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

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a b s t r a c t

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.

Keywords: Gully, Badlands, Human land transformation Sediment yield, Check dams, Upper Tagus Natural Park (Spain)

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 (Torri 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 geomor-phic 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 (Lecce et al., 2006), and consequently gully and badland develop-ment. In addition, seasonally frozen soils have a strong effect on aggre-gate 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

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unconsolidated materials or poorly consolidated bedrock (Gallartetal., 2002; Godfrey et al., 2008). Therefore, the most commonly gullied litho-logies are marls, clay rocks and mudstones, and to a lesser extent, shales (Nadal-Romero et al., 2011). Additionally, few studies report these land-forms on sands or poorly consolidated sandstones. The low number of publications about sand gullies compared to publications on gullies devel-oped 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 geo-logic 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 assalt 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 geomor-phic 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 develop-ing other land uses (Poesen 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 (Poesen et al., 2006; Lucía, 2013). This sediment discharge can damage infrastructures (roads, buildings, bridges, pipes, etc.), reduce the water capacity of reservoirs, and produce sedimenta-tion in estuaries and harbours that can cause related ecological prob-lems such as eutrophication (Poesen et al., 2006; Nadal-Romero et al., 2011). Understanding the initial causes of gully formation and develop-ment in a particular area and quantifying their activity are key for deter-mining 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 (Poesen et al., 2006). In the southeast Iberian Peninsula, the determined ages of gully initiation are between 350 and 1940 A.D. (see Poesen 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 (Poesen 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 infor-mation 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 damsis 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) i s 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 Peralejos 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

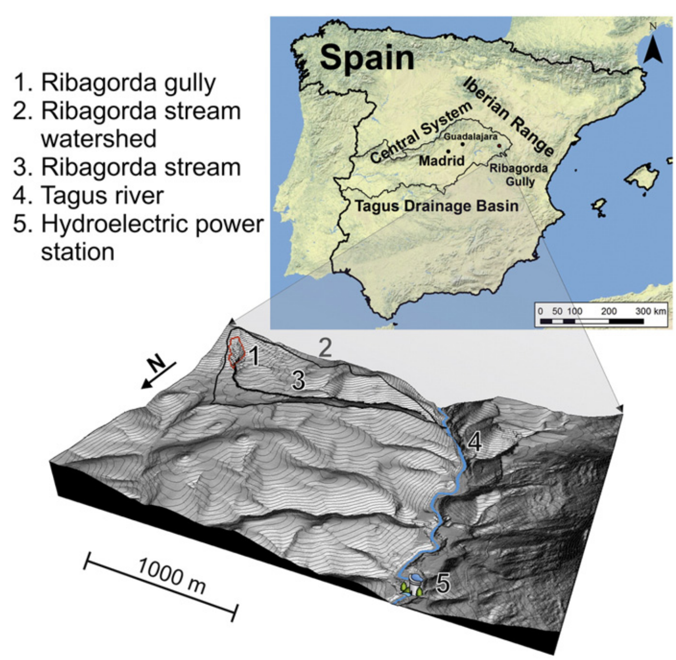


Fig. 1. Location of the Ribagorda gully.

the Tagus River has cut a canyon system longer than 100 km and up to 400 m deep (Carcavilla et al., 2008). Specifically, the Ribagorda stream watershed, where the gully is developed, is characterized by a mesa landscape with Cretaceous limestones and dolostones as caprock underlain by detritic sediments: poorly compacted sands and sandstones (Utrillas Formation) and conglomerates, sandstones, clays and limestones (the so-called Weald facies). Underlying these are Jurassic carbonates and marls. The slopes of the mesa are draped by carbonate colluvium (Olmo and Álvaro, 1989). In this mesa a wide variety of landforms can be identified, some of them reflecting a high slope erosive activity (gully, talus flatirons and debris slide; see Fig. 2). The Ribagorda gully is developed on the Cretaceous Utrillas Formation. This geologic formation, 100 m thick, has a sedimentary (fluvial) origin and consists of poorly compacted sand and sandstones with different colours (from white to red and purple, including a variety of greys and browns). These sands contain some clay laminae, thin layers of gravels and occasional pieces of lignite. Found as a matrix within the sands, kaolinite is exploited in several mines located 14 km northwest of the Ribagorda gully (Canerot et al., 1982; Olmo and Álvaro, 1989).

The most common soils are calcaric cambisols, mollic leptosols and rendzic leptosols, on top of the mesa, and carbonate colluvia with calcaric cambisols on the slopes (IUSS Working Group WRB, 2007). Maximum soil thickness on the mesa, up to 25 cm, is limited by the rock substrata. On the slopes, soil development is conditioned by the slope gradient; however soils formed on colluvia are well developed and more than 1-m thick.

The vegetation is representative of Mediterranean-continental environments. The most common vegetation consists of pastures and forests of Scots pine (Pinus sylvestris). Other trees found in the area are Portuguese oak (Quercus faginea), Spanish juniper (Juniperus thurifera) and holm oak (Quercus ilex sp. ballota). The predominant bush is the European boxwood (Buxus sempervirens) (MARM, 1997–2006).

The current climate of this area is temperate Mediterranean with dry and mild summers, Csb, according to Köppen (1918), with continental influence. This area has many freeze–thaw cycles because of its continentality and altitude (1100 m above sea level; asl). The number of annual freeze–thaw cycles ranges between 120 and 157 (for the period 1947–1974), 40% of them register temperatures between −5 ° C and −15 °C and usually last 12 h (Fernández and González, 1984). This area is in the very core of the coldest zone of the interior of the Iberian Peninsula (outside the Pyrenees), and frequently the lowest winter temperatures in Spain are reported by the Peralejos de las Truchas weather station. Mean annual precipitation is 783 mm and mean annual temperature is 10 °C (AEMET, 2013). The rainfall erosive factor, R (equi-valent to the R factor of RUSLE), is about 800 MJ mm ha^{-1} h^{-1} yr^{-1}. This value is not very high, as R ranges in Spain from 350 to 5400 MJ mm ha^{-1} h^{-1} yr^{-1} (ICONA, 1988). This factor evaluates the effect of raindrop impact on the soil surface as well as the magnitude of runoff, but neither does it consider the erosive forces of runoff from snow melting, nor the effect of rainfall impact on frozen soil, both common in this area (López-Vicente et al., 2008).

Seasonally, this area is characterized by long, cold winters with frequent snow and short dry summers with high-intensity rainstorms. The spring and fall are usually wet. Historically, the climate has changed. Evidence from the deposits of the nearby Taravilla Lake indicates that the climate was wetter in the 15th century, becoming even colder and wetter than the current climate during the Little Ice Age (LIA; 15th to 19th centuries) as shown by Valero Garcés et al. (2008). These colder temperatures and more intense freeze–thaw cycles affected soil properties and favoured soil disaggregation (González et al., 2013).

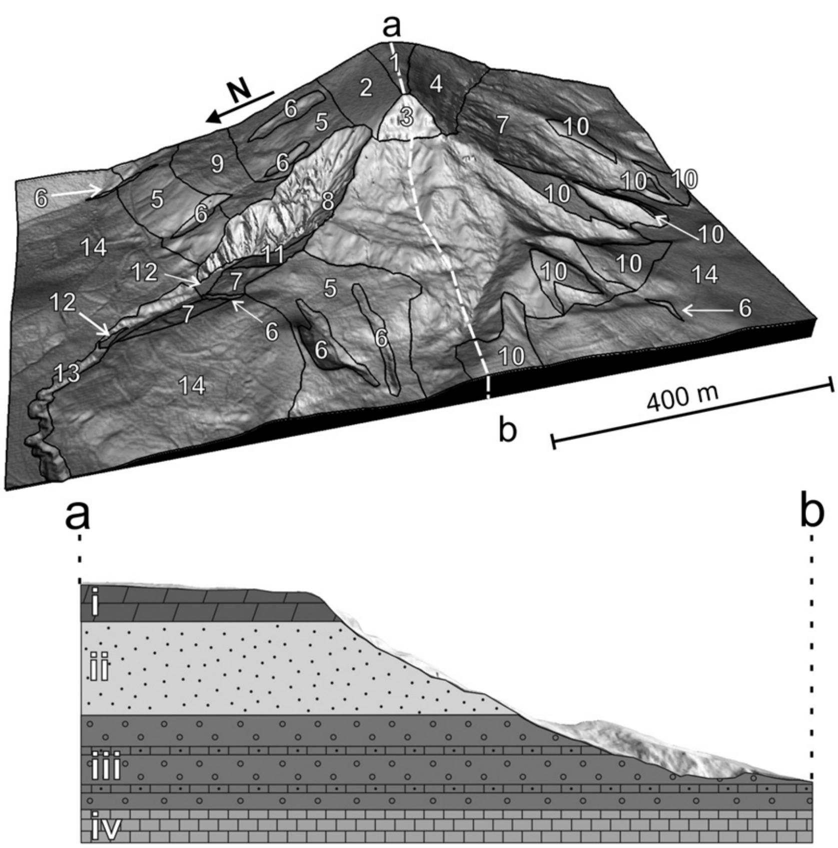


Fig. 2. 3-D view on a digital elevation model (DEM) showing the main landforms in the landscape of the Ribagorda mesa, where the Ribagorda gully has developed. 1) flat top of mesa, 2) caprock slope, 3) eroded caprock scarp, 4) caprock scarp, 5) colluvium slope, 6) incipient gullies, 7) ungullied eroded slope, 8) Ribagorda gully, 9) slope terrace, 10) talus flatirons, 11) debris slide, 12) check dam storage area, 13) gully channel, and 14) pediment. The figure also shows the underlying lithology of the mesa, on which the landforms are developed with a schematic profile at the bottom: i) dolostones and marls, ii) sands and sanstones (Utrillas Formation), iii) conglomerates, sandstones, clays and limestones (Weald facies), and iv) limestones.

According to the Water Framework Directive classification (2000/60/CE), rivers and streams of the study area correspond to ecotype 112, i.e. Mediterranean limestone mountain rivers (Toro et al., 2009). The Ribagorda stream, tributary of the Tagus River, is 2.1 km long with a mean slope gradient of 14%. Its watershed is 124 ha with a drainage density of 1.86 km km^{-2} in agreement with the light detection and ranging (LIDAR) data of Castilla–La Mancha (PNOA, 2009). Its maximum altitude is 1642 m asl and the minimum 1186 m asl.

