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Geomorphic coupling between hillslopes and channels in the Swiss Alps

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ABSTRACT: The coupling relationships between hillslope and channel network are fundamental for the understanding of mountainous landscapes' evolution. Here, we applied dendrogeomorphic methods to identify the hillslope–channel relationship and the sediment transfer dynamics within an alpine catchment, at the highest possible resolution. The Schimbrig catchment is located in the central Swiss Alps and can be divided into two distinct geomorphic sectors. To the east, the Schimbrig earth flow is the largest sediment source of the basin, while to the west, the Rossloch channel network is affected by numerous shallow landslides responsible for the supply of sediment from hillslopes to channels. To understand the connectivity between hillslopes and channels and between sources and sink, trees were sampled along the main Rossloch stream, on the Schimbrig earth flow and on the Rossloch depositional area. Geomorphic observations and dendrogeomophic results indicate different mechanisms of sediment production, transfer and deposition between upper and lower segments of the channel network. In the source areas (upper part of the Rossloch channel system), sediment is delivered to the channel network through slow movements of the ground, typical of earth flow, shallow landslides and soil creep. Contrariwise, in the depositional area (lower part of the channel network), the mechanisms of sediment transfer are mainly due to torrential activity, floods and debris flows. Tree analysis allowed the reconstruction of periods of high activity during the last century for the entire catchment. The collected dataset presents a very high temporal resolution but we encountered some limitations in establishing the source-to-sink connectivity at the catchment-wide scale. Despite these uncertainties, for decennial timescales the results suggest a direct coupling between hillslopes and neighbouring channels in the Rossloch channel network, and a de-coupling between sediment sources and sink farther downstream, with connections possible only during extraordinary events. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: source to sink; tree rings; connectivity; coupling–decoupling mechanisms; hillslope–channel processes

Introduction

It is generally accepted that mountainous landscapes can experience rapid erosion if they are in transient geomorphic states (i.e. not in a geomorphic equilibrium; Schlunegger and Hinderer, 2003; Norton *et al.*, 2008). When timescales of several tens to hundred thousands of years are considered, transience is mainly related to rock uplift pulses, base level falls or glacial–interg-lacial cycles. For shorter time intervals, spanning individual to a few thousand years, transient states can also be initiated by land use and/or climate change. In either case, these perturbations result in a modification of the erosional processes governing the coupling relationships (or connectivity) between hillslopes and channels (Bull, 1979; Montgomery and Buffington, 1997; Rickenmann, 1997; Bovis and Jakob, 1999; Harvey, 2012), which can be considered as either coupled or decoupled (Harvey, 2012). A coupled connectivity reflects the situation in which the hillslope-derived material directly reaches the channel network while a decoupling relationship refers to the case where the supplied material stops on the hillslope before reaching the channel. It is important to highlight that this distinction strongly depends on the considered temporal scale. In particular, a hillslope segment that is defined as decoupled/coupled from the channel network for a very short timescale can reveal a full coupling/decoupling to the bordering channel if longer timescales are considered (Harvey, 2001, 2002). Most important, the hillslope–channel connectivity within a catchment directly influences the sensitivity and the velocity of geomorphic response to new environmental conditions, and is therefore of significance for the understanding of landscape evolution (Harvey, 2001, 2002).

The coupling relationship between hillslopes and channels influences not only the mechanisms and velocity of sediment transfer but also the spatial and temporal direction of change. In a poorly coupled system, the effects of environmental disturbances will be visible at local scales only and over longer time periods, whereas in well-connected systems the responses to perturbations will be transmitted to the entire catchment. Responses can be downsystem (from hillslopes to channels) or upsystem (from channels to hillslopes; Harvey, 2002; Bishop *et al.*, 2005), and the response time is related to the size of the catchment (Harvey, 2001). The assessment of temporal and spatial scales of connectivity is therefore fundamental to understand the evolution of mountain catchments (Harvey, 2002; Jakob *et al.*, 2005; Kirby *et al.*, 2007).

The delineation of the connectivity within a catchment requires the capability to reconstruct the routing path of sediment at the highest possible resolution, both in space and time. To date, this has been mainly achieved at the hillslope and event scale (Stoffel and Bollschweiler, 2009), but there are only a handful of papers that have detailed the transfer of material from the hillslopes down to the channel network and finally to the depositional site at a high temporal resolution, but for the scale of an entire catchment (e.g. Berger *et al.*, 2011; Bennett *et al.*, 2012). In this paper, we focus on a 2·5 km^2-large catchment at the northern border of the Swiss Alps and explore the patterns of the hillslope–channel coupling relationships for relatively short timescales ranging from individual years, to tens and possibly hundreds of years. To this extend, we apply dendrogeomorphic methods (Stoffel and Bollschweiler, 2009) as they allow a detailed chronological reconstruction of sediment transfer patterns in channels and on hillslopes at a yearly precision. We apply this methodology because it has been widely used to determine the frequency of single geomorphic events such as rockfalls, snow avalanches, floods, debris flows and landslides at a yearly to seasonal resolution (e.g. Bollschweiler *et al.*, 2008; Corona *et al.*, 2012; Lopez Saez *et al.*, 2012; Stoffel and Wilford, 2012; Stoffel *et al.*, 2012). Most important, this information is the prerequisite to identify the temporal scales at which processes on hilllslopes and in channels have been related, and thus coupled, to each other. We apply this technique at the catchment scale in an effort to understand the sediment transfer dynamics at the highest possible temporal-resolution. In these terms, we expect to see a clear connection between processes affecting the source areas, the channel network and the depositional fan at the end of the catchment. Accordingly, the ultimate scope of our work is to trace the transport of sediment from the hillslopes down the channel network at the highest possible resolution, but for the scale of an entire drainage basin and for a temporal record spanning individual years to decades, and possibly a few hundreds of years.

