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Impacts of a large flood along a mountain river basin: unravelling the geomorphic response and large wood budget in the upper Emme River (Switzerland)

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Abstract

On July 24, 2014, an exceptionally large flood (recurrence interval ca. 150 years) caused large-scale inundations, severe overbank sedimentation and damage to infrastructures and buildings along the Emme river (central Switzerland). Widespread lateral bank erosion occurred along the river, thereby entraining sediment and large wood (LW) from alluvial forest stands. This work analyses the catchment response to the flood in terms of channel widening and LW recruitment and deposition, but also identifies the factors controlling these processes. We found that hydraulic forces (e.g., stream power index) or geomorphic variables (e.g., channel width, gradient, valley confinement), if considered alone, are not sufficient to explain the flood response. Instead, spatial variability of channel widening was firstly driven by precipitation, and secondary by geomorphic variables (e.g., channel width, gradient, confinement and forest length). LW recruitment was mainly caused by channel widening (lateral bank erosion) and thus also controlled by precipitation. In contrast, LW deposition was controlled by channel morphology (mainly channel gradient and width). However, we also observed that extending the analysis to the whole upper catchment of the Emme river, including all the tributaries and not only to the most affected zones, resulted in a different set of significant explanatory or correlated variables. Our findings highlight the need to continue documenting and analysing channel response after floods at different locations and scales. Whereas this is key for a better process understanding, the identification of controlling factors can also contribute to the identification of critical reaches, which in turn is crucial for the forecasting and design of sound river basin management strategies.

Keywords: large flood, channel changes, channel widening, large wood, woody debris.

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1 Introduction

Floods in mountain river basins are characterized by complex, yet extreme meteorological events and subsequent, equally complex process coupling between the hillslopes and channels (i.e., debris flows, debris floods, and floods), resulting in a high spatial variability of morphological responses (Harvey, 1986; Miller, 1990; Lapointe et al., 1998; Magilligan et al., 1998; Heritage et al., 2004; Arnaud-Fassetta, 2013; Savi et al., 2013; Thompson and Croke, 2013, Rickenmann et al., 2016). During high intensity events, mass-movement processes (e.g., landslides, debris flows) may affect channel morphology and sediment supply, influencing the total sediment load during a flood (Lin et al. 2008). In forested areas, mass movements and bank erosion do not only deliver large amounts of inorganic sediment, but also introduce large quantities of wood into the channel corridor. As a load component in forested rivers, large wood (defined as wood pieces exceeding 10 cm in diameter and 1 m in length; LW) can be placed in a similar framework to that used for sediment, where LW recruitment, transport, and deposition are the main processes to be understood a part of the LW budgeting (Gurnell, 2007). The presence of wood in rivers has very positive effects in general (Ruiz-Villanueva et al., 2016 and references within); however, LW and sediment in channels can also favour the creation of temporary dams and subsequently produce secondary flood pulses, thereby enhancing erosion, and/or leading to the destruction of infrastructure along the channel (Cenderelli and Kite 1998; Wohl et al., 2010; Ruiz-Villanueva et al., 2014). Flood damage and flood losses are intrinsic to the occurrence of major floods (Merritts, 2011). However, urbanization, an increase in impervious surfaces (Hollis, 1975) and river channelization or embankment constructions (Wyżga, 1997) are frequently invoked as well to explain the high economic losses caused by major flood events (Hajdukiewicz et al., 2015). Under such conditions, even frequent floods (i.e., lower magnitude events) can lead to unexpectedly high damage.

Over the last decades, several major flood events occurred in different parts of Switzerland (e.g., August 1978, August 1987, September 1993, May 1999, October 2000, August 2005, and August 2007; Hilker et al., 2009; Badoux et al., 2014), thereby causing significant financial damage costs. The August 2005 flood was by far the costliest natural disaster in Switzerland since the start of systematic records in 1972 (Hilker et al., 2009), claimed six lives and caused a total financial damage costs exceeding three billion Swiss Francs. The dominant processes observed during this event were flooding, bank erosion, overbank sedimentation, landslides, and debris flows (Rickenmann and Koschni, 2010; Rickenmann et al., 2016). Moreover, the transport and deposition of more than 69,000 m^3 of LW along alpine and pre-alpine rivers has been recorded (Steeb et al., 2017; Rickli et al., 2018). The consequences of events like the one in 2005 pose threats to important infrastructure such as roads and settlements and therefore, these processes need to be better understood and quantified to provide a valuable process understanding and improved preparedness.

However, predicting the impacts of major floods on the fluvial system is very challenging and requires a wide range of analyses (Rinaldi et al., 2016; Surian et al., 2016). Some of the most recent studies in the field focused on the (i) reconstruction of the hydrological event (e.g., Gaume et al., 2004); (ii) analysis of flood hydraulic variables (e.g., Howard and Dolan, 1981; Miller, 1990; Wohl et al., 1994; Benito, 1997; Heritage et al., 2004; Thompson and Croke, 2013); (iii) hillslope processes and channel connectivity (e.g., Bracken et al., 2015 and 2013; Croke et al., 2013; Wohl, 2017); (iv) geomorphic and sedimentological analysis of flood deposits (e.g., Wells and Harvey, 1987; Macklin et al., 1992); (v) quantification of morphological changes (e.g., Arnaud-Fassetta et al., 2005; Krapesch et al., 2011; Thompson and Croke, 2013; Comiti et al., 2016; Surian et al., 2016; Righini et al., 2017); (vi) sediment budgeting (e.g., Milan, 2012; Thompson and Croke, 2013); or (vii) more recently, the study of LW dynamics and budgeting (e.g., Lucía et al., 2015; Steeb et al., 2017).

Post-event surveys are invaluable when it comes to improve insights on flood related processes (Gaume and Borga, 2008; Marchi et al., 2009; Rinaldi et al., 2016) such as LW recruitment and factors controlling LW deposition, which are both crucial for a proper management of river basins and flood hazard mitigation (Comiti et al., 2016). Despite this fact, analyses of LW dynamics after flood events remain quite rare (Comiti et al., 2016). In this study, we added this important component to the post-event survey after the July 2014 flood in the Emme river. The specific aim thereby was to provide a quantitative description of several coupled processes (i.e., debris flows, landslides, bank erosion, and/or flooding) and the geomorphic effects of this major event (mainly in terms of channel widening). We paid attention to morphological changes, the coupling between hillslopes and headwaters to the main channel, the supply of large quantities of LW and its deposition through the river corridor. We extended the analysis to the whole upper catchment of the Emme river, including all tributaries, and not only the ones that were most affected in July 2014. By doing so we aimed at unravelling diverging responses among the different tributaries and river segments in terms of geomorphic changes and LW dynamics. The hypothesis was that in terms of morphology, similar river sub-reaches may have responded differently to the flood. As river reach response is driven by several parameters, we selected different morphological and hydrometeorological variables to identify the factors controlling channel widening, LW recruitment, and LW deposition.

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2 Material and methods

2.1 The Emme river basin

The Emme River takes its origin in the Swiss Prealps (1400 m a.s.l.) and runs through the Emmental, in the Cantons of Luzern and Bern in central Switzerland. Total drainage area at its mouth with the Aare River (near the city of Solothurn) is 963 km^2, with a stream length of 80 km.

Geology of the basin is composed mainly by Helvetic marginal limestone, the Ultrahelvetian flysch (with marls and sandstones) and sub-alpine molasse composed of sandstone, molasse conglomerates and marls (Lehmann, 2001). During the Pleistocene glaciation, a large part of the Emmental was covered by glaciers and moraines remains are preserved in the areas of Eggiwil, Oberburg or Burgdorf.

The Emme basin is extensevely accupied by agricultural lands (50%, mostly downstream), 40% of the surface remains forested today, and only about 10% is urbanized. Climate is temperate with moderate warm summers (mean temperature in July is 16ºC according to the Langnau data series from 1931-2015; Federal Office of Meteorology and Climatology MeteoSwiss) and cold winters (mean temperature -1ºC in January). Total annual precipitation averaged 1315 mm ate the station of Langnau (1901-2015), with mean montly peaks in June of 160 mm. The flow regime of the Emme River is characterized by a seasonally fluctuating flow due to snowmelt in spring and thunderstorms in summer.

This work focuses on the Upper Emme River basin (Figure 1), including the uppermost tributaries to the inlet of the Emme River into a gorge called Räbloch. At this point, the Emme river basin has a drainage area of 94 km^2 and the network is formed by 19 streams (18 tributaries and the main branch of the Emme; Table 1). These 19 streams were further divided into 64 sub-reaches as explained in the Methods (see also Figure S1 in the supplementary material).

A history of severe flooding has led to intensive river management activities in the 19^{th} and 20^{th} centuries with the construction of dams and weirs. These measures also resulted in an isolation of tributaries and low sediment transport (Figure S2). Additionally, poor riparian conditions and water extractions for irrigation strongly influenced Emme River hydrology (Burkhardt-Holm and Scheurer, 2007).

Figure 1 shows an enlarged basin up to the only existing stream gauge in the area (Eggiwil station located at 745 m a.s.l. and with a drainage area of 124 km^2), which is several kilometres downstream of the Räbloch gorge.

