; Westoby et al., 2012). However, publications that specifically focus on geomorphological methods, especially debris-flow erosion and the related challenges, are still scarce. Knowledge about the different characteristics and limitations is essential for effective selection of appropriate methods with respect to the objectives of the research questions.

5.1 Applicability of laser range finder and TLS at the Dorfbach torrent site

5.1.1 CS – inexpensive and simple measurements

To the authors' knowledge, no other studies based on the CS approach (e.g. Comiti et al., 2014) has described CS data collection using a laser range finder and dGPS. An optimized approach was developed to address the highlighted research questions based on results from fieldwork. We recommend the consideration of technical factors and applicability when choosing representative measurement sites. These sites should also be marked properly. GNSS (global navigation satellite system) reception is necessary to geo-reference measurements, otherwise only relative position-based comparisons would be possible. Furthermore, the placement or installation of measurement equipment must not interfere with the study area. Additional identification marks along the cross section line ensure comparability. In this study, measurements are conducted with a handheld dGPS placed on the surface; improvements to signal reception is possible with the use of an external antenna. Separate measurements of the ground point and tripod height is advisable to ensure the comparability of data from different epochs. A heavy monopod with supporters provides more stability and can be placed more precisely at the measurement site. It is also necessary to fix the horizontal axis to prevent misalignment due to human error. Such errors are clearly detectable in the data set during the post-processing stage (cf. Table 3).

Considerations of the data quality led to the application of measurement principle b) (cf. 3.1 and Fig. 4). Both principles are associated with respective advantages and disadvantages (Table 5). Principle (a) is more time-consuming but can be conducted by one person. Principle (b) is only applicable to easily accessible channels, but enables relative comparisons to be made, which is especially essential when GNSS reception is weak. Both measurement principles are limited when the channel of interest is rugged and the banks are steep. Additionally, for both approaches, at least two data sets are necessary to counter shading effects.

Representative CS locations are essential to guarantee that relevant data are collected for every homogenous channel section. Apart from this requirement, practical issues like site accessibility, stability, the position of the instrument relative to expected flood levels along the channel banks and good visibility into the channel are also crucial factors to consider.

A comparison of the aforementioned methods revealed that CSs can be considered as an inexpensive and simple alternative to TLS and ALS-based investigations. In many situations, the required equipment is handy, quickly deployable and easy to operate. Therefore, in situations where the precision requirements are low (>0.5 m), traditional measurement devices such as tape measures, levelling boards or slope profilers can be used as more affordable alternatives to laser range finder and dGPS.

5.1.2 TLS – efficient and precise data collection

When applying TLS, planning the setup for measurements is the most important step. Measurement and target sites should be chosen carefully as data quality is directly linked to this step. In particular, data accuracy is determined by the amount and size of data shadows and registering precision. Multiple overlapping areas and increased number of scans lowers the extent of data shadows. Targets that are spatially well distributed increase target-based registration precision (Heritage and Hetherington, 2007). Elevated positions near the torrent channel are useful measurement sites; these provide an overview of the area of interest. For repeated measurements, at least three fixed targets are advantageous and facilitate registration and relative comparison. However, these target sites, need to be situated outside the influence of torrent processes and remain relatively stable. Accessibility to the targets has to be considered even in the case of larger channel changes.

Registering precision in this study (cf. Table 3) is comparable with results from Schürch et al. (2011b). With reference to their study results, target-based registration was found to be too imprecise and they optimized the results with the help of algorithms. In this study, algorithms could been applied to lower the estimated margin of uncertainty of ± 0.25 m in the difference model. We only used five targets for each of the two areas of about 1100 and 1400 m^2, respectively. Imprecision during the registration process could have been reduced with the inclusion of a greater number of fixed targets (Schürch et al., 2011b). Additional errors attributed to the application of the measurement devices have to also be taken into account. In contrast to the suggested distance between scans recommended by Schürch et al. (2011a), overlapping was significantly higher in this study. The overlapping of three to five scans resulted in a very high point density (~ 100 points per 0.1 m^2), which has to be lowered 100 times to calculate a 0.1 m raster. Comparison of raster data with different point densities indicated that the point density of the scan could be reduced by half without any significant loss of data quality. Thus, resources dedicated to field work and post-processing can be considerably reduced compared to the recommendations presented in the Supplement. Consequently, too much reduction of the resolution complicates data processing, as objects (i.e. vegetation, people, features that should be removed) are hardly visually recognizable in the point clouds. In summary, the higher the surface roughness in the scan region, the higher the associated scan resolution should be (Schürch et al., 2011a). Nonetheless, if the problem requires optimization based on finite costs or resources, a low scan resolution is recommended, rather than working with fewer measurement sites.

