EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **36**, 1604–1623 (2011)

(wileyonlinelibrary.com) DOI: 10.1002/esp.2172

Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment

Irene Marzolff,[1]* Johannes B. Ries[2] and Jean Poesen[3]
[1] Department of Physical Geography, Johann Wolfgang Goethe University, Frankfurt am Main, Germany
[2] Department of Physical Geography, University of Trier, Trier, Germany
[3] Division of Geography, Department of Earth and Environmental Sciences, K.U.Leuven, Heverlee, Belgium

Received 10 January 2011; Revised 1 April 2011; Accepted 20 April 2011

*Correspondence to: I. Marzolff, Department of Physical Geography, Johann Wolfgang Goethe University, Frankfurt am Main, Germany.
E-mail: marzolff@em.uni-frankfurt.de

ESPL
Earth Surface Processes and Landforms

ABSTRACT: This study investigates how medium-term gully-development data differ from short-term data, and which factors influence their spatial and temporal variability at nine selected actively retreating bank gullies situated in four Spanish basin landscapes. Small-format aerial photographs using unmanned, remote-controlled platforms were taken at the gully sites in short-term intervals of one to two years over medium-term periods of seven to 13 years and gully change during each period was determined using stereophotogrammetry and a geographic information system. Results show a high variability of annual gully retreat rates both between gullies and between observation periods. The mean linear headcut retreat rates range between 0·02 and 0·26 m a^{-1}. Gully area loss was between 0·8 and 22 m^2 a^{-1} and gully volume loss between 0·5 to 100 m^3 a^{-1}, of which sidewall erosion may play a considerable part. A non-linear relationship between catchment area and medium-term gully headcut volume change was found for these gullies. The short-term changes observed at the individual gullies show very high variability: on average, the maximum headcut volume change observed in 7–13 years was 14·3 times larger than the minimum change. Dependency on precipitation varies but is clearly higher for headcuts than sidewalls, especially in smaller and less disturbed catchments. The varying influences of land use and human activities with their positive or negative effects on runoff production and connectivity play a dominant role in these study areas, both for short-term variability and medium-term difference in gully development. The study proves the value of capturing spatially continuous, high-resolution three-dimensional data using small-format aerial photography for detailed gully monitoring. Results confirm that short-term data are not representative of longer-term gully development and demonstrate the necessity for medium- to long-term monitoring. However, short-term data are still required to understand the processes – particularly human activity at varying time scales – causing fluctuations in gully erosion rates. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: gully development; human impact; small-format aerial photography; photogrammetry; semi-arid regions

Introduction

The evaluation of gully development rates under various climatic and land-use conditions provides important data for modelling gully erosion and predicting impacts of environmental change on this major soil erosion process. Soil erosion by water has been receiving a lot of attention from scientists, soil conservationists and policy-makers. However, the main focus of investigations has been and continues to be on sheet and rill erosion rather than on gully erosion. In Europe, for instance, more then 2200 plot-year data on annual soil loss by sheet and rill erosion have been published over the last decades (Poesen *et al.*, 2006), whereas during the same period less then 50 gully-year data on annual soil loss by gully erosion were reported (Poesen *et al.*, 2011).

Among the reasons for this scarcity of data are the methodological difficulties associated with the temporal and spatial scales and variability at which gully erosion occurs. Gully erosion is usually caused by intense and hence rather infrequent rainfall events, making it difficult to capture by regular monitoring. The wide range of sizes and forms of gullies often are beyond the traditional scale for investigating soil erosion by water, and at the same time, gullies may develop in locally very restricted parts, with active retreat areas shifting irregularly between headcut, sidewalls or individual gully branches. Gullies may be subject to rapid cycles of alternating incision and infilling, and material eroded at the gully edges may be deposited within the gully, not even leaving the system during the same observation period (e.g. Vanwalleghem *et al.*, 2005a; Marzolff and Poesen, 2009). Thus, linear, areal and volumetric retreat rates are not necessarily proportional or deductible from each other. Also, gullying involves a wide range of subprocesses related to water erosion and mass movements, such as headcut retreat, piping, fluting, tension-crack development and mass wasting, and it is the complex interaction of these subprocesses on varying time scales which complicates reliable measurements as well as forecasting by gully erosion models. Therefore, Poesen *et al.* (2003) have called for increased efforts in establishing appropriate and standardized monitoring techniques enabling the study of gully development with a higher precision than that obtained by current techniques, and for more detailed monitoring, experimental and modelling work to increase the capacity to predict impacts of environmental changes on gully erosion rates.