The Ribagorda gully can be defined as a midslope gully (Campbell, 1997) based on its physiographic position in a steep mesa slope, 100 m from its toe to the top. However, its catchment has a well-defined tree-fern and dense rill-and-gully network, with sharp ridges (Fig. 3) fitting Fairbridge's (1968) definition of badlands. This gully, with an area of 2.57 ha, is the main source of sediments in a watershed of 124 ha. At the gully toe slope, there is no alluvial fan formed with materials eroded in the gully, because the main stem of the gully, the Ribagorda stream, is highly incised and efficiently transports sediments to the Tagus River.

2.2. Land uses and socio-economic framework

The UTNP has a small population, because of emigration from this region during the 1960s and 1970s. This depopulation was also accompanied by the abandonment of traditional activities and farming. The mean population density is 2.3 inhabitants km^{-2} as of 1 January 2011 (INE, 2012).

Historically, this region was characterized by grazing, subsistence farming (limited by poor soils), industrial activities associated with wood and resin, mining and iron forges. Timber fluvial transport, locally called Maderadas (Fig. 4), was also important until 1954, when a large dam was built downstream in the Tagus River. Timber from the Upper Tagus region was transported to Aranjuez (Madrid) and Toledo, with Peralejos de las Truchas as the first point of this ‘wood itinerary’ (Piqueras and Sanchis, 2001). Nowadays, tourism and mining are the more important economic activities in this region.

One of the main concerns of all the administrative bodies involved in the management of this area, i.e., the UTNP, the Hydrographical Confederation of Tagus River (Confederación Hidrográfica del Tajo, CHT, in Spanish) and the Regional Government, is the supposed environmen-tal problems caused by sediment discharge to the fluvial network, in-cluding sediment yield from the Ribagorda gully. Therefore, two Watershed Management Plans were launched in this catchment in the early 1990s and in 2008. Those plans consisted mainly in building a se-ries of check dams downstream from the Ribagorda gully. These check dams were intended to trap sediments from the gully, preventing them from reaching the Tagus River and creating “bank stabilization by reducing channel erosion” (Consejería de Medio Ambiente y Desarrollo

Fig. 4. Maderada (fluvial transport of timbers) in the Upper Tagus. Timber accumulated after a flood. This photograph is dated between 1920 and 1930 and belongs to the Eduardo Hernández-Pacheco historical collection, stored in the Geodynamic Department of the Complutense University of Madrid.

Rural de Castilla−La Mancha, 2006). Those actions probably also had the aim of increasing the life span of a hydroelectric power station locat-ed in the Tagus River, downstream from the Ribagorda watershed (see Fig. 1). This hydroelectric power station was built in 1943, taking advantage of an old mill building (Archivo Municipal de Peralejos de las Truchas, 1943). Its dam trapped the sediments transported by the Tagus River and has never been cleaned mechanically; the only maintenance was made during its first years of operation, when the sluice gates were opened during floods.

In the 1990s, three gabion check dams were constructed (all 3 to 4 m high). By 2008, these dams were filled by sediments. Therefore, the administration increased the height of check dams #1 and #2 by approximately 2 m. A new 4-m gabion check dam (#3) was also built (Fig. 3) (Consejería de Medio Ambiente y Desarrollo Rural de Castilla−La Mancha, 2006). We took advantage of the work in 2008 to initiate the measurement of the sediment yield of the Ribagorda gully.

3. Materials and methods

3.1. Landforms and substrata of the Ribagorda gully

In order to characterize the Ribagorda gully topography and landforms, selected morphological parameters were calculated from LIDAR

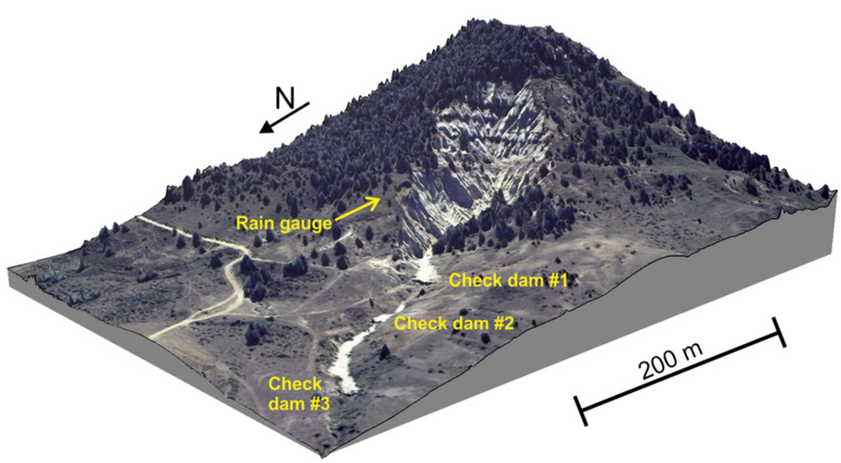


Fig. 3. Digital elevation model of the Ribagorda gully indicating check dams and rain gauge position.

raw data, analysed with ArcGIS 10.2 software (ESRI, 2013). We calculated slope gradients classified at intervals of 10° and measured slope orientation (aspect). In addition, a field geomorphic reconnaissance of landforms and active processes within the gully was conducted.

To characterize the Ribagorda's sandstones and to evaluate their erodibility, we randomly selected 12 sites within the gully and measured their surface strength. Specifically, we measured the surface mechanical resistance, using a geotester pocket penetrometer with the 1/4-inch tip, and the shear resistance, using a torvane with the medium-size vane. Five measurements were made at each site and the mean was calculated. Measurements were made after a two-month period without rain (dry conditions). At these 12 sites, samples were taken to classify texture. Particle size distribution was measured by the pipette method (Gee and Bauder, 1986), using the USDA textural classification.

3.2. Sediment yield and its relationship with rainfall

The sediment yield of the Ribagorda gully was quantified by measuring the amount of sediment trapped by the gabion check dams built downstream from the gully (see the locations of check dams in Fig. 3). We monitored sediment yield from January 2008, when the check dams were repaired (see Section 2.2), to January 2014. The monitoring was made following the order of filling of the check dam's storage area — a ‘cascade’ process. Initially, we monitored the filling of the storage area behind the first check dam (dam #1). Once this area was filled, i.e., when the sediment reached the check dam's spillway, we started monitoring the storage area of dam #2, located downstream from dam #1. We repeated the process for dam #3, further downstream. The monitoring consisted of periodically measuring the unburied height of a series of rods installed in the storage area behind each check dam, using a measuring tape. These rods are similar to erosion pins described by other authors (Haigh, 1979; Sancho et al., 1991). The periodic measurements provided information about the accretion of the surface into which they had been driven (Romero-Díaz et al., 2007).

The iron rods were homogeneously distributed, so that they would cover, equidistantly and evenly, the upper surface of sediment. The rods were 2-m long, with a diameter of 16 mm. They were numbered and driven perpendicularly 50 cm into the surface of the storage area, leaving 1.50 m of their length exposed. The exposed and buried heights were recorded. The storage area size of each check dam varied, resulting in a different number of rods in each of them: #1, 34; #2, 25; and #3, 20 (Fig. 5). In addition, we conducted a detailed topographical survey of each storage area and its surroundings, including the precise rod positions. These surveys used a differential global positioning system, the Leica GPS model number 1200.

Using the topographical survey and the rods' successively buried heights, we calculated the sediment volume trapped by the check dams. For that, we first built a DEM of each empty storage area. Then, using the buried height of the rods within each storage area, we obtained successive DEMs that reflected the filling process of the storage areas by sediment. To build the DEMs, we used the kriging interpolation method from point data and adjusted the data to the semi-variogram calculated for these same points. Finally, by comparing those DEMs, we obtained a quantification of the successive volumes of storage-area fill. These comparisons and DEMs were made with Surfer 11 software (Golden Software, 2013).

To calculate the sediment yield, which was our objective, we first computed the incremental sediment amount (Mg) confined behind each check dam between two measurements of the exposed height of the rods. To calculate the amount of sediment, we multiplied the volume (m^3) occupied by the sediment in the storage area by the sediment's bulk density (g cm^{-3}). The mean bulk density was calculat-ed by the core method (Blake, 1965), using a total of 16 samples taken at different depths of the storage area behind dam #1. The bulk density of sediments in the storage area of dams #2 and #3 was assumed to be similar to that in dam #1. Then, we added the amount of sediment trapped by the three check dams during each year of study. The sediment yield was expressed as Mg ha^{-1} yr^{-1}. To calculate the annual sediment yield, we divided the amount of sediment calculated for each study year by the area draining to each check dam. This area included the Ribagorda gully (2.57 ha) and the slopes around, yielding a contributing area of 5.42 ha for dam #1, 7.45 ha for #2, and 9.23 ha for #3.

To measure rainfall quantity and intensity, we installed a tipping-bucket 0.2 mm/pulse automatic rain gauge (Davis Instruments, 2005) with a HOBO Event data logger in January, 2008 within the Ribagorda watershed near the Ribagorda gully (see Fig. 3). From these data, we calculated the total rainfall volume (mm), the maximum rainfall volume in 24 h (mm), the maximum rainfall volume in 30 min (mm h^{-1}), the maximum rainfall volume in 5 min (mm h^{-1}) and the number of rainfall days per year.

To test possible relationships between the mass of sediment trapped by the check dams and rainfall characteristics, we calculated Spearman's rank correlation coefficient. We defined the mass of sediment as the sum of the sediment trapped by the three check dams between two measurement dates. The variables we compared were: 1) mass of sediment (Mg) vs total rainfall (mm), 2) mass of sediment (Mg) vs maximum rainfall in 24 h (mm), 3) mass of sediment (Mg) vs maxi-mum rainfall in 30 min (mm h^{-1}), and 4) mass of sediment (Mg) vs maximum rainfall in 5 min (mm h^{-1}). Statistical analyses were made using Statgraphics Centurion XVI.I software, version 16.1.17 (StatPoint Technologies, 2012). The significance level used was $\alpha \leq 0.05$.

