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The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream

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The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter

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Abstract

Export rates of coarse particulate organic matter (CPOM) from mountain catchments have been observed to strongly increase with rising discharge, but the mechanism leading to this strong relationship is unclear. Here, we show that log jams in the Erlenbach, a steep headwater stream in the Swiss Prealps, are an effective barrier for the transport of CPOM pieces, and thus become sites of storage of large quantities of material over time. Exceptional discharge events with return periods exceeding 20 years play a dual role in CPOM transport. First, they destroy existing log jams, releasing the stored material (wood and sediment). Second, they intensify channel-hillslope coupling, thereby recruiting new logs to the channel, around which new jams can form.

1 Introduction

Coarse particulate organic matter (CPOM) in streams is typically defined as organic material with a diameter larger 1 mm, and thus encompasses a wide range of different types and sizes, from leaves and twigs to wood fragments to entire trees (Turowski et al., 2013a). CPOM is an important component both of the physical and the ecological system of the stream; it affects flow velocity, stream morphology and sediment transport, and provides food, shelter, and variable habitats (Harmon et al., 1986). The largest size classes of CPOM are known as large woody debris (LWD), comprising pieces longer than 1 m (e.g. Abbe and Montgomery, 2003; Wohl and Jaeger, 2009). LWD specifically affects stream morphology and habitat by forming log jams that act as barriers for sediment movement, and that are sites of energy dissipation (Wohl and Beckman, 2012). Thus, log jams create sites with both lower and higher flow velocities than the average of the stream, and facilitate habitats for different life stages of both fish and invertebrates (Wohl, 2013).

CPOM is recruited to the stream by various processes, including litter fall, gravitational movements of the banks, and natural dieback of trees. Once in the stream,

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CPOM is degraded by various physical, chemical, and biological processes, or can be flushed out by fluvial processes. CPOM leaving the catchment represents a loss of nutrients and energy to the stream ecosystem (Fisher and Likens, 1973), and, in case of LWD, can lead to an increased hazard downstream (Comiti et al., 2006; Ruiz-Villanueva et al., 2014). It is known that CPOM export from a catchment strongly depends on discharge (e.g. Bormann et al., 1969; Fisher and Likens, 1973; Wallace et al., 1995). From detailed short-term measurements over a range of discharges, Turowski et al. (2013a) found that 90 % of the total CPOM load of the Erlenbach, a prealpine mountain stream in Switzerland, was exported by floods with return periods > 5 years. There, CPOM export rates increase by a factor of more than 30 000 upon a ten-fold increase in discharge. The results from Fisher and Likens (1973) and Wallace et al. (1995) indicate similarly strong relationships. Still, conceptual models of wood dynamics formulated in studies of larger streams suggest more continuous export rates and seemingly do not apply to headwater streams like the Erlenbach (Hyatt and Naiman, 2001; O'Connor et al., 2003; Wohl, 2013).

In the present contribution, we investigate the physical mechanisms behind the strong dependence of CPOM export rates and discharge in the Erlenbach. Wallace et al. (1995) observed a strong increase in CPOM export after log jam failures. We thus hypothesize that log jams play a crucial role in CPOM transfer, and demonstrate that they indeed represent barriers for transport. We elucidate the role of exceptional events in log jam stability and propose a conceptual model of wood dynamics in headwater streams.

2 Study site

The Erlenbach is a small tributary of the Alp river and is located in the Alptal valley in the Swiss Prealps (Fig. 1, Table 1). With a catchment area of 0.7 km^2 and a mean channel slope of 18 %, its elevation ranges from 1100 to 1655 m a.s.l. (Badoux et al., 2012). Discharge and meteorological variables are recorded at 10 min intervals, while sedi-

