The Ribagorda sand gully (east-central Spain): Sediment yield and human-induced origin

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Abstract
Gullies are developed under different climatic conditions and lithologies; however, those formed on sands have been scarcely described. This paper reports the study of the Ribagorda sand gully, 2.57 ha in area (east-central Spain). The main objectives were to characterize and quantify its geomorphic dynamics and to trace its origin. We described the landforms of the gully and measured the surface strength of the sand. We monitored, for six years, the filling of the storage areas of three check dams built downstream from the gully, and related it with rainfall characteristics. We also described the nature of the sediments trapped by the dams and estimated the amount of sediment eroded since the gully formation. Finally, we consulted historical records and maps to determine past land uses and transformations that may have affected the origin of the gully.

The study shows a high diversity of landforms, denoting active processes, consistent with a measured mean annual sediment yield of 114 Mg ha⁻¹ yr⁻¹. A statistically significant relationship exists between the mass of sediment (Mg) and: 1) the total rainfall (mm) (P = 0.0007) or 2) the analysed rainfall intensities. Among five identified facies in the sedimentary wedge, the sandy ones are predominant. The total amount of sediment eroded by the Ribagorda gully since its origin was 962,800 Mg. The results are unequivocal signs of an intense geomorphic activity within the gully, with an alluvial-fan type deposition in the dams. We interpret that the Ribagorda gully was initiated by deforestation after the 13th century, when forests began to be intensively logged, and before the 18th century, when the gully was first indirectly described in print. The age, origin, evolution and dynamics of this gully indicate that this landscape is currently evolving towards a new steady state, after human disturbances over centuries. Given the gully evolution and local extent, we suggest that no correction measures are needed for its management.

1. Introduction

A gully is defined as a linear incision characterized by intense erosion and sufficient extent to be a permanent landform of the landscape (Tori and Borselli, 2003). Gullies have steep slopes and headwalls and transmit ephemeral flows. Two types of gullies have been distinguished, depending on physiographic position: hillslope or midslope gullies and valley-floor gullies, with both possibly found in the same locale (Campbell, 1997). Sometimes it is difficult to differentiate between gullies and rills, due to unclear definitions about their size. Besides, it may also be difficult to distinguish between gullies and badlands because some gullies or gully systems tend to evolve into badlands. According to Fairbridge (1968), badlands are densely dissected and severely degraded areas within which soil has been removed or most fertility has been lost. In these areas, erosion prevails due to a combination of climate and inappropriate land use that prevents soil formation and vegetation growth (Torri et al., 2000). One characteristic of badlands and gully systems is their high diversity of landforms and active geomorphic processes, with erosion rates in badlands higher than those in surrounding areas (Nadal-Romero et al., 2011).

Gullies and badlands are found around the world in a wide range of climatic regions (Valentin et al., 2005). It is generally accepted that intense rainfall and runoff events trigger most soil erosion and sediment yield (Lecco et al., 2006), and consequently gully and badland development. In addition, seasonally frozen soils have a strong effect on aggregate stability, soil structure and erodibility, which favour runoff and erosion (López-Vicente et al., 2008). For these reasons, gullies and badlands are especially common in the Mediterranean region, which has a great variation of temperature and moisture, as well as high-intensity rainstorms (Poesen et al., 2006; Nadal-Romero et al., 2011).

The development of these landforms is also conditioned by lithology and the lack of vegetation protection (Bryan and Yair, 1982; Kasanin-Grubin and Bryan, 2007). Gullies and badlands develop mainly in
unconsolidated materials or poorly consolidated bedrock (Gallart et al., 2002; Godfrey et al., 2008). Therefore, the most commonly gullied lithologies are marls, clay rocks and mudstones, and to a lesser extent, shales (Nadal-Romero et al., 2011). Additionally, few studies report these landforms on sands or poorly consolidated sandstones. The low number of publications about sand gullies compared to publications on gullies developed in other lithologies, mostly clayey to silty, suggests two possibilities: that sand gullies are scarce worldwide, or that they just have not been widely studied (Lucía et al., 2011).

Similar to the Ribagorda gully we analysed, there are sand gullies located in the Northern piedmont of the Guadarrama Mountains, central Spain (Lucía et al., 2011). Both are developed on the same geological formations (Utrillas Formation) and under similar physiographic and climatic conditions. Worldwide, there are examples of sandy gullies at other locations (e.g., Brown, 1983; Peugeot et al., 1997; Esteves and Lapetite, 2003; Karambiri et al., 2003). The gully system developed in the Providence Canyon State Park (PCSP), in southwest Georgia, USA (Donovan and Reinhardt, 1986), is also similar to the Ribagorda gully.