3.3. Nature of the sediment trapped by check dams

To characterize sediment deposition in the storage areas of the check dams, we described the facies of the sedimentary wedge originated upstream of dam #1. For that, we dug three backhoe trenches: the first one (trench #1) was 75 m upstream of the dam, the second one (trench #2) 44 m upstream, and the last one (trench #3) 10 m upstream. The trenches were 2-m deep, reaching the 2008 surface of

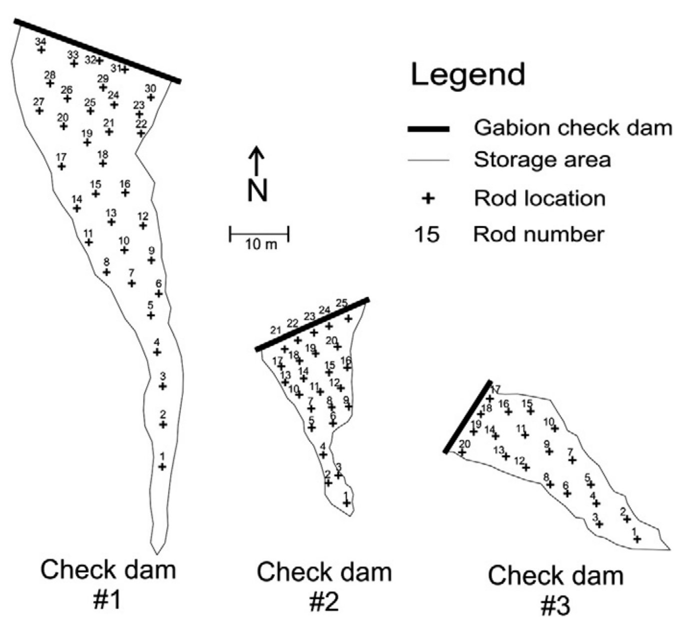


Fig. 5. Plan views of the storage areas and check dams built downstream from the Ribagorda gully, showing the position and number of the series of rods installed to quantify sediment yield. Rod positions and storage area boundaries were surveyed using a differential global positioning system (GPS), Leica model 1200.

the dam's storage area. We assumed that the characteristics of the sediment accumulated in the storage area of dams #2 and #3 were similar to that in dam #1.

Different layers of sediment were recognized and described in terms of lithology (texture and composition), sedimentary structures and geometry. The facies identified were classified using the Miall code system (Miall, 1978). We also took samples at different depths to calculate grain-size distribution and bulk density.

3.4. Cumulative amount of sediment eroded from the Ribagorda gully

We quantified the total volume of sediment eroded from the Ribagorda gully since its inception based on the assumption that, before the gully existed, the slope where it was later formed had the same morphology and morphometry as the equivalent positions of the current mesa's slopes in the surrounding area.

To calculate this eroded volume, we first built a triangular irregular network (TIN) representing the detailed topography of the gully, and a portion of the surrounding ungullied slope. To build this TIN, we used the available high resolution LIDAR data, with a minimum point density of 0.5 points m^{-2} (PNOA, 2009), and ArcGIS 10.2 software (ESRI, 2013). From this TIN, 1-m contours were generated and the area occupied by the gully was delineated. The contours within the gully were deleted. Then, the contours of the presumed original ungullied slope for the same area were interpreted as radius of curva-ture and contour spacing by topographical correlation and replication of equivalent ungullied morphologies occupying the same geomorphic position. After that, we built a TIN representing the presumed slope without the gully. Finally, the two TINs, the one of the slope without the gully (reconstructed) and the one with the gully (current situation), were compared geometrically, using the surface difference tool of the ArcGIS 10.2 software. The difference in volume between the two TINs (Fig. 6) was obtained, representing the total volume of eroded material since the inception of the gully.

To convert this eroded volume to the total sediment yielded, we took into account that the volume is higher when the material is eroded and re-deposited than when it is in situ. This ratio is defined by the swell factor for sandstones of the Utrillas Formation. We also considered the bulk density of the eroded sediment in converting the volume (m^3) into the mass of sediment (Mg). We used the bulk density calculated from the sediment (material deposited) trapped by check dam #1. Therefore, total eroded volume times the swell factor and bulk density of the sediment represents the total sediment yielded by this gully over its existence.

3.5. Land use and transformation by humans

We analysed numerous historic records and maps to determine past and current land uses and transformation of the Ribagorda gully's surroundings. We searched also for the first time that the Ribagorda gully was identified in a document or a map. For that, we used documents from a variety of national, regional and municipal archives includ-ing the Cartographic and Geographic Studies Archive of the Geographic Centre of the Spanish Army (Archivo Cartográfico y de Estudios Geográficos del Centro Geográfico del Ejército, in Spanish), the Municipal Archives of Peralejos de las Truchas and Molina de Aragón, the Archive of Señorío del Común y Tierra de Molina (to which the municipality of Peralejos de las Truchas belongs) and the Archive of the Diputación Provincial de Guadalajara. In addition, we examined writings of early naturalists, engineers and travellers (Briz and Simó, 1755; Bowles, 1789; Castel, 1882), who visited this area in the 18th and 19th centuries. For signifi-cant historic and geographic information about this region, we examined two famous Spanish dictionaries: Miñano (1826−1829) and Madoz (1845−1850). Catastro del Marqués de Ensenada (1752) (Cadastre of Marquis de Ensenada) compiled information about the physical environ-ment as well as the economic activities of Peralejos de las Truchas. We used the Mine Statistics of Spain (IGME, 1861–present) (Estadística Minera de España, in Spanish) for data about metallurgic and mine activities in this area.

We consulted maps from the 18th century to the present, including the maps of Briz and Simó (1755); the map of Cuenca, which is part of the General Map of Spain (López, 1780); the Map of El Señorío de Molina (López, 1785); the map of Guadalajara Province (Coello, 1865); and maps published by the National Geographic Institute (Instituto Geográfico National, IGN, in Spanish) from 1936 to the present. Finally, we examined available aerial photographs from 1946, the earliest one available for this region, to the present.

4. Results

Current landforms and sediment yield indicate very active erosion processes at the Ribagorda gully. These processes are related to the characteristics of both sandstone and rainfall. The historic records and maps consulted do not report concise information about the age of the Ribagorda gully, but every datum points to its human-induced origin, with deforestation as the main factor for the gully development.

4.1. Landforms and substrata of the Ribagorda gully

The most common landforms within the Ribagorda gully are the knife-edged ridges or divides, rill and gully networks, and sand and debris cones. We also found small pedestals, talus flatirons, pinnacles or hoodoos, and exposed roots (Figs. 7 and 8). The Ribagorda gully is also characterized by steep slopes; 81% of them have a slope greater than 20°. The mean gradient is 35°, with a standard deviation of 16°. The dominant orientations (slope aspect) are northeast (26%), west (23%) and north (19%).

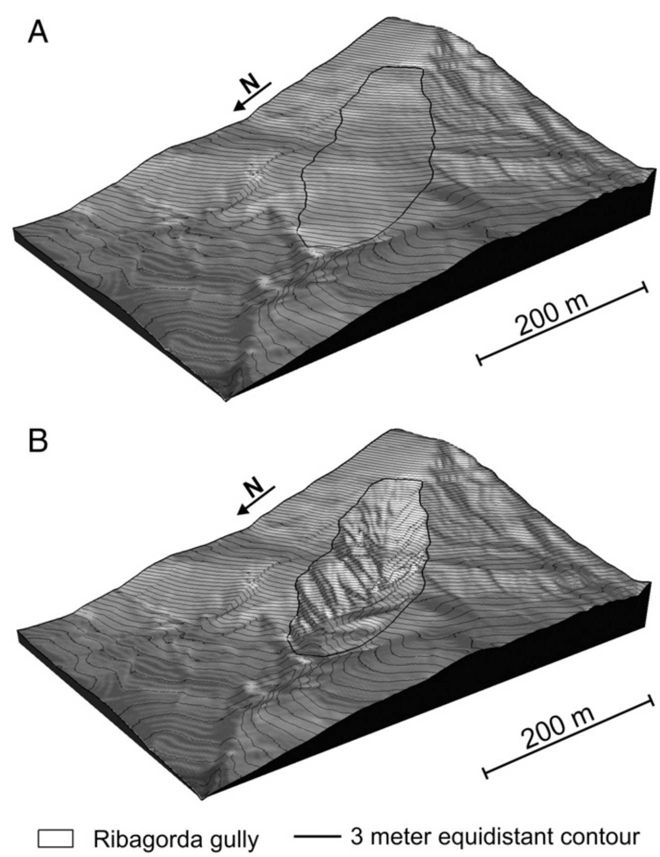


Fig. 6. Digital elevation models of the Ribagorda mesa slope. A) DEM of a topographic reconstruction of the slope before it was gullied; B) DEM of the current shape of the gully.

The Ribagorda gully was developed on well-sorted sands and fairly compacted (weakly cemented) sandstones. The main texture of these sands and sandstones is loamy sand, with the percentage of sand always higher than 79% and a very low content of clay (from 1.5% to 6.0%). Surface mechanical resistance varied from 0.8 kg cm^{-2} (value for a sand cone) to 3.3 kg cm^{-2}, but we could not measure resistance in some locations because the surface was too hard. Shear resistance ranged from 0.4 kg cm^{-2} (at the sand cone) to 5.3 kg cm^{-2} (Table 1).

4.2. Sediment yield and its relationship with rainfall

The total volume of sediments trapped by the three check dams during the 6-year span of monitoring was 3400 m^3 Adjustingfora. mean bulk density of 1.13 g cm^{-3} (mean bulk density of sediments trapped by check dam #1, see Section 4.3) gives a total sediment of 3800 Mg. The maximum standard error in Z of the DEMs built to calculate the volume of sediment ranged from 0.003 to 0.028 m, and the calculated volume varies from 0.2% to 1% (according to the grid data and grid volume reports generated by the Surfer 11 software).

