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DEBRIS-FLOW ACTIVITY IN FIVE ADJACENT GULLIES IN A LIMESTONE MOUNTAIN RANGE

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Abstract: Debris-flows are infrequent geomorphic phenomena that shape steep valleys and can represent a severe hazard for human settlements and infrastructure. In this study, a debris-flow event chronology has been derived at the regional scale within the Gesäuse National Park (Styria, Austria) using dendrogeomorphic techniques. Sediment sources and deposition areas were mapped by combined field investigation and aerial photography using an Unmanned Aerial Vehicle (UAV). Through the analysis of 384 trees, a total of 47 debris-flows occurring in 19 years between AD 1903 and 2008 were identified in five adjacent gullies. Our results highlight the local variability of debris-flow activity as a result of local thunderstorms and the variable availability of sediment sources.

Keywords: debris-flow, dendrogeomorphology, growth disturbances.

1. INTRODUCTION

Torrential processes like debris-flows and debris floods are highly concentrated mixtures of sediment and water in steep channels which occur when a critical combination of sediment, inclination and water is reached. In the Alps these flows are commonly triggered by intense rainstorms of short duration and high intensities or long-lasting precipitation, often in connection with snowmelt (Brunetti *et al.,* 2010). Information on long-term torrential activity is only rarely available. Apart from archival data, dendrogeomorphology has often been used to derive temporal and spatial information of previous debris-flow activity (Alestalo, 1971; Strunk, 1992; Baumann and Kaiser, 1999; Jakob, 2010; Šilhán, 2012; Tumajer and Treml, 2013; Stoffel and Corona, 2014). Hereby investigations of growth failures in year rings of trees affected by debris-flows, allowing deduction of information on past events (Hupp, 1984; Strunk, 1991) is combined with information on the spatial distribution of the affected trees to estimate deposition areas of past debris-flows (Bollschweiler and Stoffel, 2007; Stoffel *et al.,* 2008). Dendrogeomorphology was repeatedly used to reconstruct event magnitudes of (flash) floods based on the analysis of peak flow scars (e.g. Gottesfeld and Gottesfeld, 1990; Ballesteros *et al.,* 2011). Jakob and Bovis (1996) or Stoffel (2010) assessed the frequency by dendrochronological records and magnitudes by a combination of data from field surveys of deposition material and empirical methods. So far only a limited number of studies has focused on the dendrogeomorphic reconstruction of debris-flows at the regional scale (e.g. Bollschweiler and Stoffel, 2010; Pelfini and Santilli, 2008; Procter *et al.,* 2012).

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Geomorphic analysis of the surface through field investigations and areal pictures provide additional information on the flow and depositional behavior of hydrogeomorphic processes. Geomorphic mapping through aerial pictures of an unmanned aerial vehicle (UAV) is a relatively new method of surface analysis. In the context of detecting previous landslide processes, only scarce literature is available (e.g. Hugenholtz *et al.,* 2013; Stumpf *et al.,* 2013).

The aim of the study is to investigate debris-flow activity in these steep, adjacent channels and to obtain an as complete as possible time series of events over the last century. The results are interpreted in connection with sediment sources available in the upper part of the catchment which was assessed by aerial photography by using an UAV and field work.

2. STUDY SITE

We investigated the forested fans of five neighboring gullies located in the Gesäuse National Park, Styria (47°35'N, 14°38'E) opposite of Gstatterboden. All gullies are episodic channels. The steep, north facing catchments cover an area of >1 km^2 per gully and extend from 2117 m a.s.l. at the summit of Planspitze to ~570 m a.s.l. at the confluence with the Enns river (**Fig. 1**). All catchments are dominated by Triassic limestone (*Dachsteinkalk*) and dolomites. The sediment delivered to the fans is angular and has a mean grain size of 84 mm using the surface sampling method. Based on levees observed at fan apex, tongue-shaped deposition patterns with unsorted material, the absence of any signs of snow avalanches, mean travel angles ranging from 69 to 74% as well as Melton numbers ranging from 1.7 to 2.0 (Melton, 1965), we conclude that debris-flows are the only process in these channels. Below the steep north face of the Planspitze summit (>50°), relevant snow accumulation zones are clearly absent and reports of snow avalanches do not exist in archives. A summary of geomorphic parameters for each catchment is given in **Table 1**. The regional climate is characterized by humid temperate, oceanic conditions, prevailing westerly winds and frontal systems from the Atlantic. Mean annual precipitation at Gstatterboden varies between 1000 and 1700 mm, with a mean of 1347 mm for the period 1971–2008 (Hydrographic service Austria, 2013), which is located approximately 500 m from the study site. The forest stand growing on the fans is dominated by Norway spruce (*Picea abies* (L.) Karst.) and European larch (*Larix decidua* Mill.). At the contact of the fan with the alluvial belt of the Enns River, vegetation is characterized by a spruce-fir-beech mixed forest stand. Archival records report only a few debris-flows and for several years back to 1900; however, no exact locations are reported except for one event in 2005 at the Planspitzgraben, located between torrents 2 and 3. This gully is deeply incised and trees are not available for dendrogeomorphic analyses, hence the Planspitzgraben was not included in our reconstructed event history.

