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Planform changes and large wood dynamics in two torrents during a severe flash flood in Braunsbach, Germany 2016

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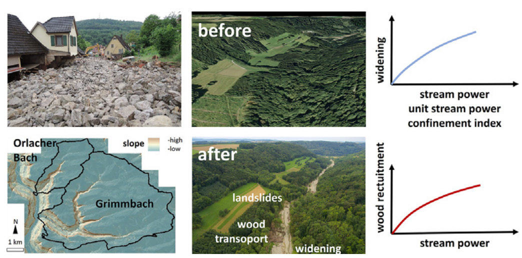
HIGHLIGHTS

- We carried out a post-event survey after a flash flood in two streams.
- Morphological changes were measured and a large wood budget calculated.
- Results were related to hydraulic and morphological control factors.
- Channel changes and large wood rates are similar to those in mountain rivers.
- Results are relevant for mitigating flash floods in low gradient basins in Europe.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents a post-event survey study, addressing the geomorphic response and large wood budget of two torrents, Grimmbach and Orlacher Bach, in southwestern Germany that were affected by a flash flood on May 29, 2016. During the event, large amounts of wood clogged and damaged a bridge of a cycling path at the outlet of the Grimmbach, while the town of Braunsbach was devastated by discharge and material transported along the Orlacher Bach. The severity of the event in these two small catchments (30.0 km^2 and 5.95 km^2, respectively) is remarkable in basins with a relatively low average slope (10.7 and 12.0%, respectively).

In order to gain a better understanding of the driving forces during this flood event an integrated approach was applied including (i) an estimate of peak discharges, (ii) an analysis of changes in channel width by comparing available aerial photographs before the flood with a post-flood aerial surveys with an Unmanned Aerial Vehicle and validation with field observations, (iii) a detailed mapping of landslides and analysis of their connectivity with the channel network and finally (iv) an analysis of the amounts of large wood recruited and deposited in the channel.

The morphological changes in the channels can be explained by hydraulic parameters, such as stream power and unit stream power, and by morphological parameters such as the valley confinement. This is similar for LW recruitment amounts and volume of exported LW since most of it comes from the erosion of the valley floor.

The morphological changes and large wood recruitment and deposit are in the range of studied mountain rivers. Both factors thus need to be considered for mapping and mitigating flash flood hazards also in this kind of low range mountains.

1. Introduction

1.1. Flash floods

Among different types of floods, flash floods cause highest mortality (Doocy et al., 2013) and are especially devastating (Jonkman, 2005).

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Flash floods are defined as sudden events with high peak discharges, produced by severe thunderstorms that are generally of limited areal extent (IAHS-UNESCO-WMO, 1974). Despite their relevance, this phenomenon is poorly understood, mainly because they cannot be extensively monitored (Borga et al., 2014). Therefore, the need of a systematic post-event monitoring of flash floods has been stated in order to improve their understanding and the assessment of hazard and vulnerability (Gaume and Borga, 2008; Borga et al., 2014).

The intense precipitation events which lead to a rapid and high increase in discharge within the channel network frequently trigger slope instabilities, such as landslides and debris flows, during the same event (Borga et al., 2014). Morphological changes in the channel are a common response to flash floods (Baker, 1977). The hillslope processes, coupled to the fluvial dynamics, supply large volumes of both sediments and large wood (LW) to the channels in forested catchments (Comiti et al., 2008; Comiti et al., 2016). Consequently, the way to approach this kind of post-event survey should contain a comprehensive analysis of this phenomenon, including precipitation, generated discharge, morphological changes and large wood transport dynamics (Rinaldi et al., 2016a).

In the last decade, huge efforts have been undertaken to understand the effects of flash floods with post-event surveys. Initially, research focussed on (dis-)entangling the hydro-response (Gaume et al., 2004; Borga et al., 2007; Marchi et al., 2009; Marchi et al., 2010; Amponsah et al., 2016). Some studies have concentrated on the morphological changes (Rinaldi et al., 2016a; Surian et al., 2016; Righini et al., 2017) while others have focussed on sediment transport (Rickenmann et al., 2016) or on the dynamics of LW (Comiti et al., 2008; Lucía et al., 2015; Steeb et al., 2017).

Most of the studies regarding morphological, sediment and large wood dynamics during flash floods investigate specific events in mountain areas with drainage areas characterized by steep slopes. In fact, this kind of events is typical for mountain regions (Jonkman, 2005) and also frequent in semiarid Mediterranean catchments. Few studies analyzed flash floods in relatively low gradient slope catchments and temperate climate, where a slower and milder response could be expected from intense precipitation due to the milder slope of the terrain than in mountain catchments and due to the land-use, which could allow higher infiltration rates than in the Mediterranean areas. The hydrological response to a flash flood has been investigated in a catchment in central Germany with 12% average drainage area slope (Ruiz-Villanueva et al., 2012) and the hydro-morphological response in small Carpathian catchments (from 17 to 20% slope) (Bryndal et al., 2017).

According to current climate models, that predict a change in global precipitation patterns, temperate areas will experience intensified rainfalls, increasing the probability of extreme rain events (IPCC, 2013) which could lead to eventual occurrence of flash floods (Doocy et al., 2013). Therefore, there is a need to understand the morphological and large wood dynamics also in the low gradient catchments of low mountain ranges of central Europe in order to better forecast and reduce the flash flood associated risks.

Following a flash flood that occurred on May 29, 2016, and severely affected two small catchments in southwestern Germany (Grimmbach and Orlacher Bach) with average slopes of 10 and 12%, respectively, we aim to:

- provide detailed data on the morphological changes in terms of planforms (landslides and widening) and large wood dynamics by a post-event survey,
- identify the controlling factors of the morphological response and the large wood dynamics,
- compare the response of these relatively low slope catchments to mountain channels, that are so far better documented in the available literature,
- and, finally, based on the obtained results, discuss flood risk management in these low gradient mountains.

2. Study area and methods

2.1. Study area

The studied area is located in the municipality of Braunsbach, in southwestern Germany, in the northeast of the state of Baden-Württemberg (Fig. 1b). This region is part of the southwestern German Cuesta landscape and is characterized in this area by resistant rocks of the middle Triassic limestone (Muschelkalk) which is overlain by thin layers of upper Triassic clays (Lettenkeuper). The resulting ondulated plateaus are often covered by loess or loam (Koster, 2005) in which fertile soils have developed. In fact, they are characterized by intensive agricultural land-use. These plateaus are dissected by valleys, resulting in relatively steep slopes covered by forest. In the studied area, the Kocher valley is incised 200 m deep in a plateau of Upper Muschelkalk limestone (Fig. 1a). The town of Braunsbach is located at the right bank of the Kocher River and at the outlet of the Orlacher Bach. The Orlacher Bach is a small torrent that drains an area of 5.98 km^2 with an average slope of 12.0%. In this catchment the village of Orlach is located just at the rim of the plateau, exactly at the point where the incision begins (Fig. 2). The Grimmbach is the adjacent torrent to the south of Orlacher Bach, and drains an area of 30.02 km^2, with an average slope of 10.7% (see Table 1, with a summary of the catchments characteristics).

The climate of the area is temperate, with mild summer and precipitation all over the year. The climate classification according to Köppen and Geiger is Cfb (temperate, without dry season, warm summer). Its average annual temperature is 9.5 °C and mean annual precipitation is 750 mm (ABW, 2017).

On May 29, 2016, there was a precipitation event of 153 mm in one day, with 131 mm accumulated in only 2 h in the afternoon (16:00–18:00) and with a maximum 5-minute-intensity of 157 mm/h (Bronstert et al., 2018). This event was exceptional for the area, with the hotspot of the storm over the catchments of the Orlacher Bach and Grimmbach. The estimated precipitation exceeded the 100 year return period (Bronstert et al., 2018). It generated flash floods that had devastating effects in the towns of Orlach and Braunsbach, damaging also a cycling path at the outlet of the Grimmbach. Both catchments are not gauged and discharges of large return periods can only be estimated based on regionalized basin characteristics. For a 1000 year return period in this area the local authorities determined values below 3 m^3 s^{-1} km^{-2} (LUBW, 2015), which were by far exceeded during the flood in 2016. Luckily, there were no casualties, but the material costs are estimated at >100 million euros. Even 1 ½ years later, the municipality has not recovered from the damages (Frank Harsch, Mayor of Braunsbach, pers. com.).