Considering this variability in the spatial and temporal development of gullies, ideal gully erosion data should be spatially detailed and continuous, three-dimensional (3D), of sufficient duration to avoid a bias due to short-term fluctuations, and taken at frequencies that accurately capture the erosion dynamics. Obviously, such data do not exist and would require great efforts in collecting. Reported studies on gully erosion rates only partly meet these requirements. Spatially and temporally detailed studies, usually conducted by rather intensive fieldwork, rarely exceed short-term durations of three to five years (e.g. Oostwoud Wijdenes and Bryan, 2001; Vandekerckhove *et al.*, 2001; Hu *et al.*, 2007; Wu *et al.*, 2008; Brooks *et al.*, 2009; Rodzik *et al.*, 2009). Medium (5–15 years) to long-term studies (> 15 years) are more often based on existing aerial photography, analysed in retrospect, and consequently of much lower spatial and temporal resolution (e.g. Nachtergaele and Poesen, 1999; Martínez-Casasnovas *et al.*, 2003, 2009; Vandekerckhove *et al.*, 2003; Campo *et al.*, 2006).

Analysis of some of the rare existing medium to long-term data on gully erosion by Vanwalleghem *et al.* (2005b, Figure 4) disclose that gullies show a degressive exponential increase of volume and length during their lifetime. This non-linear retreat behaviour cannot sufficiently be described by (usually highly variable) short-term data – even less so when there are no clues as to the stage of age into which the current measurements fall. Consequently, the following questions need closer examination in order to improve the value of short- to medium-term monitoring data on gully development rates:

- Do medium-term data inform us better about the development of a gully?
- How do medium-term averages differ from short-term and from long-term averages of gully erosion?
- What are the causes for fluctuations in gully retreat rates (a) in the short term, (b) in the medium term?
- Which processes at the gully itself and within the gully catchment are responsible for the spatial and temporal variability of gully development?

The objectives of this paper are to address these questions and to demonstrate that spatially detailed and continuous, medium-term monitoring data on gully erosion are much superior to short-term data for capturing and interpreting the medium-term development of gullies and for differentiating between the individual subprocesses involved.

Study Area

The gullies analysed in this study (Figure 1 and Table I) are situated in four Spanish basin landscapes – the Ebro Basin (Barranco des las Lenas, Barranco Rojo), the Guadalentín Basin (Salada 1 and 3, Luchena 1), the Baza Basin (Freila A and B) and the Guadix Basin (Casablanca, Belerda 1). Particularly in southeast Spain, gullies are prominent features in the landscape, and a large number of studies resulting from a long tradition of research on soil erosion in Spain (e.g. Bennett, 1960; Sala, 1991; Solé Benet, 2006; García-Ruiz, 2010) show that gully erosion plays an important role on the Iberian Peninsula. The semi-arid climate prevailing in Spanish agricultural regions, the erodibilities of the soils and a long history of land use and land-use changes are among the key factors controlling soil-erosion processes in Spain (Thornes, 1976; Poesen and Hooke, 1997).

As is known from previous studies (e.g. Vandekerckhove *et al.*, 2000; see Poesen *et al.*, 2011 for a review), catchment area is the most important topographic parameter controlling concentrated flow discharge and hence gully-head development. Thus, the selected permanent gullies were chosen to span a wide range of catchment areas while representing

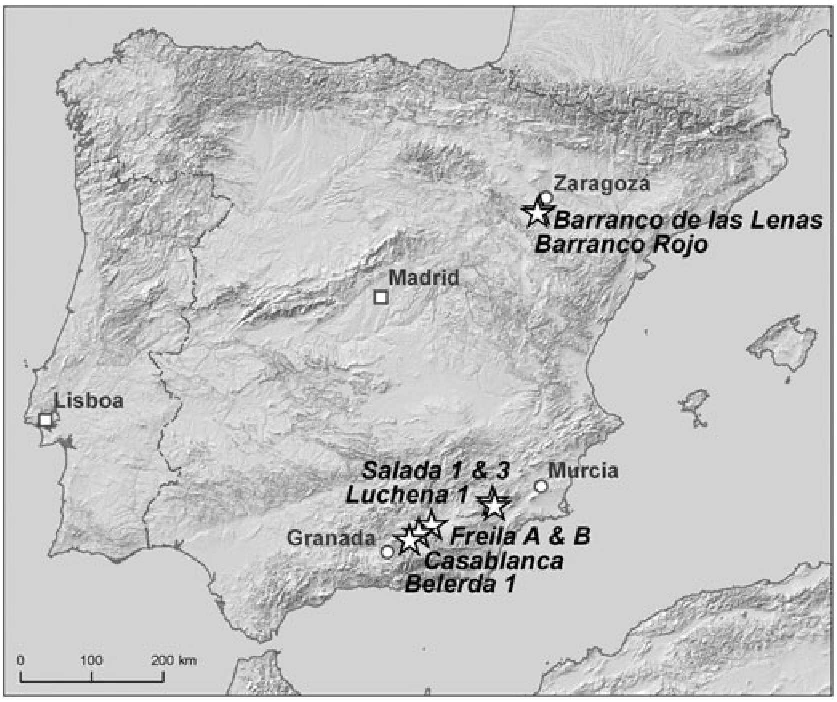


Figure 1. Map of the location of the gully sites in Spain.

