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Fire-related debris flows in the Iberian Range, Spain

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ABSTRACT

Debris flows occurred three weeks after a wildfire in August 1986 in the Najerilla River valley in the Iberian Range, northern Spain. The flows were triggered by a brief, intense rainstorm (approximately 25 mm h^{-1} over 15 min) in a small area with steep slopes covered by a thick colluvium of quartzite clasts. This storm resulted in the development of several unconfined hillslope debris flows and the formation of an alluvial fan at the mouth of the Pítare stream, which partially blocked the Najerilla River. We analysed the conditions that led to the development of the debris flows, and estimated the rainfall threshold for the debris flows to occur as well as the total volume of mobilised sediment. Four factors contributed to the debris flows: (i) the occurrence of a rainstorm three weeks after a wildfire, which had removed the plant cover from the soil; (ii) the steep slopes in the area (>30°), which were the most affected by debris flows; (iii) the presence of quartzite scarps on the hillslopes, which favoured the development of a 'firehose effect' involving channelised surface runoff; and (iv) the low plasticity index values of the fine material of the colluvium (indices of 7 to 8), which enabled rapid liquefaction. Estimates of rainfall intensity derived from the estimated peak flow in the Pítare stream suggests that around 80 mm of rainfall fell in approximately 15 min, although this is clearly an overestimated value given the high proportion of sediment load transported during the peak flow. Various equations estimated a rainfall-threshold of approximately 25 mm h^{-1} considering a concentration time of 15 min. The total sediment transported by the debris flows was 10,500 m^3 (15,750 Mg, 6800 Mg km^{-2}), and the Pítare stream alone transported a minimum of 4000 m^3 (6000 Mg, 2500 Mg km^{-2}). These results suggest that the rainfall threshold for initiating debris flows decreases following a wildfire, such that an ordinary rainstorm is able to trigger a severe erosion and sediment transport event. Given the absence of fresh landslide scars on the hillslopes, the origin of the fire-related debris flows in the Najerilla River valley appears to have been directly linked to increased rates of overland flow having a greater effect than infiltration for triggering debris flows.

1. Introduction

Wildfires have been shown to be one of the most important factors controlling soil erosion and land degradation throughout the world (Cannon et al., 2001a,b; Moody and Martin, 2001; Wondzell and King, 2003; Shakesby and Doerr, 2006; Santi et al., 2008). The absence of plant cover in the months following a wildfire, and associated changes in soil characteristics, can lead to the occurrence of very high erosion rates until the vegetation recovers 6–24 months later (Cerdà, 1998; Prosser and Williams, 1998), with sheet wash and rilling being the dominant erosion processes. The vulnerability of wildfire-affected steeplands to debris flows has frequently been cited in recent decades as the most important mode of post-fire erosion, and such flows are capable of transporting tons of sediment in response to individual rainstorms (Swanson, 1981; Wells, 1987; Cannon et al., 1997, 2001a,b; Cannon and Reneau, 2000; Gabet, 2003; Beguería, 2006; Shakesby and Doerr, 2006; Gabet and Bookter, 2008; Gartner et al., 2008; Santi et al., 2008; Nyman et al., 2011). Debris flows have commonly been related to shallow landslides triggered on sparsely vegetated hillslopes during intense rainstorms, which increase pore water pressure and destabilise a portion of the slope (Blijenberg, 1998). Materials mobilised by shallow landslides become the main sediment source for debris flows (Johnson and Rodine, 1984; Blijenberg, 1998; Lorente et al., 2002, 2003; Beguería, 2006; Bathurst et al., 2007). However, recent reports have attributed the triggering of fire-related debris flows to increased rates of runoff that favour the erosion of the uppermost areas of hillslopes (Cannon et al., 2001a, 2011; Gabet and Bookter, 2008; Parise and Cannon, 2011). This fire-related erosion progressively increases the volume of sediment transported downslope, where concentration in zero- and first-order hollows leads to the development of debris flows. Nyman et al. (2011) noted that following a fire, most rills developed in

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previously unchannelised areas within the upper portion of the hillslope led to the formation of small and thin debris flows with levees, prior to the initiation of channel scouring. In many cases, increased runoff has been related to the development of a hydrophobic layer (Cerdà, 1998; Prosser and Williams, 1998; Wondzell and King, 2003), consumption of the soil-mantle litter and duff (Moody and Martin, 2001), and limited rainfall interception by vegetation.

Fire-related debris flows have been frequently reported in Spanish mountainous areas, particularly the Pyrenees (Lorente et al., 2002, 2003; Beguería 2006; García-Ruiz et al., 2010) and the Iberian Range (García-Ruiz et al., 1988). In most cases, the triggering of these debris flows has been attributed to periodical fires ignited by humans to convert shrublands into grasslands. For example, Lorente et al. (2002) reported that most debris flows in the mid-altitude belt of the Pyrenees occur in zones affected by recurrent fires, thereby resulting in degraded soils and open shrublands.

In the case of the Iberian Range, García-Ruiz et al. (1988) described a debris flow event triggered by an intense rainstorm that occurred soon after a wildfire in the Najerilla River valley. More than 20 years later, questions remain regarding the intense erosion caused by this single rainstorm: (i) which were the most significant factors that favoured the generation of debris flows?; (ii) how much material was mobilised in the debris flows?; and (iii) what were the main characteristics of the rainfall event? This paper uses direct and indirect information to describe and explain the geomorphic consequences of the Najerilla River valley wildfire of 1986 and the subsequent rainstorm event.

