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Controls and feedbacks in the coupling of mountain channels and hillslopes

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ABSTRACT

Mountain channels can be strongly coupled with adjacent hillslopes, exchanging both mass and energy. However, hypotheses of the underlying cause and effect relations are based on indirect observations that do not resolve the mechanics of channel-hillslope coupling at the process scale. Here we present direct observational data of a coupled channel-hillslope system in the catchment area of the Erlenbach, a mountain stream in Switzerland. A slow-moving landslide flanking this alpine stream failed after a flood had eroded an alluvial step in the channel at its base, representing evidence for an upsystem link in channel-hillslope coupling. Progressive accumulation of landslide debris in the channel resulted in a renewed step, stabilizing the hillslope and restoring the channel step in a downsystem link. Thus, upsystem and downsystem coupling mechanisms are joined in a negative feedback cycle. In this cycle, debuttressing and rebuttressing due to channel bed erosion and alluviation are the dominant controls on hillslope stability. Based on an order of magnitude estimate it is plausible that the observed feedback mechanism is a relevant process in the production of coarse (>2 mm) sediment in the Erlenbach.

INTRODUCTION

In mountain valleys, channels and hillslopes are in a permanent feedback relation (Montgomery and Buffington, 1997). Sediment input from hillslopes affects sediment availability (Hovius et al., 2000) and channel flow hydraulics (downsystem coupling). Conversely, erosion of the channel bed affects the stability of adjacent hillslopes (upsystem coupling) (Harvey, 2002; Azañon et al., 2005). The characteristics of these coupling mechanisms determine the sediment dynamics of catchments on large scales. A precise identification of the processes and their dominant controls is therefore key to quantitative landscape evolution theories. However, direct field observations are scarce. Molnar et al. (2010) observed, in a steep mountain stream, that active landslides are located in close proximity to steps in the channel. This qualitative observation suggests a link but does not identify its direction: landslides may form channel steps or step migration may induce landsliding. Bigi et al. (2006), in an experimental landscape, recorded a greater number of failing slopes downstream of sharp changes in the channel gradient, reflecting upsystem coupling. However, it remains unclear how this mechanism scales up to natural environments and conditions, for example for vegetated hillslopes under natural flood cycles. Wistuba et al. (2015) found evidence both for upsystem and downsystem coupling along a semialluvial channel, but their dendrochronological data could not resolve the triggers, dominant controls, and time scales of the processes involved. On regional scales, increased hillslope erosion correlates spatially with local channel bed lowering (Gallen et al., 2011; Roering et al., 2015; Bennett et al., 2016), but the dominant controls and process-scale mechanics have not been determined. Moreover, feedbacks between the mechanisms responsible for upsystem and downsystem coupling have not yet been demonstrated.

Here we present direct observational data of a channel reach featuring a channel step and an adjacent hillslope with a suspended landslide in the catchment of the Erlenbach, a mountain stream in Switzerland. There, landslides are deep seated and slow moving, permitting documentation of the processes and feedbacks in the coupled channel-hillslope system with time-lapse photography. Our monitoring captured two rare flood events that eroded the channel step, followed by the activation of landslide movement, ultimately resulting in the formation of a new channel step and the end of landslide activity. Thus the data provide insight into an entire cycle of channel-hillslope interactions. We propose a conceptual model of channel-hillslope coupling in steep streams and explore its implications for the sediment dynamics in headwater catchments.

FIELD SITE AND METHODS

The Erlenbach stream drains a 0.74 km^2 catchment in the Swiss Prealps (Fig. 1) and hosts a sediment transport observatory (e.g., Rickenmann et al., 2012). The channel has an average slope of 17% and an alternating step-pool–cascade morphology (Turowski et al., 2009); 92