For this period, the mean sediment yield was 114 Mg ha^{-1} yr^{-1}, with a standard deviation of 73. The highest sediment yield calculated was 243 Mg ha^{-1} yr^{-1} for 2010. The lowest value, 63 Mg ha^{-1} yr^{-1}, was recorded for both 2009 and 2011 (Table 2).

The Spearman's rank correlation coefficient shows a significant relationship between the mass of sediment (Mg) and the total rainfall (mm) (P = 0.0007). There also exists a significant relationship among

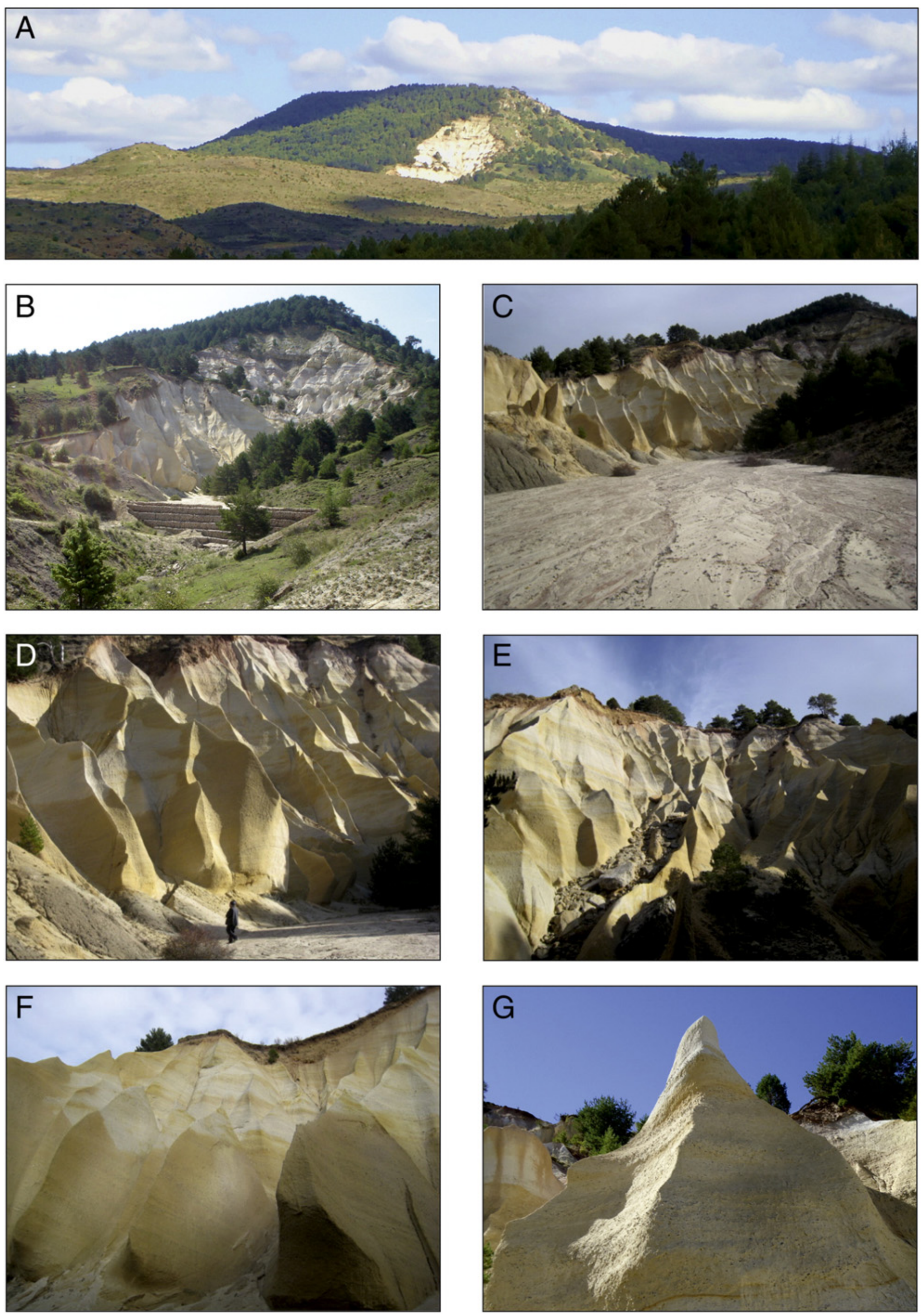


Fig. 7. Photographs of the Ribagorda gully and its landforms: A) general view of the Ribagorda mesa and gullied slope; B) Ribagorda gully and check dam #1; C) sediment trappedbycheck dam #1; D, E, and F) sharp (knife-edged) ridges and sand and debris deposits; G) pinnacle or hoodoo.

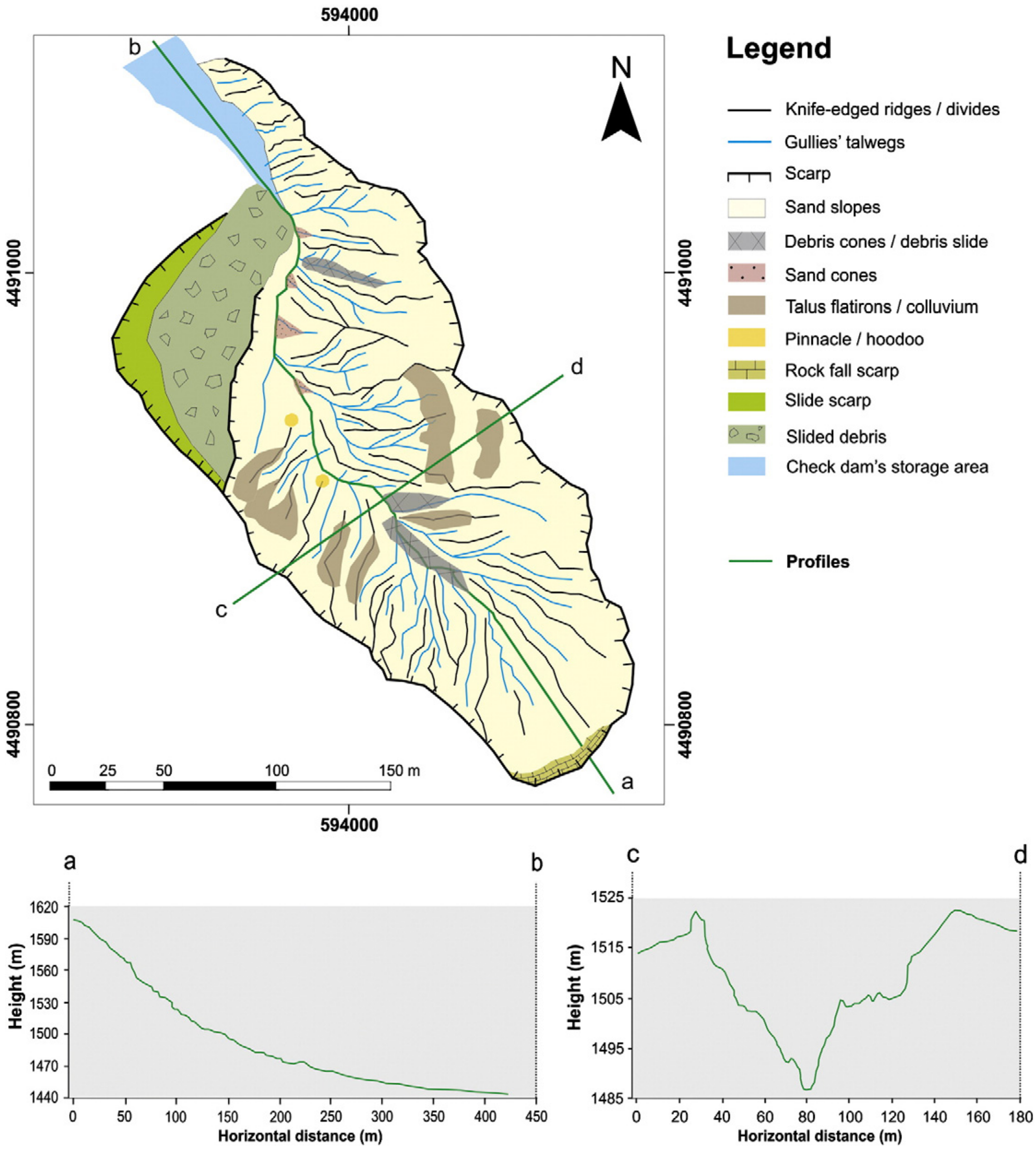


Fig. 8. Plan view and sections of the Ribagorda gully. Landforms within the gully and cross and longitudinal sections (Coordinate system UTM-30 N, Datum ETRS 1989. Elaborated from LIDAR files and field geomorphic reconnaissance).

Table 1
Mean values of surface mechanical resistance and shear resistance and texture of the Ribagorda gully underlying sediments (sands and sandstones).

Sample	Surface mechanical resistance	Shear resistance	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay b0.002 mm	Texture (USDA classification)
	kg cm^{-2}	kg cm^{-2}	percent	percent	percent	
RB1	[a]	2.8	84.5	10.7	4.8	Loamy sand
RB2	[a]	2.5	84.3	10.9	4.8	Loamy sand
RB3	3.0	2.8	83.1	11.4	5.5	Loamy sand
RB4	[a]	5.3	85.2	11.5	3.3	Loamy sand
RB5	0.9	2.2	88.1	9.9	2.0	Sand
RB6	2.9	2.4	83.4	11.1	5.5	Loamy sand
RB7	[a]	[a]	84.8	11.2	4.0	Loamy sand
RB8	2.4	2.4	79.4	14.8	5.8	Loamy sand
RB9	3.3	1.0	79.7	14.8	5.5	Loamy sand
RB10	2.6	3.4	80.8	13.2	6.0	Loamy sand
RB11-cone-1	0.8	0.4	93.2	5.3	1.5	Sand
RB12-cone-2	1.0	0.6	93.9	4.1	2.0	Sand

The surface mechanical resistance was measured by a geotester pocket penetrometer using a 1/4-inch tip. The shear resistance was measured by a torvane using a medium size vane.
[a] Impossible to measure.

the mass of sediment and the analysed rainfall intensities, i.e., the maximum rainfall in 24 h (mm) ($P = 0.0305$), in 30 min (mm h^{-1})($P = 0.0374$) and in 5 min (mm h^{-1}) ($P = 0.0374$) (Table 3).