5.2 Strengths and weaknesses of the compared methods

The overview of the aforementioned methods presents a wide range of applied methods and measurement devices. Geomorphological mapping and CSs are recognized as established methods. When new surveying techniques are transferred to geomorphology – such as TLS and ALS – erosion research groups have embraced them. In the following section, we discuss the strengths and weaknesses and the applicability of the methods, with respect to monitoring debris-flow erosion and deposition as a result of the Dorfbach torrent (cf. Table 6 for an overview).

Geomorphological mapping is the most simple, affordable and easily deployable method. It is applicable to any tor-

Table 5. Advantages and disadvantages of the two tested CS measurement principles. Principle **(a)**: direct measurement from two sites. Principle **(b)**: direct measurement from one site only with indirect measurement of the hidden parts of the cross section with a prism on a levelling pole.

	Measurement principle **(a)**	Measurement principle **(b)**
Advantages	– No work inside the torrent channel, however crossing necessary – Measurements conductible by only one person – Twice detailed investigation of the torrent channel: high resolution	– Only one measurement site – Relative comparison possible – Georeferencing with only one dGPS measurement point: reduces errors – Fast and efficient measurement
Disadvantages	– Both banks need to be accessible – No relative comparison possible – It's hard to harmonize data with the given data quality – Measurements from two sites is time-consuming	– Work inside the torrent channel – Assistance needed – Fewer indirect measurements: punctually low resolution – Indirect measurement not applicable in steep banks

Table 6. Advantages and disadvantages of the compared methods to localize and quantify erosion and deposition in the Dorfbach torrent.

	Advantages	Disadvantages
Erosion-sensors (Berger et al., 2010)	– Detects time, duration and amount of erosion – Permanent installation – Very fast data preparation and analysis – Accuracy: 0.05 m resolution	– Cannot measure deposition – Measures erosion <1 m – Only few point data – Applicable in fine-grained channel beds
Cross sections with TruPulse and dGPS	– Simple method – Handy devices – Data collection over the whole transit area	– 3-D data quality $\sim$ 0.5 m – Only punctual cross sectional data – Comprehensive error correction – Depending on GNSS reception
TLS	– Spatially comprehensive survey inside the study reach – Highly precise data and high raster resolution (0.1 m)	– Heavy, multi-piece material – Two people necessary for field work – Time-consuming field work and post-processing
ALS (Scheidl et al., 2008; Bühler and Graf, 2013)	– Spatial comprehensive survey over the whole study reach – Precision 0.1–0.5 m – No access to the torrent channel needed – Applicable in case of major event	– Raster resolution 0.5–5.0 m – Expensive method: helicopter – Low temporal resolution – Not applicable in steep or overgrown channels or gorges
Geomorph. mapping	– Simple, handy and very fast method – Data collection by one person for the whole study reach	– Qualitative data: only tendencies of channel changes detectable – Only major changes detectable – Low horizontal resolution (several metres)

rent channel, as long as the channel and banks are accessible or visible from a nearby observation point. While other qualitative methods are mainly used for retrospective analysis (James et al., 2012), mapping also supports event-based studies. Mapping is capable of providing a rough overview of channel changes. Detailed mapping on a small scale may depict patterns of erosion and deposition that should be reproducible by debris-flow models. Hence, geomorphological mapping is practical for model validation. Ideally, mapping is accompanied with volume and height change estimates or measurements. In combination with debris-flow monitoring, data mappings contributes to the understanding of process-based developments.

Cross sectional measurements deliver spatially high-resolution data with simple measurement devices. In homogeneous channels, interpolation is an effective way to detect approximate channel-wide changes. In complex channels, such as where the Dorfbach torrent occurred, the application of this method was limited, due to the inability to adequately detect the channel geometry and its changes in key sections of the channel. CSs enable long-term comparisons to be made with a reasonable amount of effort. CS-based methods will benefit from more precise surveying technologies that continue to be developed (cf. e.g. Theule et al., 2012).

Combined with debris-flow and channel parameters, detailed DTMs based on TLS data are valuable to furthering the understanding of processes. If TLS data are acquired over a sufficiently large channel section, the patterns and dimensions of channel changes can be analyzed. In comparison to other methods, this approach provides the most precise calculations of erosion and deposition volumes and yield rates ($m^3\,m^{-1}$). More data can be applied in a higher number of contexts ways by increasing surveyed area. The resultant DTMs are also used to validate debris-flow simulation models; further improvements to models can be expected as a result. The increase in the number of research projects using TLS have highlighted the range of advantages and applications with this method.