Table I. Characteristics of gully sites used in this study. Catchment size defined as the area draining to the headcut at beginning of the monitoring (GPS measurements and aerial photograph analysis)

Gully site	Geology/lithology	Current land use/land cover	Gully catchment size (ha)	Monitoring period (yr)
Barranco de las Lenas (MDH2)	Holocene valley fill in Miocene sediments, loamy sands	Sparse matorral, abandoned fields	2·2	13
Barranco Rojo (BR)	Holocene valley fill in Miocene sediments, sandy loams	Cereal fields, young fallow land	4·6	7
Salada 1 (SA1)	Pleistocene valley fill; sandy loams	Almond plantation	21·3	6/11[a]
Salada 3 (SA3)	Pleistocene valley fill; sandy loams	Young fallow land	1·3	11
Luchena 1 (LU1)	Miocene sediments, marls	Very sparse matorral	0·08	10
Freila A (FR-A)	Modern-age valley fill in Pliocene sediments, silty-loamy sand	Rangeland, abandoned fields	4·3	7
Freila B (FR-B)	Modern-age valley fill in Pliocene sediments, silty-loamy sand	Rangeland, abandoned fields	1·2	7
Casablanca (CAS)	Holocene valley fill in Pliocene sediments, silty sand	Rangeland, recent afforestation	3·3	7
Belerda 1 (BEL1)	Pleistocene valley fill; sandy loams	Cereal fields, olive and almond plantations	1622	1/13[b]

[a] Gully head infilled after six years; erosion parameters taken from the first six years.

[b] Aerial photomonitoring started in 2008; values of previous years estimated from terrestrial photographs and measurements.

typical active gullies, following the criteria identified by Oostwoud Wijdenes *et al.* (2000). All four Spanish basin landscapes have a semi-arid climate, with average annual precipitation around 310 mm in the Ebro Basin and Guadalentín, and 325–390 mm in the Baza and Guadix Basins. The current land use (cf. Table I) varies from cropland to abandoned fields to matorral shrubland. In the cultivated area, almond and olive plantations and dry-farming systems (*secano de año y vez* or *al tercio*) with cereal (mostly barley) and unseeded fallow (*barbecho blanco*) rotation are typical. Abandoned cropland, which is often grazed, usually shows sparse vegetation cover of matorral succession stages (open *Lygeum spartum* or *Stipa tenacissima* formations, or open *Thymus vulgaris* garrigues).

In the central Ebro basin south of Zaragoza, the Miocene clay, gypsum and marl series are mainly dominated by gypsum and form an impressive erosion landscape. This landscape is characterized by buttes and mesas (*plataformas estructurales*) with mainly straight to convex curved upper and mid-slopes. Their transition to the debris-covered footslope (Span. *glacis*) is recognizable by a characteristic change in gradient. The *glacis* merge smoothly into the flat valley bottom. They are covered by open *Rosmarinus* matorral and are used as pasture land for sheep and goats where not too steep (their gradient may reach up to 55°). The Holocene valley fills (local name: *val*), with slopes of 3° to 5° and a thickness of up to 20 m, are composed of alternating layers of silty loams, sandy-loamy to sandy silts, clayey loams as well as loamy clays, interrupted by 5–20 cm thick discontinuous stone and gravel layers with silty-sandy matrix. They are mostly used for agriculture – mainly barley cultivation – but large parts of these areas have been abandoned several decades ago and are nowadays covered by *Artemisia* steppe or *Lygeum spartum* grass. Gullies have been incising the valley fillings since post-Roman times.

In the Guadalentín basin, the landscape can be described as a basin and range topography. The intermountain sedimentary basins consist of marls and marly limestones of Cretaceous to Tertiary age, covered by Quaternary deposits. These basins were uplifted in the late Neogene and early Quaternary, and consequently, the valley bottoms were incised by ephemeral rivers from which the studied bank gullies developed into the lower hillslopes with a mean slope of 8.7°. The Quaternary sediments consist of alluvial and slope deposits, but they often have an undifferentiated composition, and are difficult to distinguish from each other. Current land use is a mixture of cropland (mainly wheat), orchards (almond), abandoned cropland, matorral and forest (Oostwoud Wijdenes *et al.*, 2000; Vandekerckhove *et al.*, 2000).