4.3. Nature of the sediment trapped in the check dams

We identified five facies in the sedimentary wedge of check dam #1, with the sandy ones predominant: 1) massive or matrix-supported gravels leaning slightly horizontal to subhorizontal (Gms); 2) coarse-medium sands with planar to subhorizontal lamination (Sp); 3) medium-fine sands with horizontal to subhorizontal lamination (Sh);
4) silts with parallel lamination and very small ripples (Fl); and 5) massive silts and clays, with unrecognizable sedimentary structures. The proportion of each facies varies among trenches. The range in proportion of the most sandy, common facies (Sp and Sh) is 72% to 92%, the coarser-grained facies Gms 2% to 13% and the fine-grained facies Fl and Fm 5% to 12%. Table 4 shows the facies characteristics and a brief sedimentary interpretation.

In general, we identified a cyclic repetition of grain-size decrease. First, gravels appear, in 5-to-10 cm layers. Above them there are sands, which include disperse gravels and some layers with smaller size grains (very fine sand and silt). These sands can reach thicknesses of up to 70 cm. Finally, layers of sediments with smaller size, silt and clay, appear. These layers have thickness of millimetres or decimetres and are sometimes wavy. The layers are concordant, with continuous parallel lamination, except the gravels, which can have discontinuous parallel lamination. A decrease in thickness of some layers can also be observed, corresponding to a non-parallel planar lamination. No erosive scars were identified. Layers were slightly leaning, subhorizontal with a maximum slope of 3°. This angle is due to base level rise as a result of damming (Fig. 9).

As far as texture is concerned, samples taken in the three backhoe trenches dug in the sedimentary wedge in different positions and at different depths are mainly sandy, with a very high percentage of sand — always higher than 80% (Table 5). We did not observe any variation of texture among the positions of the trenches or at different depths, although we observed a slight increase in the percentage of silt and clay in the trench closest to the check dam. Textures were calculated only for sediments smaller than 2 mm and thus do not give information about gravels. However, we observed that gravels are less abundant than sands, appearing dispersed or in layers of 5 to 10 cm. The mean bulk density was 1.13 g cm^{-3}, with 0.99 g cm^{-3} being the lowest value and 1.40 g cm^{-3} the highest (Table 5).

4.4. Cumulative amount of sediment eroded from the Ribagorda gully

The total volume of materials eroded by the Ribagorda gully from its inception until present was estimated at 692,700 m^3. This volume corresponds to in situ sedimentary rocks (sand and sandstones). The mean swell factor of the Utrillas Formation calculated for the Upper Tagus region is 1.23 (Lázaro Sánchez, engineer at the Upper Tagus active mines, pers. comm.); therefore, the expanded volume of sediments yielded by the Ribagorda gully since its origin is 852,000 m^3, approximately 962,800 Mg, considering a bulk density of 1.13 g cm^{-3}.

4.5. Land use and transformation by humans

4.5.1. Historical evidence of the Ribagorda gully

The first time that the Ribagorda gully is directly mentioned in print was in the mid-20th century by Sanz-y-Díaz (1948), who called it by its local name, "terreras" (meaning sandy gullied or badland terrain), and explained that it was originated by a landslide. A small landslide is recognizable in the 1946 aerial photograph (see Fig. 10), but it has not been proved that the Ribagorda gully was originated by landslides, and certainly not for this one, located in one side of the gully, and therefore, triggered by the gully. Prior to this clear direct reference, we found likely indirect references to the gully. The oldest reference was made by Bowles (1789), who describeda "White Range" (Sierra Blanca, in Spanish) located three-quarters of a league towards the midday (South) from Peralejos de las Truchas. According to Bowles's (1789) description, this white range was isolated and had limestones as caprock and slopes of white rocks. Castel (1882) also described the landscape around Peralejos de las Truchas, noting that loose, white sands could be seen from far away in different places, such as at the Ribagorda's mesa. Both descriptions and locations fit very well with the current appearance of the Ribagorda gully. However, we could not find the placename 'Sierra Blanca' in any other written or cartographic source examined.

The Ribagorda gully, or its local name Terrera, is not named at any of the cartographic sources consulted, not even in current maps, where it is considered part of the Ribagorda stream. However, the earliest available aerial photographs for this area (dated 1946) clear-ly show the Ribagorda gully, with a shape similar to that seen today but approximately 5% smaller than in the 2009 orthophotograph (Fig. 10).

4.5.2. Land uses and deforestation

The primary traditional land uses in this area were not only related to forest resources, such as wood and resin, but also included grazing, farming and mining. The presence of an important Herrería (iron forge) could have intensified both iron mining and deforestation because wood was needed to be used as fuel. These activities may have caused important landscape transformations.

Every document of the 18th and 19th centuries we consulted claims profound forest deterioration in this area during different historical periods and asserts that forests were 'magnificent' in the past. The first significant change of the vegetation cover in the region seems to have been caused by tree cutting and fluvial timber transport (Maderadas, Fig. 4). The Maderadas started here in the 13th century and became very important during the 16th century, when Madrid became the capital of the kingdom, and large amounts of wood were needed for buildings (Fernández Izquierdo, 2012). For example, from 1540 to 1597, 150,000 logs were transported in the Tagus River and other tributaries to Aranjuez and Toledo (Fernández Izquierdo, 2012). Two centuries later, according to Catastro del Marqués de Ensenada (1752), this Upper

Table 2
Annual and mean sediment yield of the Ribagorda gully. Annual rainfall and rainfall days per year are also included.

Year	Rainfall days	Annual rainfall	Annual sediment yield
	#	m	m $^{-1}$ yrM
2008	105	527	76
2009	117	614	63
2010	127	900	243
2011	118	493	63
2012	118	374	158
2013	200	923	81
Mean			114 (73)

Number in parentheses is standard deviation.

Table 3
Spearman's rank correlation coefficients of mass of sediment versus rainfall characteristics.

Compared variables	Spearman's rank correlation coefficient		
¯g ¹h a	n	r^2	P value
Mass of sediment (Mg) vs total rainfall (mm)	22	0.74	0.0007*
Mass of sediment (Mg) vs max. rainfall in 24 h (mm)	22	0.47	0.0305*
Mass of sediment (Mg) vs max. rainfall in 30 min (mm h^{-1})	22	0.45	0.0374*
Mass of sediment (Mg) vs max. rainfall in 5 min (mm h^{-1})	22	0.55	0.0116*

N = number of data. r^2 = coefficient of determination. Statistical significance level *$\alpha \leq 0.05$.

Table 4
Description and interpretation of facies identified in the sedimentary wedge originating behind check dam #1.

Facies code[a]	Description	Interpretation
Gms	Massive or matrix-supported gravels. Gravels and pebbles, up to 6 cm diameter in a sand matrix. Gravels mainly are quartzite with some more angular fragments of limestone. Several 5–10 cm thick layers with planar discontinuous lamination.	Moderate energy sediment. This energy facilitates the mobilization of the coarsest sediments.
Sp	Coarse-to-medium sands with planar-subhorizontal lamination. Including dispersed gravel particles. The sands are mainly siliceous with white and grey to pinks tones. Together with Sh facies these are the most common. May reach thickness ≤70 cm.	Sandy facies are the most abundant in these sedimentary deposits. They indicate energy reduction, compared to the previously deposited gravels.
Sh	Medium-fine sands with horizontal-subhorizontal lamination with characteristics very similar to Sp facies.	
Fl	Layers 3–7 cm thick of silts with parallel lamination and very small ripples or wavy stratification showing pinkish and dark tones (black or brown) that may indicate the presence of organic matter.	Silty facies are more common close to the check dam. Interpreted as sedimentation of fine suspended particles from a stagnating water column with high turbidity. Formation of desiccation cracks on the surface could have led to an uneven surface that, in section view appears wavy. Where Fm is lacking, these are likely the upper couplet representing a sedimentation event.
Fm	Massive silts and clays, unrecognizable sedimentary structures. Very similar to Fl facies with darker colours.	Derived from stagnant zones; may encourage growth of plants, algae and microorganisms, hence darker colours typical of organic matter. However, plant residues have not been identified. These are likely the upper couplet representing a sedimentation event.

[a] Facies codes correspond to Miall (1978).

Tagus landscape was mostly deforested. Regarding the Peralejos de las Truchas municipality, this Cadastre described the abundance of new and small pines and some species of bush (e.g., Berberis vulgaris), which usually grow on degraded lands, and signal the abundance of “uncultivat-ed and barren lands”. Briz and Simó (1755) explained that, upstream of Peralejos de las Truchas, where there were no villages, larger pine forests existed but had been altered by logging activities. Near the Peralejos village, the landscape was dominated by crops. Bowles (1789, p. 138) stated that some places of the Upper Tagus region and the area surround-ing Peralejos were “barren, without shadows, nor moisture, nor moss, neither plants”. This bleak landscape continued through the next century. The Madoz (1845–1850) dictionary reported the abundance of beehives, which are directly related to flowering and aromatic bushes. Other authors insisted on the presence of a rich and large forest in the past that, due to what they refer to as disastrous management, was in “ruins” in the 19th century (Castel, 1882; Perruca-y-Díaz, 1891), and had likely been that way since the 16th century.

Plowing and herding must have contributed, also, to deforestation. This region was characterized from the Roman period by having high quality wool for weaving, with 400,000 sheep by the 16th century and 700,000 sheep and 50,000 horses, donkeys, pigs and cows in 1650 (Elgueta, 1663, in Perruca-y-Díaz, 1891, p. 87). In the 18th century, the number of sheep decreased to 200,000, of which approximately 100,000 were nomadic. These livestock moved from Molina de Aragón to Andalusia (South Spain) by crossing the Tagus River at the Martinete bridge (Abánades López, 1962, Vol. I, p. 349) located very close to the Ribagorda gully.

