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Geomorphic dynamics of gullies developed in sandy slopes of Central Spain

Ana Lucía[1], José Francisco Martín-Duque[1], Jonathan Benjamin Laronne[2], Miguel Ángel Sanz-Santos[1]

[1]*Dept. of Geodynamics and Institute of Geosciences (CSIC-UCM), Complutense University of Madrid, Madrid, Spain*
[2]*Dept. of Geography & Environmental Development, Ben Gurion University of the Negev, Beer Sheva 84105, Israel*
e-mail: aluciave@geo.ucm.es

Abstract: Gullies developed on sandy lithologies are scarce. Such landforms have developed in the sandy deposits of the Cretaceous 'Utrillas' facies within the Segovia province of Central Spain. They appear at the slopes of a group of mesas and cuestas located at the edge of the northern piedmont of the Guadarrama Mountains of the Spanish Central System. The activity of the different geomorphic processes acting in these gullies, as well as their connectivity, are being characterized and quantified. This study was preceded by reconnaissance methods, whereas presently technologically advanced and more accurate techniques are being utilized. The new methods are applied in an experimental catchment (1.26 ha). They include: i) an automatic Reid-type (formerly termed Birkbeck) slot bedload sampler for continuous monitoring of bedload flux and for continuous sampling of bedload; siphons for sampling the suspended load; and a Parshall flume to monitor water discharge. Jointly, these instruments allow to study the fluvial dynamics at the catchment mouth; ii) topographic surveys undertaken by a Terrestrial Laser Scanner (TLS) to quantify the activity of gravitational, overland flow and fluvial processes in different sediment source areas within the gully basin; iii) micro runoff and erosion plots to monitor the infiltration and erosive response of different Hydrologic Response Units (HRU) comprising the interior of the catchment. This ensemble of novel methods has started providing patterns of sediment movement within the gully system.

Keywords: sand, gullies, Terrestrial Laser Scanner (TLS), Reid bedload sampler, erosion-runoff plots, Spain

Introduction

Gullies and badlands are usually associated with clayey lithologies (García Ruiz & López Bermudez 2009). Gullies developed in sands or sandstones are exceptional, in part explaining why few studies (e.g.: Boardman et al. 2003, Crouch 1990, Lindquist 1980, Okagbue & Ezechi 1988, Osterkamp & Toy 1997) have been undertaken on such gullies. In most of these studies only reconnaissance methods have been used. Therefore, obtaining accurate data about the geomorphic activity and connectivity of sandy gullies is expected to cover a knowledge gap.

The studied sandy gullies of Central Spain are located at the edge of the northern piedmont of the Central System (Fig. 1), appearing at the slopes of a group of mesas and cuestas. These landforms are not only interesting because they form in sands, but particularly as it has become obvious that their formation was triggered by quarrying activities starting at least 800 years ago (Moreno 1989, Vicente et al. 2009). The sediment yield from these gullies frequently affects human land use, burying roads, crops and pasture fields, as well as damaging village structures. Therefore, human activities and gully dynamics are intricately interconnected in this region, having interacted since the beginning of gully formation.

For both academic and applied purposes, our broad objective is to understand the geomorphic processes which operate within these gullies. Detailed description of the specific aims are described elsewhere (Lucía et al. 2007). They focus on evaluation of the rates of different processes acting within