Study Area

The Schimbrig catchment is located in central Switzerland, in the UNESCO world heritage site of Entlebuch (canton of Lucerne – GCS_CH1903: coordinates on Figure 1). The basin covers an area of ~2·5 km^2 and can be divided into three major areas (Figure 1). The lower and upper areas are characterized by steep slopes and thus unsuitable for agriculture and partially covered by forest. Contrariwise, the middle part is characterized by gentle slopes, allowing cattle and sheep to graze. During the past centuries this area has been mainly covered by meadows. This spatial restriction of agricultural use is partially due to differences in the litho-tectonic architecture, which likewise controls the landscape topography. In the upper part, the Helvetic nappe formations comprise an Early Cretaceous and Early Tertiary suite of marls, limestones, siliceous limestones and quartzites, which form bedrock walls

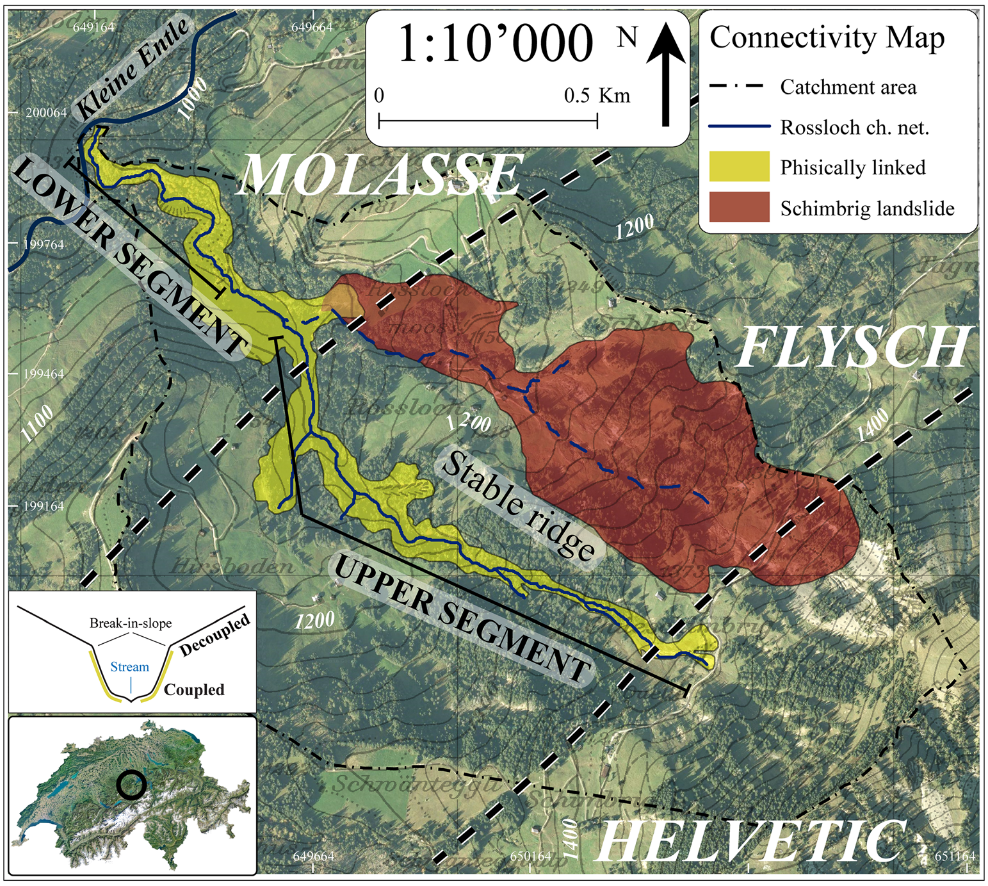

Figure 1. Location of the Schimbrig catchment and main geomorphic features. The orthophoto (2008) shows the areas used as graze and the ones covered by forest. It is possible to observe that the whole channel network does not show any human activity but it is, instead, fully covered by trees. The figure also shows the main lithological subdivisions: the central portions of the catchment are occupied by Flysch, which has been reworked during and after the Last Glacial Maximum, while northern and southern parts belong Molasse and Helvetic units, respectively. The figure highlights the Schimbrig landslide and the Rossloch channel network, divided in upper and lower segments. The sketch at the left-bottom of the figure, as well as the coloured area around the Rossloch channel network, highlight the hillslopes that are physically linked (coupled) with the channel system. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

with nearly vertical slopes (Mollet, 1921) (Figure 1). In the middle portion of the basin, the low mechanical strength of the Eocene Subalpine Flysch has allowed the formation of gentle hillslopes, more suitable for pasture, while in the lower segment, Molasse conglomerates with high erosional resistance (Kühni and Pfiffner, 2001) form stable ridges that confine the catchment to the north (Figure 1; Mollet, 1921). A stable north–south (N–S) oriented ridge in the central part of the study area divides the basin into two unstable geomorphic segments: a large landslide body (Schimbrig earth slide; Schwab *et al.*, 2007, 2008) in the east and a channel network (Rossloch torrent) in the west (Figure 1).

The Schimbrig earth slide lies almost entirely in the Flysch domain. This unit has been strongly subjected to earth-flow and landslide processes, as already noted by Mollet in 1921. The earth slide, with a spatial extent of 482×10^3 m^2, has recently experienced a period of intense activity between September 1994 and May 1995 when slip rates reached maximum values of several metres per day (Liniger and Kaufmann, 1994a, 1994b; Schwab *et al.*, 2008). Its episodic movement resulted in large damages to meadows, cowsheds and infrastructure, and farmers had to be evacuated by helicopter. The volume of sediment displaced in this period has been estimated to $\sim 350 \times 10^3$ m^3, of which $\sim 120 \times 10^3$ m^3 was transferred from the landslide to the channel network farther downstream (Schwab *et al.*, 2008). The landslide clearly shows features of a complex rotational earth-flow, with development of escarpments and areas of sediment accumulation in different localities. Due to the morphology of the catchment, the earth slide has been forced to converge into the channel network upstream of the Molasse ridges. Here, large volumes of unconsolidated material have been transferred to the channel network (Schwab *et al.*, 2008; Mackey *et al.*, 2009) and deposits from the 1994–1995 event are still visible in the channel bed.

The Rossloch torrent, which occupies the western segment of the catchment (Figure 1), is characterized by a network of trunk and tributary channels. The main trunk channel has a length of ~2 km and runs from 1400 to 975 m above sea level (a.s.l.) where the Rossloch torrent joins the Kleine Entlen River, forming a small depositional fan with multiple cut-and-fill terrace levels. The trunk stream segment, which has been incised into the Flysch bedrock several tens of metres deep, is bordered by hillslopes with steep angles of up to 48°. The result of this incision is the development of a well defined break-in-slope (Figure 1) that allows a very precise differentiation between hillslopes segments that have transferred unconsolidated material to the channel network through a directed coupling, and decoupled hillslopes that have not supplied material to the channel network. This has been considered by Schlunegger *et al.* (2002) and Schwab *et al.* (2008) to reflect the situation for the past years and decades, which is the timescale of consideration in this paper (see earlier). On the coupled hillslopes, the material transfer has mainly occurred either through landsliding, creep or earth flows (Mollet, 1921), while episodic processes between flooding with suspended material and debris flows (*sensu largo*) have mainly affected the Rossloch stream. For clarity of reading, the term 'hillslope' hereafter always refers to an area coupled to the channel network (light colour in Figure 1).