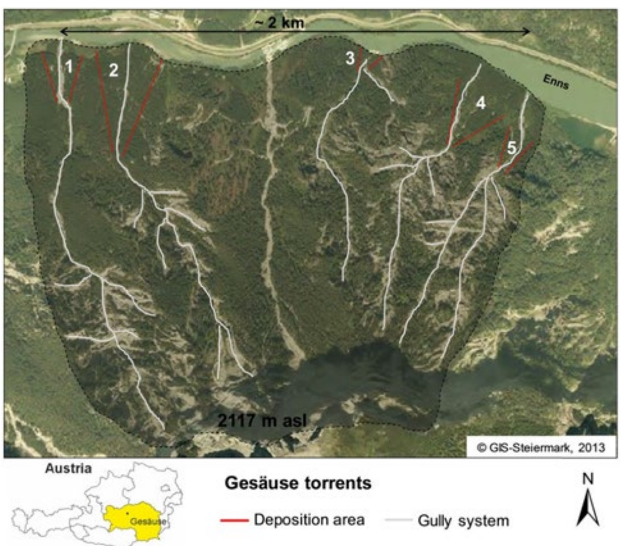

Fig. 1. *The source areas (grey dotted lines) as well as the deposition areas (in red) of the five investigated torrents in the Gesäuse catchment (source aerial photo: GIS-Steiermark, 2013).*

3. METHODS

Geomorphic mapping

Fieldwork started with a detailed mapping (scale 1:1000) of geomorphic features relating to past debris-flows. As a result of the steep slopes and the dense forest cover, mapping was not possible using a Global Positioning System (GPS) and was therefore performed with a compass, inclinometer and tape measure.

Field investigations in the transit zone were carried out by climbing all channels as far as possible, mapping sediment sources and by estimating yield rates for sediment entrainment in the channels using the method suggested by Hungr *et al.* (1984). A detailed ground-based survey was not possible in the initiation zones due to the steepness of the terrain, so that an UAV (View Copter V6) had to be used there. The UAV used in this study is a battery-powered octocopter equipped with a digital photo camera (16 Mpix resolution) which can be rotated re-

Table 1. *Altitude of the maximum runout on the fans, catchment area, Melton number, fan and travel inclination of the torrents where dendrogeomorphic analysis were performed.*

Torrent	Fan altitude (m)	Catchment (km^2)	Melton Nb. (-)	Mean fan slope (%)	Mean travel angle (%)
1	570	0.6	2.0	16	69
2	590	0.7	1.7	20	72
3	570	0.3	2.0	18	74
4	600	0.4	1.8	27	76
5	600	0.4	1.7	17	70

motely in 3 dimensions. Areal pictures were taken from this unmanned drone to estimate sediment availability as well as the structure of the gully system.

Tree-ring analysis and dating of torrential events

Based on the geomorphic map and an inspection of their morphology, trees obviously influenced by past torrential activity were identified and sampled with an increment borer. Field work was performed in spring 2011 during which at least two samples were taken per tree (see Stoffel and Bollschweiler (2008) for details on the sampling strategy). In addition, a limited number of trees were felled and cross-sections taken. The position of each sampled trees was determined on the geomorphic map. In total, 754 samples (370 increment cores, 14 cross-sections) were selected from 384 trees at the five cones.