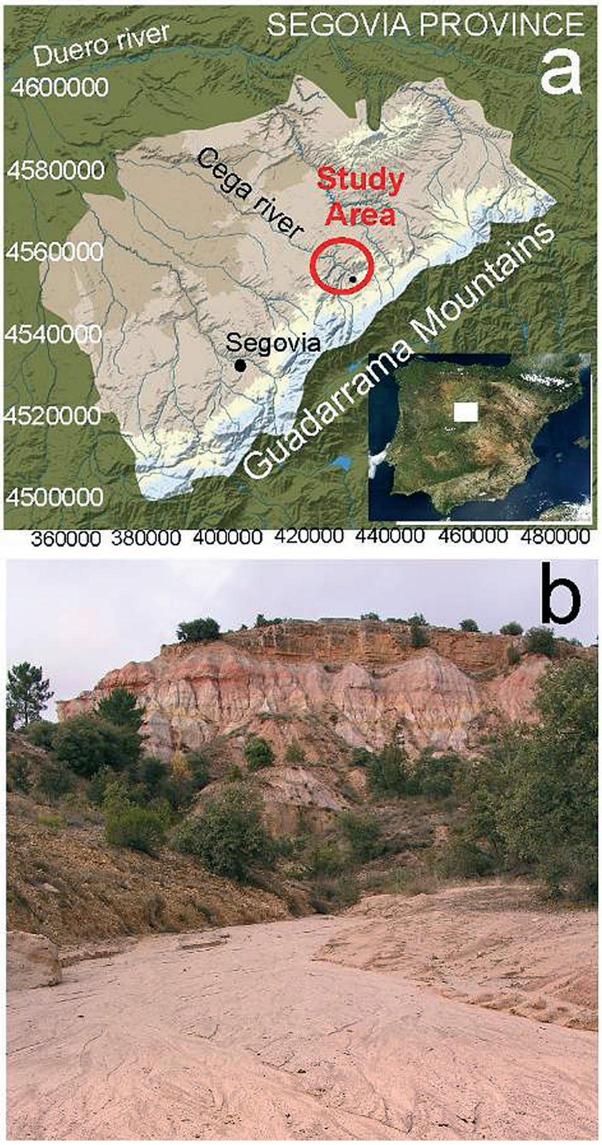

Fig. 1. Location of the sand slope gullies in the Segovia Province, UTM coordinates, 30 zone (a) and view of the interior of one of the studied sandy gullies (b)

these landforms, their frequency of occurrence, their triggering factors and the interconnection and coupling between them (Harvey 2001, Thomas 2001).

Based on a detailed landform analysis of 75 gullies in the area, the geomorphic activity was characterized (Lucía et al. 2008). The more active processes in the catchment are mass movements at the headwalls and sheet erosion on the sandy inner slopes and catchment ridges. Both processes provide sediments to the channels. The sediments transported to the dry washes are evacuated by pulses of fluvial activity, depositing sediments onto small alluvial cones at the toe of the slopes. Most of the sediment stored in the channels is sand. Therefore, the majority of the sediment is transported as bedload instead of in suspension, the latter predominating in most gullies at the catchment scale (Mathys et al. 2003, Gallart et al. 2005, García Ruiz et al. 2008).

A reconnaissance study was undertaken during 2007–2008 to monitor the main processes which move sediments within the gullies (Lucía et al. 2008). Reconnaissance methods are suitable when no previous data are available and when erosion and sedimentation are located in specific areas (Hudson 1997). Being the case, erosion pins were used to determine the variation in pedestal heights in inner divides, thereby measuring sheet erosion. For the quantification of the sediment yield in different catchments, two types of sediment traps were installed – a small gabion dam built in a scour channel and a metal pit box located at the outlet of a gully. The quantification of the volume of cone deposits on roads after storm events completed the reconnaissance of the geomorphic activity. The above-mentioned methods allowed to measure high erosion rates: on average 11.7 mm sheet erosion in some inner gully divides and 115 Mg ha^{-1} yr^{-1} of sediment yield in a gully for a single rainfall event (69 mm; I_{30} = 72 mm hr^{-1}), occurring on Sept. 9, 2008. The obtained rates indicate the high mobility of the sands in which the gullies form.

A second phase of the research on the geomorphic activity of the sandy gullies includes the use of more accurate, technologically advanced methods to measure processes in one experimental catchment.

A set of instruments has been deployed at the outlet of this catchment to measure the suspended load, the bedload and the water discharge, the latter two by automatic devices. Aiming to study gully-channel coupling, detailed topographical surveys with Terrestrial Laser Scanning (TLS) are being carried out at selected locations. These areas were located according to an accurate survey of sites in which slope and channel activities are connected. Also, to better understand the hydrological response of hydro-geomorphic units forming the interior of the gullies, a set of erosion and runoff microplots have also been installed.

The use of these methods allows studying the geomorphic dynamics of this selected gully, considered to be representative in this area. Specifically, the use of TLS to monitor slope and channel interconnectivity with respect to sediment movement and the installation of the automatic bedload sampler at the gully outlet are novel and of interest within the framework of gully erosion studies.