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ment export can be monitored with various types of equipment (Badoux et al., 2012; Rickenmann et al., 2012; Turowski et al., 2013b). The banks of the channel are prone to hillslope creep and are actively supplying the channel with sediment and woody debris (Schuerch et al., 2006; Turowski et al., 2009). Around 40 % of the catchment area is covered by multi-level subalpine forest, dominantly Norway spruce (*Picea abies*) and silver fir (*Abies alba*), and the remaining 60 % of the area are grass- and wetlands (Burch, 1994). CPOM export from the Erlenbach was measured in detail by Turowski et al. (2013a). In the recent past, two very intense rainfall events hit the catchment. The first one occurred in June 2007, featuring the highest discharge recorded to date with a peak runoff of 14.6 $m^3 s^{-1}$ and an estimated return period of around 50 years (Turowski et al., 2009, 2013b). In August 2010, a second event occurred with a peak runoff of 10.9 $m^3 s^{-1}$, corresponding to a return period of approximately 20 years (Turowski et al., 2013b), which was the last exceptional event before the present study was conducted.

3 Methods

We mapped LWD in a 320 m long study reach of the Erlenbach, focusing on log jams (Fig. 1). A log jam was defined as an accumulation of coarse wood deposited against or around at least one initial key piece of LWD (Warren et al., 2009). The perimeters of log jams were surveyed with an electronic total station, and their extent and height were recorded using a measuring tape. The volumes and dry masses of the pieces of wood longer than 1 m stored in log jams were approximated by measuring their length and diameter in the field, and by assuming a cylindrical shape and a dry wood density of 410 $kg\,m^{-3}$, which is characteristic for *P. abies*. The total combined volume of pieces shorter than 1 m was estimated visually with the help of a measuring tape. This estimation made up for 29 % of the total volume of all log jams. Log jam step heights were derived from long profile measurements (Turowski et al., 2013b). The analyses were conducted in July and August 2012.

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A population of 236 cylindrical logs (Fig. 2), divided in four classes with approximate lengths of 10, 20, 50, and 100 cm, were tagged with Radio Frequency Identification (RFID) transponders, a technique that has successfully been employed to monitor bedload (Lamarre et al., 2005; Schneider et al., 2010, 2014) and woody debris (MacVicar et al., 2009; Schenk et al., 2014). A total of 114 pieces initially featured branches whereas in the case of the remaining 122 tracers branches were removed. The tracer logs were emitted in the stream in June 2012, and they were surveyed and their positions recorded six times after rainfall events until October 2012 (Fig. 3). Two locations for the emission of the tracers were chosen because of the relative absence of obstacles, steps and pools compared to most other channel reaches and were hypothesized to enhance the probability of a first displacement. The tracer pieces were spread out along approximately 5–10 m of the thalweg axis without trying to mimic a natural deposition. It was assumed that after an initial mobilisation during a flood event, tracers would be deposited in a natural way. During this time eleven events with discharges exceeding 0.5 $m^3 s^{-1}$ were recorded (Fig. 3, Table 2). Peak discharge during the entire study period was 1.25 $m^3 s^{-1}$, a flood size that typically occurs several times a year in the Erlenbach.

To obtain approximate residence times of the logs stored in the jams, tree-ring analysis was conducted using the methodology described by Stoffel and Corona (2014). Cross-dating deadwood with a reference chronology of living trees gives the calendar year of the trees' terminal ring and therefore the date of their dieback. A number of 30 undisturbed *P. abies* in the vicinity of the Erlenbach channel were sampled for the reference chronology, showing a series intercorrelation of 0.471. The sampling of logs stored within the dams was limited to conifers since the catchment is covered by subalpine forest with only 10–15 % deciduous trees. A minimum diameter of 30 cm has been defined as necessary to conduct reliable age dating (Hyatt and Naiman, 2001). Too few broad-leaved trees of the appropriate size were available near the stream for study, but only two out of 26 LWD samples in the stream were from broad-leave trees. Thus, the survey yielded a total of 24 dated logs in 9 log jams, and the focus on conifers

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can be assumed to not bias the results. Four of the sampled logs stored in the channel had already substantially decayed or were damaged during flood events. Still, for all logs, more than half of the outermost circumference corresponded to a single tree ring, which means that the terminal ring of the last year of growth was likely present in the sample. The kill date is assumed to be the year when the logs were introduced to the channel. There is a chance that trees remained outside the channel for an unknown period of time before entering the stream. However, our assumption is based on the fact that the channel slopes are very steep and large wood particles are unlikely to remain on the slopes above the channel for extended times.