Samples were then prepared and analyzed following the standard dendrogeomorphic procedures as described in Stoffel and Bollschweiler (2008, 2009). Individual working steps included drying and sanding of the samples, counting of tree rings and measuring ring widths. Subsequently, growth curves were cross-dated with local reference chronologies to correct faulty tree-ring series from disturbed samples and to separate natural variability (e.g., climate, insect breaks or damage caused by forest work) from growth disturbances (GD) induced by torrential processes (Stoffel *et al.,* 2010; Stoffel and Wilford, 2012). A reference chronology was built from 20 trees (2 cores per tree) growing within the study area but obviously not influenced by geomorphic processes. The samples from the reference trees were averaged and standardized. The resulting mean curves of the reference chronology were then compared with growth curves of disturbed trees to detect false or missing tree rings (Schweingruber, 1996).

Within this study, the analysis of growth disturbances focused primarily on the presence of (i) tangential rows of traumatic resin ducts (TRD) as a sign of mechanical impacts (Bollschweiler *et al.,* 2008; Stoffel *et al.,* 2008; Schneuwly *et al.,* 2009a, 2009b), (ii) compression wood reflecting unilateral pressure and tilting of stems (Kogelnig-Mayer *et al.,* 2011; Lopez-Saez *et al.,* 2012), (iii) sudden growth suppression following decapitation, loss of branch material, exposure of roots or deposition of material at the stem base (Stoffel *et al.,* 2012; Kogelnig-Mayer *et al.,* 2013), and (iv) the presence of growth releases in tree-ring records caused by stem burial (Strunk, 1997; Mayer *et al.,* 2010).

The dating of past events was based on the number of trees showing a growth disturbance within the same year, the intensity of the tree-ring signal and the position of the disturbed trees, following the approach initially proposed by Shroder *et al.* (1978) and adapted by Kogelnig-Mayer *et al.* (2011) and Schneuwly-Bollschweiler *et al.* (2013).

4. RESULTS

Age structure and growth disturbances of the sampled trees

The oldest tree sampled showed 131 growth rings (AD 1879) at sampling height, whereas 12 increment rings were counted in the youngest tree. The age structure of the trees sampled at the cones range between 60 and 85 yrs. Comparable young trees were identified on the second fan (~60 yrs), whereas the oldest trees can be found on the fan of the fourth gully (~84 yrs). The distribution of tree ages on the different cones is represented in 50 yr classes in **Fig. 2**.