Material and Methods

Landscape architecture

The geomorphic features in the landscape were identified following the guidelines of Schlunegger *et al.* (in press) and mapped at a scale of 1:1000. Landslides and earth slides were categorized based on the morphology of the hillslopes and the sedimentary fabric of related deposits. Channels were mapped as either bedrock or non-bedrock channels, and the sedimentary fabric of channel floor deposits was used to characterize the mechanisms of sediment transfer (e.g. floods, debris flows, mud flows, creeping, etc.). Likewise, we mapped deposits at channel borders as levees if aligned parallel to the channel course, or as crevasse splays if they form individual lobes perpendicular to the channel orientation. Both levee and crevasse splay deposits were often overgrown by trees, which were subsequently sampled for the purpose of this study.

At a larger scale, a lidar 2-m Swisstopo digital elevation model (DEM) was used to delineate hillslope segments that have transferred unconsolidated material to the channel network. Here, we applied the approach of Schlunegger *et al.* (2002) and Korup and Schlunegger (2007) to delineate the coupling relationships between hillslopes and the channel network in our study area. In particular, hillslopes which have supplied material to the channel network mainly by mass wasting processes (earth slides and landslides) during the past few decades to hundreds of years are characterized by nearly straight slopes. These have higher gradients than those hillslopes farther upslope which have not supplied material to the channel network by mass wasting. Both hillslope segments, the channel–hillslope coupled and the non-coupled ones, are then separated by distinct breaks-in slope (see inset on Figure 1 as example), which are readily visibly on high-resolution DEMs, as outlined by Schlunegger *et al.* (2002) and Korup and Schlunegger (2007). Accordingly, we mapped these break-in-slopes on hillslopes to separate hillslope segments with a direct physical coupling to the channel network from those that are decoupled (where sediment is not reaching the channel network). According to Korup and Schlunegger (2007), this method constrains the coupling mechanisms in the Alps for timescales spanning years to decades, and in some cases even hundreds of years. Orthophoto analyses were then used to identify major changes in the hillslope–channel coupled segment.

Sampling strategy

Dendrogeomorphic methods are based on the fact that trees react to geomorphic events with growth anomalies or growth disturbances (GDs), which are visible in the tree-ring series (Stoffel and Bollschweiler, 2008). The year(s), and sometimes even the season, of the impact can thus be determined through a backward counting of the rings. Trees affected by landsliding normally show an inclined stem base and react with the formation of compression wood to regain the vertical position (e.g. Fantucci and Sorriso-Valvo, 1999). Figure 2 shows an example of a tilted tree in the study area. The tree suffered from a sliding ground movement, which destabilized its roots. Trees affected by torrential activity can be inclined, injured or show a buried stem base if material transported in the flow is deposited around the stem. Tree reactions will be abrupt growth changes (suppression or release), compression wood or injuries and associated tangential rows of traumatic resin ducts (TRDs; e.g. Bollschweiler and Stoffel, 2010). The spatial position of the trees showing simultaneous GDs provides information on areas affected by past landsliding or torrential processes.

The method has, however, limitations. The reconstruction is mainly limited by the age of trees. In addition, trees removed by intense processes (e.g. rockfalls, large debris flows, and similar events) will no longer be available for reconstruction (Stoffel *et al.*, 2006; Procter *et al.*, 2012). Likewise, low-intensity processes, e.g. a small flood constrained to the river bed, will not affect trees, and no growth reactions in the tree-ring series

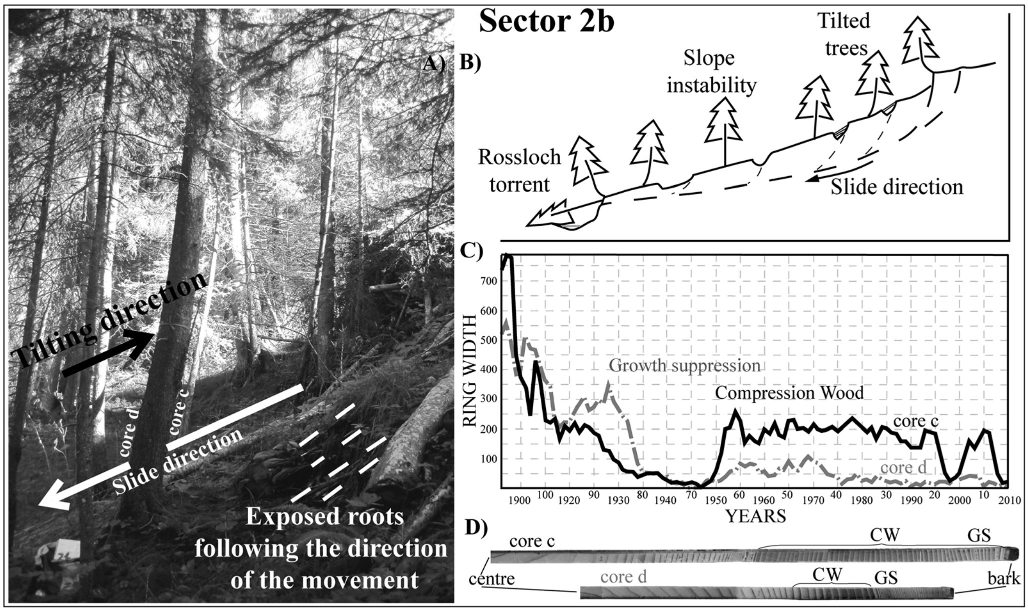

Figure 2. Example of a tilted tree in sector 2b (landslide). (A) Picture of the sampled tree with indication of sampling positions. (B) Sketch of the sliding slope with trees being tilted in different directions and suffering from root exposure as a result of landsliding. (C) Tree-ring series of two cores from a tree affected by several sliding phases and showing compression wood (CW) formation due to the tilting and a growth suppression (GS). (D) Cores sampled from the tree with clearly visible CW and GS.

will therefore show the event (Schneuwly-Bollschweiler and Stoffel, 2012).