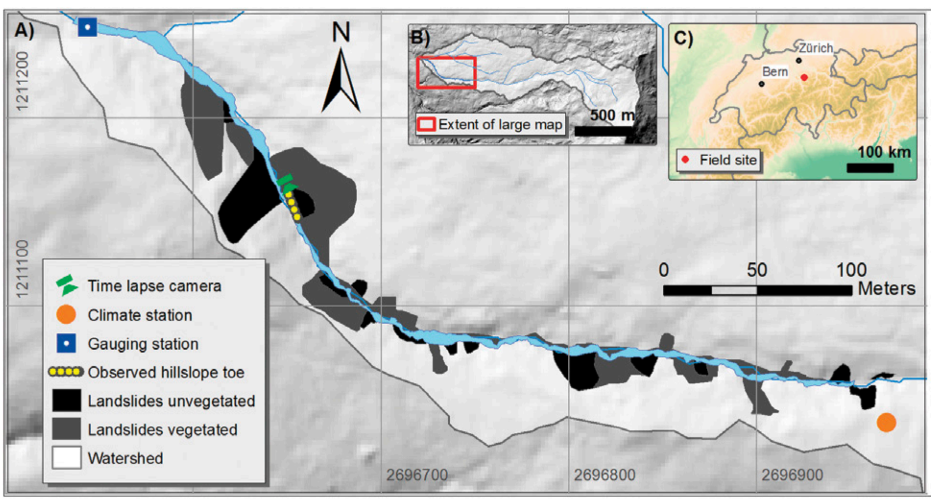

Figure 1. A: Study site with mapped landslides (Schuerch et al., 2006). B: Location in the Erlenbach catchment. The time-lapse camera (green symbol) points upstream to a channel-hillslope ensemble with the monitored landslide toe (yellow dotted line). Coordinates refer to the CH1903+ system [source: dhm25 © 2016 swisstopo (5704 000 000)].

steps with a mean height of 0.79 m were identified from a long-profile survey in April 2014. Stream discharge is measured at the catchment outlet and precipitation rates are measured at a climate station located within the catchment (Fig. 1) (Turowski et al., 2009), both at 10 min intervals. The mean annual precipitation is 2300 mm, 80% of which falls as summer rain, and the mean annual peak discharge is ~2 m^3/s. Bedload transport begins at a water discharge of ~0.5 m^3/s (Turowski et al., 2011) and is frequent, with ~20 events per year, mainly driven by convective summer storms. The catchment is underlain by clay-rich flysch and glacial tills hosting a large number of slow-moving landslides with exposed subsoils that occupy 35% of the channel banks (Schuerch et al., 2006).

In the Erlenbach we monitored the evolution of a 20-m-long channel reach ~150 m upstream of the gauge (Fig. 1) that initially featured a 0.5-m-high alluvial step spanning the 1.6-m-wide stream. The step was located at the downstream end of a suspended slow-moving landslide with a width of 16 m along the channel bank and a hillslope length of 12 m. We used stationary time-lapse cameras to monitor the channel and the suspended slow-moving landslide at 30 min intervals during 3 periods: 12–16 April 2014, 11 July to 27 November 2014, and 2 August to 3 October 2015. Schuerch et al. (2006) identified this landslide as being embedded within a larger, dormant landslide complex (65 × 35 m). From frequent field visits we know that there has not been significant movement in this larger complex during the observation period. We determined the migration of the step from the time-lapse images. The landslide exhibited episodic movement, which was measured in units of image pixels by manual tracking of features at the landslide surface (e.g., a tree root or boulder) between the time-lapse images. The pixel coordinates, which were translated into a constant, independent reference frame, scale linearly to real-world coordinates because the viewing distance stayed constant throughout the monitoring period, and there is no camera lens distortion. The pixel length in the zone of hillslope movement ranged from 1.5 to 1.65 mm.

OBSERVATIONS

Rainfall can drive channel and hillslope activity. Between 12 April and 27 November 2014, 129 rainfall events (rainfall episodes delimited by at least 5 h without precipitation) occurred in the Erlenbach catchment, totaling 1998 mm precipitation. Here we give long-term average precipitation intensities in millimeters/day, event-averaged intensities in millimeters/hour, and maximum intensities in millimeters/10 min to reflect the relevant time scale. Before 26 July 2014, no measurable surface displacement of the landslide occurred (Fig. 2), despite 55 precipitation events totaling 1073 mm of rain (10.1 mm/d on average). The largest event during that time delivered 149 mm of rain within 4 days, ending on 11 July 2014. The highest event intensity occurred on 10 June 2014 with 3 mm/h over 7.7 h, while the highest peak intensity was 13.4 mm/10 min on 23 June 2014. Bedload transport occurred on 8 occasions before 26 July 2014, during floods with peak discharges between 0.7 and 1.5 m^3/s.