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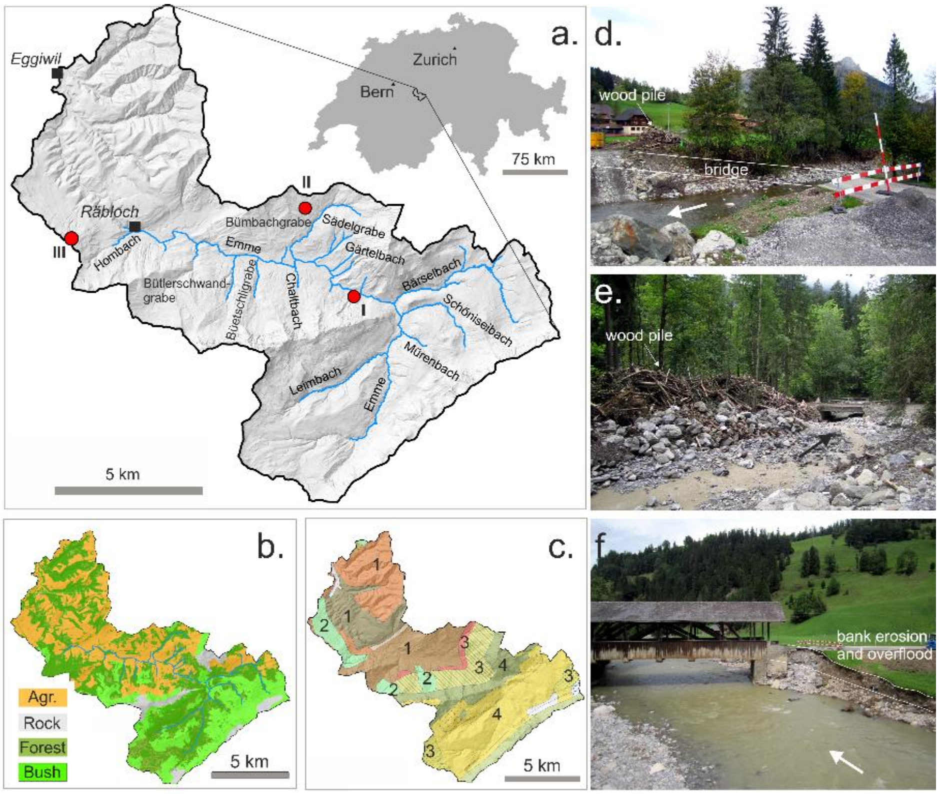

Figure 1: Location of the basin in central Switzerland (a) Hill shade of the Upper Emme River basin (up to Eggiwil), red dots show the location of the rain gauges (I: Kemmeriboden; II: Marbachegg; III: Schallenberg), blue lines show the 19 streams analysed (18 tributaries and the main river Emme); (b) Land use: Agr.: Agriculture; Rock: Bare soil; Forest; Bush: Shrubs and bushes; (c) Geology: 1 Quaternary and Neogene molasses; 2 Moraines; 3 Paleogene Flysch; 4 Cretaceous and Jurassic sedimentary rocks; (d) Debris flow and LW deposits in the lower part of the Sädelgrabe torrent upstream its confluence with the Emme river (photograph: V. Ruiz-Villanueva); (e) Road and bridge washed away during the flood in Bumbach (photograph: V. Ruiz-Villanueva); (f) Räbeli bridge damaged during the flood (photograph: V. Ruiz-Villanueva). Arrows show the flow direction.

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Table 1: Overview of the 19 study streams, sub-reaches in each stream and number of transects analysed, morphological characteristics (Av.: averaged or total values) and total maximum and mean precipitation registered during the event in 2014 at each sub-catchment (explained in the text).

Stream name	Sub-reaches	Total Nº of transects	Drainage Area (km^2)	Total stream length (m)	Total forested channel length (m)	Av. stream Gradient	Av. Width before (m)	Av. Width ratio	Av. Sinuosity	Total max. Precip. (mm)	Total mean precip. (mm)
Bärselbach	12, 14, 15, 17, 18, 21, 23, 26, 27	127	13.1	7017	6276	0.048	7	1.74	1.27	92	69
Buembachgrabe	42, 43	86	4.9	4553	3913	0.062	10	1.48	1.14	97	86
Büetschligrabe	50, 51	17	2.3	1000	841	0.051	5	1.00	2.54	65	46
Bütlerschwandgrabe	53	28	2.8	1580	1248	0.137	11	1.01	1.21	62	46
Chaltbach	45	10	1.5	563	493	0.090	4	1.07	1.37	70	48
Emme	3, 4, 7, 11, 28, 30, 33, 36, 37, 40, 41, 44, 46, 48, 49, 52, 54, 55, 58, 59, 61, 62, 63	352	93.7	20571	12361	0.023	15	1.40	1.36	97	87
Gärtelbach	38	39	0.7	1769	1769	0.185	5	3.11	1.07	94	91
Hombach	64	19	2.8	922	907	0.082	8	1.48	1.37	50	38
Leimbach	1, 2	80	9.2	4402	4167	0.054	6	1.35	1.27	49	36
Sädelgrabe	39	79	1.6	3434	3219	0.123	6	4.75	1.25	97	94
Schöniseibach	8, 9, 10	28	4.5	1476	1280	0.085	7	1.06	1.27	81	65
Schwarzbach	56, 57	13	5.4	768	768	0.080	7	1.18	1.28	59	41
Stream	16, 22, 24, 25, 31, 32	37	1.0	1915	1787	0.133	5	1.82	1.30	92	89
Stream (Gerbehüsi)	60	3	0.2	227	227	0.193	6	1.00	1.25	53	48
Stream (Kemmeriboden)	29	12	0.3	610	610	0.256	5	3.11	1.09	92	67
Stream (Kemmerli)	34, 35	13	0.5	647	564	0.142	5	2.42	1.15	93	90
Stream (Schneeberg)	19, 20	16	1.1	846	751	0.099	6	1.57	1.34	87	79
Stream (Unterlochseite)	47	12	1.2	607	79	0.073	3	2.08	1.31	76	71
Mürenbach	5, 6	12	2.4	650	650	0.092	5	0.99	1.47	67	52

2.2 The July 24, 2014 flood event

July 2014 was a very wet month in Switzerland with frequent and extensive rainfall in the first three weeks, interrupted by a few dry intervals. Data of MeteoSwiss showed that the western half of Switzerland registered twice to three times the long-time precipitation average for the month of July 2014 (FOEN, 2015). These wet episodes have led to saturated soils, especially in the western and northeastern parts of Switzerland (FOEN, 2015; ARGE LLE Schangnau-Eggiwil, 2015). Between 24 and 28 July 2014, several thunderstorms

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occurred over different Swiss regions. Until 27 July, the storms were related to a weak pressure system over Western Europe (MeteoSwiss, 2017). Generally, such relatively uniform pressure distributions result in light and variable winds at ground level which allows for the formation of cumulonimbus clouds, typically over regions with rough topography such as, e.g., the Swiss Prealps. On 24 July, an extremely violent stationary thunderstorm developed with a precipitation hotspot located over the upper Emmental. The storm cell caused intense rainfall in the headwater catchments of the upper Emme basin where it triggered very severe floods. According to hourly CombiPrecip data of MeteoSwiss (Sideris et al., 2014), the heavy precipitation yielded maximal hourly values of approximately 65 mm locally (with totals reaching 96 mm during the 7-hour event; Figure 2). Heavy rainfall was largely restricted to the upper Emme catchment with a local maximum just north of the Sädelgraben catchment. The cantonal rain gauge Marbachegg (red dot II in Figure 1) that recorded the highest event precipitation value of 76 mm is located roughly two kilometres northwest of the confluence of the Sädelgraben torrent with the Emme river. According to ARGE LLE Schangnau-Eggiwil (2015) the rainfall event was associated to a recurrence interval between 100 and 200 years.

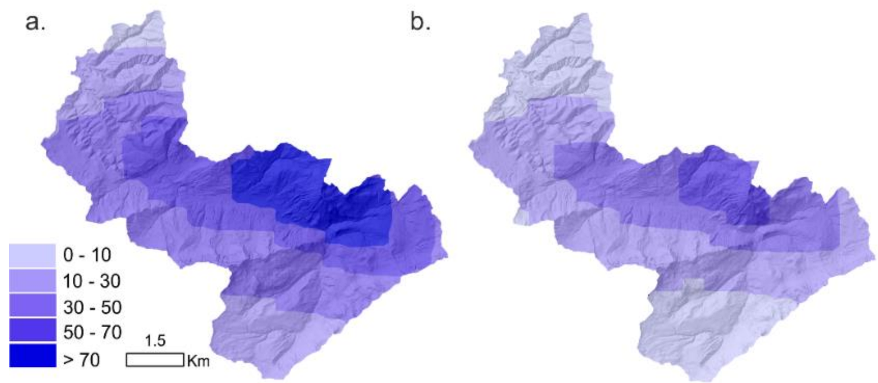

Figure 2: Map of the spatial distribution of the precipitation (mm) on the 24 July 2014 in the Upper Emme catchment: (A) Total event precipitation (mm) from 04:00 to 17:00h; (B) maximum hourly precipitation recorded at 07:00 AM.

Due to the wet soil conditions caused by all the antecedent rain, several of the small steep tributaries of the Emme river reacted very quickly to the 24 July 2014 rainstorm.

The receiving Emme river produced an exceptionally large flood. The discharge station in Eggiwil (124 km^2 catchment area, 38 years of records) registered a peak discharge of 338 m^3 s^{-1} which corresponding to a recurrence interval of ~150 years (FOEN, 2017). Runoff in Eggiwil rose very quickly and reached a maximum

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within only a few hours. In the framework of the local post-event analysis, peak values of the Emme runoff upstream of the gauging station Eggiwil were estimated for this flood based on downstream measurements and by using local flood marks (ARGE LLE Schangnau-Eggiwil, 2015; Table 2).

Table 2: Peak discharges along the Emme during the 24 July 2014 flood, measured or estimated in the framework of the local event analysis for several sites along the Emme river (data source: ARGE LLE Schangnau-Eggiwil, 2015). Note that the drainage area given here does not precisely correspond to data in Table 2 because estimates were carried out where flood marks were available.

Point along the Emme	**Drainage area (km^2)**	**Peak discharge (best estimate) ($m^3\ s^{-1}$)**	**Range of peak value ($m^3\ s^{-1}$)**
Kemmeriboden	51	240	204-276
Bumbach	67	300	255-345
Schangnau	86	330	281-380
Räbloch	94	280*	238-336
Eggiwil (Heidbüel)	124	338	Stream gauge record

** the reduction in discharge at these two sections is due to the clogging of the Räbloch gorge and related backwater effects.*

Hydrographs were reconstructed for Schangnau and Räbloch (ARGE LLE Schangnau-Eggiwil, 2015). Peak discharge amounted to approximately 240 $m^3\ s^{-1}$ at Kemmeriboden (51 km^2 catchment area). Along our study reach, peak values probably increased until Schangnau where they reached about 330 $m^3 \cdot s^{-1}$. In a natural gorge between the villages of Schangnau and Eggiwil (a place called Räbloch; 94 km^2 catchment area), the Emme river was impounded due to clogging. A temporary lake formed and according to field surveys peak runoff was reduced to about 280 $m^3\ s^{-1}$ (ARGE LLE Schangnau-Eggiwil, 2015).