In this study, sampling was done in the Rossloch channel network and on the Schimbrig earth slide, and tree ring samples were collected during summers 2009 and 2010. Note that along the Rossloch stream on the western side of the study catchment (Figure 1), we only collected tree rings from hillslopes with a direct physical link to the channel network. On the Schimbrig earth slide, however, the restoration of the coupling relationships to the channel network has not been so obvious (Mollet, 1921). This is the reason why we decided to sample nearly all trees situated on this earth slide body. Note also that the identification of geomorphic processes in the field is essential for the dendrogeomorphic sampling of trees, as reactions of trees to geomorphic disturbances do not (necessarily) vary between different geomorphic processes (e.g. trees can react in the same way even if the damage is caused by different kinds of events) (Stoffel and Hitz, 2008; Stoffel *et al.*, 2011). Therefore, while sampling trees, careful attention was given to their position in the landscape (levees, crevasse splays, channel floor deposits, landslides) and to external signs of disturbances (i.e. anomalous morphology, injuries or trunk burial) (e.g. Alestalo, 1971; Bollschweiler and Stoffel, 2010). Trees that showed no evidence of external damage were also sampled to establish a reference chronology. This is necessary to represent the local growth pattern of tree-rings, to avoid climatic signals, and to identify missing rings (Cook and Kairiukstis, 1990). The uppermost area at the foothills of the Helvetic limestone cliffs was not sampled as it is located outside the coupled hillslope (Figure 1).

Our sampling strategy was slightly different in the upper and lower segments of the study area. In the upper segment, samples were taken from four sectors along the main trunk channel (Figure 3; sectors 1, 2a, 2b and 3). In the narrower parts of the channel (sectors 1 and 3), trees were generally sampled very close to the channel bed and on the lower part of bordering hillslopes to reconstruct past torrential activity. We likewise sampled trees where large deposits were present on the channel bed and field observations indicated the presence of coupled hillslopes, which represent a major source area (earth slide or landslide; sectors 2a and 2b). At these sites, trees were sampled higher on the hillslopes and (where possible) on the deposits associated with the movement of an earth slide or landslide to reconstruct the movement activity (Figure 3). Note that very few trees were available for sampling these latter deposits. Because the lack of a single event at the scale of a single hillslope-scale does not interfere with the sediment dynamics of the entire catchment, this limitation can be neglected and sampled tree density can be considered sufficient to record all major events that affected this portion of the channel network.

In the lower segment, trees were sampled homogeneously throughout the channel bed in order to cover the entire depositional area (Figure 3, sectors 4 and 5) and to reconstruct past torrential and depositional activities in this area at the end of the Rossloch channel network. The sampled trees were generally located on levees, crevasse splay deposits or in the immediate vicinity of the actual river bed. Note that in sector 4, the 1994–1995 activity of the Schimbrig earth slide destroyed almost all trees in the channel bed over the entire length of the depositional area (~120 m). In this sector, we could only collect tree samples from the bordering hillslopes.

Samples were also taken from the Schimbrig earth slide (Figure 3, sector 6), since our detailed mapping, the analysis of the orthophotos and previous studies (Schwab *et al.*, 2008) revealed that this landslide has been an important sediment source for the Rossloch channel network. Here, trees with obvious signs of past sliding activity (i.e. inclined trees) were sampled on the upper landslide body. Note that the lower part could not be sampled due to the absence of suitable trees.

Tree positions were measured using an inclinometer, laser distometer and compass, as the global positioning system (GPS) signal did not pass through the dense vegetation. Following this strategy, a total of 994 increment cores were taken from 485 Norway spruces (*Picea abies* (L.) Karst.) and Silver firs (*Abies alba* Mill.). Within the Rossloch channel network, we sampled 116 trees in the upper segment (sectors 1–3) and 161 trees in the lower segment (sectors 4 and 5). On the Schimbrig earth slide, we sampled 208 trees (sector 6). Of the 277 trees sampled in the Rossloch channel network, 191 showed up to five signs of damages per tree, while 86 did not show any

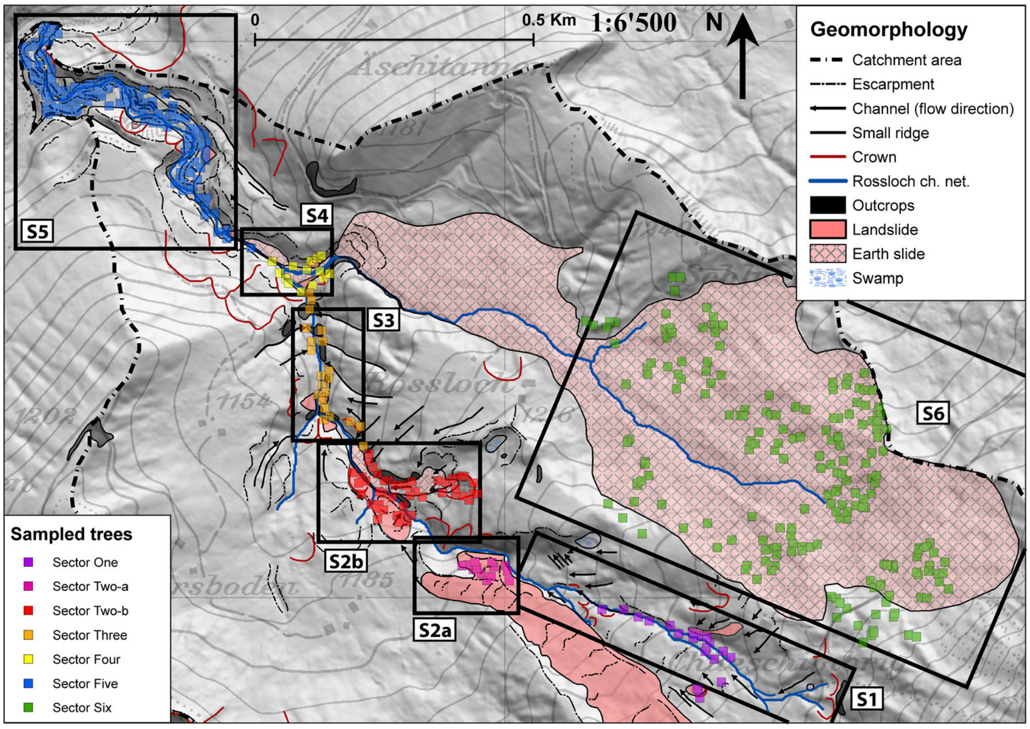

Figure 3. Geomorphic map with the indication of the six sectors individuated in the catchment. The map shows the main geomorphic features recognized in the channel network (earth- and land-slides, small channels, ridges and outcrops) and the location of the sampled trees, divided into sectors. Trees are highlighted with different colours for the different sectors. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

GDs. These latter trees were either used to construct a reference chronology or to derive a minimum age of the deposit on which they grow.