4 Results and interpretation

We identified nine log jams (LJ1 to LJ9) in the study reach (Table 3), corresponding to 2.8 log jams per 100 m of channel or 16.7 % of the study reach's bankful channel area (Fig. 4). The values observed in this study are high, but not unusual for streams with similar characteristics and size as the Erlenbach (Kraft et al., 2011; Warren et al., 2009; Wohl and Beckman, 2014). Seven of the jams were most likely caused by a large (initial) tree that entered the stream, presumably due to bank erosion (Fig. 5b, c and d). The bank erosion either directly undercut the trees' rootwad or initiated hillslope creep that resulted in trees falling across the channel. The remaining two jams (LJ1 and LJ7) likely formed because large boulders constricted the channel (Fig. 5a). In the case of LJ7 the boulder acted as a barrier for transport, recruiting large logs from the adjacent riparian vegetation. With the exception of LJ1, for which the situation is not clear, the initial trees all originated from the contiguous adjacent riparian vegetation, and had not been moved (far) from their original growing position.

The tracer study revealed that log jams in the Erlenbach are an efficient barrier to the movement of CPOM pieces. The tracer logs preferably deposited in log jams (Fig. 4), and once there, it was very unlikely that they moved further downstream during the study period (Fig. 6). Given that pieces initially inside of log jams have a median trans-

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port distance at or near zero (Fig. 6), and that this observation is valid equally for all measured size classes, it is likely that this discrepancy is also valid for sizes substantially smaller than our smallest tracers with 10 cm length. The observations also imply that we expect large CPOM export rates only in case of log jam destruction, i.e. when the material stored within them is released into the stream bed. This raises the question on when log jams are mobilized.

Based on the tree-ring analysis, the residence times of jammed logs within the channel varied between 1 and 13 years with a median of 4 years (Table 3). Only two logs, both in LJ1, entered the stream prior to 2007 (these trees died in 1999 and 2002, respectively). The residence time of trees within the same log jam varies between zero (LJ5, with two kill dates in 2007), and 4 years (LJ6, with kill dates in 2007 and 2011). The number of trees with simultaneous kill dates varied strongly, and peaked in 2007 ($n = 7$) and 2010 ($n = 5$) with decreasing numbers in the subsequent years (Fig. 7). We did not find correlations between residence time of the logs in the stream and the longitudinal position of the respective log jam within the study reach, effective jam area, log jam volume or dry mass.

However, the input of trees to the channel is strongly related to the occurrence of exceptional discharge events. The years with the largest discharge events (2007, 2010) correspond to the years with the highest numbers of tree kills. More than one kill date was also observed in 2008 ($n = 3$) and 2011 ($n = 2$), i.e. in the years following exceptional discharge events. Exceptional events in the Erlenbach have effects on stream dynamics and bedload transport that can last several years (Turowski et al., 2009), and we hypothesize that the observed LWD input in 2008 and 2011 is a consequence of the exceptional discharge events in 2007 and 2010, respectively, rather than being attributed to the current years' flood history.

Observations suggest that almost all LWD that entered the study reach before the 50 year flood in June 2007 would have been removed by this exceptional event. The pieces present in the reach were thus recruited and deposited after the 2007 flood. The subsequent 20 year flood in August 2010 did not cause a complete renewal of the in-stream wood population but nonetheless did mobilize several jammed pieces. The exceptional discharge events not only led to the failure of all (2007) or some (2010) log jams, but also reactivated or intensified the LWD input, thereby promoting the formation of new log jams. The stream bank side from which the new jam-forming logs presumably originate (as indicated by the side of their root wads) spatially concurs with zones of active landslides along the channel bed (Fig. 4, cf. Schuerch et al., 2006).