At the Eggiwil gauging station, a first slight increase in discharge was recorded just after 06:00 AM and runoff reached 50 $m^3 \cdot s^{-1}$ (a discharge statistically reached during one day per year based on data from 1975-2016) at approximately 09:00 AM. Five and a half hours later, at 02:30 PM, the runoff along the falling limb of the Emme hydrograph decreased below 50 $m^3 \cdot s^{-1}$. Peak discharge at Eggiwil was reached at approximately 10:30 AM, about half an hour after the peak occurred at Räbloch. Hence, the 24 July 2014 flood event in the Emme was short. Similarly, short floods with a very steep rising hydrograph limb took place in June 1997 (245 $m^3 \cdot s^{-1}$) and July 2012 (178 $m^3 \cdot s^{-1}$), both caused by very intensive convective rain storms as well. Further major floods that occurred in the 42 years of measurement were registered in 2005 and 2007 (both with peaks slightly above 175 $m^3 \cdot s^{-1}$). However, these events were much longer due to the long-lasting nature of the triggering precipitation event (Bezzola and Hegg, 2007; Bezzola and Ruf, 2009).

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The Emme River overflowed at various points in the upper catchment and caused large-scale inundations and severe overbank sedimentation (Figure 1). Infrastructure, flood protection structures as well as buildings were damaged, and in some cases, even destroyed. Moreover, widespread bank erosion occurred all along the Emme River, thereby entraining sediments and wood from alluvial forest stands.

The steep torrents produced considerable debris floods and debris flows and transported large amounts of sediment and LW. The two most active torrents (Sädelgraben and Gärtlebach) overtopped their channels and deposited ample amounts of material on their fans. Near the confluence of the Sädelgraben and the Emme River, the road was obstructed by several meters of coarse material from the torrents. Furthermore, shallow landslides and hillslope debris flows occurred on steep locations of the upper Emme catchment.

The lower part of the Gärtelbach (from an elevation around 1300 m a.s.l.) delivered around 2000 m^3 of sediment to the Emme river, most of it recruited in the fluvial corridor, with 5000–7000 m^3 sediment deposited on the fan. The other main sediment source into the Emme river was the Sädelgrabe, where around 2000 m^3 of sediment was deposited in the channel, and around 15,000 m^3 of sediment deposited on the cone (according to ARGE LLE Schangnau-Eggiwil, 2015). However, sediment budgeting or deeper analysis about sediment dynamics was out the scope of our work.

Financial damage to private property and infrastructure (e.g., roads, bridges, hydraulic structures) in the worst affected municipalities of Schangnau and Eggiwil was estimated at approximately 20 million Swiss Francs (Andres et al., 2015).

2.3 Methods

2.3.1. Field survey

A post event survey was carried out right after the flood and during the following weeks. The Swiss Federal Office for the Environment (FOEN) initiated a project to study the recruitment, transport, and deposition of large wood in the upper catchment of the Emme River (Badoux et al., 2015; Böckli et al., 2016; Rickli et al., 2016), in which the main geomorphic effects of the flood were analysed as well (Zurbrügg, 2015). This project was elaborated in close collaboration with the local authorities (ARGE LLE Schangnau-Eggiwil, 2015).

The field survey after the flood focused on the quantification of deposited wood, identification of recruitment sources, and identification of changes in planform geometry (i.e., bank erosion). The field survey was carried out along 9.5 km of the Emme River and two of its main tributaries (Sädelgrabe and Gärtelbach), although other tributaries were visited as well. Regarding large wood, source areas (including landslides or debris floods and bank erosion) were identified in the field and mapped in GIS, and wood deposits were measured. Moreover, we noted whether LW from hillslopes processes reached the streams, as most of the mass movements were shallow landslides and not directly connected to the channel network.

Each piece of LW (length > 1m and diameter > 10 cm; Wohl et al., 2010) deposited during the flood along the studied reaches was assigned to a class relative to its mid-length diameter and length (Marcus et al., 2002; Daniels, 2006; Lucía et al., 2015; Rickli et al., 2016), i.e., seven classes were distinguished from < 10 cm to > 40 cm in diameter and nine classes from < 2 to > 16 m for length. Log volume was calculated as solid cylinders (Thévenet et al., 1998). Wood accumulations were also measured. The wood volume of each jam was calculated geometrically through its area and height (measured in the field), considering a 50–80% range in porosity (Thévenet et al., 1998).

In the tributary catchments where large quantities of wood were deposited, mainly along the Sädelgrabe fan, the extension of wood deposits and size of accumulations prevented the measurement of individual pieces. Areas with similar density of wood were identified and plots were measured to estimate total wood volume in the area (see Figure S3). Most of the recruited wood from the Gärtelbach was deposited along the Emme floodplain.

Civil protection services removed some of the wood deposits immediately after the flood, storing the material at two sites close to the river, one near the confluence between the Sädelgrabe and the Emme and another near the Bumbach bridge (Figure 1). These piles (five in total) were analysed as well and wood samples were measured to estimate the stored wood volume and wood size distribution (Rickli et al., 2016).

2.3.2. GIS analysis

The field survey was complemented with GIS analyses with the aim to extend the study to the upper catchment and to include all tributaries. The entire upper catchment was analysed by splitting the stream network into 64 sub-reaches according to the tributaries junctions and the location of bridges, as bridges may act as obstacles to the downstream transfer of wood (see Figure S1). A total of 54.5 km of stream network length were analysed.

For all sub-reaches, we calculated key morphological and hydrological parameters, such as maximum and minimum elevation, channel gradient, channel sinuosity, or drainage area by using the available DEM for the

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catchment (SwissALTI3D, 2 m spatial resolution) and spatial analysis and the hydrological geoprocessing. Other morphological parameters such as valley bottom width were extracted from the DEM using the Fluvial Corridor tool (Alber and Piégay, 2011; Roux et al., 2014). Moreover, the available aerial orthoimages (Swisstopo) were used to map the active channel before (image from March 2014, resolution 25 cm) and after (image from May 2015, resolution 25 cm) the flood. The post flood units were mapped as well in the field, with a focus on bank erosion, as well as on the measurements of length and width of eroded banks (mostly along the Emme River). GIS measurements were compared and validated with field observations. The width of the active channel before and after the flood and valley bottom (i.e., alluvial plain) width were calculated at several transects within each sub-reach. The centreline to the active channel polygon was obtained using the polygon to centreline tool (Dilts, 2015) and perpendicular transects were obtained with the transect tool (Ferreira, 2014); width was measured based on these transects. Transects were delineated at approximately regular intervals, ranging between 20 to 50 m in length, with a total of 980 transects along the stream network.

We calculated the confinement index (C_i) as the ratio between the valley bottom width (W_{valley}) to the initial channel width (pre-flood; W_i):

$$Ci= W_{valley}/ W_i \qquad [1]$$

and the width ratio (W_r) as the ratio between the width of the channel post-flood (W_f) to the channel width pre-flood (W_i), as proposed by Krapesch et al., (2011):

$$W_r= W_f/ W_i \qquad [2]$$

Discharge was not measured except at the outlet of the basin (Eggiwil stream gauge station; Fig.1), but estimations at other river sections were available (Table 2), using this data and the drainage area (A) we used a potential equation to estimate peak discharges at all sub-reaches:

$$Q= 23{\cdot}A^{0.6} \qquad [3]$$

Because the estimates using equation [3] were relatively uncertain, stream power was not calculated using the estimated peak discharge of the flood, but instead we used the stream power index proposed by Marchi and Dalla Fontana (2005) calculated as the product of the channel slope (S) and the square root of the drainage area (A):

$$SPI= S{\cdot}A^{0.5} \qquad [4]$$

The geomorphic response of the catchment and the initiation of processes such as LW recruitment due to mass movements or bank erosion might be driven by precipitation, among other variables (e.g., channel width, depth, and gradient). However, the rainfall patterns and subsequent disturbance regimes that influence the

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temporal variation in LW export in a given watershed network are not yet understood fully (Seo et al., 2012, 2015). Therefore, we include the event precipitation as an explanatory variable in our analysis. We hypothesize that differences in the spatial precipitation pattern would have led to differences in the geomorphic response, thereby regulating LW dynamics. The spatial and temporal distribution of the precipitation was available from the CombiPrecip database recorded by MeteoSwiss, which is calculated using a geostatistical combination of rain-gauge measurements and radar estimates with a regular grid of 1 km resolution (Sideris et al., 2014). For each sub-reach the drainage was computed as explained above, and the hourly and cumulative or total precipitation, total mean and total maximum values (i.e., the mean and maximum value of the total precipitation registered at each sub-catchment) were calculated.

The forest stands volumes ($m^3 \cdot ha^{-1}$) present before the event and eroded during the flood were assigned based on land use maps available for the study area and on information provided by the Canton of Bern and the Swiss National Forest Inventory (NFI; Brassel and Lischke, 2001) to calculate recruited wood volume (in terms of eroded vegetation; see example in Figure S4) and forested channel length. Forested channel length was determined by intersecting the forest cover with the river network. For this calculation, a wood buffer strip of 10 m was added to the forest boundary to account for potential LW recruitment due to tree fall. The width of the strip was chosen to be half of the average tree height and to correspond to the area of possible location of the centre of gravity of recruited wood logs (Mazzorana et al. 2011). The dataset used for this calculation is based on the digitized topological landscape model of Switzerland 1:25,000 (source: Vector25 © 2007, swisstopo, DV033594). Recruited wood volumes were normalized by channel area (i.e., $m^3 \cdot ha^{-1}$) and channel length ($m^3 \cdot km^{-1}$) to better compare sub-reaches and compare with other studies in other regions.

Deposited wood was directly measured in the field as explained above and by Rickli et al. (2016). Besides the field survey and the GIS analysis, all available media data, including a video recorded from a helicopter (http://www.heliweb.ch), were also analysed (Zurbrügg, 2015). This analysis allowed mapping of the original depositional sites of the removed wood right after the flood and complementing the wood budget calculations. Deposited wood volumes were also normalized by channel area (i.e., $m^3 \cdot ha^{-1}$) and channel length ($m^3 \cdot km^{-1}$) for comparisons.

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2.3.3. Statistical analysis

First, an exploratory analysis of the potential factors at the sub-reach scale was done by applying simple linear regression and correlation (non-parametric Spearman rank test). The explanatory variables analysed were width ratio, wood recruited volume (in total volume –m^3–, volume per area –$m^3 \cdot ha^{-1}$–, and volume per stream length – $m^3 \cdot km^{-1}$) and wood deposit volume (in total volume –m^3–, volume per area –$m^3 \cdot ha^{-1}$–, and volume per stream length – $m^3 \cdot km^{-1}$). The controlling factors included were initial channel width, width ratio (for wood recruitment and deposition), channel gradient, sinuosity, confinement index, SPI, forested channel length, and total maximum and mean precipitation.