2.2. Post-event survey

In order to understand the morphological changes and large wood dynamics during the flash flood, we have followed the approach of Rinaldi et al. (2016a). It consists of an integrated methodology that combines geomorphological, sedimentological and hydraulic data and evidence that helps to identify the most critical reaches. The hydro-meteorological analysis, with special focus on the Orlacher Bach, has been done by Bronstert et al. (2018).

In this study, we have focused on aspects related to channel changes and sources and dynamics of wood at a subreach scale. In order to analyse these two aspects, field surveys have been combined with remote sensing. The detailed methodological approach is explained in the following subsections.

In total, seven field surveys were carried out on June 1, three days after the event, June 22 and 28, July 5 and 11, August 18, 2016, and, one year after the event, on June 27, 2017.

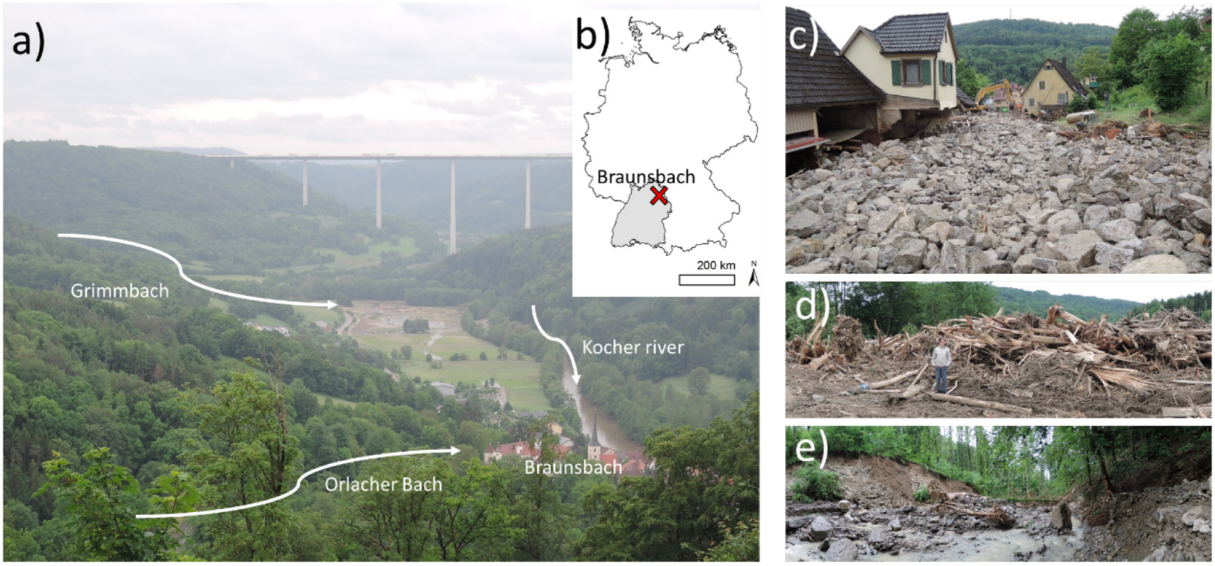

Fig. 1. a) Physiographic location of the studied area with the Kocher River and the forested steep slopes incised in the middle Triassic Muschelkalk Plateau. The location of the town of Braunsbach as well as the Orlacher Bach and the Grimmbach torrents are indicated. Also, the large wood (LW) deposit at the outlet of the Grimmbach is visible. b) Location of the studied area in Germany (in white) and Baden-Wüttemberg (in grey). c) Debris deposits covering the road and damaging houses in the town of Braunsbach. d) Large wood deposited at the outlet of the Grimmbach catchment, clogging the bridges. e) The Orlacher Bach channel flowing to Braunsbach, with landslides, widening, and large wood deposited.

2.2.1. Peak discharge estimation

In order to understand the hydrological response and its potential correlation with the morphological response, we have estimated the peak discharge in the Grimmbach catchment with the methodology proposed by Gaume and Borga (2008). This comprises the topographic survey of cross sections and water surface slope through peak flow marks that, assuming uniform flow, is a close approximation of the energy slope, and the subsequent application of the Manning-Strickler equation. Two cross sections were surveyed in areas with no indication for changes in channel morphology during the flood. The channel width at the downstream cross section was 23 m and the peak flow marks were surveyed along 131 m of the channel. At the upstream cross section, the channel width after the event was 19 m and peak flow marks were surveyed along a channel segment of 102 m. The selected Manning coefficients varied between 0.083 in the floodplains to 0.05 in the channels.

For the Orlacher Bach catchment, we have used the discharge data estimated by Bronstert et al. (2018). A rainfall-runoff model to check the consistency of rainfall and discharge data.

2.2.2. Morphological pre-event characteristics

In order to analyse the morphological characteristics before the flash flood event, orthophotos from 2015 with 20 cm resolution (LGL, 2009) and a LiDAR derived DTM of 1 m resolution and vertical accuracy of ± 0.2 m have been used (LGL, 2009) and processed with a Geographic Information System (GIS) software (ArcGIS 10.4).

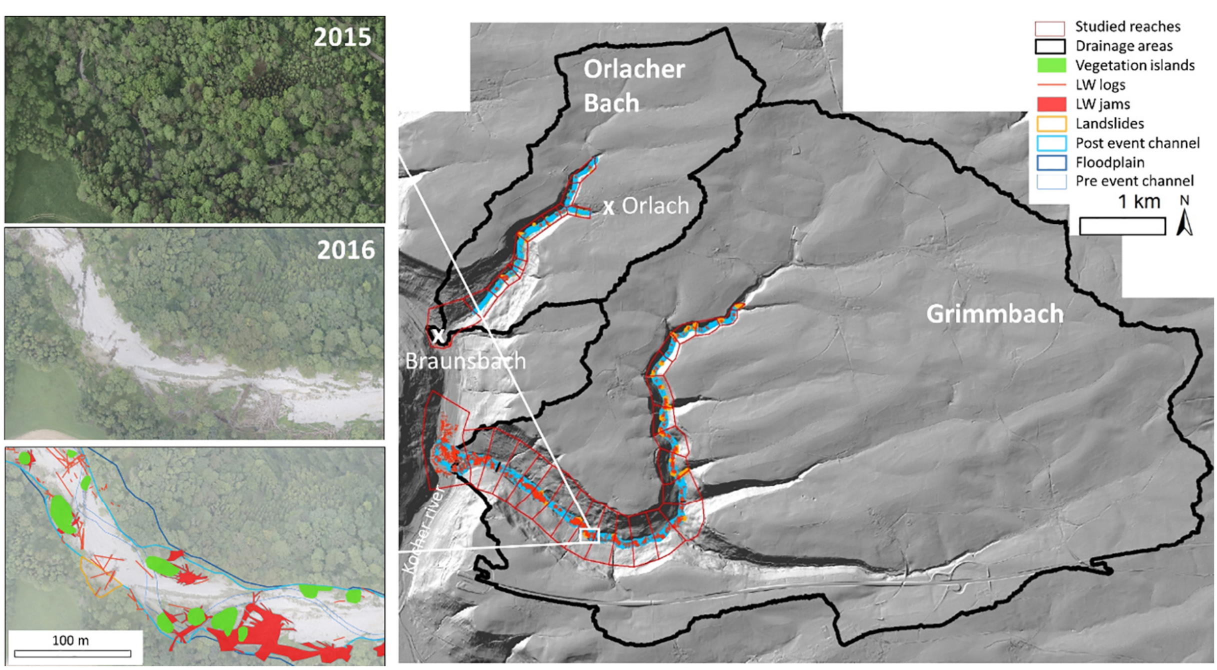

Fig. 2. Left: Orthophotos before (2015) and after (2016) the event, and a step of the LW budget analyses in a reach of the Grimmbach catchment, located within the white square in the DTM (right side). Right: The Orlacher Bach and Grimmbach drainage areas and studied subreaches represented by the hill-shaded DTM (1 m resolution), where the low gradient slope in the catchments and the steep slopes of the incised valleys are clearly distinguishable.

Table 1
Summary of characteristics and results in the two studied catchments.

		Grimmbach	Orlacher Bach
Catchment characteristics	Area (km^2)	30.02	5.98
	Range of elevation (m)	245–476	238–474
	Average catchment slope (%)	10.7	12.0
	Land use	Agricultural, forest and urban	
	No. of subreaches surveyed	25	14
	Length of channel analysed (km)	10.29	3.33
Morphology and LW	Widening (times previous width)[a]	6.9	3.1
		(3.04–13.7)	(1.5–5.2)
	Landslide area (m^2)	6390	8987
	Total LW deposited (m^3)	3448	124
		(2573–4323)	(99–149)
	Total LW recruited (m^3)	5011	1026
		(1714–6674)	(351–1367)
Control parameters	Channel slope (m/m)	0.015	0.055
		(0.013–0.038)	(0.041–0.151)
	Unit peak discharges (m^3 s^{-1} km^{-2})	22.6–25.1	20
	Unit stream power (kW/m^2)	24.3	15.9
		(10.0–37.2)	(7.49–33.3)
	Confinement index	10.1	2.8
		(4.4–26.3)	(1.1–7.7)

[a] In mountain-hilly reaches.