Study area. The *Barranca de los Pinos* experimental catchment

The *Barranca de los Pinos* (Fig. 2) is one of the many well developed sandy gullies scattered throughout the slopes of a set of mesas and cuestas of the northern piedmont of the Guadarrama Mountains of Central Spain. The gullied catchments occupy an area

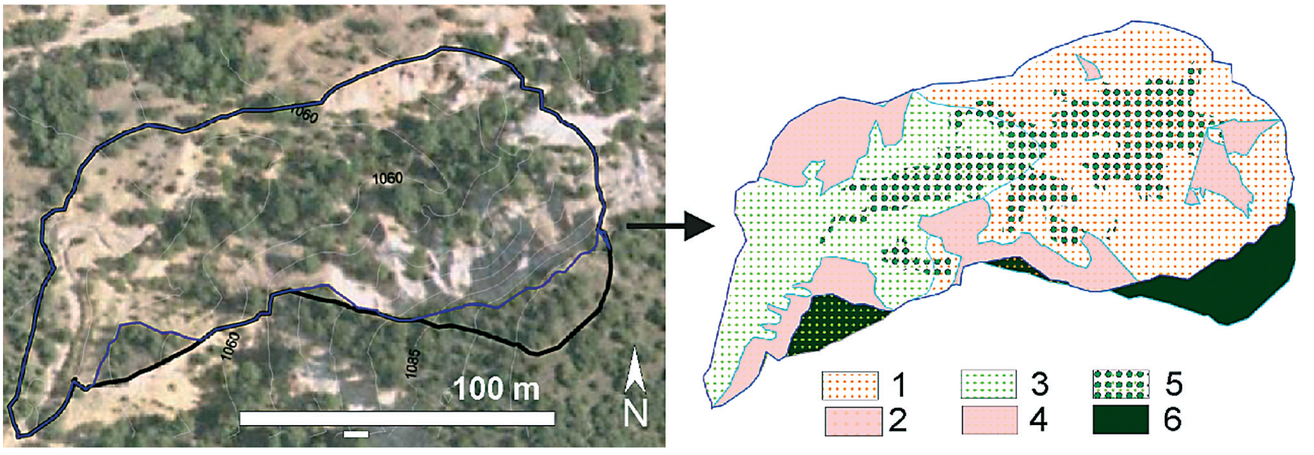

Fig. 2. *Barranca de los Pinos* experimental catchment and location of Hydrologic Response Units (HRU): 1 – exposed higher cohesive sands, 2 – limestone-dolostone colluvium deposits on higher cohesive sand substrata, 3 – exposed lower cohesive sands, 4 – limestone-dolostone colluvium deposits on lower cohesive sand substrata, 5 – exposed sands under pine canopy, 6 – ungullied slope

exceeding 18 km^2, underlain by Cretaceous sediments of marine (limestone and dolostone) and fluvial (sands, gravel and clay) origin. The catchment is capped by limestone and dolostone. The rest of the catchment substrata are mainly sands of two different geologic formations – *Arenas de Segovia* and *Arenas de Carabias* (Alonso 1981). The main difference between the two sandy formations is the dinimished cohesion within the lower slope. The sand is exposed in 85% of the gullied area, and only 15% of the gullied surface is covered by limestone-dolostone colluvium derived from the ungullied slopes and the caprock.

The area of the catchment (1.26 ha) was determined by a detailed topographical survey using a differential GPS. Altogether 90% of this area is gullied. The derived Digital Elevation Model (DEM) of 2×2 m shows steep slopes (20° and 60°) in the gullied surface. The main channel heads westwards, hence the dominant aspects of slopes are south and north. These slopes are dissected by secondary gully channels, which are more abundant in northern slopes. The drainage density of the channels visible in an orthophoto of 0.5 m pixel size is 40.9 km km^{-2}. The main channel has a longitudinal slope of 6.6% and its sediment is medium sand (D_{50} = 0.555 mm; Fig. 3).

The soils developed on the limestone-dolostone caprocks and colluviums are rendzic and calcic leptosols, and sandy cambisols where the substratum is sand. Most of the gullied surfaces lack soils; the sandy rocks and their regolith are exposed. Within the gullies the vegetation is very scarce, with some pine stands on sandy substrata. These were introduced 60 years ago by the Regional Forestry Agency of the region. The colluvium is covered by scattered junipers and holm oaks. The experimental catchment is located within a broad region, the climate of which is Continental Mediterranean. The mean annual rainfall (registered nearby during 79 years) is 677 mm. The mean temperature is 11.9°C (INM 2001).