The already mentioned iron forge (Herrería) was very important in the region surrounding the Ribagorda gully. It was located at the Hoz Seca, or the Oceseca River, a tributary of the Tagus River, at about 5 km southeast of the gully. It had to be significant because it appears on maps of the 18th and 19th centuries with the name of Herrería de Franco (Fig. 11). This prominent iron forge had different periods of activity: it was closed down in 1604 because of a fire (Perruca-y-Díaz, 1891) and it was reopened around 1750 (Catastro del Marqués de Ensenada, 1752; Briz and Simó, 1755). This forge production was projected to be 8250 arrobas of iron per year (equivalent to 94,875 kg yr^{-1}); arroba is a historical Spanish measure of weight and the Castilian arroba corresponds to 11.5 kg. For that production, they needed one carga of charcoal per arroba, which means 1287 to 1782 t of charcoal per year (Catastro del Marqués de Ensenada, 1752). Carga is the weight that could be transported by a horse. The Aragonese carga is equivalent to 216 kg and the Catalonian carga to 156 kg. The charcoal consumption was therefore enormous. Thus, according to Karr (1862), in the 19th century, forges in Spain needed 6000 cargas of charcoal per year, equal to 25,000 to 30,000 cargas of wood, approximately 432 t. However, in 1760, the forges of the Upper Tagus consumed double that value: 12,000 cargas of charcoal (Archivo de la Comunidad del Señorío de Molina y su Tierra, 1790, Legajo 31 no 17). According to Archivo de la Comunidad del Señorío de Molina y su Tierra (1763; Legajo 4 no 20), the ancestral forested slopes of the current Ribagorda gully were among the lands logged for the Herrería de Franco's forge charcoal needs.

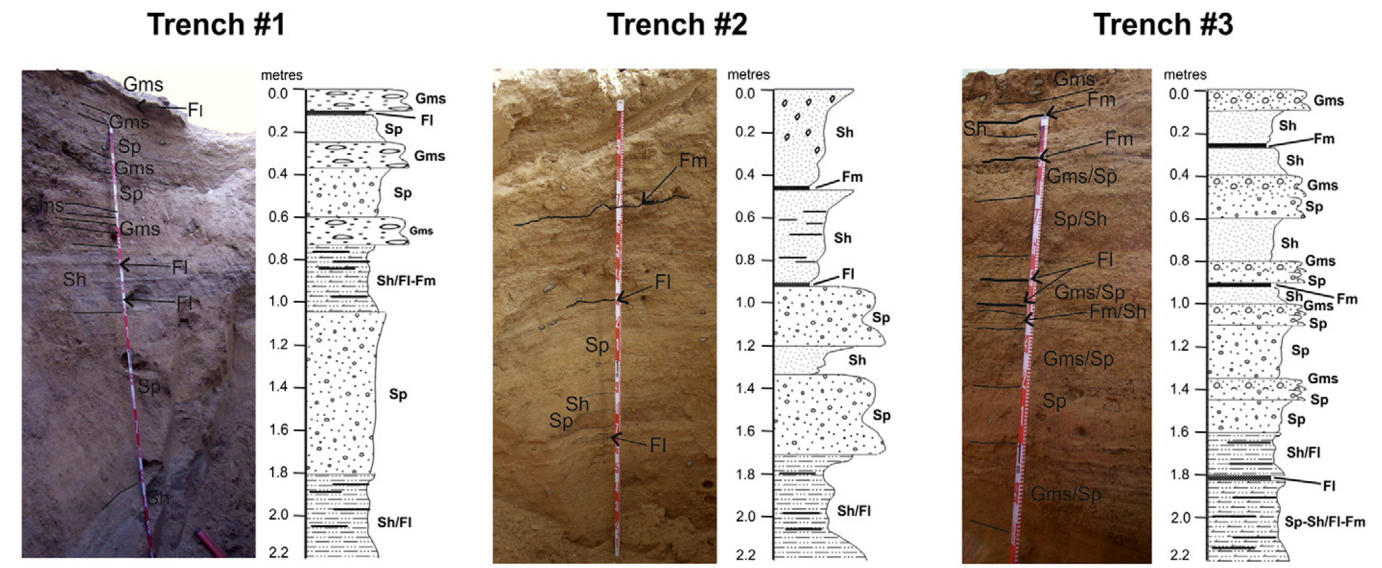
From 1861 to 1864, the forge was closed again, due to the scarcity of wood as a result of intense deforestation and the increasing price of charcoal (Risueño, 1869). Different periods of inactivity were repeated since then and the last activity was mentioned in 1886 (IGME, 1861−present).

Only in the last few decades, after hundreds of years of deforestation, vegetation cover has been recuperating. The aerial photograph of 1946 (Fig. 10) shows the area surrounding the Ribagorda gully with hardly any wild vegetation, with some identifiable crops. In 2009, the vegetation cover was denser and more widespread, specifically close to the gully, and it became hard to identify the crops (Fig. 10). This increase in natural vegetation cover and changes in land use were also represented in current maps (Fig. 12).

5. Discussion

5.1. Gully processes and landforms

Landforms observed in the gully are similar to, but much more prominent than, those described for other sand gullies in Spain (Lucía et al., 2011; Lucía, 2013). Landforms and gully processes are governed by the characteristics of the underlying sandstones. As a general statement, these poorly compacted sands and sandstones are highly erodible, and we observed in the field that surface erosion occurs virtually every rainstorm, even when they have high surface mechanical resistance and shear resistance in dry conditions. The surface strength values are higher than those reported for similar sand gullies in wet conditions (Lucía et al., 2011). We interpret that this difference is due to the formation of a superficial crust or cement in dry conditions, which is dissolved by water in wet conditions. However, in dry conditions, this crust is easily detached by rain splash (Lucía et al., 2011).



0-0.75 m Coarse-to-medium sand (Sp) alternated with centimetric layers of matrix-supported gravels (Gms). Gravel layers are 5 to 8 cm thick and they are composed of quartzite and limestone fragments . There are also milimetric layers with silt and very fine sands (Fl).
0.75-1.0 m Alternation of fine sand layers (Sh) with silt and clay ones (Fl, Fm). Sands are whitish and grey, whereas silt and clay layers are darker. Layers with planar lamination are slightly sloping.
1.0-1.7 m Very massive coarse-to-medium pink sands , where lamination is not recognized. They contain dispersed gravels.
1.7-? m Medium-fine sands (Sh) alternated with silt, clay and very fine sands (Fl).

Very homogeneous vertical facies sequence. Coarse-to-medium and medium-fine sands (Sp and Sh) alternated with layers of silts and clays (Fl and Fm). There are dispersed gravels but they do not draw a continuos layer. Gravels are more abundant in the upper part.

A fine, irregular and wavy layer highlights at 0.45 m depth. This layer has silt and clay particles (Fm) and dark colours.

0-0.1 m Matrix-supported gravels (Gms). Very rounded gravels, mainly quartzite, with 2 to 4 cm size.
0.1-0.25 m Fine sand layers (Sh) alternated with silt and clay layers (Fm/Fl). These layers have planar lamination and are slightly sloping. Sands have whitish colors whereas silt and clay are pink
0.25-1.05 m Layers with small size gravels (>2 mm to 1 cm) alternated with coarse-to-medium sands (Gms/Sp). There are also milimetric layers of silt and clay (Fm/Fl), dark layers, and medium-fine sand layers (Sh).
1.05-1.3 m Massive coarse-to-medium sands (Sp).
1.3-1.8 m Gms/Sp alternated with Sp /Sh. At a 1.80-depth there is a centimetric wavy and dark layer of silt and clay (Fm).
1.8-? m Sp alternated with Sh.

Fig. 9. Photographs, stratigraphic column, and descriptions of vertical facies of the sedimentary wedge originating behind check dam #1.

5.2. Sediment yield and its relationship with rainfall

The sediment yield of gullies and badlands depends not only on lithology, climatic characteristics, topography, watershed size, etc., but also on the method used to measure erosion. We believe that the meth-odology used to calculate the sediment yield from the Ribagorda gully, i.e., monitoring the filling of the storage area of the check dams, offers reliable data and useful information (Romero-Díaz, 2008).

However, this methodology has some limitations. Thus, the measured sediment yield corresponds to the sediment trapped by the gabion check dams, primarily coarse and medium particles, whereas fine particles (silt and clay) can pass through the gabion structure (Conesa García, 2004). In addition, clay and silt are usually in colloidal suspension. Therefore, during moderate or intense rainfalls, if the water spills over the check dam, the clay and silt have no time to settle.

Calculating an accurate trap efficiency of gabion check dams is difficult. Methods available were designed for structures intended to control discharge (reservoirs), which have very different characteristics compared with gabion check dams. Besides, these methods are not appropriate for small dams. Martín Rosales (2003), trying to calculate gabion check dams' trap efficiency, concluded that only 35% of suspended sediments are trapped by these dams.

For these reasons, the calculated sediment yield from the Ribagorda gully most likely represents the minimum value. As much as 65% of the content of silt and clay may not be included in this estimation. Relative to this issue, Lucía (2013) points out that, in similar sandy gullies, the majority of sediment eroded (N70%) is transported as bedload, whereas the content of suspended sediments is 0.1% to 28.7%. Although the suspended sediments could increase the estimate by up to 65%, the Ribagorda gully sediment yield still would not be considerably different, because this 65% applies only to a maximum of 28.7% of material eroded in the gully.

As for the errors associated with the creation of DEMs and with the interpolation of volumes, we assess them as fairly acceptable. We interpret those low errors (up to 1%) as a consequence of the modelled landforms \ almost planar surfaces with gently gradient slopes towards the check dams.

Regarding the relationship between sediment yield and watershed size, the sediment yield of 114 Mg ha^{-1} yr^{-1} is considerably lower than the mean sediment yield of 475 Mg ha^{-1} yr^{-1} for watersheds

Table 5
Texture and bulk density of the sediments in the wedge originating behind check dam #1.