In a first step, the studied channels have been delimited according to the landscape units that are divided into mountain-hilly and inter-mountain plains. Following the methodology proposed by Rinaldi et al. (2013), homogeneous reaches within the river network have been defined according to significant changes in the drainage area due to tributaries. In addition, differences in morphological or LW responses as well as abrupt changes in slope that had been assessed during field work (walks along the total river network) were taken as indicators to subdivide a river reach accordingly. Reaches that were quite homogeneous over a distance longer than 500 m have been split up into two subreaches of equal length. This maximum length of 500 m was determined after an analysis of the variation of the slope for different lengths (Vocal Ferencevic and Ashmore, 2012). This procedure thus finally resulted in subreaches with a variable length of 200 to 500 m.

For every subreach, morphological characteristics such as pre-flood channel areas, alluvial plain areas, lateral confinement, and channel slope were determined. The pre-event channel was digitized based on the orthophotos. When the pre-event channel was not visible it was extrapolated as constant between the areas where it was visible. This value was double-checked by consulting the local population. The fluvial corridor or floodplain was visually identified and manually digitized. We used the DTM and the DTM-derived slope map to identify the limit where the gradient in the slope shows a break and to identify flatter areas near the channel not higher than a certain threshold above the lower point. This threshold can help to exclude old terraces and, even if it could vary from one catchment to other, we used as reference 4 m after the field surveys. It was manually digitized. Channel slope was estimated as the difference in elevation, based on DTM data, divided by the length of the channel centreline.

2.2.3. Morphological changes resulting from the flash flood

In order to analyse the channels of the two basins on changes after the flash flood event we combined remote sensing with field information. During the field surveys, we walked through the entire length of the channels for the Orlacher Bach and Grimmbach. Furthermore, we used remote sensing to compare the situation before and after the event. The situation after the event was surveyed within the frame of this study with an Unmanned Aerial Vehicle (UAV) (DJI Phantom 4) along the channels of Grimmbach and Orlacher Bach. The obtained aerial photos were processed with Structure from Motion (SfM) technology with the software Agisoft PhotoScan to obtain high-resolution topography and orthophotos (Smith et al., 2016). The flights with the UAV were done on July 5, 2016, along the lower part of the Grimmbach and the entire Orlacher Bach, and on August 18, 2016, along the upper part of the Grimmbach. The camera was calibrated with Agisoft lens. We used 27 targets for georeferencing the orthophotos. The coordinates of the targets were measured with a differential GPS (<10 cm accuracy). In case of the Grimmbach, we also used 25 fixed points in the terrain (marks on the roads) to georeference the orthophoto post-event with the orthophoto pre-event (LGL, 2015) in ArcGIS 10.4 obtaining a final root mean square error of 0.16 mm. For the Grimmbach and the Orlacher Bach, 662 photos and 261 photos were used, respectively, to obtain 247 million points and 132 million points, respectively, in the dense point cloud. The obtained orthophotos had a resolution of 5 and 6 cm, respectively. The situation before the event was given by the orthophotos of 2015 with a resolution of 20 cm (LGL, 2015). The comparison of the two sets of orthophotos was carried out in ArcGIS 10.4.

The mean channel width was calculated dividing the remotely sensed channel area by the channel length, measured along the centerline. In order to validate the measurements made by remote sensing, post-event channel widths also were measured at several (25) points in the field with a range finder. The measurements in the field were helpful in order to prevent possible errors due to the existing vegetation partly covering the channel, however the width measured from the orthophotos is considered more appropriate because it includes the variability of width along the reach, while the direct measurements in the field are punctual, and were not available for all the subreaches. The bias between both measurements was 1.16% of the width measured on the orthophotos.

With the information from the orthophotos taken before and after the flood event the widening ratio has been calculated as the ratio between the channel width after the event and width before the event.

In addition, the areas that were affected by landslides were digitized. The information gathered from the field survey was key to locate the landslides that occasionally were partially covered by vegetation and not clearly visible on the orthophotos. During the field surveys, the landslides locations were marked with a GPS point and their dimensions were measured with the rangefinder. It also helped to gather visual information directly from the point cloud to better estimate the total landslide area. The connectivity of the landslides with the channel in terms of sediment and LW was visually assessed in the field; this is done because in some cases the LW can be deposited on the slopes, and can eventually trap the sediment. This occurs especially when the shape of the landslide is elongated and its width is smaller than the tree height, which means that the trunks can interact with the trunks of the slope that did not slide.

2.2.4. Large wood dynamics

In order to analyse the LW dynamics during the event, we have estimated a LW budget (Benda and Sias, 2003) following an approach that was especially adopted to flood conditions (Comiti et al., 2016):

$$V_{o;ds} = V_{i;us} + Vi_{i;LS} + V_{i;LF} - V_{d;L} \quad (1)$$

$V_{o;ds}$ represents the downstream exported LW volume during the flood for a certain reach, $V_{i;us}$ the LW volume input from the upstream reach, $V_{i;LS}$ the LW volume recruited along the reach by lateral inputs from the slopes, mainly due to landslides, $V_{i;LF}$ the LW volume recruited along the reach by lateral inputs from the fluvial corridor, and $V_{d;L}$ the volume of wood deposited along the reach.

The methodology used to calculate the different components of the LW balance is based on Lucía et al. (2015). The areas from which LW was recruited were identified (i) on the slopes, removing the zones from the landslide areas that did not have forest cover on the orthophotos of 2015, (ii) in the fluvial corridor, removing the zones that did not have forest cover on the orthophotos of 2015 (including the channel pre-event, and also the zones in which the vegetation remained standing such as vegetation islands from the channel post event. With these areas and the volume of LW present in the forest, it is possible to estimate the LW that was recruited during the event from the different zones (slopes, $V_{i;LS}$, and fluvial corridor, $V_{i;LF}$). The forest standing wood volumes present in these areas before the event were estimated based on the land use maps available for the study area and on the information provided by the Third German National Forest Inventory (https://bwi.info). There are eight clusters of plots in the slopes and valleys of the rivers of the study area, the Orlacher Bach, the Grimmbach and the Kocher. They comprise the data of 16 sampling plots of a mixed forest composed by beech, English oak, ash, field maple, hornbeam, linden tree and wild cherry among the broad leaves and fir, spruce, and Scots pine representing the conifers. The averaged wood density in the sampled plots is 329 $m^3\ ha^{-1}$, the range of the percentiles 25 and 75 (112 and 438 $m^3\ ha^{-1}$) has been used to include the uncertainty in this estimation.

Among the LW volume that can be mobilized during a flood, the most uncertain component of the LW balance is the dead LW already present in the channel. In this study, this component has been neglected, since field observations during the survey revealed that most of the LW mobilized during the event was fresh.

Volumes of LW deposited were estimated from the orthophotos depending on the type of wood accumulation. Individual logs were digitized as lines, assuming that the projected length represents the actual log length given the high-resolution of the orthophotos. The average diameter also was measured from the orthophotos and the logs' volume was calculated assuming a cylindrical shape (Cordova et al., 2007). The minimum log diameter identified had 10 cm. The measurements of the diameter were not validated with field measurements, so the accuracy of the results would be given by the resolution of the orthophotos (5 and 6 cm resolution in the Grimmbach and Orlacher Bach). This accuracy would probably be in the same range as the one given by considering the tree logs as cylindrical shapes, so this uncertainty has not been taken into account for the uncertainty calculations, but it may affect the final results. In case of LW jams, the respective area of the jam was digitized and the height was estimated from field observations. The wood volume of each jam was calculated geometrically by its area and height, considering an 80–90% range in porosity (Thévenet et al., 1998; Andreoli et al., 2007). The porosity values were not validated with field measurements.

The volume of LW input from the slopes and the fluvial corridor and deposit are calculated for each subreach. For the most upstream subreach, if the volume of input is bigger than the deposit, the difference is the LW output of that reach, and at the same time it is the LW volume input from the upstream reach to the downstream reach. For the next reaches, this LW volume output and input from upstream is calculated taking into account all the components of the LW budget.