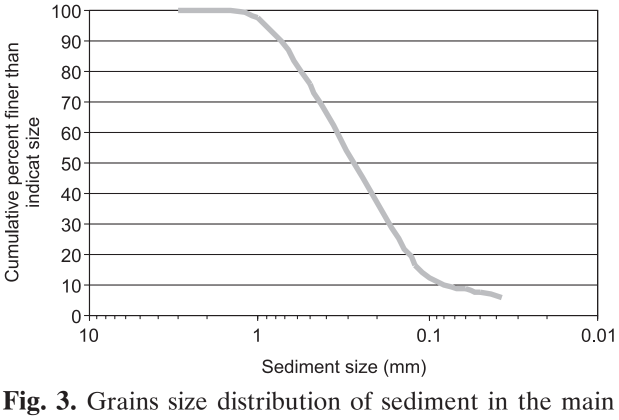

Fig. 3. Grains size distribution of sediment in the main channel of the experimental catchment

Methods

The experimental methods are concentrated in a representative experimental catchment (*Barranca de los Pinos*, Orejana Municipality, Segovia Province). They are grouped in three categories: fluvial activity measurements of sediment transport and water discharge, slope activity measurements by means of TLS and erosion and runoff measurements at the plot scale.

Fluvial activity measurements – sediment transport

The fluvial activity is being monitored at the outlet of the catchment. Bedload is monitored continuously and automatically by two independent, side-by-side Reid-type slot samplers (Reid et al. 1980). This apparatus samples and weighs a slot width portion (the slots can vary from 0 to 160 mm; with the maximum aperture, both samplers represent 26% of the channel width) of the total bedload transported in the channel. The cumulative mass of the sediment entering and filling each sampler is monitored by means of a pressure transducer connected to a pressure pillow (having a pressure-mass calibration) upon which an internal box is located. A separate, calibrated pressure transducer is located inside the sampler but outside the inner box to monitor the pressure of the water column. These vented pressure transducers are connected to a data logger registering each 30 s the average of three 10 s readings. For every 30 s time interval the difference in added pressure between the pillow and the water column is the added pressure of sampled bedload. Details of the functioning and use of the Reid bedload sampler are provided elsewhere (Laronne et al. 2003).

The specific characteristics of our two samplers are:

- slot width is adjustable (0–160 mm);
- the volume of each of the metal boxes is 0.225 m^3. This dimension was calculated from the sediment yield assessments made in the two sediment traps, gabion and metal box (Lucía et al. 2008). Because of the size of the inner box, the sensitivity of the bedload sampler is estimated to be 0.3 kg (Laronne et al. 2003). The effectiveness of the sampler is considerably reduced when it is 80% full (Habersack et al. 2001), hence bedload data will be used up to this stage of sampler filling;
- the length of the slot is 65 cm, so designed given that 90% of the GSD is sand and is mainly transported by saltation and the saltation length of the sand particles was estimated using the following expression:

$$\lambda b/D = 3D^{*}\ 0.6\ \mathrm{T}0.9 \tag{1}$$

where:

$\lambda b/D$ – is the nondimensional transport rate with an accuracy of 50%,

D^{*} – the nondimensional sediment diameter,

T – the transport stage parameter; the calculated saltation length is 8.8 cm, hence the saltations lenght is expected not to exceed 18 cm; to ensure that sand will saltate beyond the slot, a broad safety factor was applied.

A Parshall flume was installed downstream of the bedload sampler to monitor water discharge. The elevation of the water surface is measured in a stilling well by a vented pressure transducer. This transducer is also connected to the data logger, so the measurements of bedload and water discharge are logged simultaneously.

Altogether six siphon samplers were installed in one of the sides of the Parshall flume. They were placed at different heights to sample the suspended sediment during hydrograph rise. Figure 4 shows the setting of the equipment at the outlet of the experimental catchment.

Slope activity measurements by means of Terrestial Laser Scanner (TLS)

Detailed topographical surveys are being carried out with a TLS to quantify the activity of gravitational and runoff (e.g., rilling and cone deposition) processes in sediment source areas within the experimental gully catchment. The TLS model is a Leica Scan Station 2, which can reach a precision of 2 mm at a scanning distance <120 m. In total, 8 gully locations have been identified and scanned with a spatial resolution which ranges from 0.5×0.5 cm to 1×1 cm. The point cloud (Fig. 6) is 'cleaned' using the Cyclone software. In this process, the scattered vegetation is removed from the data to obtain a representation of the gully surface. The cleaned cloud is exported in a .ptx format to the Polyworks software, where a Triangulated Irregular Network (TIN) digital model is constructed.