The observations made at the Erlenbach stream allow formulation of a four-stage conceptual model for log jam dynamics and associated wood transport in steep mountain streams (Fig. 8). In steep streams, log jams form along the channel around large initial logs, and mainly consist of trees that died in the immediate vicinity of the jam. After a period of no exceptional flood events these logs obstruct the stream, reduce flow velocities as well as transport capacity of sediment and wood particles, but also stabilize adjacent banks (Fig. 8a). These log jams represent temporary storage sites and grow with time, thereby collecting an increasing amount of material including both logs and sediment. Exceptional discharge events, by contrast, as observed in 2007 and 2010 at Erlenbach, fulfil a dual role. They may mobilize log jams and evacuate even the coarsest pieces from the reach, thus cleaning the channel and increasing connectivity (Fig. 8b). At the same time, the mobilization of steps formed by boulders and log jams as well as bank erosion activates hillslope processes (Fig. 8c) and thereby intensifies the coupling between channel and hillslopes (cf. Molnar et al., 2010). Subsequently, new logs are recruited into the channel, allowing for the formation of new jams around key pieces and the initiation of a new cycle (Fig. 8d).

The conceptual model proposed herein can well explain the steep rating relationship between CPOM transport rates and discharge in many streams (e.g. Turowski et al., 2013a). Log jams act as storage sites for CPOM pieces, collecting the steady supply of small- and medium-sized pieces to release them during large flood events, when the jams are at least partly mobilized. Log jam mobilization will release large amounts of CPOM for transport, which may in turn affect the stability of jams further downstream and result in a runaway effect due the increase in process intensity.

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The conceptual model described above (Fig. 8) refers to LWD dynamics in low-order steep mountain streams and thus differs substantially from models that have been developed for larger streams (e.g. Hyatt and Naiman, 2001; O'Connor et al., 2003; Wohl, 2013). In the latter type of streams, supply and evacuation of logs is generally assumed to occur more or less continuously, and the recent discharge history has been largely ignored. This implies that residence times show a broad distribution, and that large deviations from the mean in the residence times of individual logs can frequently be observed. For example, for the Queets River (USA), Hyatt and Naiman (2001) reported a mean residence time of around 30 years, but the time since recruitment of individual logs ranged from 1 year to more than 1400 years. By contrast, we observe that most logs in the Erlenbach have been recruited during or shortly after the last exceptional discharge events, therefore yielding a much narrower age distribution of logs with well-defined peaks corresponding to years with large floods.

From a mechanistic perspective, the difference in behavior of large and small streams can be explained by wood transport processes. Various log jam types have been described (Abbe and Montgomery, 2003). At the Erlenbach, eight out of nine log jams were log steps, a jam type typical for streams with small drainage areas in which at least one key member has a length larger than the channel width (Abbe and Montgomery, 2003). Pieces of LWD longer than the channel width are known to be rarely transported (Bilby and Ward, 1989; Nakamura and Swanson, 1993), and LWD moves farther and more frequently in larger streams (Lienkaemper and Swanson, 1987; Wohl, 2013). Thus, log steps can be expected to be less mobile than other jam types typical for larger streams. Again, this highlights the role of exceptional events for CPOM export in streams like the Erlenbach.

5 Conclusions

Extreme discharge events play a key role in CPOM dynamics in steep mountains streams. These events mobilize LWD in the channel, thereby favoring the evacuation

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of CPOM material stored in log jams out of the catchment. By intensifying channel-hillslope coupling, extreme discharge events also facilitate the recruitment of new logs into the channel.

These dynamics explain the steep rating relationship observed between CPOM transport rates and discharge in various streams. The residence times of large logs stored in Erlenbach jams varied between 1 and 13 years at the time of measurement, and most logs entered the channel during or in the aftermath of the last two exceptional floods. The CPOM dynamics observed at the Erlenbach are thus in stark contrast to the more continuous transport of LWD in larger streams, where wood piece residence times have a wide distribution.