2.2.5. Control factors

Several morphological and hydraulic parameters were estimated at the reach scale in order to investigate their possible role in explaining the variability of morphological response and large wood dynamics. These parameters are the average channel slope (S), the drainage area (A) at the upper limit of the reach, the stream power (Ω), the unit stream power (ω), the stream power index (SPI) and the confinement index (CI). The DTM available for the catchments (1 m resolution) was used to obtain morphological parameters such as drainage area and channel slopes.

Stream power Ω ($W\ m^{-1}$) was calculated as $\Omega = \rho g Q S$, being ρ the fluid density ($kg\ m^{-3}$), g is the acceleration due to gravity ($m\ s^{-2}$), Q is the peak discharge ($m^3\ s^{-1}$) and S the channel slope. The unit stream power ω ($W\ m^{-2}$) was calculated as $\omega = \Omega/w$, being w the channel width. The stream power index (Marchi and Dalla Fontana, 2005) was calculated as the product of the channel slope and the square root of the drainage area ($SPI = S{\cdot}A^{0.5}$), so it only depends on the morphological characteristics of the catchment. The use of SPI is proposed because it provides a surrogate of stream power that can be applied also in catchments where, differently from this study, no data on peak discharge are available. For the calculation of stream power and unit stream power in the studied subreaches, we have conservatively used the estimated specific peak discharge of the downstream cross section for the Grimmbach in conjunction with the respective catchments of the subreaches. This is a conservative proceeding since the specific peak discharge is strongly dependent on the catchment area and may well be larger in smaller subcatchments which were also indicated by a second peak discharge estimate further upstream (see Results section). Hence, our stream power and unit stream power results may be understood as minimum estimates. For the Orlacher Bach catchment, we have used the specific peak discharge estimated upstream the Braunsbach town by Bronstert et al. (2018). In both catchments, a rainfall-runoff model was used to check the plausibility of the determined peak discharges.

Another morphological property that has been analysed is the confinement index (CI). The CI is the ratio between the width of the fluvial corridor and the channel width before the event ($CI = W_{fluvial\ corridor} / W_{channel\text{-}pre}$)(Rinaldi et al., 2013).

The statistical analysis of the results (Spearman correlation, Man-Whitney (Wilcoxon) test and multiple regression analysis among others) have been done using the software Statgraphics Centurion 18.

3. Results

3.1. Discharge

The peak discharge in the Grimmbach catchment was computed for two cross sections. The downstream cross section was near the outlet and drained an area of 29.6 km^2; the measured water surface slope was 1.9% and the estimated peak discharge was 668 $m^3\ s^{-1}$ equivalent to a specific peak discharge of 22.6 $m^3\ s^{-1}\ km^{-2}$. The upstream cross section drained an area of 13.8 km^2 and the water surface slope was 2.6%; the estimated peak discharge was 345 $m^3\ s^{-1}$ and the unit peak discharge 25.1 $m^3\ s^{-1}\ km^{-2}$. These values are well in line with the one estimated for the Orlacher Bach by Bronstert et al. (2018) which is 20 $m^3\ s^{-1}\ km^{-2}$.

3.2. Morphological changes resulting from the flash flood

We have analysed the morphological changes along 3.33 km of the Orlacher Bach and 10.29 km of the Grimmbach. Both rivers have been divided into 14 and 25 subreaches, respectively. The most downstream reaches in both catchments correspond to a different landscape unit, which is the area of the river mouth before the confluence with the Kocher (termed intermountain plane following the guidelines (Rinaldi et al., 2016)). The rest of the reaches belong to the landscape unit of mountain-hilly reaches.

All the reaches have widened, however, in the Orlacher Bach, the downstream intermountain plain reach corresponds with the alluvial fan where the center of the village of Braunsbach is located and morphological changes are not recorded in this reach. The intermountain plain reach of the Grimmbach widened by up to 39 times its previous width. In order to be more consistent, all analysis (correlation and regression) have been done with the intermountain-hilly reaches only, so the last reach of the Grimmbach has been excluded from the correlation analysis. In the mountain-hilly reaches of the Orlacher Bach, the average widening is 3.1 times the previous width (ranging from 1.5 to 5.2 times). The Grimmbach has widened on average by 6.9 times the previous width (ranging from 3.04 to 13.7) (Table 1). Without taking into account the intermountain plain reaches, widenings in both catchments have a normal distribution and the *t*-test showed that the two rivers responded significantly different (p-value < 0.001) (Fig. 3).

The landslide area in the Orlacher Bach and Grimmbach catchments is 0.9 ha and 0.64 ha, respectively. Since the Orlacher Bach is characterized by a smaller basin and shorter channel the ratio of the landslide area per channel length is 0.27 ha km^{-1} in the Orlacher Bach and 0.06 ha km^{-1} in the Grimmbach catchment. The landslide areas in both catchments have a normal distribution and the *t*-test showed that, again, both catchments behaved differently (p-value < 0.05) (Fig. 3).

Correlations of the widening ratio, landslide areas of those landslides where sediment and LW are connected to the channel, and LW budget components with the different control factors are displayed in Table 2.

The widening ratio correlates the strongest with the stream power (0.83). This is followed by the unit stream power calculated with the width of the channel before the event (0.75). For the confinement index, which is a parameter related to the valley morphology and independent of the hydraulics, almost the same correlation coefficient (0.74) was calculated. The correlation with the stream power index, another parameter that can be calculated without having information about the discharge, was not statistically significant.

The landslide data had very weak correlations with all the studied control parameters. The strongest significant correlation was positive with the slope (0.58) and negative with the confinement index (−0.41).

3.3. Large wood dynamics

In the analyzed channels we have mapped in total 139 logs in the Orlacher Bach (with an average length of 4.7 m (3.7 m standard deviation) and more than one order of magnitude more in the Grimmbach, 1950 logs, with an average length of 6.0 m (5 m standard deviation). The number of jams of LW detected in the channel of the Orlacher Bach was only 5, while on the Grimmbach 139 in total. This gives the first impression about the different amounts of wood mobilized in the two catchments. These differences are explored within this section.

With the information of the LW accumulation and the digitalization of the areas where wood had been recruited during the events and the LW density in the forested areas (see methods), the large wood budget has been calculated (Eq. (1)) and is shown in Fig. 4. In the Orlacher Bach, the total LW recruitment from the fluvial corridor is 731 m^3, ranging from 250 to 973 m^3 due to the uncertainty of the wood density of the forest, and 296 m^3 (101–394 m^3) from the slopes. The calculated average volume deposited along the channel is 124 m^3, but due to the uncertainty in the porosity of the LW jams, it could range between 99 and 149 m^3. When the flight with the UAV was done, the wood accumulated in the town had already been cleared out and it was not possible to calculate the total balance. However, due to the field survey carried out two days after the event, we could assume that the LW exported to the Kocher river is negligible and thus the total volume of LW