This 'time zero' DEM surface will be compared with later DEMs after gravitational movements or intense channelized (rill) runoff erosion occur in sediment source areas. This volume subtraction of DEMs will allow quantification of erosion and its location.

Erosion and runoff measurements at a plot scale

Six different Hydrologic Response Units (HRU) represent the experimental catchment. These have been identified according to their homogeneity in lithology, slope, surficial deposits and vegetation canopy. To understand their different hydrological and erosive response, micro-plots (0.25 m^2) have been deployed to compare their infiltration capacity, runoff and sediment production.

In order to not to disturb the studied catchment surface where fluvial activity is being monitored, representative locations of the six HRUs have been chosen in two adjacent gullies separated by the divide of the main gully. Three micro plots (0.25 m^2), which

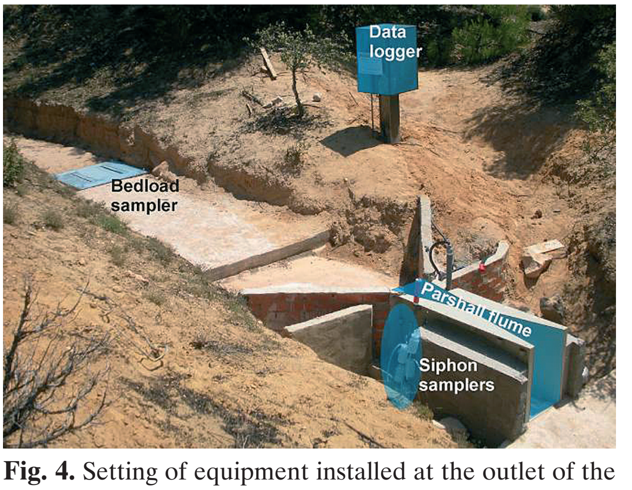

Fig. 4. Setting of equipment installed at the outlet of the *Barranca de los Pinos* experimental catchment

act as replicas of the experiment, have been installed in each HRU. Therefore, a total of 18 micro plots are currently under study. The HRUs have slight variations in aspect and gradient. To exclude the influence of these factors, the 18 micro plots were installed at constant gradient and aspect.

Rainfall

An automatic rain gauge (HOBO type) of 0.2 mm accuracy was installed. This rain gauge is located at mid-catchment elevation.

Results

The monitoring of the described new techniques started at the beginning of the hydrological year 2009–2010. Considering that the autumn of 2009 was exceptionally dry in the Segovia region, the accumulated precipitation represents less than the 50% of the mean annual till the 20th of November of 2009, (data obtained by the National Agency of Meteorology, AEMET). Only two small flow events were registered at the experimental catchment of the *Barranca de los Pinos*.

Figure 5 shows the record of the first event, which occurred on October 1, 2009. The bedload transport started after a cumulative rainfall depth of 7.1 mm and occurred with a mere 1.8 cm water depth in the channel. The cumulative rainfall depth during the event was 10.8 mm and the maximum intensity for a duration of 30 min was 3.2 mm h^{-1} or 0.36 mm min^{-1} = 26.6 mm h^{-1}. Interestingly, bedload has occurred at the inception of the flow during 6 min and was initiated from a flow depth of 0.35 cm to cessation at a 0.30 cm. Although the flux of bedload is small with reference to the shallow (low shear stress) flow, values in the range 0.2–0.5 kg sm^{-1} are considered high. Hence, considerably higher fluxes will occur in somewhat larger flow events.

Figure 6 shows an image of the point cloud obtained with the TLS at one of the inner locations of the experimental catchment. It corresponds to the caprock of the gully's headwall; the pine canopy and the sandy slopes are also seen. Because no movement has occurred as yet, a comparison of Digital Elevation Models (DEM) has not yet been made.