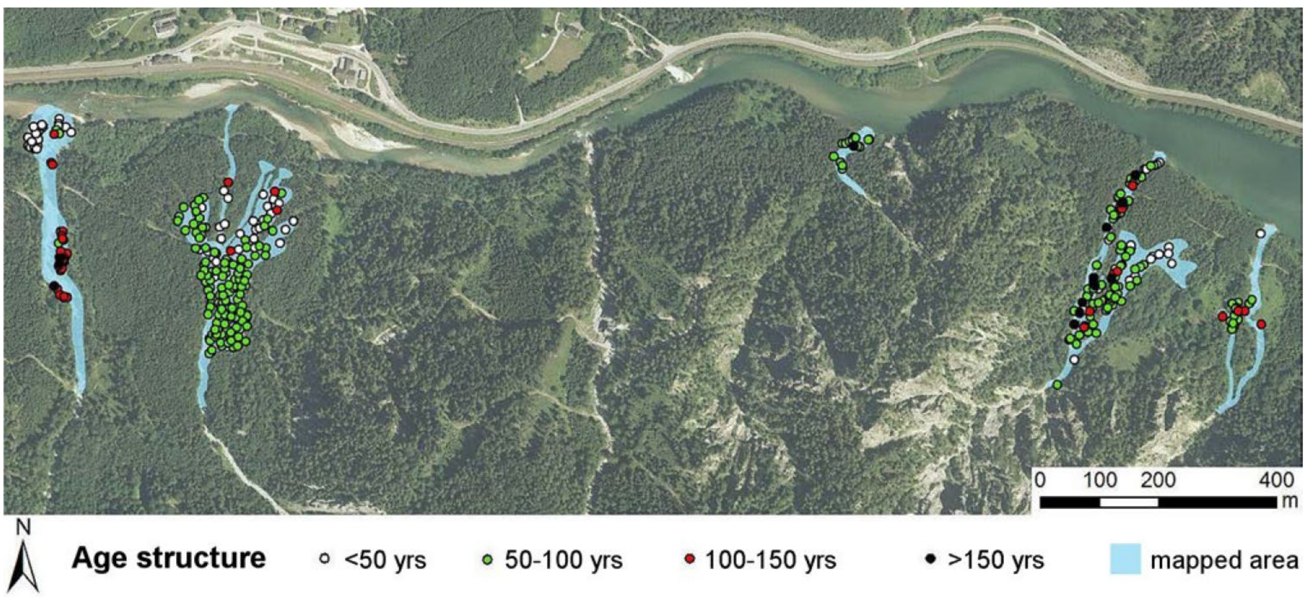

Fig. 2. *Position and age of sampled trees on the deposition area. Ages are in classes of 50 yr (source aerial photo: National Park Gesäuse GmbH).*

From the 384 trees sampled at study sites, 366 showed clear signs of GD and allowed identification of 3164 GD (**Table 2**). Signs of past torrential activity were predominantly present in the form of growth suppressions (GS), tangential rows of traumatic resin ducts (TRD), growth releases (GR) and/or compression wood (CW). Three-fourth of the GD identified are GS and GR, whereas TRD only accounted for 20% and CW for 4%. The quantitative occurrence of the GD in the gullies is given in **Fig. 3**. Geomorphic conditions as well as the intra-annual position of TRD indicate debris-flows as the dominating process in the catchment.

Dendrogeomorphic dating of torrential events

The simultaneous occurrence of GD in several trees on the fans was then used to reconstruct debris-flow chronologies in the area. According to the tree-ring records, debris-flows occurred in 19 years between 1903 and 2008 (**Table 3**). A total of 18 events was documented for channel 4 (AD 1903–2008), whereas only 3 debris-flows were reconstructed in channel 3. In 14 years debris-flows could be observed in more than one channel, but the only year with debris-flow occurrence in all gullies was 2006. The reconstructed regional time series of debris-flows is shown in **Fig. 4**. Events represented with bold lines are

Table 2. *Growth disturbances (GD) determined in the 382 P. abies and L. decidua trees sampled in five adjacent gullies in the Gesäuse National Park. TRD = tangential rows of traumatic resin ducts.*

Growth disturbances	No	%
Growth suppression (GS)	1369	43
Growth release (GR)	1034	33
TRD	623	20
Compression wood (CW)	138	4

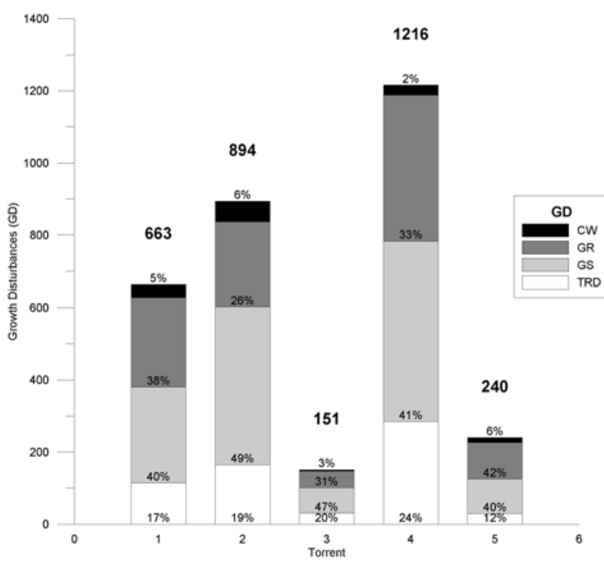

Fig. 3. *Relative distribution of growth disturbances in the five catchments. CW = compression wood, GR = growth release, GS = growth suppression and TRD = tangential rows of traumatic resin ducts.*

Table 3. *Events dated with dendrogeomorphic records on the fans of the five gullies. Legend: ✓ events dated with high certainty where a high amount of trees were available; ~ events dated with less certainty (possible events) based on less trees available for dendrogeomorphic analysis.*