Laboratory analysis

In the laboratory, samples were prepared and analysed using standard dendrogeomorphic methods (Stoffel and Bollschweiler, 2008, 2009). Tree rings were counted and ring widths were measured using a digital LINTAB position table connected to a Leica stereomicroscope and with the TSAP-Win Scientific 4.63 software (Rinntech, 2011). Individual growth curves were then compared to the local reference chronology (Cook and Kairiukstis, 1990; Vaganov *et al*., 2006) in order to identify any missing or false rings. GDs in the tree-ring series, such as injuries, callus tissue, tangential rows of TRDs, abrupt growth suppression or release and compression of wood were dated to the year. Finally, master plots were created to outline the number of trees with simultaneous disturbances. For all years with a concentration of GDs, maps were created in ArcGIS to visualize the spatial distribution of affected trees.

Results and Interpretation

Geomorphic architecture

The Rossloch channel network can be divided into two major segments. The upper segment comprises the reach between 1400 m a.s.l. where channels originate, and 1150 m a.s.l. where the toe of the Schimbrig earth slide debouches into the Rossloch stream. The lower segment continues until the Rossloch stream discharges in the Kleine Entlen River, located at 975 m a.s.l.

Detailed geomorphic mapping reveals that the two segments are characterized by different features, suggesting different mechanisms of sediment supply, transfer, bypass and deposition (Figure 4). The upper segment presents the typical morphology of a mountain stream where first-order non-dissected channels converge to one larger second-order channel. A few hundred metres farther downstream, this second-order channel starts to incise into the Flysch and rapidly creates a narrow and steep path. The channel is thus characterized by a narrow bed bordered by steep hillslopes that are often undercut and affected by earth slides and landslides. The channel bed alternately consists of bedrock reaches and segments where the channel floor is covered by boulders and pebbles.

The lower segment covers a wider area (~25 000 m^2, with average lengths and widths of 550 and 45 m, respectively). It is characterized by channel reaches where sediment has accumulated as several decimetres- to metres-thick levee or crevasse-splay deposits, respectively. In this lowermost segment, however, the trunk occupies a much narrower area and has a ~7 m cross-sectional width, mainly bordered by levees and higher terrace levels.

At a smaller scale, four distinct sectors can be identified in the uppermost headwater segment. Sector 1 (Figure 3, S1) comprises a ~600 m-long headwater reach where the trunk channel is perched on Flysch-bedrock that is exposed in places. Along this section, the incision depth of the trunk is initially $<$ 2 m and increases downstream. The downstream end of this uppermost sector is defined by the site where the incision depth increases to a maximum of 50 m over a ~225 m-long reach, delineating a knickzone in the longitudinal stream profile. This knickzone then sets the upper boundary of sector 2a (S2a). This latter reach is characterized by exposed bedrock in places, but also hosts metre-thick deposits of pebbles and boulders embedded in a muddy matrix. This reach is also bordered by the toe of the 47 900 m^2-large landslide with sources in the southwest (SW). Farther downstream (sector 2b, S2b), the channel hosts a metre-thick cover of a muddy matrix and individual boulders in places over a ~215 m-long reach. This is also the segment where 3000 to 6000 m^2-large landslides and earth slides border the channel

Figure 4. Photographs of the Rossloch channel network. (A) and (B) represent the lower segment; in (C) is visible the Schimbrig earth slice toe in correspondence of the input in the Rossloch channel network; (D) and (E) represent the upper segment. It is possible to realize the differences between lower and upper segments. In the first one, there is almost no input from the lateral slopes, which are generally situated at a larger distance from the stream (5 to 10 m). In the second one, the input from lateral slopes is evident: there is a large amount of material directly affecting the channel and the trees situated on the slopes. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

on both the south-western and north-eastern sides, respectively. Here, the fabric of the channel fill mainly corresponds to that of the earth-slide deposit. The subsequent sector 3 (S3) is 300 m long and extends down to the confluence with the Schimbrig earth slide. The Flysch bedrock is exposed nearly along the entire 300 m-long reach of S3, and metre-thick conglomerate beds of the Molasse bedrock are exposed on the channel floor near the downstream end of this sector, forming a second knickzone. The bordering hillslopes are dissected by a network of steep, up to 2 m-deep channels. Evidence of landslides is sparse.

The reach down to the confluence with the Kleine Entlen is characterized by the presence of a channel fill, which is several metres thick. The uppermost reach immediately downstream of the confluence with the Schimbrig earth slide is occupied by a metre-thick suite of matrix-supported boulders and pebbles that form a terrace with a sharp lower termination (sector 4, S4). These deposits were derived from the foot of the Schimbrig earth slide by the 1994 surge (Schwab *et al.*, 2008) and occupy the entire channel over a ~120 m-long reach. This deposit covers a surface of ~5000 m^2, and has been dissected 2·5 m deep since its deposition. The orthophotos, taken before and after these years (Schwab *et al.*, 2008), clearly show that this event changed the stream path over the entire length of the deposit, pushing it to the west side of the channel bed. The orthophotos also show that the trees immediately close to the material source were destroyed or removed, while those farther downstream appear to have survived this event. The lowermost sector 5 (S5) is characterized by a continuous increase in the width of the channel bed from <10 m to >150 m at the confluence with the Kleine Entlen where the Rossloch stream forms a terminal fan. The trunk channel meanders along this sector at short wavelengths of < 40 m, causing bank erosion on the lateral sides.

The Schimbrig earth slide is referred to as sector 6 (S6) in this paper and has been described in detail by Schwab *et al.* (2008). It is a 482×10^3 m^2-wide landslide with various compartments, which have displaced at rates up to more than 2 m per day (Schwab *et al.*, 2008). A detailed photogrammetric survey revealed that this earth slide has experienced a surge between 1994 and 1995, translating a total of 120×10^3 m^3 of mass to the Rossloch stream (Schwab *et al.*, 2008, and see also earlier).