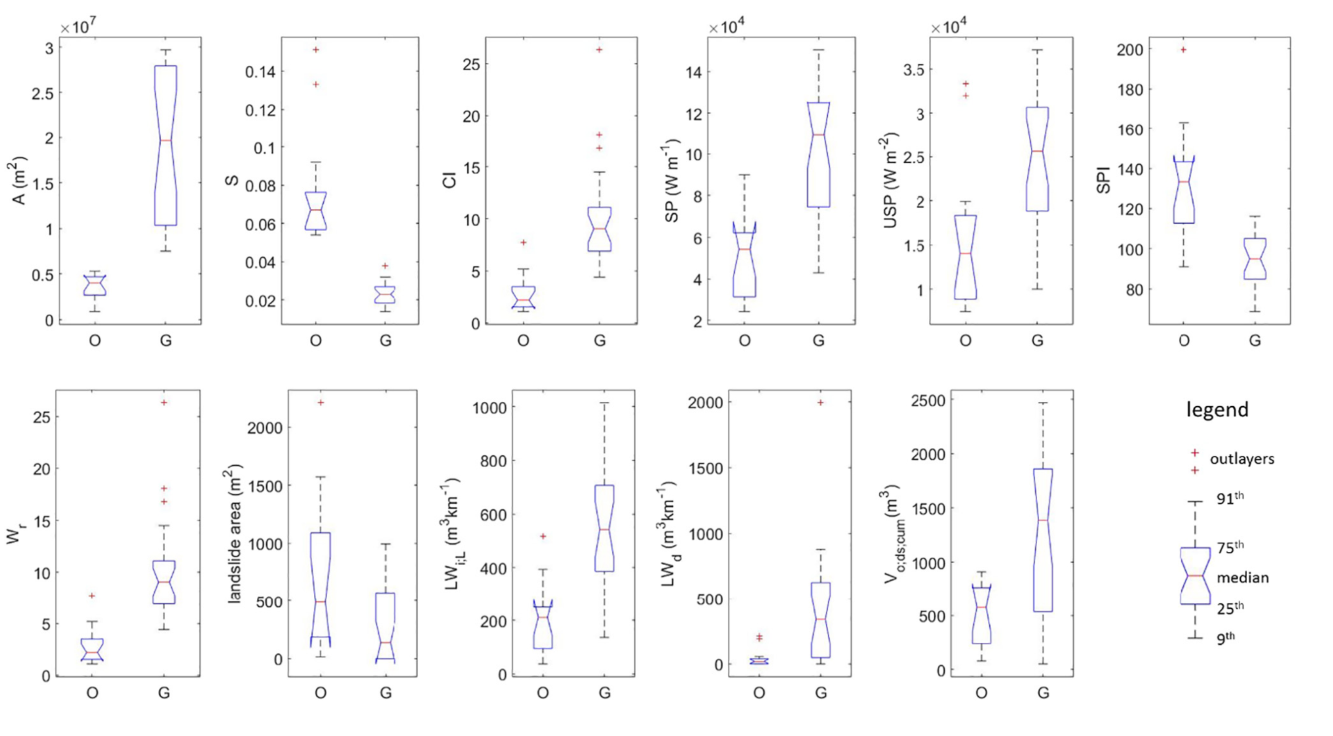

Fig. 3. Box and whiskers plots of the studied control factors (up) and the main morphological and LW-related variables (down) analysed in this study in the two different catchments: O: Orlacher Bach ($n = 13$); G: Grimmbach ($n = 24$). This analysis has been done in the intermountain-hilly reaches of both catchments. All the variables are significantly different for the two catchments according to the Mann-Whitney (Wilcoxon) text (at 5% significance level). This can also be indicated by notches of the median that do not overlap The folding back behaviour occurs when a notch, that indicates confidence interval estimated for the median of each group, extends beyond the edge of the box. A: Upstream drainage area; S: Slope; CI: Confinement index; SP: Stream Power; USP pre: Unit stream power calculated with the width before the flood; SPI: Stream Power Index; W_r: Widening ratio; $LW_{i;L}$ (m^3 km^{-1}): Total LW recruitment rate by lateral inputs (Volume of LW divided by length of the reach); LW_d (m^3 km^{-1}): LW deposition rate (volume of wood by length of reach). $V_{o;ds}$ (m^3): cumulative downstream exported LW volume.

Table 2
Spearman rank correlation analysis of the control factors and morphological changes and LW related parameters of the intermountain-reaches.

	Widening ratio	Landslide area	LW_d	$LW_{i;LF}$	$LW_{i;LS}$	$LW_{i;L}$	$V_{o;ds}$	$V_{o;ds;cum}$
S	**−0.62**	**0.58**	**−0.73**	**−0.75**	**0.63**	**−0.65**	−0.29	**−0.69**
A	**0.69**	**−0.47**	**0.78**	**0.82**	**−0.53**	**0.75**	**0.35**	**0.81**
SP	**0.83**	−0.17	**0.76**	**0.86**	−0.21	**0.86**	**0.41**	**0.63**
USP_{pre}	**0.75**	0.12	**0.40**	**0.58**	0.06	**0.60**	**0.56**	0.29
SPI	−0.30	**0.40**	−0.25	−0.28	**0.49**	−0.14	−0.17	−0.06
CI	**0.74**	**−0.41**	**0.69**	**0.80**	**−0.48**	**0.73**	**0.45**	**0.76**

In bold *p* values <0.05. Blue negative correlation and red positive correlation.
S: Slope.
A: Upstream drainage area.
SP: Stream Power.
USP pre: Unit stream power calculated with the width before the flood.
SPI: Stream Power Index.
CI: Confinement index.
LW_d ($m^3\ km^{-1}$): LW deposition rate (rate here refers to volume of wood normalized with length of reach).
$LW_{i;LF}$ ($m^3\ km^{-1}$): LW recruitment rate along the reach by lateral inputs from the fluvial corridor.
$LW_{i;LS}$ ($m^3\ km^{-1}$): VLW recruitment along the reach by lateral inputs from the slopes mainly due to landslides.
$LW_{i;L}$ ($m^3\ km^{-1}$): Total LW recruited along the reach by lateral inputs.
$V_{o;ds}$ (m^3): the downstream exported LW volume for a certain reach (without considering the input from upstream).
$V_{o;ds;cum}$ (m^3): the cumulative downstream exported LW volume.

accumulated in the town of Braunsbach during the event is estimated to be around 900 m^3 (202–1268 m^3).

The total LW recruitment from the fluvial corridor in the Grimmbach was 4801 m^3 (1642–6394 m^3) while 210 m^3 (72–280 m^3) were added from the slopes. Thereof, 3450 m^3 (2573–4323 m^3) were deposited along the channel. In this catchment, it was possible to deduce the total LW balance, and 69% (39–100%) of the recruited LW was deposited along the fluvial corridor, the rest was exported to the Kocher River.

The two basins were different in terms of total volume of LW mobilized and deposited. According to results from the Mann-Whitney (Wilcoxon) W-test, medians of all elements of the LW budget are significantly different in the two catchments, being always larger in the Grimmbach catchment (Fig. 3).

The LW deposition rate correlates negatively with the channel slope and positively with the drainage area and the stream power and the confinement index (Table 2). The correlation with the unit stream power and the stream power index is very weak.

LW recruitment rate from the fluvial corridor has a similar pattern in dependence on control factors, but with slightly stronger correlation coefficients. The LW recruitment from the slopes exhibits totally different and weaker correlations.

The volume of LW exported from each reach has weak correlations. The strongest correlation is positive with the unit stream power calculated with the width before the event. However, the cumulative volume of LW exported is strongly and significantly correlated with the drainage area, the unit stream power and the stream power; it correlates negatively with the longitudinal slope of the channel.

There are significant correlations between the different parameters of the LW dynamics and the channel slope and the upstream drainage area. This is due to the difference in LW dynamics and morphology of

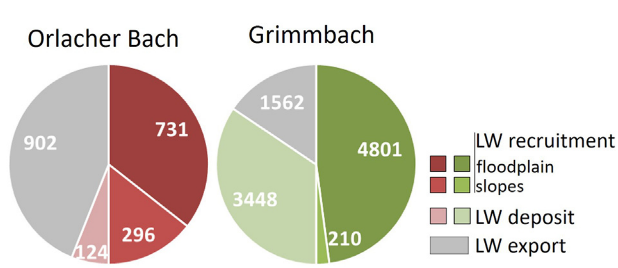

Fig. 4. Large wood budget expressed in m^3 in the two studied basins with the average values of jam porosity and LW volume in the forest.

the two basins. In Fig. 3, the data ranges of area and slope of the two catchments do not even overlap, all the subreaches have steeper slopes in the Orlacher Bach than the steepest reach of the Grimmbach, and all the subreaches have larger drainage areas in the Grimmbach catchment than the largest drainage area in the Orlacher Bach catchment. As a result, there are two groups of data with two different slopes when they are plotted together. For this reason these data have not been analysed for the regressions since the big scatter and the data distribution could lead to misleading conclusions even if the correlations were significant. Therefore, relationships with further factors such as those derived from the stream power and confinement index were analysed based on the data that overlap for the two basins (Fig. 3).

Once the different possible control factors are analysed, the difference on the volume of LW mobilized may be explained mainly by two aspects: (i) the stream power and unit stream power, which were higher in the Grimmbach since the discharge was higher due to the larger drainage area affected by similar precipitation and (ii) the valley morphology; since the Grimmbach valley is wider, there is more LW available to be mobilized, and at the same time deposited.

4. Discussion

4.1. Controlling factors of the morphological response and the large wood transport

The strength of the relation of the morphological changes and the LW response with different controlling factors is indicated by the determination coefficients deduced from the regression analysis presented below (Figs. 5 and 6). Although the stream power (Fig. 5a) seems to be the better predictor for the widening ratio in this case, it generally appears more reasonable to use the unit stream power (Fig. 5b). Otherwise, as the stream power is a factor that is proportional to the total discharge, widening ratios would directly correlate to the size of the river.