Event year	1	2	3	4	5
1903				✓	
1906				✓	
1909				✓	
1917	~			~	
1927	~			✓	
1943				✓	
1947				✓	✓
1950	✓	✓			
1955				✓	
1978	~	~		~	
1980	✓	✓		✓	✓
1983		~		✓	✓
1990		✓	✓	✓	✓
1992	✓	✓		✓	
1996			~	✓	~
2000	✓	✓		✓	
2005	✓	✓		✓	
2006	✓	✓	✓	✓	✓
2008	✓			✓	✓
Events	10	9	3	18	7
Return period	9.4	6.8	7.0	6.0	9.1

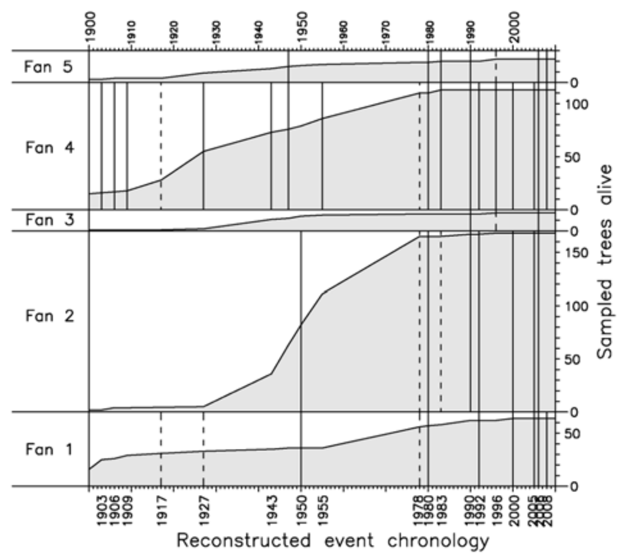

Fig. 4. *Reconstructed debris-flow frequency at Gesäuse National Park. Solid lines represent torrential events reconstructed with a large number of GD in trees spread homogenously over the fan. Dashed lines indicate events where the quantity and/or quality of GD were less abundant for which a spatial delimitation of events was not possible. The grey area indicates the number of trees available for reconstruction (i.e. sample size).*

based on a very large number of GD and a large fraction of trees were available for analysis. By contrast, dashed lines refer to torrential activity for which tree-ring records were less readily available due to the limited age of the trees sampled or where a small number of reacting trees and/or weak intensity GD did not allow for a reconstruction of events with equal confidence. The number of increment cores available for analysis is shown by the grey, dashed line. The average return period of debris-flows varies between 6 years in channel 4 and 9.4 years in the channel 2.

Geomorphic evidence

Field investigations and pictures from an unmanned aerial vehicle (UAV) reveal that single point sources (such as landslide-type initiation zones) do not exist for debris-flow initiation in the five gullies under investigation. **Fig. 5A** gives an overview of the source areas of gullies 1 and 2 as well as of the Planspitzgraben torrent. The gullies are characterized by a few reaches with lateral sediment sources (probably Quaternary moraine deposits; **Fig. 5B**) as well as dense networks of linear sediment sources in the gullies (**Fig. 5C**). Estimated sediment volumes stored in the different gullies are in the order of several hundreds to several thousands of m^3 each. Average deposition heights of individual debris-flow deposits on the fans have been estimated between 0.4 and 1.0 m.

Fig. 5. *Sediment sources of the Planspitze north face as observed from an UAV. (A) View of the source areas of gullies 1 and 2 as well as Planspitzgraben. Point sources (B) as well as complex structures of the small gullies will ultimately (C) provide material for debris-flows (areal pictures by UAV).*

5. DISCUSSION

Event reconstruction

The analysis of 384 *P. abies* and *L. decidua* trees allowed identification of 3164 growth disturbances (GD) and thereby the identification of 19 years with debris-flow activity at Gesäuse National Park between AD 1903 and 2008. The reconstruction of debris-flows was based primarily on growth suppressions (GS = 43%) and growth releases (GR = 33%), but much less frequently with compression wood (CW = 4%) following stem tilting or the presence of tangential rows of traumatic resin ducts (TRD = 20%) after wounding. The scarcity of wound-related tissues and the abundance of GS and GR are somewhat unusual for debris-flows (Stoffel, 2008; Stoffel and Corona, 2014), but reflective of the nature of the sediment (*i.e.* clast size, lithology). Calcareous material has been described in the past to lead to GS in case of massive stem burial as a result of limited water, nutrient and oxygen supply (Kogelnig-Mayer *et al.,* 2013). In case of light stem burial, sedimentation may also lead to a GR in case that the delivered material is rich in nutrients which may fertilize the soil layers surrounding the tree (Mayer *et al.,* 2010).