Trench	Depth	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay b0.002 mm	Texture (USDA classification)	Bulk density	Mean bulk density
#	m	percent	percent	percent		g cm^{-3}	g c m^{-3}
1	0	88.7	7.3	4.0	Sand	1.23	1.16 (0.09)
	0.7	92.4	6.3	1.3	Sand	1.23	
	0.9	90.2	7.3	2.5	Sand	n.d	
	1.2	n.d	n.d	n.d	n.d	1.04	
	1.7	n.d	n.d	n.d	n.d	1.19	
	1.9	91.4	5.8	2.8	Sand	n.d	
	2.2	94.2	4.3	1.5	Sand	1.10	
2	0	80.1	14.9	5.0	Loamy sand	1.17	1.02 (0.10)
	0.3	n.d	n.d	n.d	n.d	0.91	
	0.5	89.8	7.7	2.5	Sand	n.d	
	0.7	92.1	5.4	2.5	Sand	1.01	
	1.2	89.5	6.2	4.3	Sand	1.02	
	1.6	91.5	4.5	4.0	Sand	0.99	
3	0	86.6	8.9	4.5	Sand	1.40	1.22 (0.12)
	0.5	91.0	6.3	2.8	Sand	1.27	
	0.8	n.d	n.d	n.d	n.d	1.09	
	0.9	88.7	7.3	4.0	Sand	1.10	
	1.3	90.0	7.0	3.0	Sand	1.19	
	1.8	89.6	7.4	3.0	Sand	1.27	
	Mean						1.13 (0.10)

Numbers in parentheses are standard deviations. n.d = no data.

b10 ha (Nadal-Romero et al., 2011). Interestingly, the sediment yield from the Ribagorda gully is higher than that of other sand gullies in central Spain, where single gullies (watershed areas of 0.1 to 1.32 ha) yielded 45 to 74 Mg ha^{-1} yr^{-1} (Lucía et al., 2011; Lucía, 2013). This difference can be explained not only by climatic conditions, which are much more erosive in the Upper Tagus region than in central Spain, but also by differences in gully size.

Concerning the relationship between sediment yield and rainfall, the statistical analyses show two results: 1) the highest statistically significant dependence (r^2 = 0.74) occurs between mass of sediment and total rainfall; and 2) there is a high statistically significant dependence between mass of sediment and each of different rainfall intensities. In addition, the regression coefficient increases as the duration of rainfall intensity decreases from 24 h to 30 min, and then to 5 min. In our interpretation, this means that both low intensity but continued rains (typical of winter fronts), and also high-intensity rains (typical of summer convective cells), are responsible of mobilizing considerable amounts of sediment. As it has been explained before, different factors act here at different conditions: the superficial crust is dissolved by water due to winter frontal rainfall and detached by rain splash in intense summer rainstorms. The low cohesion of the sands at the Ribagorda gully and a high availability of sediment guarantee common erosion and sediment transport within the gully.

5.3. The sedimentary wedge

Based on field observations, the sediment trapped by check dam #1 is similar to that trapped by check dams #2 and #3. It may have been expected that sediment in the storage area of check dam #1 would have a higher proportion of gravels than in check dams #2 and #3. However, we observed that once the storage area was completely full,

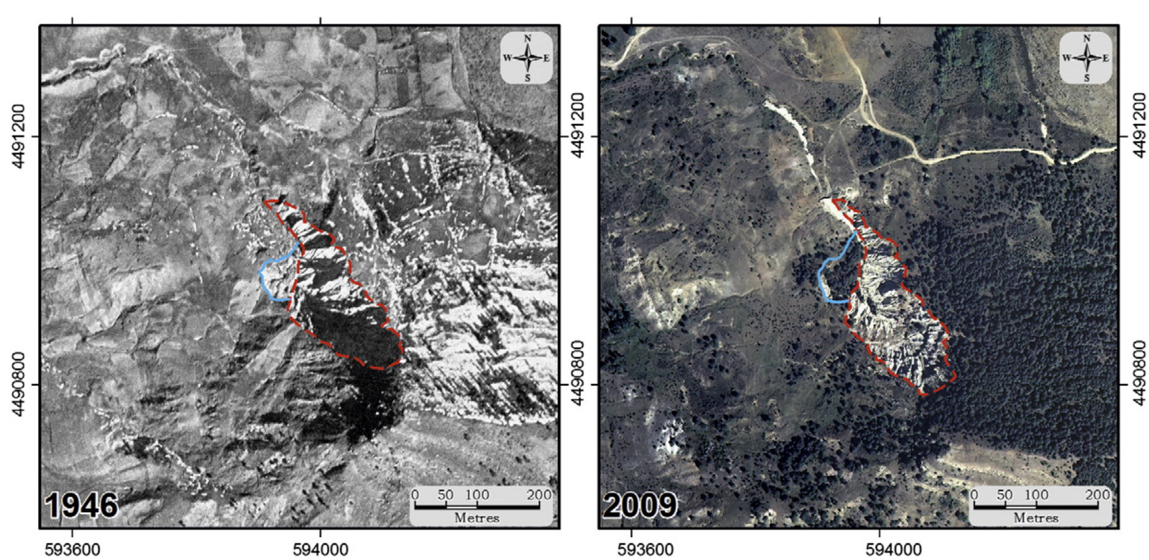


Fig. 10. Aerial photographs of Ribagorda gully dated 1946 and 2009 (Coordinate system UTM-30 N, Datum ETRS 1989). The original scale of the 1946 photo is 1:43,400. The 2009 digital orthophoto has an original resolution of 0.5 m. The discontinuous red line represents the boundary of the Ribagorda gully, and the continuous blue line represents the boundary of a landslide covered by vegetation in 2009. Part of the gully in 1946 was covered by shade.

Fig. 11. Location of Herrería de Francos in maps of the 18th and 19th centuries. A) detail of the Geographic Atlas of Spain and Portugal, Cuenca Province, by López (1780); B) Detail of the Geographic Map of El Señorío de Molina, by López (1785); C) Detail of the Guadalajara Province Map, by Coello (1865). The scale is approximated. Maps provided by the Cartographic and Geographic Studies Archive of Geographic Centre of the Spanish Army, Ministry of Defense of Spain.

sediment and water moved directly downstream to the storage area of check dam #2, and then to check dam #3.

The observed sedimentary facies allowed us to deduce the hydraulic conditions under which the sediment was deposited. We compared the identified facies with those defining a filling model for check dam storage area with characteristics similar to those of the Ribagorda watershed (Conesa García and García Lorenzo, 2007).

This model differs from the common filling models of reservoirs and lakes. The main difference is that often in the storage area of a check dam, there is no water body and the storage area is very small compared with that of reservoirs and lakes; indeed it is small with respect to flood volume, as in the estimations of trapping efficiency (Brune, 1953). Thus, check dams are obstacles for water and sediment, and sedimentation is rapid. In addition, due to the small capacity of check dams and their typical location in steep channels, sediment does not have time to be sorted (Conesa García and García Lorenzo, 2007). In our case, these processes were accentuated by the proximity of the check dams to the sediment source (Ribagorda gully).

Thus, matrix-supported gravels were transported as bedload, indicating greater-than-low energy conditions (Conesa García and García Lorenzo, 2007). For the sedimentary wedge described in this study, this facies occurs in the upper part of trench #1 and is associated with coarse sand facies (Sp) in trench #3. The most common facies is sandy (Sh and Sp), which is deposited in lower energy conditions compared with the gravel facies. The abundance of this facies is logical considering that the Ribagorda sandstones are sand-rich.

Clay and silt (Fl and Fm) are usually deposited by flood conditions. In the Ribagorda dams, they correspond to small puddles as they occur in the three trenches. In addition, a slight increase of fine sediment typified trench #3 (the closest to the check dam). This is consistent with the check dam being an obstacle stopping the flow of sediment and water, and giving sediments more time to deposit in trench #3 than in trenches #1 and #2. Taking these characteristics into account, this sedimentary wedge may be more similar to alluvial fan deposits than to purely fluvial ones. It is also likely that fine-grained Fl and Fm facies represent the upper couplets of event sedimentation (e.g., Laronne, 2000). As the Ribagorda sands contain very low amounts of silt and clay, these facies are few and thin, among others, because some of the suspended sediment was not trapped by the check dams during greater-flow events.

5.4. Origin of the Ribagorda gully and human land transformation

Based on historic records and maps, and geomorphological evidence, we interpret that intense human deforestation is likely the main cause of the Ribagorda gully development, assisted by grazing and farming. We believe that ancient climatic conditions did not cause the gully initiation, but that they probably had an important role in the gully development. Our conclusion is consistent with those of others who demonstrated that changes in land use and forest clearing have been most important in gully development elsewhere, although for dif-ferent lithologies (Schmitt et al., 2003; Stankoviansky, 2003; Poesen et al., 2006; García-Ruiz, 2010; Dotterweich et al., 2013). This information can have critical consequences for our understanding of present landforms, as reported in Walter and Merritts (2008) where supposed 'natural' streams were later interpreted as filling terraces resulting from milling damming. There are consequences for the environmental management of these landscapes, as stressed by Dotterweich et al. (2013): "The human–environment interactions of the past contain crucial lessons for our understanding of what constitutes environmental sustainability" (op. cit., p. 1) and "…possible future land use trajectories are strongly connected with the legacies of past land use changes and soil erosion" (op. cit., p. 17). In other words, we cannot understand present landscapes without knowledge about historical land uses (Reiß et al., 2009).

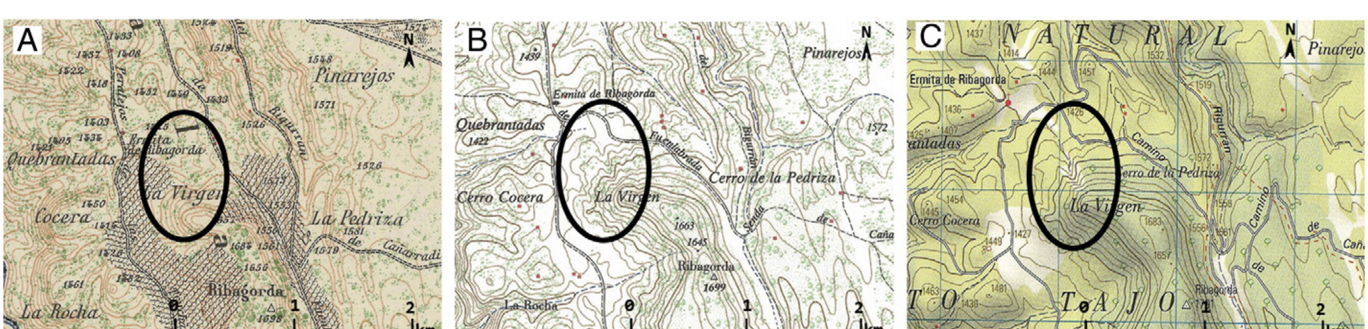


Fig. 12. Surroundings and soil-use changes of the Ribagorda gully in 1:50,000 National Topographic Maps of the National Geography Institute (Instituto Geográfico Nacional, IGN, in Spanish). Map of Peralejos de las Truchas, sheet 539, dated in A) 1947 (IGN, 1947); B) 1987 (IGN, 1987); and C) 2002 (IGN, 2002b).