Sediment sources and sinks

Based on the detailed geomorphic mapping, we identify the reaches along S1 to S3 (including the Schimbrig earth slide) as major sediment sources. We base this interpretation on the abundance of landslides with a straight physical linkage and thus a direct coupling with the channel network particularly in S2b. There, the up to 50 m-deep incision appears to have destabilized the bordering hillslopes causing landslides, which have directly supplied material from the lateral borders. Farther upstream in S1, the poor incision of the channel appears to not have influenced the processes operating on the hillslopes. As a result, a direct physical coupling with the channel network only occurs in places in this headwater sector. A second major source of sediment has been provided by the Schimbirg earth slide (S6) where photogrammetry-based analyses have revealed the transfer of large volumes of sediment to the Rossloch steram during past decades, particularly in 1994 (Schwab *et al.*, 2008). Material derived from the Schimbrig earth slide is found as terrace deposits near the downstream end of S4. Likewise, S5 appears to be a major sediment sink as evidenced by abundant matrix and clast-supported breccia deposits testifying the occurrence of repeated floods and debris flows. Note, however, that the fraction of deposited versus transferred and exported material is not known in sufficient detail (Schwab *et al.*, 2008).

Tree-ring analyses

The sampling strategy followed the geomorphic architecture described earlier, with trees collected in every sector. The overall age patterns point to a mean age of 94 years (with 43% of the samples older than 100 years) and exhibit distinct differences between the trees situated on the Schimbrig earth slide (S6) and those sampled along the Rossloch stream (S1–S5). At Schimbrig (S6), trees were generally older (with 59% > 100 years) compared to those sampled in the Rossloch channel network (30·5% > 100 years) (Table I). In contrast, only minor age differences exist between trees in the source (S1–S3) and sink (S4 and S5) areas within the Rossloch channel network. The oldest tree yields 291 rings at sampling height (AD 1720) and grows in S6.

A total of 700 GDs were identified in the tree-ring samples of the entire study area. In the headwaters of the Rossloch channel network, S1 and S2 show a high percentage of GD related to stem tilting and the subsequent formation of compression wood (~40% of trees) (Table II). In addition, 34% of the trees in S1 show evidence of mechanical damaging (injuries and TRDs). In S3, where bedrock is exposed, almost 70% of the trees show abrupt growth suppression as a reaction to impaired growth conditions (decapitation, root shear or exposure). Evidence of impaired growth conditions is also prominent in the reach below the junction with the Schimbrig stream within S4 and S5, where abrupt growth suppression makes up > 40% of all GDs. Interestingly, trees in these sectors are also characterized by growth releases (> 30%) reflecting improved growing conditions possibly after the elimination of neighbouring trees. On the Schimbrig earth slide (S6), growth suppressions predominate by 48%, whereas the formation of compression wood following stem tilting and mechanical damaging of the trunks are similarly represented with 22 and 25%, respectively.

Chronology of recorded activity

Periods of high activity were recognized on the bases of the growth anomalies registered in the trees. Tree-ring series showed evidence of disturbances prolonged in time, with slow reactions in the years following the first year of growth anomaly. Counts of GDs in a yearly temporal framework yielded evidence for multiple hillslope and channel events that are delineated here in the downstream direction (Figure 5).

The upper segment of the Rossloch channel network (S1–S3) reveals ongoing activity spread along the entire channel network with tree rings recording movements for the period 1905–2010. In S1, GDs allow the reconstruction of five major periods of activity between 1940–1946, 1952–1956, 1976–1981, 1990–1994 and 2001–2005. In S2a, trees registered a period of high activity between 1947 and 1952 and periods of activity registered in 1958–1959, between

Table II. Growth disturbances observed in the tree-ring records of sectors S1–S6

		%CW	%GS	%GI	%I or TRDs
Source areas	S1	38	13	15	34
	S2a	38	23	13	15
	S2b	43	16	19	22
	S3	21	68	7	4
Depositional area	S4	21	42	32	5
	S5	16	41	30	13
Schimbrig landslide	S6	25	48	6	22
Total		202	251	132	115

Note: CW, compression wood; GI, growth increase; GS, abrupt growth suppression; I, injury; TRDs, tangential rows of traumatic resin ducts. For details see text.

Table I. Overview of the trees selected for analysis and their age at sampling height

	Total trees	Trees > 100 years	Percentage	Trees <100 years	Percentage	Mean age	Oldest tree (AD)	Oldest tree (yr)	Youngest tree (AD)	Youngest tree (yr)
Source areas (S1–S3)	116	34	29	82	71	85	1766	245	1994	17
Depositional area (S4 and S5)	161	52	32	109	68	89	1785	226	1998	13
Schimbrig landslide (S6)	208	123	59	85	41	109	1720	291	1994	17
Total	485	209	43	276	57	94				

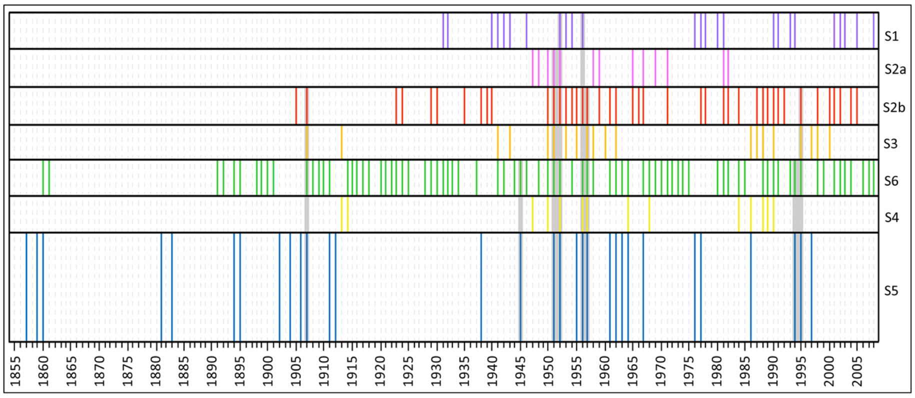

Figure 5. Reconstructed hillslope and channel events in the source areas and on the fan of the Schimbrig catchment. The most obvious coupling events are marked with grey lines in the background. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

1965 and 1971, and in 1981–1982. S2b is one of the most active sectors within the channel network, with GDs registered in the tree-ring records on both sides of the channel. Periods of high activity were also identified between 1935–1940, 1950–1957, 1961–1967, 1987–1992 and 2000–2005, while sporadic events are registered before the 1950s and between the 1970s and the mid-1980s. Trees in S3 registered three periods of high activity (1950–1960, 1986–1990 and 1995–1999) and sporadic events before the 1950s. At the confluence with the Schimbrig earth slide, trees in S4 registered spread activity between 1913 and 1990. The trees sampled in S5 allow the reconstruction of multiple events between 1857 and 2010.