Our findings have implications for the management of headwater streams, both in terms of natural hazard mitigation, and for fish habitats. Whereas damage potential is often limited along headwater streams, it becomes more accentuated where mountain streams meet densely populated areas and infrastructure. We therefore suggest to refrain from clearing forest stands on hillslopes adjacent to headwater channels. If headwater streams do not account for significant damage potential, allowing for log jam development would promote their beneficial impact for example on fish and invertebrates habitats. Instead, in case of a hazardous event and significant damage potential, management measures in the adjacent forest stands with the aim to reduce CPOM input are required, and/or CPOM can be retained at the interface between headwater and receiving streams.

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Table 1. Catchment characteristics of the Erlenbach catchment in Switzerland (cf. Turowski et al., 2009; Badoux et al., 2012).

Catchment parameter	Value
Basin area (km^2)	0.7
Elevation range (m a.s.l.)	1110–1655
Average channel gradient (%)	18
Mean annual precipitation sum (mm)	2290
Mean annual temperature (°C)	4.5
Forest cover (%)	39
Wetland and grassland (%)	61
Unvegetated land (%)	$\ll 1$

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Table 2. Parameters of elevated discharge events in the Erlenbach that occurred between 22 June to 25 October 2012.

Discharge event	Date	Duration [h:min]	Q_{max} [$m^3 s^{-1}$]	Q_{eff} [m^3]
1	25 Jun 2012	3:00	0.86	8077
2	16 Aug 2012	2:40	0.78	6779
3	25 Aug 2012	3:20	1.21/0.91*	10 497
4	1 Sep 2012	0:20	0.54	952
5	12 Sep 2012	8:40	1.25/1.17*	21 045
6	19 Sep 2012	2:10	0.81	5705
7	26 Sep 2012	0:10	0.53	317
8	27 Sep 2012	2:10	0.96	6445
9	7 Oct 2012	2:20	0.97	6425
10	9 Oct 2012	5:00	0.86/1.16*	13 951
11	10 Oct 2012	4:30	0.74	11 930

* Event with two discharge peaks.

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Table 3. Log jam (LJ) characteristics and tracer log point densities for the log jam perimeters in the Erlenbach.

Log jam number	Area (m^2)	Step height[a] (m)	Volume[b] (m^3)	Dry mass[c] (kg)	Mean tracer density ($1\,m^{-2}$)	Max. tracer density ($1\,m^{-2}$)	Min. tracer density ($1\,m^{-2}$)	Number of dated logs	Mean age of logs (a)	Mean residence time (a)
LJ 1	30.0	1.4	7.98	3272	0.05	0.11	0.00	2	58.0	11.5
LJ 2	26.8	1.1	1.41	578	0.14	0.25	0.00	2	71.0	1.5
LJ 3	40.0	0.4	1.50	614	0.80	1.70	0.00	4	98.2	2.3
LJ 4	37.2	1.9	2.12	869	0.23	0.46	0.00	2	72.0	4.5
LJ 5	14.5	1.0	0.65	266	0.50	0.78	0.07	2	90.5	5.0
LJ 6	6.4	1.1	0.51	211	0.40	0.53	0.25	2	94.0	3.0
LJ 7	14.5	0.7	1.55	636	0.68	0.95	0.11	1	37.0	5.0
LJ 8	60.0	1.6	5.70	2335	0.83	2.30	0.00	3	55.3	3.7
LJ 9	17.7	2.1	3.76	1542	0.50	0.71	0.14	2	72.5	4.5

[a] Steps and pools derived from long profile using the algorithm proposed by Zimmermann et al. (2008).
[b] Based on measurement of length and diameter of woody debris pieces stored in log jams longer than 1 m and assuming a cylindrical shape of the pieces.
[c] Calculated from volume assuming a dry wood density of $410\,kg\,m^{-3}$