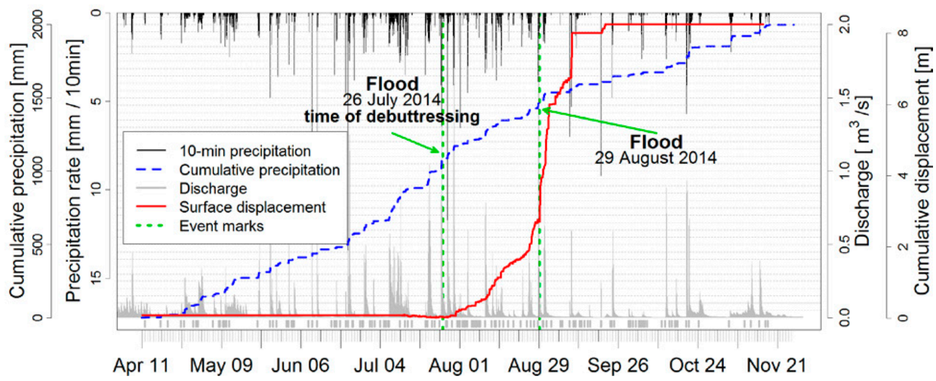

Figure 2. Timeline of precipitation rates (black bars), cumulative precipitation (dashed blue line), discharge (gray graph), and hillslope surface displacement (red line) between April and November 2014 in the Erlenbach catchment. Vertical green lines indicate large flood events on 26 July and 29 August 2014.

A rainfall event starting on 26 July 2014 (86 mm of rain, maximum intensity 6.4 mm/10 min, averaged intensity 2.1 mm/h) caused a flood with a peak discharge of 3.9 m^3/s (~5 yr return time; Liechti, 2007). While earlier events had not noticeably modified the monitored reach, this larger flood resulted in an ~4 m upstream migration of the alluvial step at the downstream end of the landslide (Fig. 3; Movie DR1 in the GSA Data Repository[1]). During the flood, a bank failure ensued between the initial and the new step position (Fig. 3B), doubling the channel width. A deep-seated hillslope motion was not apparent during and shortly after this discharge event, and base flow conditions were restored 20 h after peak discharge. Then, 40 h after peak discharge, the landslide entered a 45 d phase of continuous integral motion (Fig. 2), during which precipitation averaged 10.8 mm/d. Another flood on 29 August 2014 (peak discharge 4.8 m^3/s, return time ~7 yr) caused the step to migrate a further 4 m upstream (Figs. 3C and 3D). Subsequently, hillslope surface displacement rates increased by 400%, causing the channel to narrow gradually until its original width was restored on 11 September 2014. During a subsequent rainstorm on 21 September, hillslope motion further narrowed the channel so that boulders and large wood of the landslide built a new ~1-m-high channel step at the landslide toe near the position of the original step. The total landslide displacement length amounts to 8 m over a width of 10 m. The largest total event precipitation after this date was 71.2 mm on 4 November 2014; the highest rainfall intensity was 5.8 mm/h over 8 h and peak intensity was 5.7 mm/10 min on 20 October 2014. Over the remaining monitoring period, occasional hillslope motion occurred in patches 10 m upslope of the hillslope toe. Further sediment supply to the channel was not observed. No motion was observed in the larger vegetated landslide complex, within which the monitored landslide was located.

[1]GSA Data Repository item 2017090, Movie DR1 and Figures DR1–DR5, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

DISCUSSION

In 2014, the monitored reach appears to have gone through a full channel-hillslope feedback cycle. To ascertain this, the dominant control on the hillslope's stability needs to be identified. Generally, hillslope stability is compromised by steepening, debuttressing of the landslide toe (Korup et al., 2010), or water infiltrating the ground, causing, for example, an increase of the pore-water pressure within the landslide body (Van Asch et al., 1999). Here, hillslope angle and substrate remained constant during the relevant period, leaving changes in the toe geometry and the soil moisture as possible drivers. Rainstorms prior to the activation of landslide motion surpassed the triggering event on 26 July 2014 in terms of maximum intensity, event-averaged intensity, and total precipitation. The average daily rainfall was similar before and during the period of movement. Therefore, hydraulic controls were unlikely to have been the root cause of the observed landslide displacement. Instead, debuttressing of the landslide front, due to erosion of the alluvial step, was the likely trigger. Landsliding accelerated after the step had migrated further upstream in late August 2014, suggesting that the degree of debuttressing influences the rate of sliding. At the time hillslope displacement ceased the hydrological and meteorological conditions had not changed significantly, but a channel step had