In his work in calcareous environments, Strunk (1997) reported limitations in dating accuracy in case events were defined with CW, GS and GR alone, as these GD may appear with some delay (up to three years) after the occurrence of a debris-flow in the growth rings of trees (Stoffel *et al.,* 2010; Kogelnig-Mayer *et al.,* 2011). The inclusion of TRD considerably helps in this respect as resin is produced in the days following impact and as ducts are being formed in the weeks after the event, thus allowing dating of debris-flows with annual and sometimes seasonal accuracy. The position of TRD within the tree rings provides indications on whether the causative process of damage was snow avalanches or debris-flows (Stoffel *et al.,* 2006; Szymczak *et al.*, 2010). In this study, TRD represent 20% of all GD, which adds considerable confidence to the chronology of dated event. Further independent evidence for the accuracy of the reconstructed time series is provided by the "Planspitzgraben", located between gullies 2 and 3. Local authorities as well as the Austrian Torrent and Avalanche Control report a series of past events in this gully (the last one in 2005) which are in good agreement with the results of our study.

Debris-flow activity

With the exception of the events in 2006, debris-flow activity was mostly limited to only one or a few gullies, but was not recorded in all systems at the same time. We also observe substantially higher activity in gullies 1 and 4 as compared to the other gullies. Differences in activity are not so much due to different source area conditions (*i.e.* sediment availability, catchment size, *etc.*), but reflective of the larger number of old trees present for analysis. **Fig. 4** illustrates that fan 2 hosts the smallest number of old trees for dendrogeomorphic analysis as compared to fans 1 and 4. During the first half of the 20th century, only gully 4 shows clear signals of debris-flow activity. In case that the time window of analysis is restricted to AD 1950–2010, we identify 12 (out of 19) years with debris-flows, and the number of years with flows in only one gully can be limited to two (**Fig. 4**), whereas in most other years three out of five channels produced debris-flows. Provided that this study is limited to the past 60 years, results become fairly comparable with the regional, dendrogeomorphic studies of Pelfini and Santilli (2008) in Valle del Gallo (Italy) and of Bollschweiler and Stoffel (2010) in the Zermatt Valley (Switzerland).

Local debris-flow processes at Gesäuse National Park are considered as the result of extreme weather conditions. In our study, distances between individual torrents vary from 0.3 to 1 km. Inclination and mean relief energy are very similar for all channels, so that differences in channel activity can be assigned to the local variability of rainfall and/or to varying sediment availability (*i.e.* disposition for debris-flow initiation).

The meteorological station Gstatterboden is located less than 1 km from the gullies and records daily precipitation since 1971 (Hydrographic Service Austria, 2013). Despite the fact that the station is unusually close to the study sites, even more so when compared with the settings of previous work in the field, we are aware of the limitations inherent to the temporal resolution and limited spatial information, and of the effects that these might have on a reliable identification of conditions leading to the release of debris-flows. However, this limitation is quite typical for the estimation of rainfall thresholds for mass-wasting processes (Guzzetti *et al.*, 2008), and even more so in mountainous environments (Schneuwly-Bollschweiler and Stoffel, 2012). Besides possible limitations in the completeness of dendrogeomorphic time series (Stoffel *et al.,* 2013) and the inability of meteorological records in valleys to record small-scale rainfall events in mountains, sediment availability possibly represents another reason for varying channel activity.

6. CONCLUSION

In this study, dendrogeomorphic techniques were applied to reconstruct a regional chronology of debris-flows in the Gesäuse National Park. Tree-ring records revealed 47 debris-flow events in five adjacent gullies over the last 110 years. Field investigations and the use of an unmanned aerial vehicle (UAV) allowed detection of sediment sources which mainly originate from recent weathering, thereby allow restricting event magnitudes to be in the order of 1000–10,000 m^3.

The coupling of different methods and the inclusion of UAVs in field-based research has been shown here to be a powerful tool for the documentation of debris-flow systems and for the monitoring of inaccessible areas where sediment transfers play a critical role. A detailed investigation of the source areas (constant areal pictures and DEMs derived from permanent analysis of UAVs) would also be an asset to check sediment availability/transport.

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