The registered GDs result in the identification of specific years during which a large number of trees were damaged simultaneously along the whole area. Periods of particularly high activity were registered in 1955–1964 and 1994–1995; the latter causing damage to at least one-fourth of the trees sampled in S5. Other single events are registered homogeneously throughout the century with the most important ones (involving between 15 and 20% of the sampled trees) in 1951, 1952, 1957, 1961, 1964 and 1997. On the Schimbrig earth slide (S6), GDs in trees point to several landslide reactivations between 1860 and 2010. Activity in this area seems to be homogeneously spread and individual periods of landslide activity lasted 3–4 years in average. Before 1915, affected trees were concentrated in the external parts of the landslide body, whereas GDs registered in trees were more scattered within the main sliding area between 1928–1934, 1941–1946, 1954–1958, 1974–1975, 1994–1995, and 2001–2007. As predictable, the activity observed in 1994 and 1995 damaged the largest number of trees in S6.

Discussion

Sediment transfer dynamics

Fieldwork combined with dendrogeomorphic reconstructions of the dynamics of the Rossloch channel network provides valuable insights for the delineation of areas with different hillslope–channel coupling relationships and distinctive sediment transfer processes. The upper segment of the channel network (S1–S3) has mainly been affected by lateral earth slide and landslides supplying material into the channel network. Field observations indicate that the material has been partially stored in the channel bed and partially eroded by the Rossloch stream. Tree analyses suggest that the sediment sources, especially in S2b, have supplied material through slow and continuous ground movements. This can be interpreted from the exposition of trees' roots and from the GDs visible in trees that show signs of instability over a prolonged time (predominance of compression wood). The presence of segments free from any deposit within the channel (e.g. S3) with no particular changes in the channel profile steepness, suggests that the sediment from farther upstream has been both dammed and bypassed in this sector. It is possible that both interpretations are valid, with finer sediment being transported immediately in suspension, and thicker material blocked in the upper sectors of the channel network and transported during floods or debris flows (Reid and Page, 2002).

The lower segment (S4 and S5), on the contrary, has been primarily affected by floods, debris flows and torrential activities. This is supported by the presence of levee and crevasse splay deposits and the predominant occurrence of suppressed growth patterns in the tree ring record. This lower segment has thus operated either as a sedimentary sink, at least for a limited, yet not quantified time span, or as reach where sediment has been bypassed. The sediment reaching S5 can be derived from the Schimbrig earth slide, and through the mobilization of unconsolidated material, which has been temporarily stored farther upstream in the channel network (S1–S3). However, the absence of deposits in S3 suggests that the material derived from the upper segment of the Rossloch stream has been probably transferred during particular events (see earlier). This suggests that trees in the lower segment record the chronology of flood and debris flow events plus the supply of sediment from the Schimbrig earth slide.

Coupling mechanisms between sources on hillslopes and the channel network

Based on the reconstructions of the sediment transfer dynamics and the chronology of the events, it becomes quite clear that torrential events affecting the alluvial area of the lower segment do not necessarily coincide with years of high activity in the source areas in the upper segment – and vice versa – (Figures 5 and 6). Both fieldwork and tree analyses suggest that upper and lower segments of the Rossloch channel network are controlled by different mechanisms of production and transfer of sediment. In the upper part (S1–S3), the geomorphic analysis suggests that the sediment supplied to the channel network has been stored for a limited timespan in the channel bed, before being transported farther downstream. However, based on the tree record, no clear link emerges between production of sediment in the upper part (S1–S3) and events registered in the lower segment (S4 and S5) (Figure 5). This can be inferred from both from the chronology of the registered activity and from the spatial distribution of the affected trees (Figure 6). The only events that are recorded by tree rings in both the upper (S1–S3) and lower (S4 and S5) segments occurred in 1951, 1952, 1956 and 1957.