Sub-reaches were grouped according to their morphological characteristics, geomorphic response (using a value of width ratio > 1.2 to characterize sub-reaches with important geomorphic changes in terms of channel widening), LW recruitment (sub-reaches with and without LW recruitment) and LW deposition (sub-reaches with and without LW deposition). Differences between groups of sub-reaches were tested using the non-parametric Mann Whitney (i.e., Wilcoxon signed rank test for two groups) or Kruskal Wallis (for > 2 groups) tests. Significance of correlations and differences was set when p-value < 0.1.

We hypothesize that one single variable may not explain the catchment response, but that the combination of multiple variables would. Thus, we applied multivariate analysis to estimate the probability and factors controlling channel widening, LW recruitment, and LW deposition. We applied multiple linear regression and multivariate binary logistic regression by using a stepwise approach in both cases to identify the best model based on the Akaike information criterion (AIC) and the determination coefficient. The multivariate binary logistic regression estimates the probability of a binary response (e.g., high channel widening and low channel widening, presence or absence of LW recruitment) based on different predictors (or independent) variables (e.g., morphological variables). As the variables analysed have very different units and different orders of magnitudes, the dataset was standardized by mean-centering (the average value of each variable is calculated and then subtracted from the data, resulting in a transformed dataset in such the resulting variable has a zero mean; Becker et al., 1988) prior to computing (logistic and linear) multiple regressions. All analyses were done for all subr-eaches together, for sub-reaches along the Emme river only, and for sub-reaches along all tributaries. Variables were considered significant for p-value < 0.1.

Statistical analyses were carried out using the statistical software R (R Core Team, 2017) and the packages xlsx (Dragulescu, 2014), Rcmdr (Fox, 2005 and 2017; Fox and Bouchet-Valat, 2017), corrgram (Kevin Wright, 2017), corrplot (Wei and Simko, 2017) and Hmisc (Harrell, 2016).

3 Results

The morphology of the sub-reaches along the Emme River and tributaries is significantly different (see Figure S5 in supplementary material), therefore we analysed their morphological response separately. Figure 3 shows the averaged values for different morphological variables, the calculated width ratio and the precipitation for the 19 study streams including the Emme River reach (cf. Table 1). Looking at the different tributaries and the Emme River reach, we observe that the morphological response in terms of width ratio was very different (Figure 3). The highest width ratio was observed in the Sädelgrabe, with nearly 5 times the initial channel width after the flood. The Gärtelbach and the tributary near Kemmeriboden also experienced significant channel widening. These streams were relatively narrow before the event, with initial channel widths smaller than 10 m, very steep (with channel gradients higher than 0.1), and highly confined (with confinement indices smaller than or near 5).

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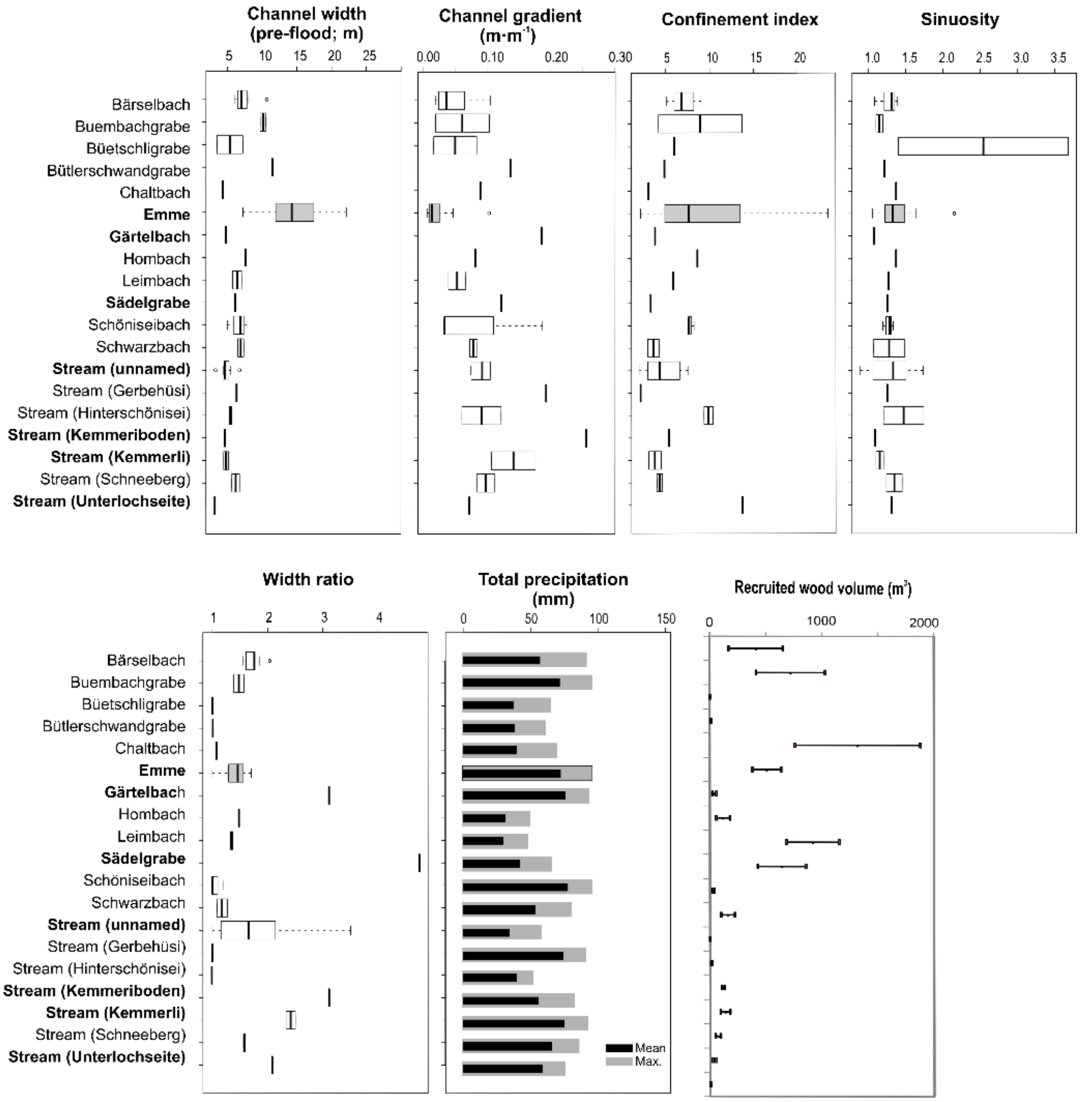

Figure 3: Boxplots of averaged initial channel width (before the flood), channel gradient, confinement ratio, sinuosity, width ratio, precipitation and recruited wood volumes for the 19 studied streams. Total maximum and mean total precipitation are calculated based on the 1 km precipitation grid cells in the respective catchments (maximum shows the highest value, mean shows the mean value recorded in each sub-catchment). Recruited wood volumes are given in ranges based on forest density ranges (as explained in the methods). In bold streams highlighted in Figure 4.

3.1 Morphological flood response: channel widening

The exploratory analysis of the morphological characteristics (Figure 4) showed that the relationships between width ratio and channel gradient, confinement index, initial channel width, SPI, sinuosity and total maximum precipitation variable substantially. A large scatter exists in the data, and in some cases, relationships are very different for the Emme sub-reaches and for the tributaries sub-reaches.

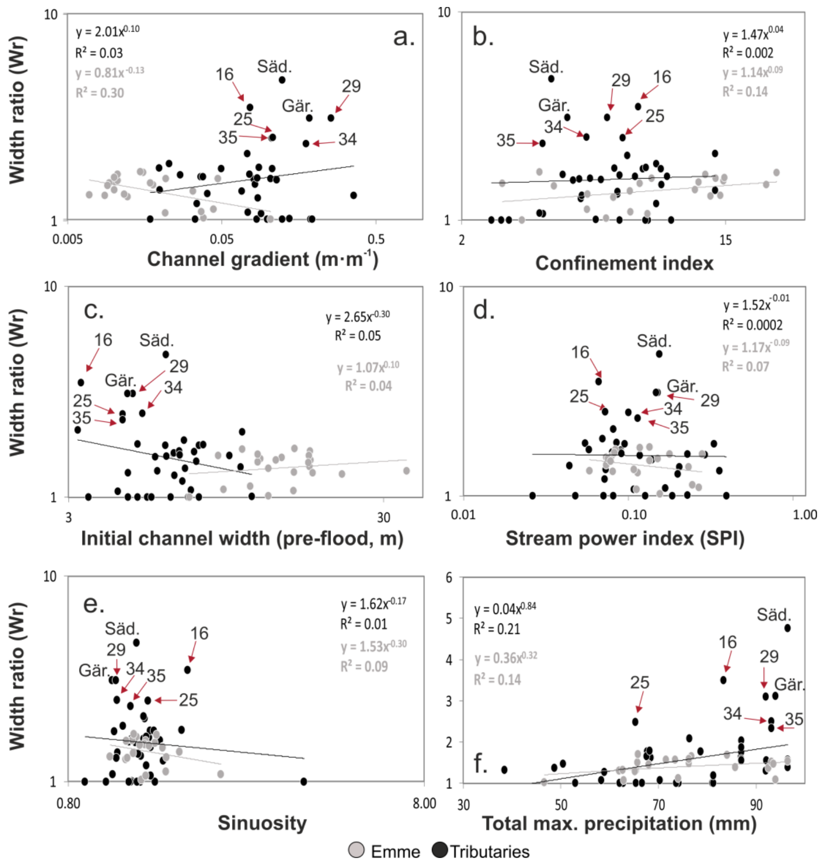

Figure 4: Relationships between width ratio and (a) channel gradient; (b) confinement; (c) channel width (pre-flood); (d) stream power index (in m·m^{-1}·km^{-2}); (e) sinuosity; (f) total maximum precipitation. Grey dots show sub-reaches along the Emme River, black dots show sub-reaches along tributaries. Säd.: Sädelgrabe; Gär.: Gärtelbach; numbers are sub-reaches as shown in Table 1. Grey and black lines show regression lines for the Emme River sub-reaches and tributaries sub-reaches respectively. Note that panel f has a linear x-axis in contrast to the logarithmic x-axis of panels a-e.

