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Rare flash floods and debris flows in southern Germany

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HIGHLIGHTS

- Rainstorms triggered rare flash floods and debris flows in a moderate-relief landscape, southern Germany.
- Intensive rainfall of up to 140 mm in 2 h mobilized 42,000 m^3 of sediment causing damage of €104 million.
- Geomorphic analysis reveals some of the highest landslide triggering thresholds and specific sediment yields worldwide.

GRAPHICAL ABSTRACT

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ABSTRACT

Flash floods and debris flows are iconic hazards in mountainous regions with steep relief, high rainfall intensities, rapid snowmelt events, and abundant sediments. The cuesta landscapes of southern Germany hardly come to mind when dealing with such hazards. A series of heavy rainstorms dumping up to 140 mm in 2 h caused destructive flash floods and debris flows in May 2016. The most severe damage occurred in the Braunsbach municipality, which was partly buried by 42,000 m^3 of boulders, gravel, mud, and anthropogenic debris from the small catchment of Orlacher Bach (~6 km^2). We analysed this event by combining rainfall patterns, geological conditions, and geomorphic impacts to estimate an average sediment yield of 14,000 t/km^2 that mostly (~95%) came from some 50 riparian landslides and channel-bed incision of ~2 m. This specific sediment yield ranks among the top 20% globally, while the intensity-duration curve of the rainstorm is similarly in the upper percentile range of storms that had triggered landslides. Compared to similar-sized catchments in the greater region hit by the rainstorms, we find that the Orlacher Bach is above the 95th percentile in terms of steepness, storm-rainfall intensity, and topographic curvatures. The flash flood transported a sediment volume equal to as much as 20–40% of the Pleistocene sediment volume stored in the Orlacher Bach fan, and may have had several predecessors in the Holocene. River control structures from 1903 and records of a debris flow in the 1920s in a nearby catchment indicate that the local inhabitants may have been aware of the debris-flow hazards earlier. Such recurring and destructive events elude flood-hazard appraisals in humid landscapes of gentle relief, and broaden mechanistic views of how landslides and debris flows contribute to shaping small and deeply cut tributaries in the southern Germany cuesta landscape.

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1. Introduction

Flash floods involve rapidly rising river-water levels, mostly after heavy and intense rainfall (Roux et al., 2011; Rozalis et al., 2010). Flash floods can be destructive in steep mountain streams and semiarid climates (Longoni et al., 2016a; Radice et al., 2016), where infiltration capacity is low because of crusted soils, sparse vegetation, and sealed surfaces (Sedlar, 2016). Fast moving overland flows and runoff concentrations exert high shear stresses on soil surfaces and in channels, allowing for little warning time (Bronstert et al., 2016). Research on flash floods was rare until the 1990s before automatic monitoring tools, such as remote data transmission networks, cost-efficient distributed sensor networks, or rainfall radar equipment became routinely available, eventually affording more systematic insights (Ficchì et al., 2016; Longoni et al., 2016b; Berne and Krajewski, 2013; Creutin et al., 2009; Creutin and Borga, 2003). Detailed monitoring campaigns now elucidate the coupling of hydrological and geomorphic processes during flash floods (Gorczyca et al., 2014; Archer et al., 2007), for example landslides that transform into debris flows (Borga et al., 2014). Still, many flash floods remain unreported, particularly in humid areas with moderate relief where they are hardly studied or even documented (Morss et al., 2016; Bradford et al., 2012).

We study the geomorphic legacy of flash floods triggered by convective rainstorms in the moderate-relief cuesta landscape of southwestern Germany in late May 2016. The rainfall in the study area around the municipality of Braunsbach (~2500 inhabitants) began on 29 May at around 4 pm (UTC). By 5 pm intensive rainfall poured down over the area, remaining high for some 70 min, triggering a flash flood and debris flow that damaged >75 households in town (Laudan et al., 2016). Braunsbach and nearby small villages suffered losses of €104 million as a result (Landkreis Schwäbisch Hall, 2016). The rainfall topped the average monthly totals of May and June of nearby stations in just 4 h. Both the 24-hour and 7-day storm rainfall totals exceeded the 200-year return period (Piper et al., 2016), whereas Bronstert et al. (2017b) estimated the 4-hour rainfall total to be a 1000-year event, producing a peak discharge of 125 ± 50 m^3/s in Braunsbach. We offer a first appraisal of the magnitude and frequency of the associated geomorphic impacts, and address the following research questions:

- What can we learn from the 2016 event in terms of flash-flood and debris-flow hazards in the greater region?
- What is the geomorphic relevance of flash floods and debris flow in steep tributaries of the cuesta landscape in southern Germany?
- How severe is the 2016 event compared with global data on landslide occurrence and catchment sediment yields?