Interestingly, the confinement index can explain the widening ratio ($R^2 = 0.64$) similarly well as the unit stream power ($R^2 = 0.66$) (Fig. 5c). Other morphological factors such as the steam power index (SPI) had low correlation coefficients, and of contrary sign to the other control factors. The reason is that it uses the square root of the drainage area as a surrogate for discharge so it implies the assumption that the flood discharge does not increase proportionally with catchment area. This was not the case in the studied catchments, since both of them had similar unit peak discharges.

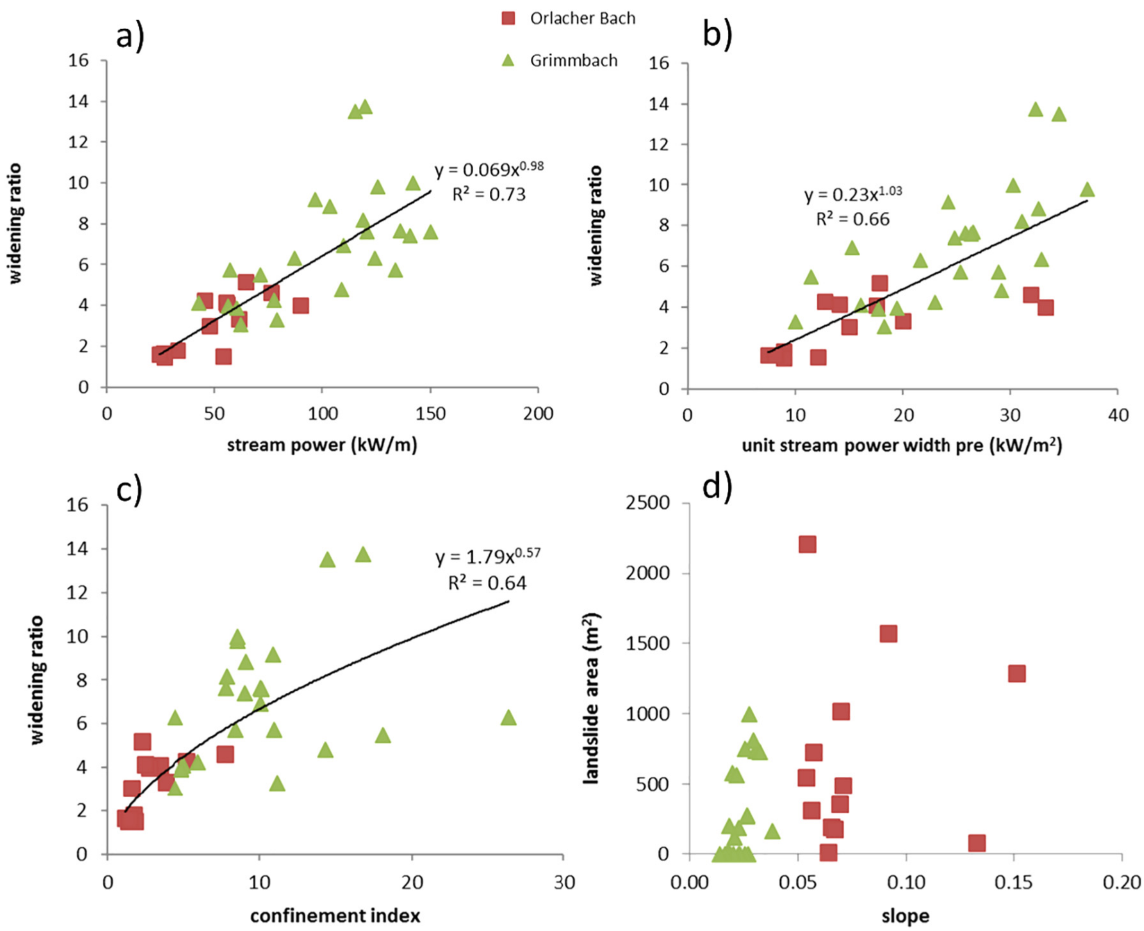

Fig. 5. Dependence of the different morphological changes, widening (a, b and c) and landslide area (d), in the two studied basins on different control factors (x-axis). The unit stream ("unit stream power width pre") power is calculated with the width of the channel before the flash flood.

The parameters that explain the flash flood induced change in channel width best are the stream power, the unit stream power and the confinement index with very similar correlation and determination coefficients. When these three parameters are combined in a multiple regression model, it only explains 37% of the data variability. If the stream power is removed, and only the unit stream power (USP) (W/m^2) and the confinement index (CI) are taken into account, the multiple regression model explains 67% (R^2) of the width ratio as follows:

$$\text{Width ratio} = -0.511 + 2.10*10^{-4}*\text{USP} + 0.208*\text{CI} \quad (2)$$

The landslide area does not have a strong correlation with any control factor. The relation between the landslide area and the slope, the control factor with which the correlation coefficient was stronger, is shown in Fig. 5d. The big scatter and lack of clear relation is obvious. Although most of the landslides seem to be triggered by channel incision or undercut, the characteristics related to the channel and stream power cannot explain the occurrence of landslides.

Regarding the different aspects of LW dynamics, the regression of the two control factors with stronger correlation (stream power and confinement index) does not show high coefficients of determination (R^2), mainly due to the high scatter of the data (Fig. 6). However, there is a high R^2 for the relation between the LW recruitment and the stream power (Fig. 6a) and the cumulative volume of LW exported downstream and the confinement index (Fig. 6f).

The total volume of LW accumulated in the town of Braunsbach is estimated to be around 900 m^3. It has been quantified that the total volume of material exported from the Orlacher Bach which finally accumulated in Braunsbach was 42.000 m^3 (Ozturk et al., 2018). Therefore, the LW fraction represents only 2% of the total debris deposit. Although this is a small proportion, given its size and floating characteristics, its role in clogging narrow sections and increasing flood hazard can be very significant (Fig. 10a).

4.2. Comparison with other catchments

It is interesting to note that a morphological control parameter (as the confinement index) can describe the widening ratio with a similar reliability as a hydrological parameter (as the unit stream power). This has also been observed in earlier studies and different regions (Surian et al., 2016; Righini et al., 2017).

In the study by Righini et al. (2017), the measured widening ratios and the confinement indexes are below 10. They are within the range of the Orlacher Bach catchment, although catchment area, range of elevation and slopes in their studied catchment were much larger than in the case of the Orlacher Bach. Overall, the widening ratios of this present study, including data for the Orlacher Bach and Grimmbach, is within the larger range obtained by (Surian et al., 2016) (Fig. 7), and also comparable to other alpine rivers (Krapesch et al., 2011). The relationships between the widening and the different control parameter in the Italian catchments investigated by Surian et al. (2016) indicate lower widening ratios than in Germany, but the data in Italy are more comprehensive and cover a wider range. Among all factors, the confinement index is the one for which the relation with the widening is the most similar (Fig. 7.b). The parameters related to the discharge, such as the stream power and the unit stream power were also in a similar range in the Surian et al. (2016) study as in the two basins of the Braunsbach study presented here. The average change of width, in contrary, studied in