According to the Spearman rank test for all sub-reaches together (Figure 5) and for the tributaries sub-reaches (Figure S7), a significant positive correlation was found between width ratio and the total maximum and mean precipitation. Forested channel length was also significantly correlated to channel widening along the Emme sub-reaches (Figure S8).

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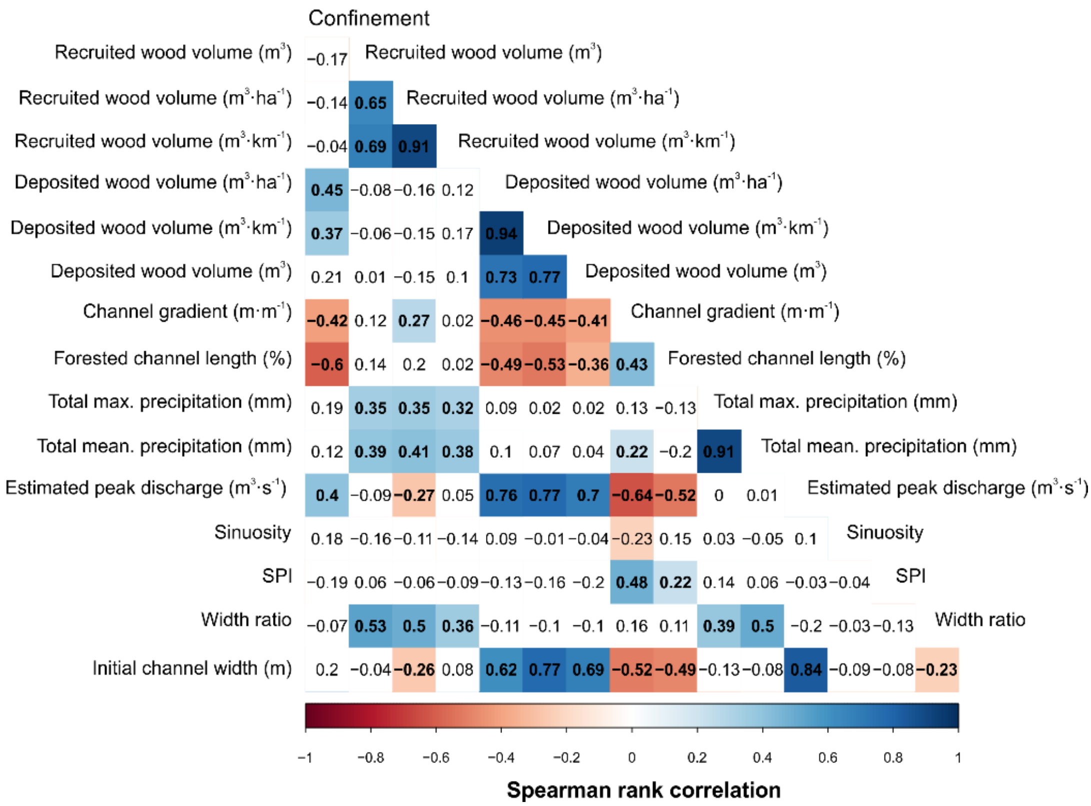

Figure 5: Spearman rank correlation matrix of all variables included in the analyses and for all sub-reaches together. Values shows the Spearman rank results (significant correlations are in bold). Red colours show significant negative correlations, blue shows significant positive correlation, white shows insignificant correlations.

When sub-reaches without widening (i.e., width ratio < 1.2) are removed from the correlation analysis, other significant correlations besides precipitation were observed (Table 3), such as channel gradient and initial channel width. Hence, the inclusion of sub-reaches which did not experience widening changed results, a fact that is discussed further in section 4.

Table 3: Spearman Rank correlation matrix for the width ratio versus different variables and for all sub-reaches, only Emme sub-reaches and only tributaries sub-reaches only with sub-reaches showing widening (i.e., width ratio>1.2). Bold indicates significant correlation.

Width ratio	**Variables** (All sub-reaches with width ratio >1.2)	**Variables** (Emme sub-reaches with width ratio >1.2)	**Variables** (Tributaries sub-reaches with width ratio >1.2)
Confinement index	-0.12	0.22	-0.06
Channel gradient	**0.46**	0.33	0.26
Total max. precipitation (mm)	**0.35**	**0.40**	0.31
Total mean precipitation (mm)	**0.32**	**0.48**	**0.38**
Sinuosity	-0.06	0.08	-0.09
Forested channel length (%)	0.22	-0.18	-0.06
Initial channel width (m)	**-0.56**	**-0.49**	**-0.43**
SPI	-0.08	0.27	-0.23

We compared the sub-reaches showing widening (i.e., width ratio > 1.2) with the sub-reaches not showing widening (i.e., width ratio < 1.2) and results revealed significant differences between these two groups (see also Figure S6) and between sub-reaches along the Emme and along tributaries (Figure 6). We find that sub-reaches with a large width ratio were significantly less confined (high values of confinement index), less steep and received a much higher precipitation during the storm. By contrast, sub-reaches where widening was important were also wider (channel width before the flood) and less forested, however, these differences were not significant. Interestingly, analysis of the sub-reaches along the Emme and along the tributaries independently showed similar trends (Figure 6).

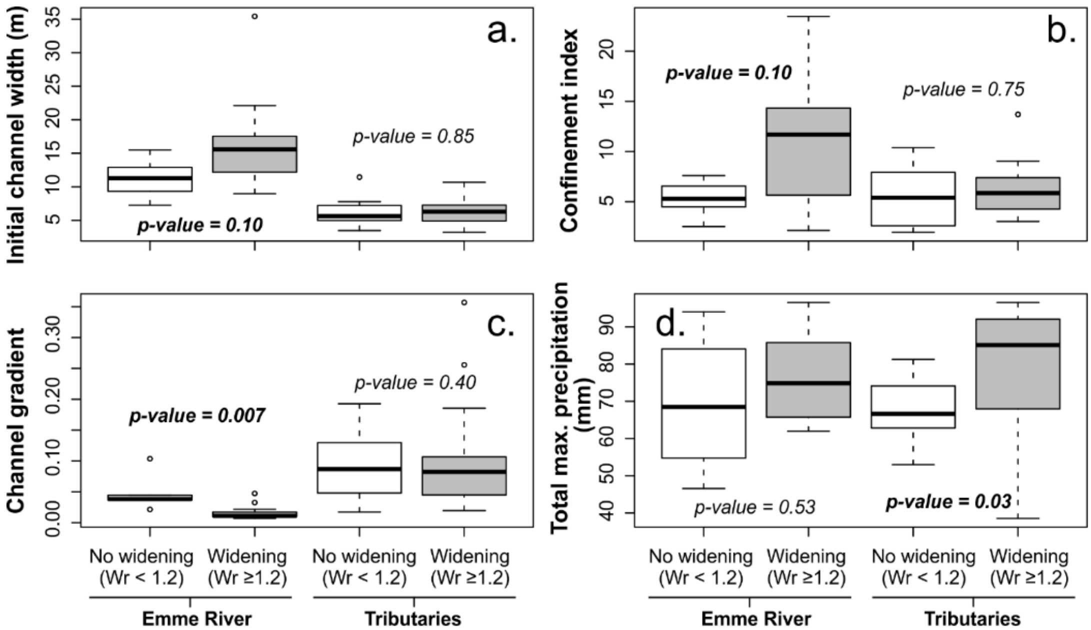

Figure 6: Boxplots of morphological variables (initial channel width, confinement index, channel gradient) and total maximum precipitation for all sub-reaches showing widening (i.e., width ratio ≥ 1.2; grey boxes) and sub-reaches not showing widening (i.e., width ratio < 1.2). The bottom and top of the box indicate the first and third quartiles, respectively, the black line inside the box is the median and circles are outliers. The Wilcoxon signed rank test result (p-value) for the significance of differences is also shown, bold indicates significant differences.

The logistic regression points to an increase in the probability of widening occurrence with increasing precipitation and confinement index. On the other hand, the probability of channel widening decreases with an increase in channel gradient, sinuosity, SPI, and forested channel length for all sub-reaches together. As with previous results, the sub-reaches along the Emme and along tributaries showed a contrasting behaviour. Along the Emme, widening probability increased for wider, gentler, less sinuous, and less forested sub-reaches, whereas in the case of tributaries, the probability for the channels to widen was larger for narrower, steeper, sinuous forested sub-reaches.

The role of precipitation is univocal in all cases, confirming our initial hypothesis about the role of the spatial distribution of precipitation. The logistic stepwise procedure revealed that the most significant variables explaining widening probability for all sub-reaches were total maximum precipitation, SPI, and estimated peak discharge (Table S1). Results obtained for sub-reaches along the Emme showed that forested channel length was also significant to explain widening.

The multiple linear regression between width ratio values and the same explanatory variables for all sub-reaches identified precipitation, gradient and SPI as significant variables. However, obtained models explained

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only between 14 and 19 % of the variability (Table S2). Separate multiple linear regression models for sub-reaches along the Emme and along tributaries further identify forested channel length, sinuosity, and initial channel width as significant variables; overall, models explained between 20 and 50% of widening variability.

3.2 Large wood recruitment and deposition

3.2.1. Factors controlling large wood recruitment

The most important sources of LW were the tributaries Bärselbach, Buembachgrabe, Gärtelbach, and Sädelgrabe, together with the main river Emme (see Figure 3). To understand the factors controlling LW recruitment at the sub-reach scale better, we explored correlations between different variables and the total LW volume, as well as the normalized recruited wood volume per stream hectare (Figure 7) and per channel length. In these analyses, we also included sub-reaches without LW recruitment.