Figure 3. The phases of the feedback cycle captured by the time-lapse camera. A: The Erlenbach stream with an alluvial step at the downstream end of a suspended landslide. B: Flood causes step destruction and an immediate bank failure. C: Channel width increases due to step destruction. D: Landslide enters a phase of integral motion as a response. E: New step formation in the channel with hillslope material (initial step position in red) leading to landslide stabilization. Note: the camera pan between D and E was considered for the calculation of displacement rates. Large image versions can be found in Figures DR1-DR5, as well as MovieDR1 (see footnote 1).

reformed at the toe of the landslide. Therefore, we argue that in our study reach, hillslope stabilization was primarily due to rebuttressing of the landslide, closing the feedback loop in the Erlenbach channel-hillslope system. Notably, after activation, hillslope displacement rates never dropped to zero until the original channel width was restored, even during dry episodes, indicating that gravitational forces exert the dominant control after the activation of movement. However, the rate of the displacement seems to respond to precipitation.

The entire feedback cycle of the channel-hillslope system can be described with a six-step conceptual model (Fig. 4). In the initial position (1) before the triggering flood, the hillslope was inactive and no hillslope-internal characteristic was able to cause displacement. The trigger (2), causing hillslope movement, was the debuttressing of the landslide due to the erosion of an alluvial channel step at the landslide toe. This solicited an immediate bank failure in the landslide toe and, after a delay (3) of 40 h, deep-seated movement of the entire landslide body. Sustained landsliding (4) delivered sediment to the channel and, as the advected material accumulated, a new channel step formed (5) at the landslide toe. Ultimately, step formation caused the end of hillslope movement and initiated a new phase of slope stability (6).

Our monitoring data are direct observational evidence for general concepts in the coupling of channels and hillslopes as proposed by previous studies based on indirect, large-scale terrain analysis. First, our observations confirm that debuttressing by channel erosion can be a main cause of landslide activation in an upsystem link. This mechanism has also been invoked for the transient hillslope response to the upstream migration of knickpoints (Gallen et al., 2011; Mackey et al., 2014; Bennett et al., 2016), and thus appears to be applicable across channel and step scales. Second, accumulation of landslide debris in the channel is the downsystem mechanism that counteracts channel incision and ultimately impedes hillslope erosion. It is important that these two coupling mechanisms are directly linked in a negative feedback loop, in which the start and end state of a local channel long profile are similar, despite the intervening reorganization of both channel and hillslope. Such a self-stabilizing feedback effect has been previously suggested (Bennett et al., 2016; Shobe et al., 2016), but not observed directly.

Next, we explore whether the proposed channel-hillslope feedback cycle can be a relevant process for the production of coarse sediment (>2 mm) in the Erlenbach. For that, we compare the recurrence interval (*RI*) of flood events known to break up a large fraction of the channel steps in the Erlenbach $RI_{trigger} \approx 20$ yr (Turowski et al., 2009), to the back-calculated *RI* of the observed feedback cycle, $RI_{feedback}$. We derive $RI_{feedback}$ for the hypothetical case that the estimated sediment volume, S_{LS} (generated during a feedback cycle activating all landslides in the catchment once) equals the total annual sediment flux, S_{tot} (scenario A), and for the case that S_{LS} equals the annual coarse sediment flux, S_{coarse} (scenario B). These scenarios reflect that over long time scales, hillslopes are the dominant source of sediment in the Erlenbach, since repeated long-profile surveys show neither significant aggradation nor erosion (Molnar et al., 2010). In scenario B, we assume that other hillslope erosion processes, e.g., surface wash, convey only fine sediment into the channel. We approximate S_{LS} geometrically by $width_{LS} \times length_{LS} \times depth_{LS}$. The landslide width, $width_{LS}$, is the total channel network length $L = 4644$ m times the measured fraction of landslides, $r_{LS} = 0.35$. Lacking better estimates, $length_{LS}$ is taken from our point observation ($L_{LS} = 8$ m). $Depth_{LS}$ is set at the average step height $\bar{h} = 0.79$ m multiplied by the cosine of the hillslope angle θ. Thus, the