The main erosive agent in gully systems and badlands is water, both surface (slope and fluvial processes) and underground (chemical erosion such as salt solution and piping) (Harvey, 1982; Valentin et al., 2005; Poesen et al., 2006; Gómez Gutiérrez et al., 2011). Mass movements (falls, slides and flows) also occur in gullies and badlands, indicating that slope gradient plays an important role in their geomorphic processes. Other erosion processes, e.g., splash erosion, creep and weathering, also favour gully formation (Nadal-Romero et al., 2011).

The development of gullies and badlands and their sediment yield often produce environmental problems within their reach (on-site effects) and downstream (off-site effects). The most obvious on-site consequences are soil loss and the impossibility of farming or developing other land uses (Poessen et al., 2006; Gómez Gutiérrez et al., 2011). Gullies and badlands can also accelerate aridification and desertification processes (Valentin et al., 2005). The off-site effects are produced mainly by sediment discharge, which can also transport both nutrients and pollutants (Poessen et al., 2006; Lucía, 2013). This sediment discharge can damage infrastructures (roads, buildings, bridges, pipes, etc.), reduce the water capacity of reservoirs, and produce sedimentation in estuaries and harbours that can cause related ecological problems such as eutrophication (Poessen et al., 2006; Nadal-Romero et al., 2011). Understanding the initial causes of gully formation and development in a particular area and quantifying their activity are key for determining whether management is needed or not to address these environmental and socio-economic problems.

Geomorphologists have been interested in the origin and age of gullies. Gully erosion in Europe is not necessarily a recent process: indeed gully and badland development in many areas in Europe has been significant at least during the last 3000 years. Of course, the age of a specific landscape may vary by country and region (Poessen et al., 2006). In the southeast Iberian Peninsula, the determined ages of gully initiation are between 350 and 1940 A.D. (see Poessen et al., 2006 for more details). In the PCSP of southwest Georgia (USA), the gully system appears to be more recent than those studied in Europe. It was formed in the early 19th century, probably as a result of deforestation and agricultural development (Hyatt and Gilbert, 2000). In fact, land-use changes and climate have been identified as the main factors initiating soil erosion and, later, gully and badland development (Poessen et al., 2006; García-Ruiz, 2010; Dotterweich et al., 2013). In particular, sand gullies in an area of central Spain (Segovia Province) are interpreted to have originated by intense erosion processes triggered by ancient quarrying of limestone caprock (Moreno, 1989).

This paper reports the work carried out for the Ribagorda gully, a sand gully located within the Upper Tagus Natural Park (UTNP; Parque Natural del Alto Tajo, in Spanish) in the east-central area of Spain (Guadalajara province). The UTNP is a protected area with a presumed environmental problem caused by the sediment discharge from kaolin mines and from sand gullies, both located in the geologic Utrillas Formation. For this reason, a series of correction measures, including the building of gabion check dams downstream from some gullies, counting the Ribagorda gully, were carried out.

The main objectives of this study were to obtain relevant information about sand gully behaviour, an issue not widely reported worldwide, and to trace the origin of the Ribagorda gully. The specific objectives to address these aims were to: (i) characterize this sand gully by describing its landforms and measuring its surface strength, (ii) quantify its geomorphic activity at present, and relate it to rainfall by measuring sediment yield and rainfall during a six-year period, (iii) characterize sediment deposition downstream from the gully by describing the aggradational wedge formed behind a check dam, (iv) estimate the total amount of sediment eroded from the gully since its formation by comparing a reconstructed former (pre-gully) digital elevation model (DEM) and the current one, and (v) trace the origin of the gully by consulting historical documents. We postulated that: (i) the Ribagorda gully has landforms and surface characteristics typical of sand gullies, which conditioned its development; (ii) the gully has a very high geomorphic activity and sediment yield at present, both related to rainfall intensity; (iii) the sedimentary wedge deposited by check dams is similar to fluvial deposits; (iv) a high amount of sediment has been eroded since the initial formation of the gully; and (v) the formation of the Ribagorda gully can be related to ancient human land uses. This information is aimed to help management plans for this area.

2. Study area

2.1. Physical environment and setting

The Ribagorda gully (locally called Terrera de la Virgen or Terreras) is located in the Iberian Range, within the UTNP in east-central Spain (Fig. 1). This protected area was established in 2000 by a regional law (DOCM, 2000) because of its outstanding biodiversity, particularly aquatic ecosystems. The gully is in the Ribagorda stream watershed, in the municipality of Perales de las Truchas (Guadalajara province. 40° 33′ 54″ N; 1° 53′ 25″ W, coordinates of the outlet of the gully, Datum ETRS 1989; IGN, 2002a).

The UTNP landscape is characterized by plateaus and mesas capped by Cretaceous carbonate rocks (limestones and dolostones), on which...