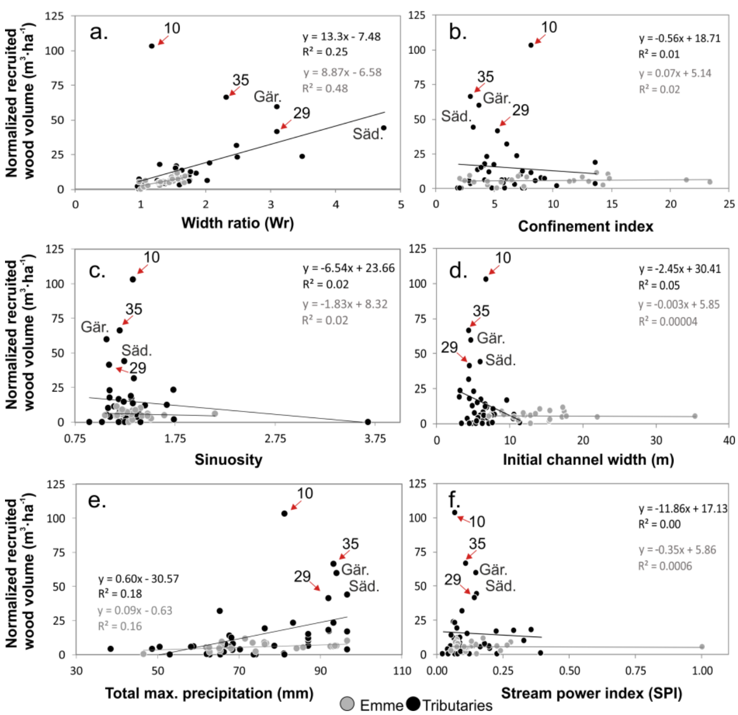

Figure 7: Relationships between recruited wood volume normalized by stream hectare ($m^3 \cdot ha^{-1}$; mean value according to mean value of forest density) and (a) width ratio; (b) confinement index; (c) sinuosity; (d) initial channel width (m); (e) total maximum precipitation (mm) and (f) SPI. Grey and black lines show regression lines for the Emme river and tributaries sub-reaches respectively. Säd. = Sädelgrabe; Gär. = Gärtelbach; numbers correspond to sub-reaches as shown in Table 1.

Even though the results showed a large scatter, some relationships can be identified. For instance, we found a positive significant correlation between recruited wood volume (m^3, $m^3 \cdot ha^{-1}$ and $m^3 \cdot km^{-1}$) and width ratio (Figure 5). This confirms that bank erosion (i.e., channel widening) was the main recruitment process. Again, sub-reaches receiving larger amounts of precipitation recruited higher quantities of LW and we observe a statistically significant positive correlation between total maximum and mean precipitation and recruited wood volume (for all three recruited wood volume variables). This is explained by the control of precipitation driving discharge, and thus driving the widening of channels and the wood recruitment process. Channel morphology may play a role in wood recruitment as well; we observe a significant negative correlation between recruited LW volume and initial channel width and a significant positive correlation with channel gradient (Figure 5). However, these significant correlations were found only for wood volume per stream hectare and not for total wood volume or wood volume per stream length (Figure 5).

Independent analyses for sub-reaches along the Emme or along tributaries showed similar results (correlation matrices shown in Figures S7 and S8). We also performed the same analysis with sub-reaches showing LW recruitment (i.e., removing those in which no LW was recruited) and found similar results in terms of significant correlations with the different variables (results not shown here). However, the comparative analysis of sub-reaches with and without LW recruitment (Figure 8) revealed that LW recruitment was observed primarily in sub-reaches characterized by a significantly greater confinement index (i.e., unconfined sub-reaches) and significantly smaller slope.

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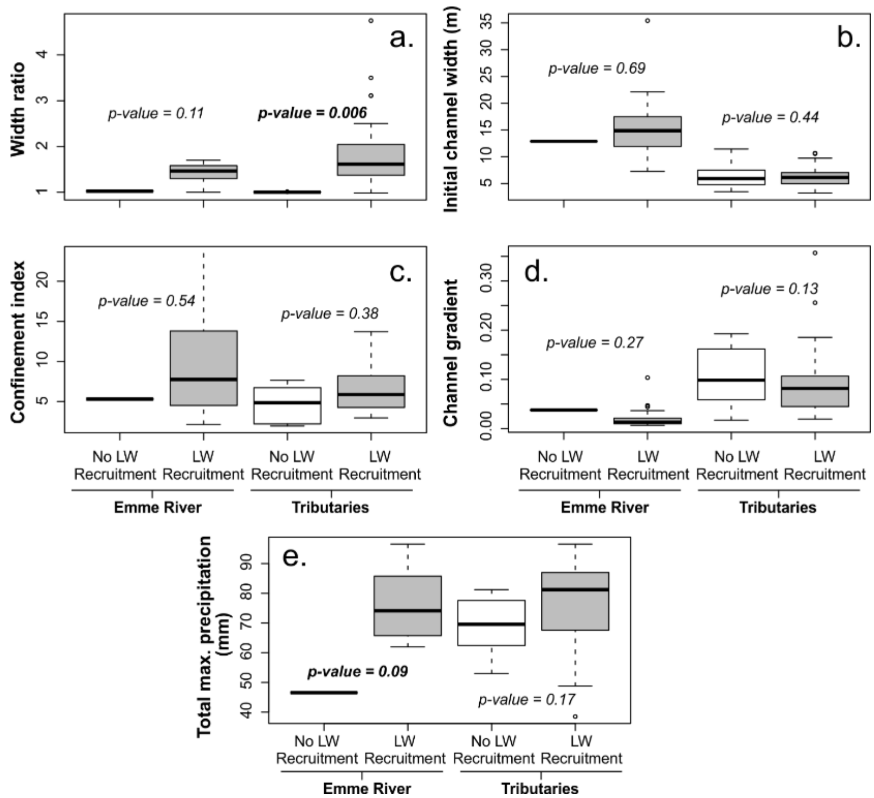

Figure 8: Boxplots of morphological characteristics (width ratio, initial channel width, confinement index, channel gradient and), total max. precipitation of sub-reaches showing wood recruitment and not showing LW recruitment. The bottom and top of the box indicate the first and third quartiles, respectively, the black line inside the box is the median and circles are outliers. The Wilcoxon signed rank test result (p-value) for the significance of differences is also shown, bold indicates significant differences.

Figure 8 shows that sub-reaches with LW recruitment were in general wider and wi thsub-reaches longer forested lengths than sub-reaches with no LW recruitment, however, differences were not significant (the results of all sub-reaches together, without grouping sub-reaches along the Emme and along tributaries are shown in Figure S9).

The logistic regression allowed calculation of the probability of LW recruitment occurrence. According to results, the probability of LW recruitment increases with channel widening and precipitation; and decreases with initial channel width and channel gradient. However, none of the variables were significant (Table S3), and the final stepwise logistic regression model selected just width ratio and confinement index as variables explaining LW recruitment probability.

The multiple linear regression points to total maximum precipitation and width ratio as the most significant variables explaining total LW recruitment volume (total m^3) variability, but forested channel length was also

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included in the final stepwise regression model for all sub-reaches. Between 10 and 32 % of the variability was explained by these models (adjusted R^2) (Table S4).

3.2.2. Large wood deposition along the Emme River

LW deposits were analysed along the Emme River and its tributary Sädelgrabe. However, because LW was mostly deposited on the Sädelgrabe fan and piled up nearby, only results obtained along the Emme sub-reaches can be provided here. The exploratory analysis of LW deposit distribution showed a positive relationship between deposited wood volume (normalized by stream area; $m^3 \cdot ha^{-1}$) and width ratio, confinement index, initial channel width, and total precipitation; and a negative relationship with SPI (Figure 9).

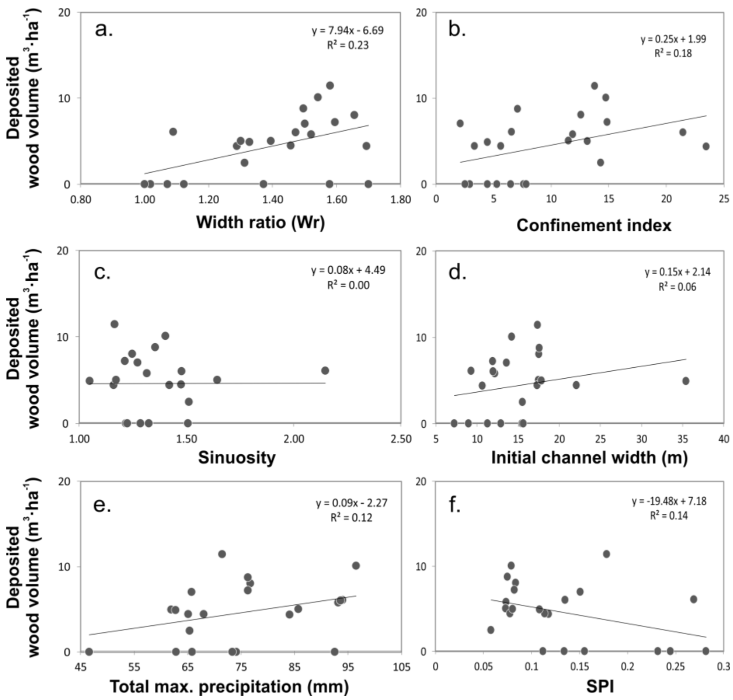

Figure 9: Relationships between deposited wood volume per stream hectare ($m^3 \cdot ha^{-1}$) along the Emme River sub-reaches and (a) width ratio; (b) confinement index; (c) sinuosity; (d) channel width pre-flood; (e) total maximum precipitation (mm); and (f) SPI.

The Spearman test yielded a negative significant correlation of deposited LW with channel gradient and SPI, and a positive correlation with estimated peak discharge (Figure 5). By contrast, the confinement index and initial channel width were only significantly correlated with deposited LW volume per hectare and per kilometre, respectively.

The comparison between Emme sub-reaches where LW was deposited or not showed statistically significant differences in terms of confinement index, channel gradient, and SPI (Figure 10).