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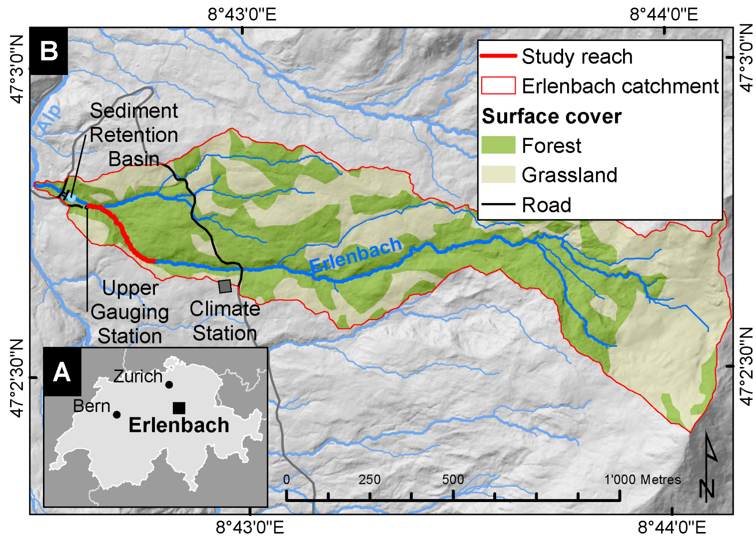

Figure 1. Overview map of the Erlenbach catchment showing **(a)** its position within Switzerland as well as **(b)** its topography, instrumentation features and the study reach (cf. Fig. 4). Data source: DTM-AV© 2014 Swiss Federal Directorate of Cadastral Surveying (DV033531).

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Figure 2. Tracer log with length 100 cm lying loose on the Erlenbach channel surface in the foreground. Other tracer logs are visible in the background.

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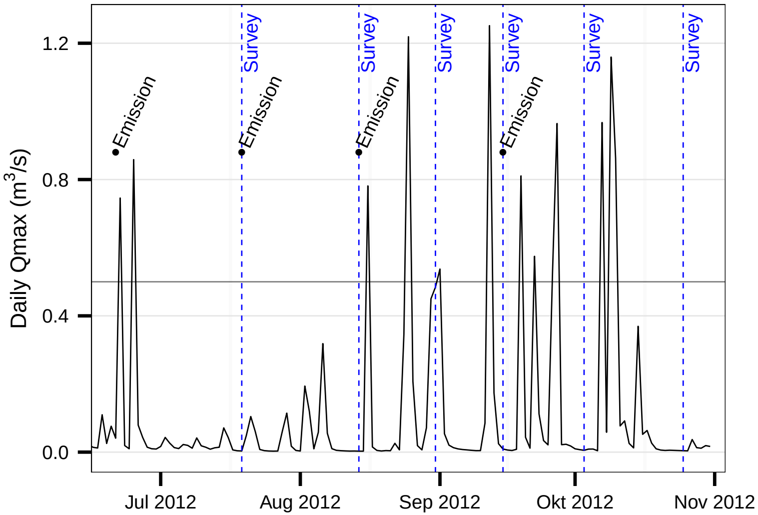

Figure 3. Daily peak discharge of the Erlenbach between 20 June and 31 October 2012 measured at the gauging station. According to Rickenmann and McArdell (2007) as well as Turowski et al. (2011) the critical discharge for the start of bedload transport amounts to approximately $0.5\,m^3\,s^{-1}$ (horizontal bold black line). Emission and survey dates are labelled.