In the surroundings of the Ribagorda gully, multiple stages of deforestation resulted from activities that consumed timber such as local domestic uses, timber transport outside the area, and charcoal production for iron forges. In the late 18th century, the demand for charcoal for iron industries resulted in complete removal of the Upper Tagus forests.

Our interpretation is that as vegetation was degraded or eliminat-ed, slopes were no longer phytostabilized and became locally pedo-geomorphologically unbalanced. Then, runoff on fairly compacted sands and sandstones must have initiated the gully development. This process may have been favoured also by surface disaggregation produced by a high frequency of freeze–thaw cycles, which were very intense during the LIA and are most likely similar to effects studied in adjacent areas (see González et al., 2013). Livestock grazing and timber transport by land could also have contributed to gully initiation by producing small fissures in which water could concentrate and originate the gully. Other natural processes, such as slides and falls, must have subsequently occurred, as can be seen today at the edge of the gully. Dotterweich et al. (2012) found a complex relationship between sunken roads and gully development in the Doly Podmularskie gully system; however, the role of pathways was not important here, because paths never crossed or passed close to the Ribagorda gully.

Finally, there is another possibility for gully development: traditional and minor mining activities such as caprock removal or sand extraction could have triggered Ribagorda gully formation or at least favoured its development, as reported by Moreno (1989) for another area in the central Iberian Peninsula. We believe that sand extraction could happen once sands were exposed but not before; therefore, we consider that this was not the main cause of gully formation. The most likely scenario is that all of these processes worked together and all of them contributed to the Ribagorda gully origin and subsequent development (Fig. 13).

There is also what we interpret as unequivocal geomorphological evidences of the "non-natural" origin of this outstanding gully, and therefore, of its human-induced origin. They are:

(a) Before deforestation, vegetation densely covered the land. Today, in areas where the slopes are not incised and human pressure has disappeared, a dense vegetation cover is returning. In short, we are not in climatic or geomorphic conditions favouring the formation of gullies and badlands.
(b) The gullied slope is located in a uniform slope with the constant gradient of a mesa hillslope (see Figs. 2 and 3), actually in a slope position where runoff originally diverged (before the gully), instead of being concentrated.
(c) The gullied slope is confined to this mesa, with only some scattered gullied sandy slopes in the region, some of them in the vicinity of the Hoz Seca River, where deforestation has also occurred.
(d) In the similar physiographic conditions of Central Spain, similar gullied slopes have been demonstrated to have a human-induced origin, dating from 800 to 100 years ago (Moreno, 1989).

Although our cartographic sources and documents give information about changes in land use over time, they do not offer sufficient information about the age of the gully. The fact that naturalists and travellers who visited this area were worried about the effects of logging and the consequent erosion, and the fact that they described a landscape that we consider similar to the current one, suggest that the Ribagorda

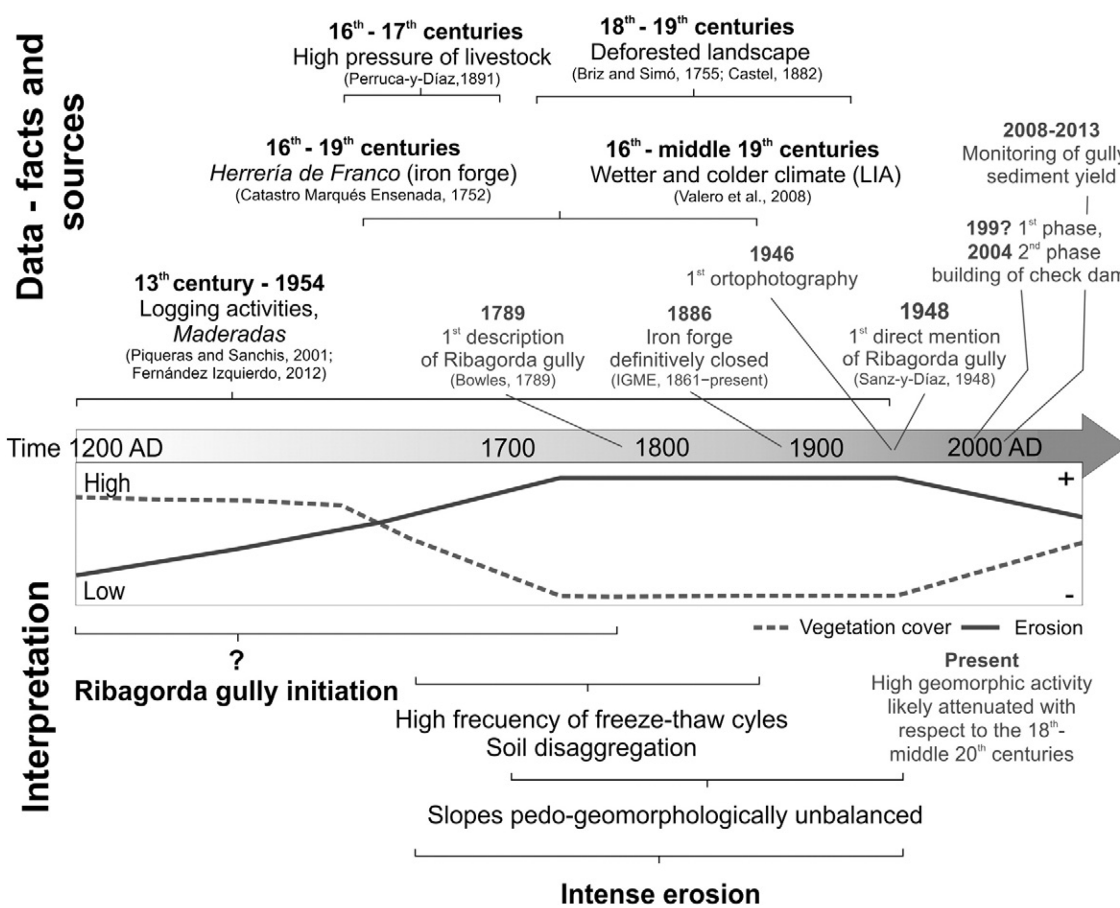


Fig. 13. Scheme summarizing the interpretation of historic geomorphic events at the Ribagorda gully.

gully was already of considerable size in the 18th century, but probably was not as large as it is today. Therefore, we can only affirm that the Ribagorda gully was initiated before the 18th century, when we interpret that Bowles (1789) unequivocally described it, and after the logging (Maderadas) started in this area in the 13th century.

The most accurate methods for determining the age and activity of gullies, as some authors point out (Malik, 2008; Dotterweich et al., 2013), are dating by ^{14}C, ^{137}Cs, or other techniques, such as the pedo-geomorphological description of alluvial fan deposits. These methods could not be applied here because the Ribagorda gully has no alluvial fan; the sediments eroded from the gully were transported by the stream directly to the Tagus River. This situation results from the high slope gradient (14%) of the fluvial channel downstream of the studied area, incised into the bedrock as a small gorge and directly connected to the Tagus River. These characteristics tell us that almost all of the sediment eroded from the Ribagorda gully (outside of some small storage at the gorge bottom), from the beginning of its formation until the present, have reached the Tagus River except for the sediment recently (from the 1990s) trapped by the check dams.

6. Conclusions

We consider that the singularity of the Ribagorda gully is due to its location, isolated in a steep mesa slope, its size (2.57 ha), and position that provides viewers sight of the beauty of its colours and landforms — a set of knife-edge divides and badlands topography. The badland topography of the interior of the gully is different from, and larger than, any other gully developed on the sandy Utrillas Formation of the Iberian Range and Central System (Centre and East-Centre of the Iberian Peninsula). We make this affirmation because there is a very detailed knowledge and mapping of the geomorphology of those regions. The information we found in consultation with regional geomorphologists, and even the postcards identifying the Ribagorda gully as a visually appealing geomorphic site, confirm this.

The evidence of landforms denoting very active water erosion and mass movement processes within the catchment of the Ribagorda gully, as well as the measured sediment yield, are unequivocal signs of intense geomorphic activity in this landscape. We consider this high activity to be a consequence of the human disruption of a geomorphic system in an unsteady state and an excellent example of the effects of deforestation.

We could not determine the precise date of the Ribagorda gully formation. It was very likely initiated in an embryonic form after the 13th century (origin of Maderadas in this region) and before the rise of the Modern Age (18th century, when it was first unequi-vocally described in print). The data we gathered provide evidence that the triggering factor of the erosive processes was the human transformation of this area of the Upper Tagus region, particularly deforestation for grazing and logging. Erosion may have been greatly accelerated at the end of the 18th century, when an increased demand for timber fuelled the charcoal supply of a prominent nearby iron forge.

An understanding of the age, origin, geomorphic evolution, and dynamics of this gully tells us that this landscape is currently evolv-ing towards new steady states of equilibrium, after human distur-bance of centuries. Therefore, and given its local extent, we suggest that no correction measures are needed for its management. In this regard, this work contributes to the conclusions derived from some recent papers that stress the role of humans as geomorphic agents of our recent past (e.g. Walter and Merritts, 2008; Dotterweich et al., 2013). In thecase of the Upper Tagus, where our work was conducted, this information is relevant to the significant environmental problem resulting from the hydrological impact of terrigenous sedi-ment input to fluvial systems with tufa-formation (Guerrero and González, 2000).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: http://dx.doi.org/10.1016/j.geomorph.2014.07.013. These data include Google maps of the most important areas described in this article.

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