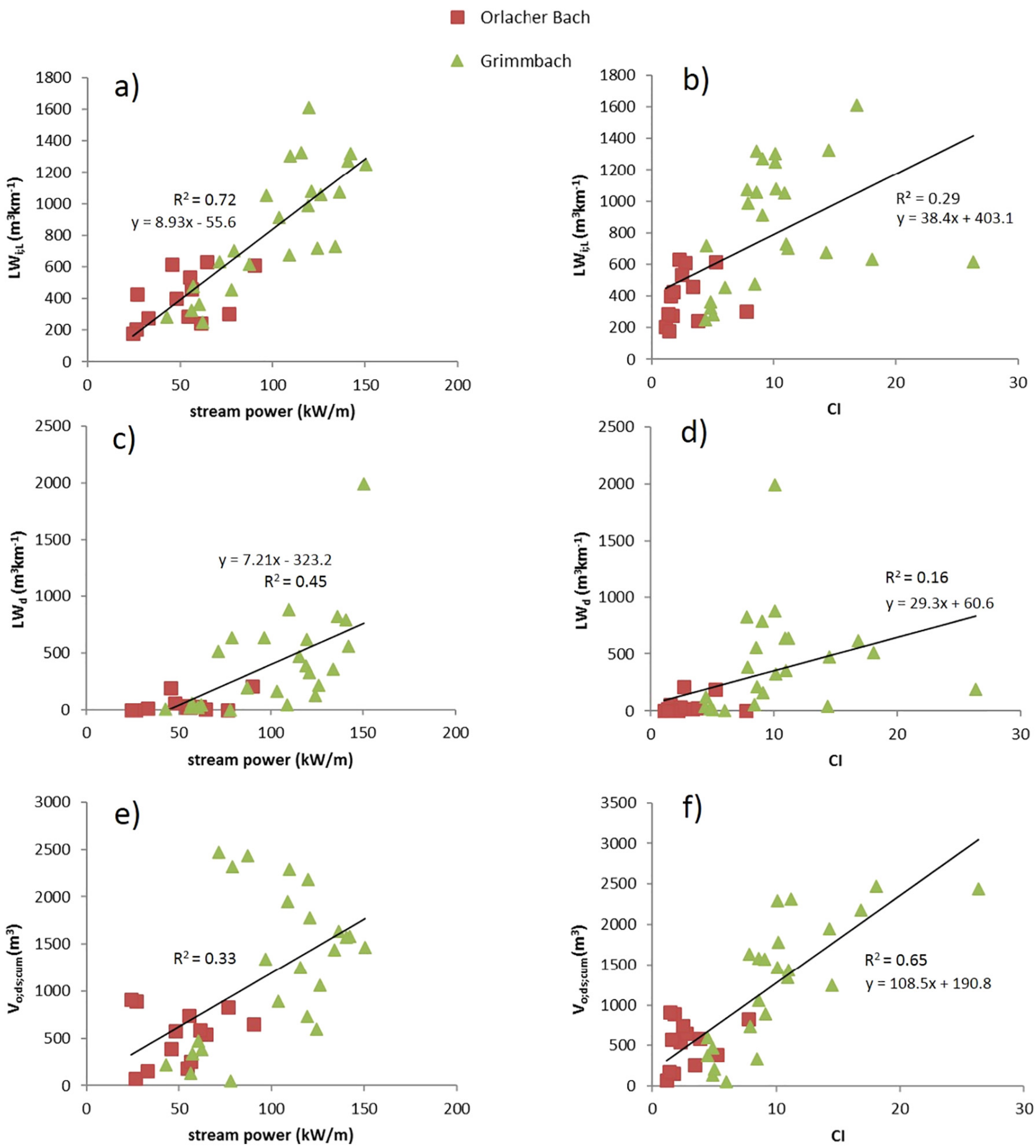

Fig. 6. Relationships between the LW dynamics in the intermountain-hilly reaches of the Orlacher Bach and Grimmbach catchments with the stream power (a, c, d) and confinement index (CI) (b, d, f). The variables of LW analysed are the total LW recruited along the reach by lateral inputs ($LW_{i;L}$) (a, b); the LW deposit rate (LW_d) (c, d) and the cumulative volume of LW exported downstream ($V_{o;ds;cum}$) (e, f). Despite having significant correlations, the big scatter is reflected by the low determination coefficients, except for the relation between the recruitment and the stream power and the cumulative volume exported downstream and the confinement index.

low gradient catchments of the Carpathians is smaller (widening ratios from 1 to 2), but also for smaller unit peak discharges and stream power (Bryndal et al., 2017).

There were more landslides observed in the Orlacher Bach than in the Grimmbach catchment. Despite the correlation with the channel slope, the determination coefficient is very low.

The surface of the landslides coupled with the channel in the Grimmbach and Orlacher Bach are 6390 and 8987 m^2, respectively (Table 1). These values are similar to two of the six catchments studied after the flash floods of Italy (Surian et al., 2016). These two basins are the Teglia and Geriola catchments with 38.8 and 8.5 km^2 of drainage area featured and 7300 and 5500 m^2 of landslides, respectively. However, landslides in the four other basins cover a much larger area ranging from 12,600 to 213,000 m^2. This could be related to the fact that, in general, the slopes are higher than in the studied basin.

The amount of LW mobilized in this event was quite high and comparable with the data from the flood in Italy 2011, where the LW balance was estimated in two of the catchments (Fig. 8) (Lucía et al., 2015). The length normalized LW recruitment and deposition amounts were similar in both studies. The proportions of LW recruitment from the slopes or the fluvial corridor are similar in the Orlacher Bach and in the two Italian basins, Gravegnola and Pogliaschina. However, the length-normalized volumes are lower in the Orlacher Bach catchment while in the Grimmbach they are more similar to the Italian systems, but the LW recruitment from the slopes is much smaller than in the three other catchments.

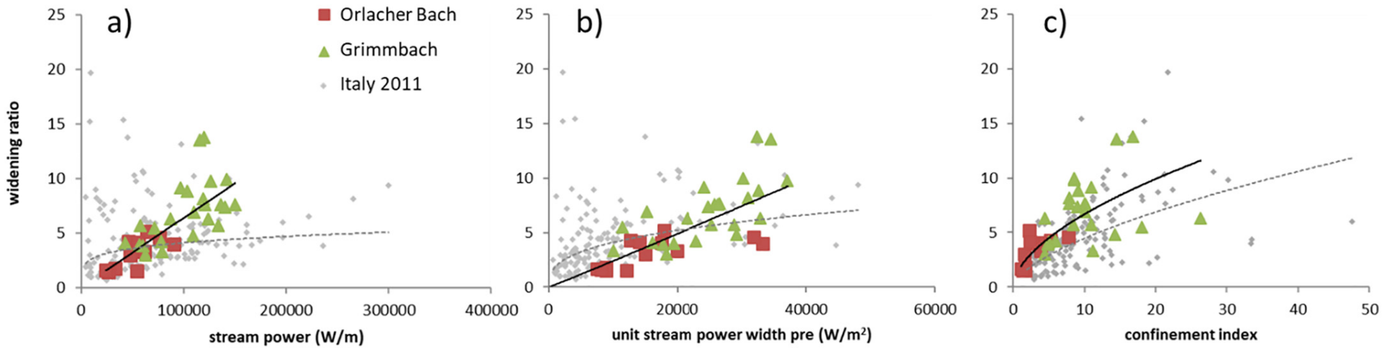

Fig. 7. Comparison of widening ratios of this study with the values obtained by Surian et al. (2016) in six mountain catchments of comparable areas and stream power, but with much higher difference in elevation in the catchment (600–1000 m) and therefore higher catchment slopes. The data are plotted against different control parameters. It can be seen that the widening ratio is in the same range in the low gradient German catchments as in the Italian basins.

Although available data on specific LW transport volumes, i.e. LW volumes normalized to the catchment area, usually comes from mountain basins (Comiti et al., 2016) the channels studied here also are characterized by very high specific LW transport volumes which are quite close to the envelope curve identified in the cited paper (Fig. 9).

LW volumes can also be normalized by the channel area, i.e. Iroumé et al. (2015). The average deposit rate with respect to the channel area before the event was 133 $m^3\ ha^{-1}$ in the Orlacher Bach and 740 $m^3\ ha^{-1}$ in the Grimmbach, while the average recruitment rates were 1167 $m^3\ ha^{-1}$ and 1779 $m^3\ ha^{-1}$, respectively.

4.3. Lessons learned? Implications for flood risk management

The severity of the morphological changes and the strong LW dynamics of these two low gradient catchments is remarkably similar to mountain channels. This should have implications for the flood risk management in this kind of basins, that could be enhanced by the combined experience in mountain channels with flash flood risk management. However, the particularities of low gradient slopes in the catchments could be considered to propose different prevention measures more related with basin and runoff management.

In Fig. 10, we show some examples of the measures that have been carried out in the Orlacher Bach basin after the flood to mitigate the flash flood risk in the future. In the village, the river remains in a culvert and the bridge upstream the village has been reconstructed (Fig. 10a and b). The diameter of the pipe of the bridge has been designed for a 100-year return period flow (without taking into account the sediment) which goes along with official agreements on the conditions for financial support. At the same time, half of the material that was deposited in the village has been reintroduced into the channel and onto those channel slopes where landslides occurred (Frank Harsch, Mayor of Braunsbach, pers. com.) This is visible in the comparative images right after the flood Fig. 10.c and e, and a few months later Fig. 10.d and f. Most of the material has been reintroduced in one of the steepest parts of the channel (Fig. 10.c and d) with a wedge of sediment deposit of about 4 m at the highest point. The Figures also show how the geometry of the slopes with landslides has been reconstructed with un-cohesive material.

Moreover, as part of the risk management strategies, two big filtering structures have been installed in the Orlacher Bach and in the Schloss Bach to prevent that large wood and coarse sediment will reach the village of Braunsbach in case flash food occur in the future (Fig. 10g). Furthermore, non-structural measures such as a scientific event from the Universities of Potsdam and Tübingen have been organized to increase the public awareness and knowledge about the flash floods.