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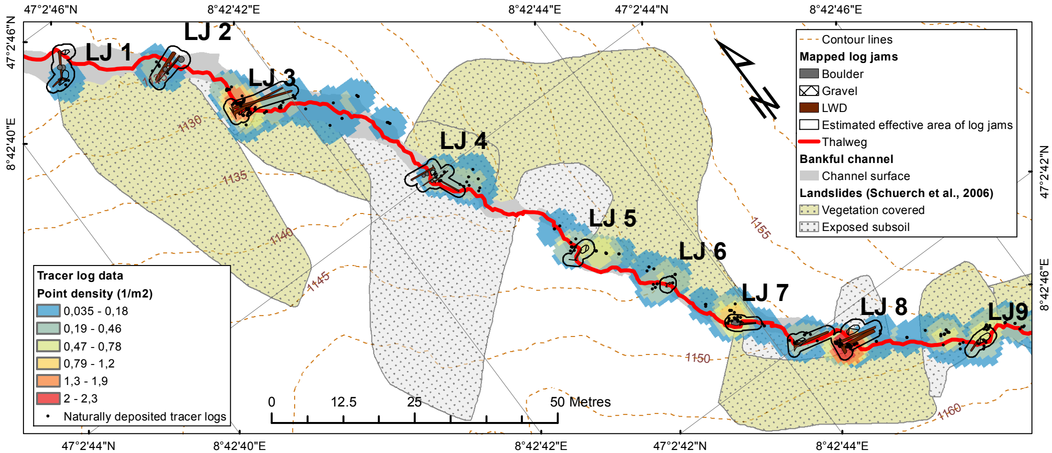

Figure 4. Map of the study reach including visualizations of the log jams (LJ1 to LJ9, cf. Table 3) and the point densities of naturally deposited tracer logs. The effective area of LJs was estimated by adding a buffer of 1 m around the mapped LJ perimeter to account for survey inaccuracy.

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Figure 5. Four exemplary log jams in the study reach: LJ1 **(a)**, LJ2 **(b)**, LJ4 **(c)**, LJ5 **(d)**. For the positions and characteristics of the jams within the study reach refer to Fig. 4 and Table 3. Each log jam shows a distinct key piece blocking the channel, thereby being responsible for the upstream accumulation of woody debris and sediment.

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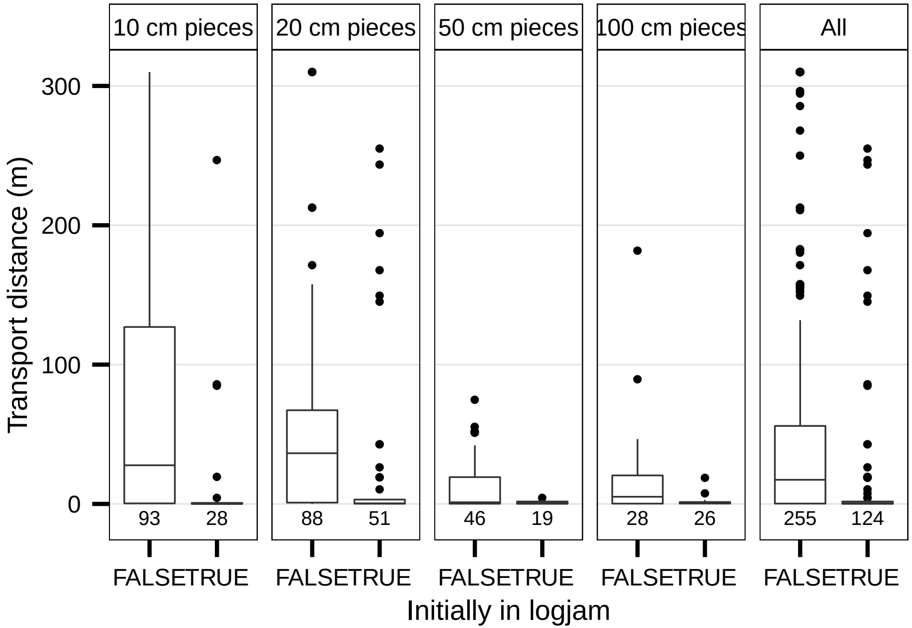

Figure 6. Transport distances of the tracer logs that were situated within or outside a log jam before the discharge event. The data is presented for four classes of pieces of different length. The number below the plot gives the number of data points used in the analysis. The differences in median transport distances between pieces inside and outside log jams in the 10 and 20 cm classes, as well as for all pieces combined, are highly significant.