2. Study area

The Najerilla River, which is a tributary of the Ebro River, runs from south to north through two of the main geostructural units in northern Spain: the Ebro Depression and the Iberian Range (Fig. 1). The area affected by the fire and debris flow event in 1986 is located in the Sierra de la Demanda (Iberian Range). The Sierra de la Demanda is a Paleozoic massif uplifted by alpine tectonics (Lemartinel, 1985; Arnáez and García-Ruiz, 1990). Quartzite, shale, schist and sandstone with small limestone outcrops dominate the bedrock, which is intensely folded and faulted. The main drainage divide is approximately at 1900–2100 m a.s.l., with secondary divides at lower altitudes. These drainage divides are considered to represent old planation surfaces (Arnáez and García-Ruiz, 1990). The hillslopes are covered by a relatively thick mantle of scree, partially active above 1800 m a.s.l., and consisting of loose and angular clast-supported coarse debris with 20% of fine material). The hillslope gradients are very steep (>20°; Fig. 2), and gradients >40° are relatively common, particularly in the area most affected by debris flows. Scree deposits play an important role in the hydromorphological behaviour of the massif, favouring infiltration of water from snowmelt and rainstorms, and inhibiting overland flow on hillslopes (Arnáez, 1987). Erosion problems in the Sierra de la Demanda are primarily related to rills and gullies in the uppermost part of planar hillslopes, active headwaters of ravines, and deep-seated landslides, frequently associated with faults at the front of moraines.

The average annual precipitation is approximately 948 mm at the Valvanera weather station (4 km from the study area; 1020 m a.s.l.). Winter and spring are the wettest periods, whereas the summer is relatively dry (154.1 mm of precipitation from July to September). Peak 10-intensities (I10) of 95 and 120 mm h^{-1} correspond to return periods of 10 and 25 years, respectively. For I30, intensities of 52.5 and 67 mm h^{-1} have been estimated for return periods of 10 and 25 years, respectively (De Salas-Regalado and Carrero-Díez, 2008).

Prior to the 1986 fire, vegetation was dominated by common broom (*Cytisus scoparius*) and tree heather (*Erica arborea*), with isolated stands of evergreen oaks (*Quercus rotundifolia*), thus forming a small forest in the southwestern part of the study area (Fig. 3). The recovery of the plant cover following the fire was rapid, and 25 years later most of the hillslopes have 100% vegetation cover, with a composition similar to that prior to the fire. In the area most affected by debris flows, the abandoned bench-terraced crop fields are scarcely visible, although their presence indicates that the farmers previously considered these slopes to be stable.

3. Methods

Altitude and gradient maps for the area affected by debris flows were obtained using the Digital Elevation Model (with a 10 m resolution grid)

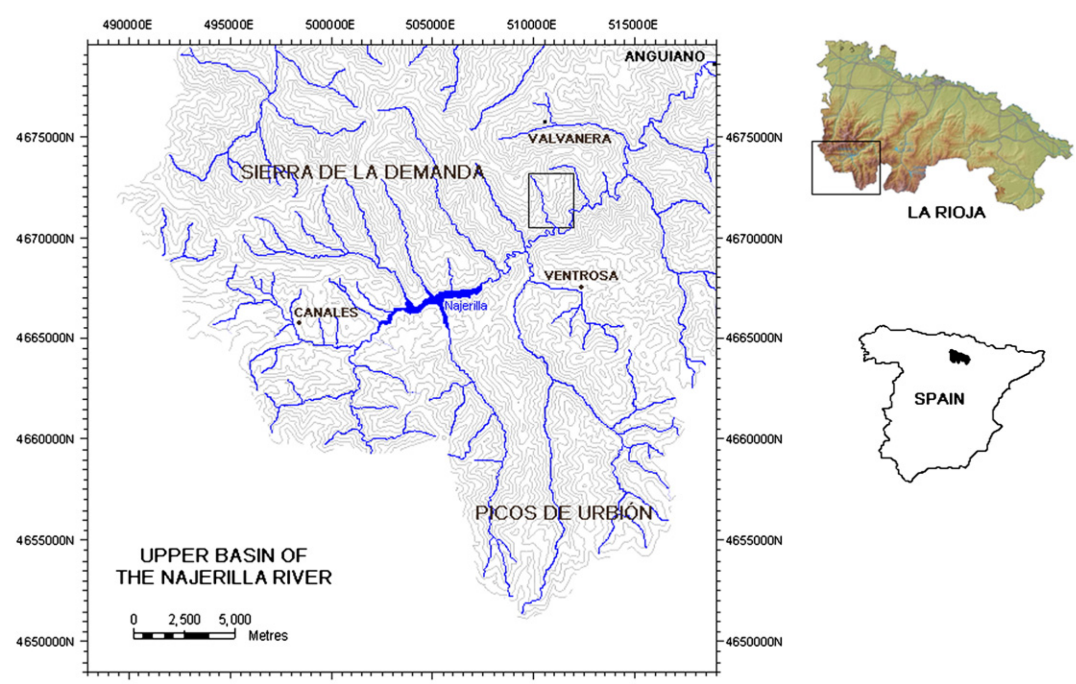

Fig. 1. Map of the study area within the Sierra de la Demanda. The box indicates the area affected by debris flows.