We focus on the geomorphic impacts of the flash flood and debris flow that hit Braunsbach. Our main objectives are (i) to estimate the amount of sediment eroded and moved during the event and to identify the sources of sediment and modes of its delivery; (ii) to test whether various hydro-meteorological, topographic, geological, and geomorphic catchment characteristics were unique for the Orlacher Bach or whether neighbouring catchments in the region were similarly susceptible; and (iii) to place the geomorphic relevance of this event into a global context.

2. Study site

The municipality of Braunsbach is located in Baden-Württemberg, Germany (Fig. 1a). The town is situated in the Kocher River valley that cuts through the Hohenloher, Haller, and Kocher-Jagst plateaus made up mostly by Triassic limestones. Small and steep, gully-like tributaries (locally called “Klingen”) of the Kocher River emphasize the dissected nature of this cuesta landscape. The historic center of Braunsbach is built on a tributary-mouth fan formed by the Orlacher Bach that drains a catchment of ~6 km^2. The stream has a pronounced, and mostly dry, head cut at ~440 m above sea level (a.s.l.) and meets the Kocher after descending ~180 m over 3.1 km of horizontal distance. The plateaus in the headwaters of the upper catchment are mostly sustaining agricultural fields, whereas dense forest flanks much of the channel and steep side slopes of the Orlacher Bach (Fig. 1d).

The formation of the modern landscape around Braunsbach began in Cretaceous times, when southwest Germany experienced crustal uplift, followed by the formation of the Upper Rhine Graben in the Upper Eocene (Rotstein and Schaming, 2011). The resulting southeast tilt and dissection of the South German Basin pronounced the differences in mechanical rock resistance to erosion, and formed a cuesta landscape between 150 m and 580 m a.s.l. (Fig. 1b), exposing in distinct morphological steps successively older rock formations towards the shoulders of the Upper Rhine Graben. Braunsbach and the upper Orlacher Bach catchment are cut in Middle Triassic limestones known as Muschelkalk, which is rich in karst landforms such as dolines, caves, and springs. Water infiltration into the fissured limestones may have promoted the growth of the short and steep V-shaped Klingen of the Orlacher valley (Hagdorn and Simon, 1985). A simplified geological profile of the catchment from top to bottom goes from Lower Upper-Triassic (Lower Keuper) in the plateau headwaters to Lower Middle-Triassic (Lower Muschelkalk) rocks at the fan head (Fig. 1c). The region has a sub-humid climate with a mean annual temperature of 9.5 °C varying between 0 °C (January) and 18 °C (July). The mean annual precipitation (MAP) is ~650 mm; June is the wettest month (80 mm) with 15 rainy days, while March is the driest (40 mm) according to the nearest weather station at Kirchberg/Jagst–Herboldshausen (Agarwal et al., 2016).

3. Methods and data

3.1. Rainfall

We used weather radar estimates of rainfall to complement the spatially limited data of rain gauges (Borga et al., 2007). We analysed the 5-minute DX product of the Türkheim radar (48.58°N, 9.78°E) 68 km south of Braunsbach provided by the German Weather Service (DWD) for the interval from 27 to 30 May 2016 (Fig. 1a). The DX product consists of raw polar reflectivity data with a 1° beam width, and we used the open-source library *wradlib* to process the radar data (Heistermann et al., 2013). We crosschecked our estimates with hourly data from the DWD rain gauges (Kirchberg/Jagst–Herboldshausen; 49.18°N, 9.98°E; Kupferzell-Rechbach; 49.24°N, 9.68°E; Vellberg-Kleinaltdorf; 49.12°N, 9.89°E; Ingelfingen-Stachenhausen; 49.33°N, 9.70°E). Attenuation effects in the raw radar data returned some rainfall estimates below those recorded by the rain gauges (Bronstert et al., 2017a). Thus, we corrected the radar data using the modified Kraemer approach (Jacobi and Heistermann, 2016), and then derived the rainfall amounts from the corrected reflectivity using the standard Marshall-Palmer Z-R relation ($Z = 200R^{1.6}$), where Z is the radar reflectivity in *dBZ* and R is the rainfall amount in *mm*/*h*. The rainfall estimates from the radar were summed up for 48 h prior to the event (midnight to midnight of 27 to 29 May 2016) to determine the antecedent rainfall. We also summed up the radar estimates of the storm event (1 pm to 1 pm 29 to 30 May 2016) to estimate cumulative rainfall in the catchment right before the flash flood hit Braunsbach. We also calculated the maximum hourly rainfall intensity in each catchment for comparison.

We then computed from the 5-minute radar rainfall estimates the rainfall intensity and cumulated totals for different moving time intervals ranging from 5 min to 24 h. We also calculated a rainfall intensity-duration (ID) curve normalized by the MAP and rainy-day-normal (RDN), a ratio of the mean yearly precipitation by a mean number of rainy days (Wilson and Jayko, 1997). ID curves offer a simple means to document rainfall characteristics thought to be responsible for triggering erosive processes such as landslides (Caine, 1980; Aleotti,