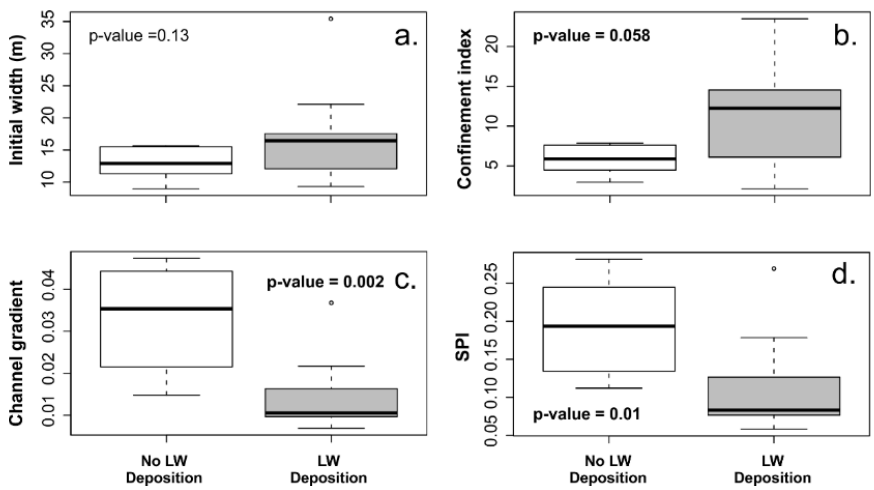

Figure 10: Boxplots of morphological characteristics (initial channel width, confinement index, channel gradient, and SPI), of sub-reaches showing and not showing LW deposition along the Emme river. The bottom and top of the box indicate the first and third quartiles, respectively, the black line inside the box is the median and circles are outliers. The Wilcoxon signed rank test result (p-value) for the significance of differences is also shown, bold indicates significant differences.

The probability of LW deposition estimated by logistic regression confirmed that LW deposition probability increases with increasing width ratio, confinement index, and initial channel width, whereas it decreases with increasing channel gradient and SPI. The multivariate stepwise logistic regression model identified both the confinement index and estimated peak discharge as significant variables explaining LW deposition, but also included the width ratio in the final model (Table S5).

The multiple linear regression of LW deposited volume (i.e. total m^3 and m^3, $m^3 \cdot ha^{-1}$ and $m^3 \cdot km^{-1}$) showed that the significant variables include channel gradient, estimated peak discharge, initial channel width, SPI, and confinement index (Table S6). The models explained between 51% and 67% of the variance. The largest variability (70%) was explained for LW deposited volume per stream length ($m^3 \cdot km^{-1}$).

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3.3. Large wood budget and size distribution

LW budget was fully analysed along the lower part of the surveyed Emme River and the Sädelgrabe tributary. This tributary delivered large quantities of LW by mass movements and debris flows, which was mostly deposited along its fan and the Emme River, however, and according to eyewitness reports, a substantial amount of LW was also transported further downstream and to clog the Räbloch gorge. At this narrow canyon (Fig. 1), wood and additional debris created a dam of 8 to 10 m in height.

Table 4: Wood budget along the Sädelgrabe. Uncertainties of up to 50% are included in the stated volumes.

Processes	**Recruited (m^3)**	**Deposited (m^3)**	**Exported (m^3)**
Landslides/bank erosion	331 ± 66		
Previously deposited in channel	150 ± 75		
Stored in the piles close to the confluence		100 ± 20	
Extracted before survey		32 ± 11	
Deposited on the fan (forests)		172 ± 34	
Deposited on the fan (pastures)		25 ± 9	
Subsequently deposited in channel (after event)		100 ± 50	
Stored in pile at fan apex		30 ± 15	
Exported to the Emme			40 ± 20
Total	**481 ± 141**	**458** ± 139	**40** ± 20

Recruited LW volumes in the Sädelgrabe were due to landslides and bank erosion; the LW volume was estimated to be equal to 331 m^3 (Table 4), together with the estimated volume of wood stored within the channel before the event (150 m^3), we obtained in 481 m^3 of recruited and entrained wood. About 458 m^3 of wood was deposited at various locations (172 m^3 were deposited on the fan, 100 m^3 were piled up along the stream bed and the municipal road and 100 m^3 were remaining in the stream bed of the Sädelgrabe after the event). Our estimations showed that only a small volume (about 40 m^3) was exported from the Sädelgrabe to the Emme River.

Another source of LW was the Gärtelbach, which delivered large quantities of LW directly to the Emme River, of which most was deposited along the floodplain in the vicinity of the Schwand bridge. The total volume of wood estimated in this area was 250 m^3. Table 5 summarizes the wood budget computed along one segment of the Emme river.

Table 5: Wood budget along the lower reach of the studied Emme River segment. Uncertainties of up to 50% are included in the stated volumes

Processes	Recruited (m^3)	Deposited (m^3)	Exported (m^3)
Bank erosion along the studied reach	192±38		
Previously deposited	100 ± 50		
Piles close to Bumbach			
Deposited along the river		360	
Temporary storage in Bumbach			360 ± 36
Stored jam in Räbloch gorge		480 ± 45	
Input from Sädelgrabe	**40** ± 20		
Total	**332**	**833** ± 64	**360** ± 36

Bank erosion along the surveyed Emme River segment recruited about 192 m^3 of wood, that together with the estimated previously stored wood (100 m^3) and the input from the Sädelgrabe was summed at 332 m^3. Roughly 250 m^3 were deposited in an area near Schwand, and the rest along the Emme River. The sum of the deposited wood was approximately 360 m^3. In addition, about 300 m^3 of LW from flooded areas were transported to a landfill as part of clean-up work and post event measures. Another important element of the balance is a large jam of approximately 480 m^3 of wood, which formed about 1.6 km downstream of the investigated section at Räbloch. Unfortunately, it is not known how much wood was transported from the upper reaches above Kemmeriboden into the considered section, and therefore a mismatch exists between the estimated recruited, deposited, and exported volumes.

Pieces of LW were surveyed and measured both along the Emme sub-reaches between Kemmeriboden and Räbloch (Figure 1) and along the Sädelgrabe tributary. In total, 1995 (i.e. 1658 along the Emme and 297 on the Sädelgrabe fan and nearby piles) pieces were measured and the size distribution was further analysed (Figure 11). For both the Sädelgrabe and Emme River, piece frequency generally decreases with increasing piece length and diameter. Regarding the relative diameter distribution, almost no differences exist between the two sites, and in both cases the range class of 10-15 cm is the most frequent with approximately 50% of the total. The mean and median values of piece length and diameter are very similar in the Emme River (mean D: 16.6 cm, mean L: 4.04 m / median D: 15 cm, median L: 2.32 m) and Sädelgrabe torrent (mean D: 17.4 cm, mean L: 3.06 m; median D: 15 cm, median L: 2.5 m). Regarding the relative length distribution, short wood pieces (<2 m) were more frequently found along the Emme River (almost 60 %), whereas longer pieces (>2 m) were more prevalent along the Sädelgrabe (around 60 %). However, the longest piece was found in the Emme (20.7 m), while the longest piece measured in the Sädelgrabe was substantially shorter with a value of 12.0 m.

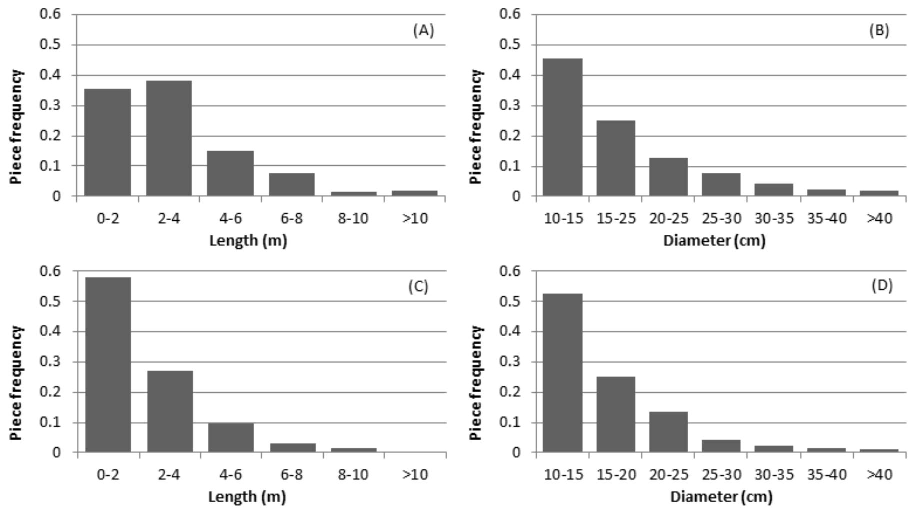

Figure 11: Size distribution (piece diameter and length) of deposited LW pieces in the Sädelgrabe (a) and (b) and in the Emme River (c) and (d). In all panels the bars relate to the relative frequency of pieces.

4 Discussion

4.1. Channel response to the 2014 flood

In this study, we presented an integration of different approaches and data sources (i.e., field survey, GIS-remotely sensed data and statistical analysis) at different spatial scales to better understand flood response in terms of channel widening and LW dynamics. We proved the importance of performing an overall analysis over the entire catchment, although the flood event and responses to it were restruicted to some areas of the catchment only. This approach allowed identification of hydrometeorological and geomorphic thresholds for channel widening, LW recruitment, and deposition. The inclusion of sub-reaches without important widening or without LW recruitment and deposition in the analysis showed that sub-reaches with similar characteristics may exhibit significantly different responses during the same event, and that variables explaining these responses may not be identified properly if only one part of the dataset is analysed.

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Previous works observed that hydraulic forces (e.g., stream power) are not sufficient to explain geomorphic effects of floods (Nardi and Rinaldi, 2015), and other variables, such as initial channel width, confinement or human interventions should be included in assessments (Surian et al., 2016 and references therein). We confirmed with this study that the flood triggering precipitation is key in understanding the magnitude and spatial variability of catchment response and that it should thus be included in future analyses. As hypothesized, differences in spatial precipitation patterns led to differences in the geomorphic response of the catchment, regulating channel widening and thereby controlling LW dynamics. Albeit this observation may have been expected, it has rarely been addressed in post-event surveys (Rinaldi et al., 2016) even in cases where data was available at the proper spatial scale (e.g., Surian et al., 2016).