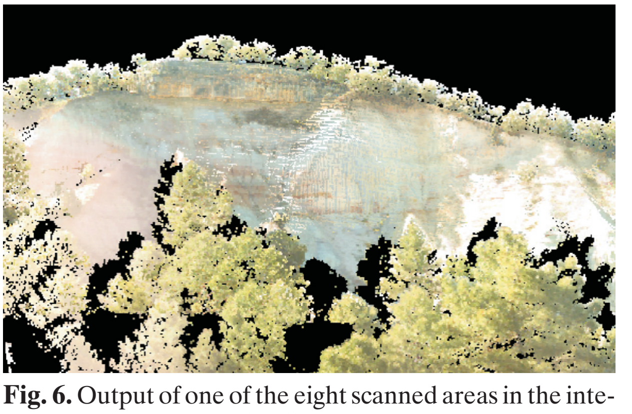

Fig. 6. Output of one of the eight scanned areas in the interior of the monitored gully

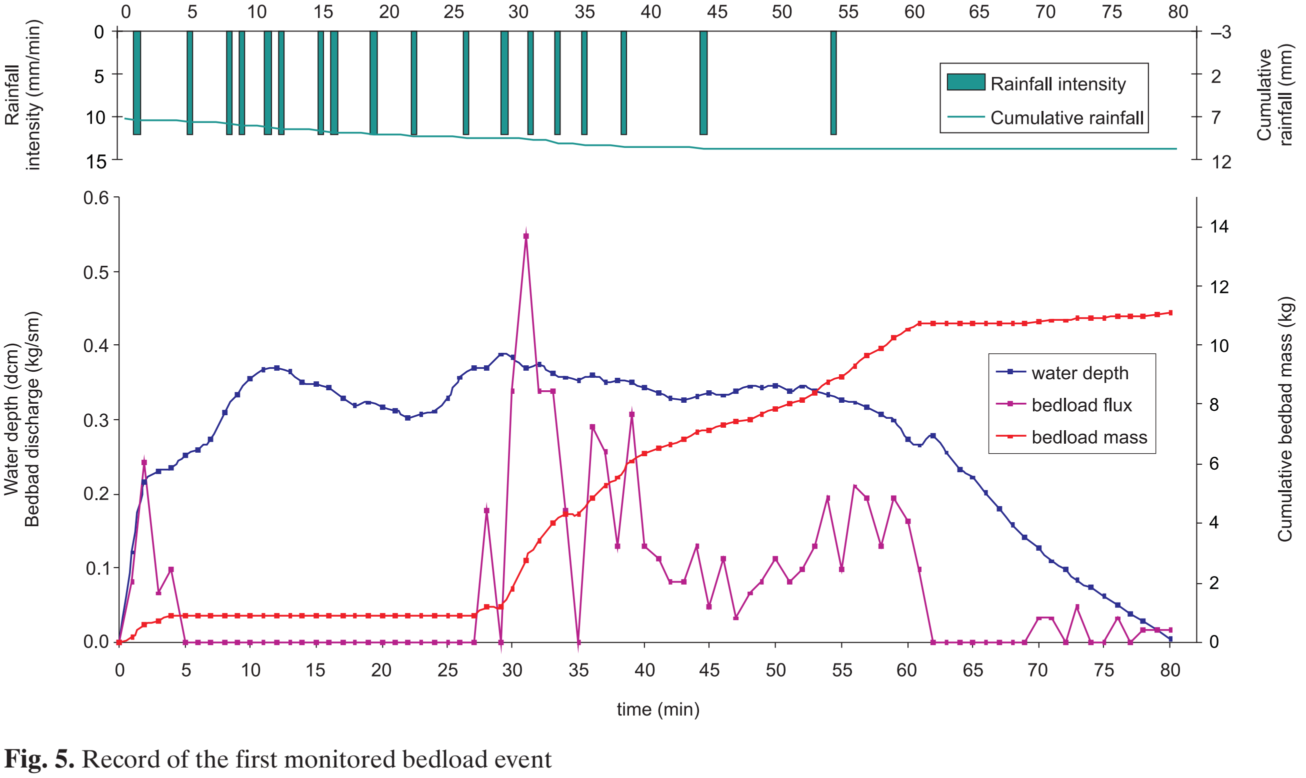

Fig. 5. Record of the first monitored bedload event

Discussion

The methods initiated at the *Barranca de los Pinos* experimental catchment are deployed to record the geomorphic activity within this sandy gully. The interest of such monitoring derives not only from the landscapes being rare, but also from the novelty of the two techniques (Reid-type bedload sampler and TLS) for this environment (sand slope gullies), by the joint use of different methods to track sediment movement, and due to the interrelations between human activity (quarrying), gullying and its effects. The scarce literature on the geomorphic activity on sand gullies is expected to secure considerable interest in the forthcoming results from this experimental catchment.

Acknowledgements

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