Erosion sensors (Berger et al., 2010, 2011) produce novel data about the amount, timing and duration of erosion. Although in situ methods have been traditionally used to monitor fluvial sediment transport (Hassan and Ergenzinger, 2003), erosion sensors represent a step forward in debris-flow research. Sensor data combined with other debris flow and channel parameters enable further insight to be gained about the processes involved. In future investigations, erosions sensors should be applied and analysed in torrent channels with varying type of debris-flows to facilitate the derivation of a general conceptual model.

The bird's eye view is the notable advantage of the ALS data collection method. Based on the comparison of all the other methods, only ALS enables detailed analyses of inaccessible torrents and steep slopes to be made, as long as visibility from above is possible. Due to the large-scale surveys involved, DTMs from ALS data are often used to analyse the whole process area from the initiation zone to the debris cone (Heritage and Hetherington, 2007; Scheidl et al., 2008) or to provide an overview of overall changes. The associated spatial resolution is reasonably accurate (0.5 m raster resolution, e.g. Bühler and Graf, 2013 for the Dorfbach torrent). Therefore, while the higher resolution is more expensive in terms of costs, it is a more accurate alternative to TLS and is suitable for many applications. ALS data are often used to analyse long-term changes (pre- and retrospective) during one season, several years or even decades. If pre- and post-event data are collected, the same data analysis and application is possible, as with TLS data (see above).

The five methods were compared based on the costs and ease of data processing with different spatial and temporal resolutions, as well as the resultant quality of results. The discussion above illustrates that the applicability of specific methods to analyse the erosion and deposition due to the Dorfbach torrent varies. There is no optimal method for event-based analysis of channel changes. However, for further developments to facilitate a better understanding of the associated processes, for debris-flow model development and the validation of large-scale study areas, extensive data sets are recommended. Similarly as important as the selection of a suitable method, is the availability of a debris-flow monitoring station to combine erosion data with debris-flow and channel parameters. Furthermore, the combination of different methods such as TLS and ALS or erosion sensors with comparative methods should be considered to enhance the collection of different types of erosion data.

6 Conclusions

This paper focused on methodological issues to detect event-based bed surface changes in torrent channels. A detailed comparison of selected methods showed that there were significant variations with respect to their temporal and spatial resolutions, the resultant data quality and the amount of resources that needed to be invested. Hence, the applicability of these methods for monitoring erosion differs as well. Using the Dorfbach torrent event as an example, TLS was found to be particularly suitable to quantify erosion and deposition by debris flows, although the amount of effort is considered to be the highest of all of the methods compared. The collected TLS data were also capable of illustrating small-scale variations of changes in the channel bed and supported the quantification of erosion and deposition volumes. The same changes are also detectable with cross section measurements and geomorphological mapping, but with lower precision and reduced spatial resolutions. Furthermore, the applicability of both methods for the detection of continuous changes is limited. Continuous changes are considered to be very small, so they can be neglected when studying event-based changes. The analysis and discussion of error sources and data quality associated with laser range finders and TLS data has led to different recommendations, especially with regards to optimizing the effectiveness of efforts and resources in the field. The optimum use of dGPS, laser range finder and TLS in a steep torrent channel depends on various aspects. These include measurement planning and the choice of methods for post-processing, which are generally accepted to be independent from the channel conditions and research interest. On the contrary, aspects such as optimal measurements or dGPS reception need to be newly evaluated for each torrent channel and with respect to the research aims. The question pertaining to the optimum applicability of methods can only be answered when considering a specific use in a particular torrent channel.

The study presented findings on optimized support for a specific case and location-based application and provided a detailed analysis about the effective quality and accuracy of the different methods. Further research is needed to develop and adapt erosion sensors to rougher terrain to broaden the applicability of these methods. To gain a better understanding of the processes involved, the collection of more erosion data are recommended – both during and after debris-flow events – in combination with debris-flow monitoring data. Such combined data sets could even be used to evaluate the effectiveness of new methods. Various authors have expressed the need of differentiated, multi-year, extended data sets on debris-flow erosion and deposition (Hungr et al., 2005; Schürch et al., 2011b). Furthermore, TLS and ALS studies were found to be promising and are currently widely used. Improvements to the understanding of processes, gained from the optimized application of methods, is nonetheless a benefit to residents in mountain areas, especially with the consideration of these insights to improve risk management.

Information about the supplement

Table S1 provides guidelines to choose an appropriate method, based on the aims of the application and analysis. The comparison is structured in several categories for all five discussed methods, namely erosion sensors, CS, TLS, ALS and geomorphological mapping.

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