Precipitation was the univocal variable to explain channel widening in statistically significant terms, provided that all sub-reaches were including, or whenever only sub-reaches along the Emme River or along tributaries were analysed. A threshold value of around 80 mm precipitation was observed in sub-reaches with the most important widening (Fig. 4). When sub-reaches without widening were removed from analysis, channel morphology (in terms of initial channel width, confinement and gradient) and hydraulic conditions (i.e., estimated peak discharge) were also significantly correlated with the width ratio. In fact, sub-reaches with a confinement index larger than 10 (i.e., unconfined channels) and wider than 10 m experienced less widening. This means that after intense precipitation events, channel morphology is a secondary driver for channel widening. Initial channel width was significantly negatively correlated with width ratio, as previously observed by Surian et al. (2016), Comiti et al. (2016) and Righini et al. (2017), who analysed reaches that showed important widening in several streams in Italy. These authors also found the confinement index to be an important variable controlling channel widening. Regarding this variable, we observed contrasting a behaviour in the sub-reaches along the Emme River (where the width ratio was positively correlated with the confinement index) and along tributaries (where the width ratio was negatively correlated with the confinement index). This is because the largest widening was observed along tributary sub-reaches, which are relatively more confined than the main river. In fact, only along the Emme River we observed that sub-reaches showing channel widening were significantly less confined than sub-reaches not showing widening at all. In contrast, differences were not significant along the tributaries. This apparently contradictory result might be explained by several reasons. First, some large width ratios derived from aerial pictures (i.e., only on planimetric observations) may possibly include erosion of parts of the adjacent hillslopes, a process that also occurs during the flood. This was observed along the Sädelgrabe, where some highly confined transects showed widening ratios exceeding the confinement index (as also observed by Comiti et al., 2016). One may argue that these slope failures should not be considered as channel widening, because the process here is more related to hillslopes movements (e.g., falls, slips, slabs, slumps) than to channel processes. Second, some of the tributaries, especially the Sädelgrabe and Gärtelbach, received the highest amounts of precipitation, resulting in a more intensive response. However, logistic regression showed that widening probability increased with increasing confinement index. Besides channel confinement, lateral constraints, mainly artificial rip-raps or channelization, or natural bedrock, were present before the flood occurred, especially along the Emme River (see Figure S2). These natural or artificial lateral constraints were not explicitly included in the analysis; however, they may have influenced results (Hajdukiewicz et al., 2015; Surian et al., 2016), therefore blurring factors controlling these processes and making their identification more difficult. In addition, major adjustments occurred during the last century, mostly channel narrowing and channel planform changes. These changes occurred at tributary confluences and along some of the Emme River sub-reaches, especially in unconfined sub-reaches where the stream changed from a braided to a single-thread pattern (Figure S2). These anthropogenic changes may have an influence on current river response to floods and should thus be taken into account as well. Historical analyses were out of the scope of this study, however, they provided key information to assess whether and to what extent the response of a flood may involve channel segments that experienced significant changes in historical times (Rinaldi et al., 2016).

As shown in the results, sub-reaches along tributaries experiencing large channel widening were significantly steeper than those without widening, while along the Emme River channel, widening happened mostly along the gentler sub-reaches. This contrasting effect is explained by the same reasons exposed above regarding widening and confinement. A negative correlation between width ratio and channel gradient as found along the flatter Emme River reaches was also observed by Lucía et al. (2015), however, channel gradient is much smaller along the Emme River than in the Italian streams analysed by these researchers. The hydraulic conditions represented here by the estimated discharge and the SPI were not found to be significantly correlated with width ratio, although the multiple linear regression identified SPI as a significant variable explaining channel widening. Due to the large uncertainties related to the estimation of peak discharge at each transect and sub-reach, we preferred not using total stream power or unit stream power for analysis, but selected SPI instead. However, even when accurate discharge estimates are available, stream power has been shown to only partially explain channel changes, as other factors might be more relevant (Krapesch et al., 2011, Comiti et al., 2016, Surian et al., 2016; Righini et al., 2017). Finally, another morphological variable included in our analysis was sinuosity. However, this variable was not significant and did not explain channel widening, even though the logistic regression revealed that widening probability may increase for medium sinuous sub-reaches. Nardi and Rinaldi (2015) also found higher width ratios for braided and wandering reaches than for straight or highly sinuous reaches.

Besides channel morphology, the presence of vegetation also influenced channel response. Forested channel length was negatively correlated with width ratio, sub-reaches that experienced large widening were significantly less forested than those not experiencing channel widening. This illustrates the role of vegetation in protecting riverbanks from erosion (Abernethy and Rutherfurd, 1998). Other variables such as bank material (e.g., cohesive, non-cohesive, bedrock), type of vegetation, and vegetation density were not included in our analysis although they can be important factors affecting flood response; they should therefore be considered in future analyses.

4.2. LW recruitment and deposition during the flood

LW recruitment was controlled primarily by bank erosion (i.e., channel widening) and thus, factors controlling this process were identified as significant factors for LW recruitment. We observed a significant correlation between LW recruited volume and width ratio, precipitation, initial width, and channel gradient (i.e. the correlation with the last two variables was significant just for volume of wood recruited per channel hectare). The confinement index was also included in the final logistic regression model. There are not many previous studies that analysed LW recruitment after a single large flood. At the time of writing this manuscript, only the work of Lucía et al. (2015) was available, reporting on results from Northern Italy. The 2011 flood in the Magra river basin recruited large amounts of LW as well, mostly by bank erosion too. In their work, the authors did not find many significant correlations for total recruited wood volume, only a negative correlation with channel gradient. Our findings agree with their study and confirm the important role of bank erosion in recruiting wood material in mountain rivers, thereby highlighting that hillslope processes were not the dominant LW supplier (contrary to what was proposed by Rigon et al., 2012).

This means that more attention should be paid to the understanding of bank erosion processes and the interactions with vegetation to predict or identify LW recruitment sources. Our findings also revealed that morphological variables alone may not explain or predict LW recruitment, and that other factors should be considered as well, such as the triggering precipitation of the recruitment processes. As expected, the percentage of forested channel was also significant in the multiple linear regression model. However, other vegetation characteristics could play a role, such as the type and density of vegetation (Ruiz-Villanueva et al., 2014).

In our study, LW deposition was controlled mostly by channel morphology. We found significant correlations between LW deposited volume and initial channel width, channel gradient and SPI. Sub-reaches where LW was deposited were significantly less confined (mainly in sub-reaches with confinement index higher than 7), wider (LW deposit was enhanced in sub-reaches wider than 15 m), and gentler than sub-reaches with no LW deposits. According the multiple linear regression model, 67 % of the variance was explained by these variables. These results are contrasting with those found by Lucía et al. (2015), who did not find any statistically significant relationship with the controlling variables, although they observed that LW was more pronounced in the wider, milder slope reaches, typically located in the lower river sections (Lucía et al., 2015). However, in their case, LW deposition was severely affected by the presence of several bridges and the formation of new in-channel islands due to bed aggradation.

We could compute wood budgets just for one tributary (Sädelgrabe) and one segment of the Emme river. Similarly to what is commonly done for sediment transport, a wood budget for a river basin should be a quantitative statement of the rates of recruited (delivered), deposited, and transported wood volumes (Benda and Sias, 2003). Detailed quantitative information about previously stored wood in the river channels was not available and we therefore had to assume that a value of 100 m^3 was reliable for this area based on previous studies (Rickli und Bucher 2006). In addition, the budget for the Emme river segment was not completed, as we could not compute all elements (e.g., previously stored wood, deposited wood during the flood) of the budget in all sub-catchments upstream. Computing wood budgets at the catchment scales is very challenging but might be crucial for the proper management of river basins and when it comes to wood-flood hazard mitigation (Comiti et al., 2016).

Regarding the size of deposited logs, the median diameter observed in the field was equal to 15 cm and the median length was equal to 2.3 m and 2.5 m in the Sädelgrabe and Emme River, respectively. These values were slightly smaller than values observed after the flood in August 2005 in central Switzerland (Steeb et al., 2017; Rickli et al., 2018), or after the flood in the Magra river (although only log length was reported by Lucía et al., 2015), but in line with logs deposited along several streams in the Italian Alps (Rigon et al., 2012). We found smaller pieces along the Emme River as compared to the Sädelgrabe, indicating that pieces in the Emme may have travelled longer distances, and that pieces have been broken during transport.

The flood event analysed here was a large flood, and although the recruited and transported LW resulted in significant damage (i.e., clogging bridges and damaging buildings), the exported volume was not extremely high. According to our estimations, most LW recruited in the Sädelgrabe (480 m^3) and along the lower reach in the Emme River (890m^3) was not transported long distances downstream but deposited nearby its source. Part of the material was clogged in the Räbloch gorge (between the villages of Schangnau and Eggiwil) including the woody material from the bridge destroyed at Bumbach. Still, LW was transported further downstream and stored in several hydropower dams and reservoirs along the Aare (downstream its confluence with the Emme river). According to the dam managers' estimations, a total of 1500 m^3 of wood was stored in five dams. However, it was not possible to compute precise budgets for the entire Emme catchment and its tributaries, and this value thus needs to be confirmed. Nevertheless, the exported LW volume in our study can be classified as very low when compared with volumes transported during the flood in August 2005 in Switzerland (Steeb et al., 2017) and with other events, as illustrated in the review by Ruiz-Villanueva et al. (2016).

Due to the complexity inherent to channel widening and LW dynamics, predictions on the location of major geomorphic changes and the magnitude of LW recruitment during large floods are very challenging (Buraas et al., 2014; Surian et al., 2016). Documenting events like the one reported here is fundamental for a better understanding of the processes involved and for the development of reliable and robust tools and approaches to facilitate the inclusion of such processes in flood hazard assessments (Comiti et al., 2016). As such, a real need exists to complement current inundation mapping with a geomorphic approach (Rinaldi et al., 2015 and 2016; Righini et al., 2017) and an integrative analysis of LW dynamics (Mazzorana et al., 2017).

5. Conclusions

Channel widening and LW dynamics are usually neglected in flood hazard mapping and river basin management. However, the present study clearly shows the importance of these processes during floods in mountain rivers. Still, a proper identification of factors controlling river basin response remains challenging. In that regard, our results also show that the identification of significant variables may be difficult, and that depending on how the data is collected and analysed (e.g., whether non-affected sub-reaches are included or not or which variables are considered), different outcomes are possible. However, we also showed that precipitation and variables such as forested channel length may play an important role in explaining flood response, and that they should thus be taken into consideration. Precipitation was the univocal statistically significant variable to explain channel widening, and only when sub-reaches without widening were removed from the analysis, channel morphology (i.e. initial channel width, confinement, and gradient) and hydraulic conditions (in terms of estimated peak discharge) were also significantly correlated with width ratio. LW recruitment was controlled primarily by bank erosion, and thus by the same variables controlling this process. This finding points to the need to better understand bank erosion processes and the interactions with vegetation so as to predict or to identify LW recruitment sources. LW deposition was mostly controlled by channel morphology (i.e., initial channel width and gradient), and studies like this one are therefore crucial to identify preferential reaches for wood deposition. This is an important component of the full wood budget, but not the only one. Further efforts in wood budgeting at the single event temporal scale are key to better understand LW dynamics during floods in mountains rivers.

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