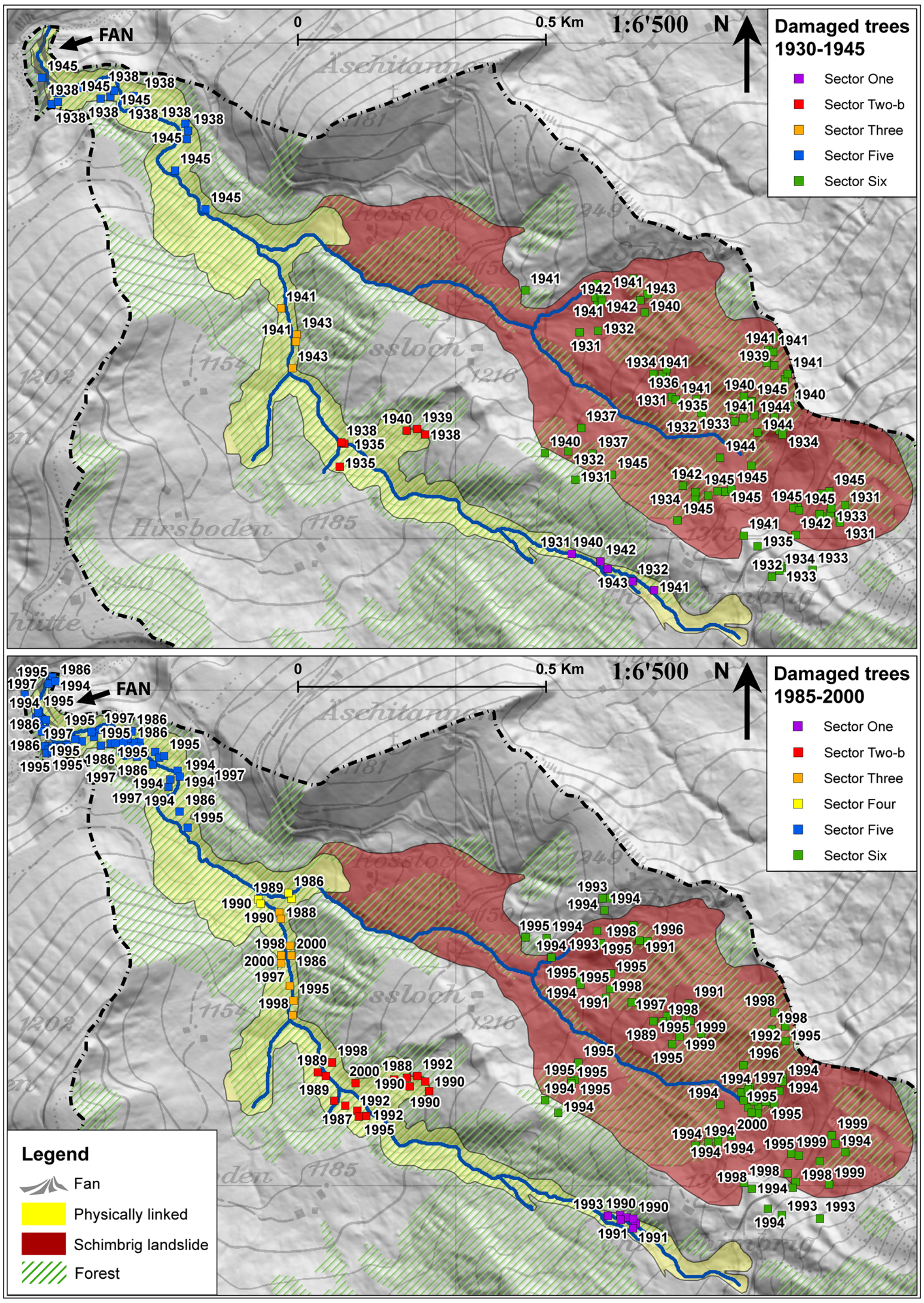

Figure 6. Examples of events registered in trees. The upper illustration represents the period 1930–1945. Two events (1938, 1945) are clearly recognizable in the fan area. However, no coupling between sources and sink appears for the event in 1938 registered on the fan, while a coupling can be hypothesized for the 1945 event, since we have evidence of movement on the Schimbrig landslide in the same year. All the others events registered both at Schimbrig and in the Rossloch channel network did not have any repercussion on the fan. The lower illustration represents the time between 1985 and 2000. Here, events on the fan occurred in 1986, 1994, 1995 and 1997. Also in this case, no coupling between sources and sink can be recognized for the 1986 and the 1997 events registered on the fan, while a coupling can be established between the Schimbrig earth slide and the fan for the 1994–1995 event. As before, all the others events registered both at Schimbrig and in the Rossoloch channel network did not have any repercussion on the fan. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Likewise, tree records dated to 1907, 1967 and 1995 in both upper and lower segments could be used to infer a coupling relationship along the entire drainage basin. However, these correlations have to be treated with caution because S4 and S3 show no records in these years. In all other years trees were damaged in different sectors along the whole channel network. In particular, the limited number of trees involved in these events, suggests the occurrences of sediment transport at local scales with no clear connection between sources on the hillslopes and transfer in the channel network. In summary, the lack of a clear correlation between tree records along the entire channel system does not allow us to reconstruct the details of the chronology sediment transfer from the sources down to the channel network. The same is generally true for the connection between the Schimbrig earth slide (S6) and the lower segment (S5). It is only for the 1994–1995 surge event where we can establish a clear link between the tree records in S6 and S5. This link can be inferred from the distribution of trees damaged in these years (Figure 6), supporting the data of Schwab *et al.* (2008). The same mechanisms and related links can be inferred from the tree records of 1945, 1951, 1952, 1956, 1957, 1962 and 1964. However, reconstructions of connectivity between landsliding at Schimbrig and sediment transfer in the channel network are more difficult to establish for time spans prior to 1945 due to the limited number of trees available to register older events.

Limits of the dendrogeomorphic technique in the study of the sediment dynamics at the catchment scale

Tree-ring analyses show that in the upper segment of the Rossloch stream (S1–S3) and on the Schimbrig earth slide (S6), the supply of sediment occurs by slow ground movement that has affected the trees over a prolonged time-span (i.e. long recovery-time in the tree-ring series or continuous signals of tilting in multiple directions). This is in contrast with the transfer mechanisms in the lower segment of the channel network, where trees recorded different individual events at a yearly precision (i.e. abrupt changes in the tree-ring wide). This distinction highlights the potential of dendrogeomorphology for reconstructing the frequency of events produced by homogeneous processes in small-size areas. However, it also shows the limitations of this technique for the analysis of basin-wide transfer mechanisms. In fact, despite the possibility to reconstruct the chronology of slip on each hillslope bordering the channel network with very high precision, we are not able to trace the transfer of sediment from these hillslopes down the channel network. It thus appears that this technique alone is not sufficient to reconstruct the details of sediment transfer at a catchment scale. However, for the periods 1951–1957 and 1994–1995, we can establish a link between S1/S3–S5 and S6–S5 by combining other sources of information like orthophotos and the results of previous studies (Schwab *et al.*, 2008). Accordingly, we can reconstruct a distinct coupling between sources and sinks only for extraordinary events such as the 1994/1995 landslide surge at Schimbrig (Schwab *et al.*, 2008).

Conclusions

In this paper, we investigated temporal and spatial scales of the connectivity within a small catchment of the Swiss Alps using dendrogeomorphic methods. The results allow the specification of dynamics and mechanisms of sediment transport, and of the coupling relationships between hillslopes and channels, and between source and sink. In particular, the upper part of the Rossloch channel network results affected by earth and landslide activity, while the lower part is mainly affected by floods, debris flows and torrential activity. The dendrogeomorphic investigation points to a prominent connection between sources and sink areas only during extraordinary events, though seems to lack information for the establishment of a more detailed sediment transfer track. In conclusion, it is possible to infer that at a scale encompassing several tens of years, the Schimbrig catchment can be interpreted as a system with a downstream-directed coupling between hillslopes and channels. In this time-framework, hillslopes have served as sediment sources, while channels have operated either as sedimentary sink for a limited time interval, or as bypass system through which the hillslope-derived sediment has been transferred from the sources to the Kleine Entle River. This characterization implies that the material can be mobilized from the channel network when the stream has enough transport capacity to carry the sediment. For short timescales, however, dendrogeomorphic results suggest a decoupling between sediment transfer processes from the source areas to the downstream end of the stream. This condition can be changed during floods or debris flows, for exceptional events or considering a longer timescale. To assess the limitations we encountered in the linkage between source and sink processes, a multidisciplinary approach is suggested for future studies in this field. Dendrogeomorphic methods alone, in spite of the high resolution in activity reconstruction, seem not to be able to provide sufficient details to study the sediment transfer dynamics at a catchment scale.

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