At present, the European Floods Directive neglects the prediction of sediment and LW transport processes, despite their importance as aggravation of flood hazards. Therefore, the inundation risk mapping should be complemented with a geomorphological approach that includes these sediment (Surian et al., 2016; Righini et al., 2017) and large wood transport processes (Comiti et al., 2016; Mazzorana et al., 2017). However, the need to provide more data from post-event surveys also has been emphasized. Thus, the data presented here on the

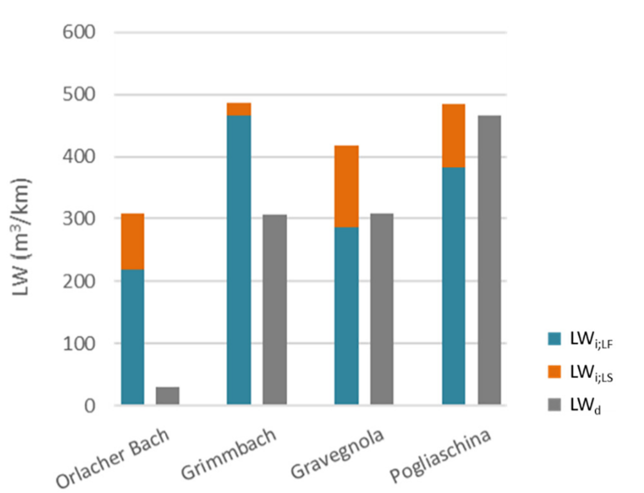

Fig. 8. Comparison of the length-normalized LW recruitment volumes from the fluvial corridor [$LW_{i;LF}$ ($m^3\ km^{-1}$)] and from the slopes [$LW_{i;LS}$ ($m^3\ km^{-1}$)] and the LW deposition volumes [LW_d ($m^3\ km^{-1}$)] in the studied catchments and in two Italian catchments where the LW balance has been estimated in an earlier study (Lucía et al., 2015).

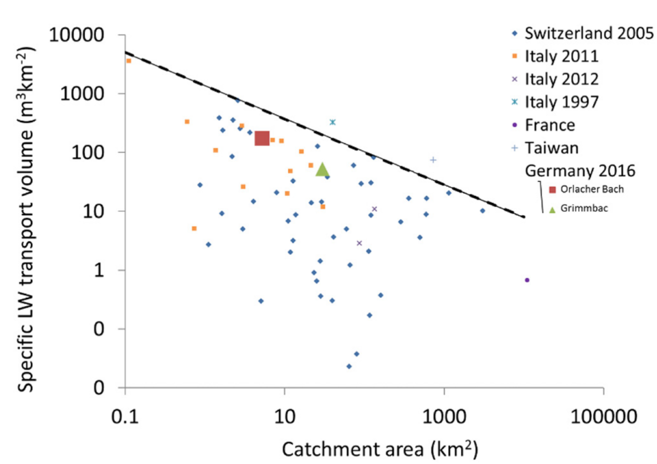

Fig. 9. Comparison of the specific LW transport volume in the basins of Orlacher Bach and Grimmbach with the data on specific LW transport compiled by Comiti et al. (2016). Both values of the studies presented here are close to the envelope curve despite the fact that most of the previous data come from mountain channels.

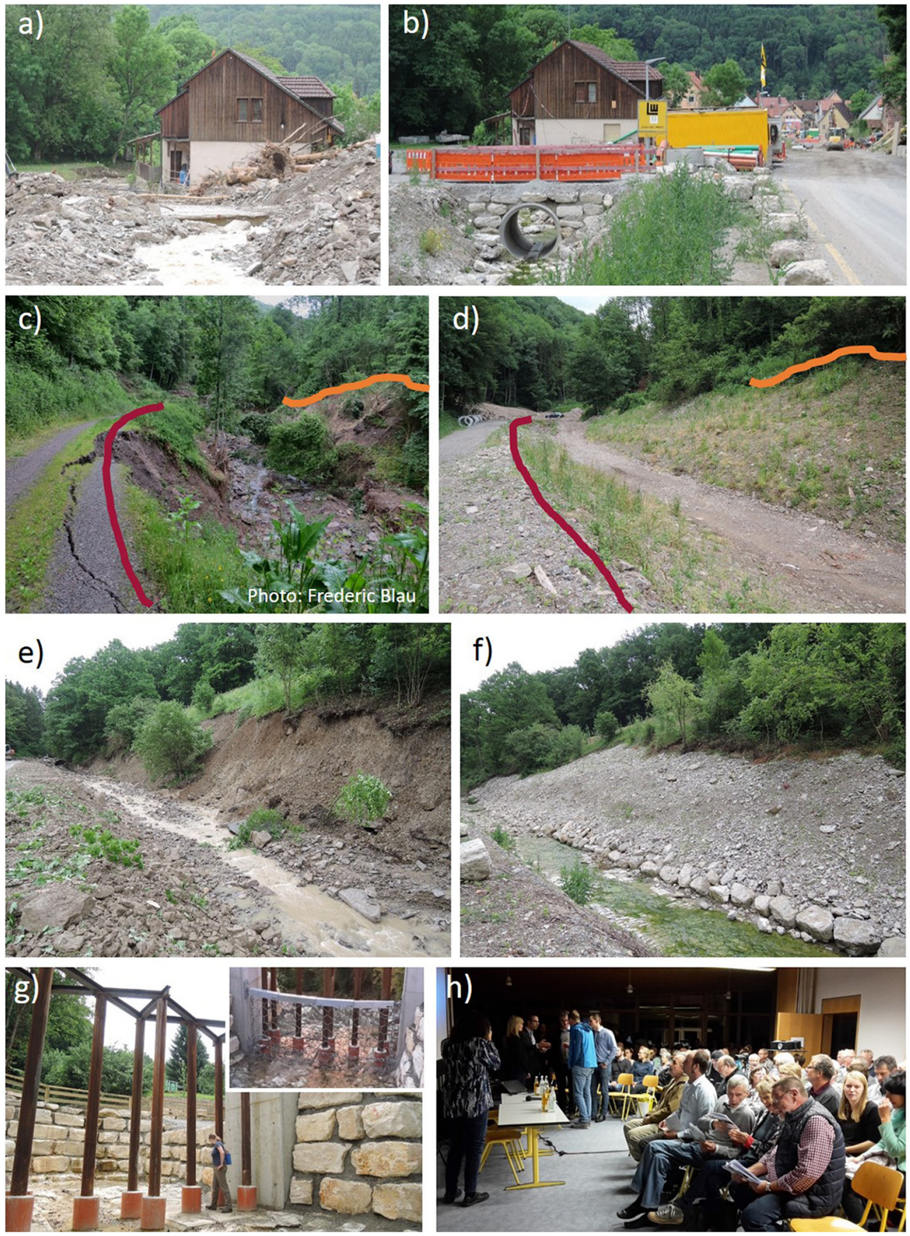

Fig. 10. a) c) and d) show the situation right after the event at different points, and the figures b), d) and f) the same locations almost a year after it. a) Even if it was already cleared out, the big deposit of sediment and LW, that clogged the old bridge, is visible. In the image b) the bridge has been rebuilt (June 27, 2017). Figures c) and d) depict a steep part of the channel, where the river incised which caused landslides after the flood. In this location, a part of the debris that was deposited in the village (̠4 m deposit in the channel) was reintroduced and the slope geometry was reconstructed. The lines on the photo mark the road and the landslides scar to support the identification of the differences right after the flood and one year later. e) and f) show the channel right upstream the village of Braunsbach. The topography of the slopes that had landslides has been reconstructed with cohesive material. g) one of the two filtering structures that have been installed in the Orlacher Bach and in the Schloss Bach. (h) a scientific event about the flash flood held on October 12, 2017, in Braunsbach, organized by the municipality and the Universities of Potsdam and Tübingen,.

two studied catchments can help in future investigations to better predict widening ratios as well as LW transport rates using the identified control factors. For this, all the available data in literature from different study cases that cover different ranges of changes and control factors should be included in the analysis.

5. Conclusions

From the obtained data in this study in two catchments with relatively low gradient slopes, we can conclude that the morphology of the catchment and channel can explain the channel response to extreme events similarly well as hydraulic parameters. The former may be used as proxies to estimate morphological changes during extreme events, as a complement to calculations made with estimated or measured water discharge. In addition, we have determined that large wood is an important component during flash floods in this kind of catchments with most of it coming from the fluvial corridor. Morphological changes and large wood rates of recruitment and deposit are in the range of studied mountain rivers. This underlines that both factors need to be considered for mapping and mitigating flash flood hazards, also in this kind of low mountain ranges.

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