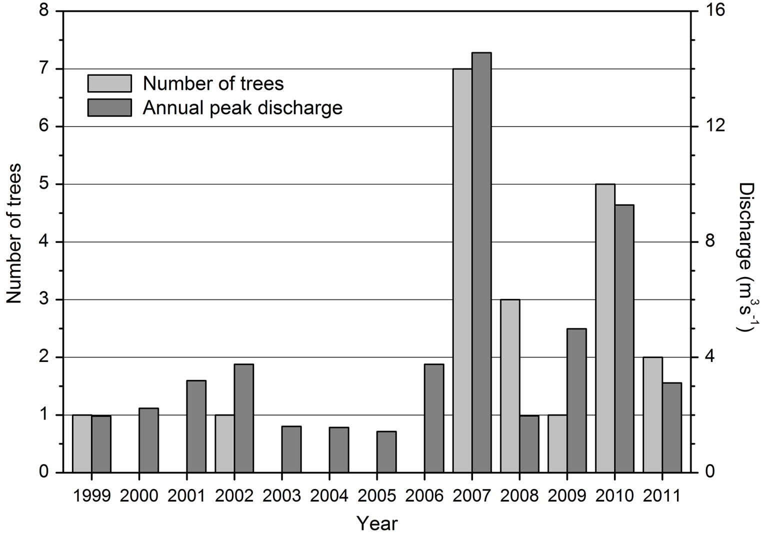

Figure 7. Histogram of kill dates of trees stored within the nine log jams (cf., Table 3) in the study reach of the Erlenbach (light grey) and annual peak discharges in the respective years (dark grey).

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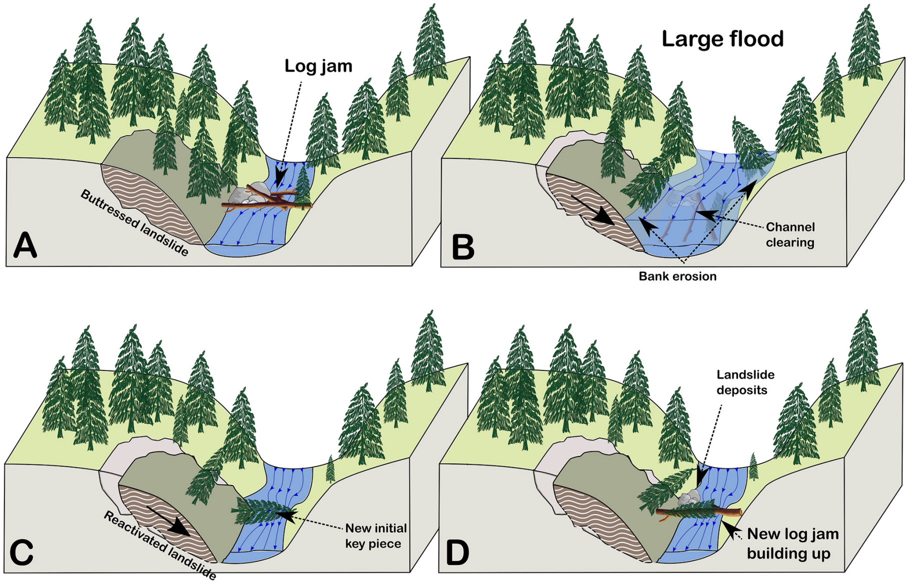

Figure 8. Visualization of the four-stage conceptual model for log jam dynamics and wood transport in steep headwater streams. **(a)** Mountain stream channel after longer period without large flood. A log jam obstructs the channel, reduces the stream's sediment and CPOM transport capacity and stabilizes the stream's banks. **(b)** An exceptional flood event mobilizes the log jam and evacuates all pieces from the channel. **(c)** The mobilization of log and boulder steps as well as bank erosion during the flood event reactivate hillslope processes and lead to the introduction of a new key piece to the channel. **(d)** The new key piece initiates a new cycle of log jam dynamics.

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