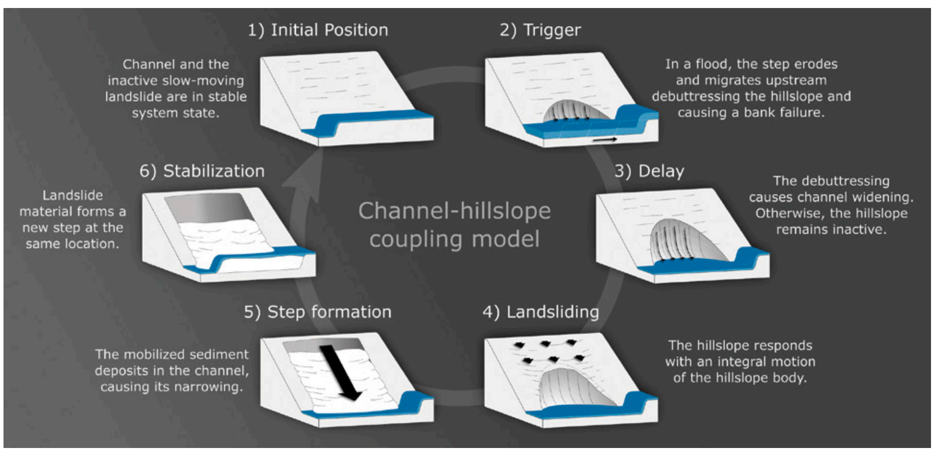

Figure 4. The proposed conceptual model of channel-hillslope coupling based on the observations of the event cycle in the Erlenbach catchment. The cycle can be reinitiated (step 6 to 1) once hillslope sediment is refilled.

back-calculated recurrence interval of the feedback cycle RI_{feedback} is given by

$$RI_{\text{feedback}} = \frac{S_{\text{LS}}}{S_{\text{tot/coarse}}} = \frac{L \times r_{\text{LS}} \times L_{\text{LS}} \times \bar{h} \times \cos(\theta)}{S_{\text{tot/coarse}}}, \quad (1)$$

with S_{LS} = ~7870 m^3, S_{tot} = 1140 m^3 (Smith et al., 2013), and S_{coarse} = 380 m^3 (Rickenmann et al., 2012). Scenario A yields an RI_{feedback} of ~7 yr, which is at least 3 times smaller than RI_{trigger}. In this case, it is not plausible that landslides triggered by debuttressing capture the total long-term sediment export from the catchment exclusively. Scenario B yields an RI_{feedback} of ~21 yr, which is of the same order of magnitude as RI_{trigger}. In this case it is plausible that the observed feedback cycle can be relevant for the total coarse sediment flux in the Erlenbach. However, the calculation is subject to large uncertainties, because we lack representative parameter values for the entire catchment. For example, the displacement length L_{LS} likely depends on local landslide and channel dimensions, and r_{LS} might not be constant throughout the catchment.

CONCLUSIONS

Our observations in the Erlenbach catchment demonstrate controls and feedbacks in the coupling of channels and hillslopes through the operation of upsystem and downsystem links. Hillslope motion and the release of sediment to the channel initiated after the erosion of a channel step debuttressing the hillslope toe. This upsystem link destabilized the coupled system and initiated a feedback cycle during which the hillslope responded in a downsystem link with sustained motion and sediment delivery to the channel. Eventually, the feedback loop closed when supplied sediment stabilized the hillslope by rebuttressing. This resulted in a net production of sediment propagating to the stream, emphasizing the relevance of the coupling mechanism for sediment availability on the catchment scale. The sequence underlines the importance of integrated channel-hillslope monitoring, as previous studies reporting landslide displacement rates in this catchment were limited to hillslope observations. The flood that triggered the event cycle had a recurrence interval of only ~5 yr, making channel-hillslope coupling processes frequent and relevant for the sediment dynamics of steep streams, since they are not limited to exceptional events as previously suggested. The time scales of the observed process links span from minutes of the triggering flood to months of inactivity, demonstrating the value of long-term high-resolution field observations for geomorphological studies.

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