The Guadix basin is a wide intermountain sedimentary basin between the Sierra Nevada, the Sierra de Baza and the Sierra Arana, uplifted and dissected by an ephemeral river network. The studied gullies in this basin are located further away from the drainage divide in relatively flat surroundings having a mean slope of 2.5°, compared to the Guadalentín, where the distance from the gully heads to the drainage divides is generally smaller and the slope of the land steeper. In the Guadix area, a combination of Tertiary to Quaternary loams and marls are the most frequently occurring formations at the gully sites. Current land use is a mixture of mainly cropland (mainly wheat), orchards (almond and olives) and rangeland (Vandekerckhove *et al.*, 2000).

In the Baza basin, the gullies incise the 5°–20° sloping surfaces of Pliocene-Pleistocene pediments that have developed on Pliocene sediments dominated by marls and interspersed with calcareous crusts. The vegetation in this landscape is dominated by open *Stipa tenacissima* or *Thymus vulgaris* steppe, which are recently under moderate to intense grazing influence. The agricultural fields have been abandoned for more than 25 years. On these *abandonados*, the small areas of valley fills accumulated behind dry-stone walls are very susceptible to gully erosion.

Methods

Gully monitoring

Photographic surveys using various unmanned, remote-controlled platforms for small-format aerial photography were conducted at the gully sites at intervals of usually one or two years starting between 1995 and 2008 (Ries and Marzolff, 2003; Marzolff and Ries, 2007; Marzolff and Poesen, 2009). Depending on wind conditions, a hot-air blimp, a large rokkaku-type kite or (in recent years) an auto-piloted model airplane were employed for carrying analogue (until 2002) or digital single-lens reflex (SLR) cameras (Figure 2). Detailed descriptions of these systems can be found in Aber *et al.* (2010). At all gully sites, ground control points (GCPs) were permanently installed with steel pipes and measured with a total station in a local coordinate system to sub-centimetre accuracy. For the photographic survey, they were marked with red-and-white signals in order to

Figure 2. Platforms used for gully monitoring with small-format aerial photography. (left) Auto-piloted model airplane (wingspan is 1·6 m; kindly provided by MAVinci); (centre) hot-air blimp (length is 11 m) with double camera system; (right) large rokkaku-type kite (height is 2·5 m) with camera sledge.

make the GCPs well visible in the aerial photographs. The surveys were usually conducted at various heights (approximately 50–300 m) in order to collect detailed vertical photographs as well as overviews with stereoscopic overlap (Figure 3).

Gully change during each monitoring period was determined using photogrammetry and geographical information system software (Leica Photogrammetry Suite including IMAGINE StereoAnalyst, ESRI ArcGIS). This involved several steps of processing and analysis. First, bundle-block triangulation was performed for selected stereopairs of each date and gully in order to create georeferenced virtual stereomodels for 3D measurements and data collection. The complete gully edge was then mapped in the stereoviewing environment for one date, and changes along the edges were subsequently mapped for all other monitoring dates, resulting in 3D polyline shapefiles.

Within the geographic information system (GIS), change polygons were created from the polyline features. Each polygon was then attributed with the monitoring period, headcut/sidewall category, its area (as calculated from the geometry), its mean depth of lost soil material (as measured in the stereomodel) and its volume (as calculated from area × depth). To increase the accuracy of the volume estimation, large change polygons with irregular depths were split into two or more subpolygons with more uniform depths. This method of gully-retreat volume determination was preferred to a more automatic method of creating digital elevation models (DEMs) using digital image matching followed by DEM surface differencing that was for example used by Marzolff and Poesen (2009) or – from smaller-scale images – by Betts *et al.* (2003) and Martínez-Casasnovas *et al.* (2003). The reason is the accuracy problem at steep gully walls associated with the latter method: vertical or even overhanging walls and deep shadowing within the gully may result in considerable errors especially along the gully edges unless the automatically derived height measurements are carefully checked and corrected (for a more detailed discussion, see Marzolff and Poesen, 2009). Considering the abundance of steep walls in our gullies, which are all of the U-shaped bank-gully type, and given the small size of the individual change areas mapped from the high-resolution images, the interactive method of stereoscopically measuring change depth must be regarded as much more precise than automatic DEM modelling and computation of volume change would have been.

Various parameters of gully retreat were computed from the GIS data and tabulated for each gully and monitoring period: Areal (A_e a^{-1}) and volumetric (V_e a^{-1}) change per year were calculated for both headcut and sidewalls; gully edge length was calculated for headcut, active sidewalls, all sidewalls and all edges. Two different measures of linear retreat – both for the entire monitoring period and normalized per year – were determined for headcut and sidewalls. The value of R_{max} was measured as the distance perpendicular to the gully edges at the point of maximum change between two monitoring dates, using measurement tools in the GIS environment. As a simple and common measure of gully development, linear retreat rates reflect the average annual backward migration of gully heads in the upslope direction of the drainage line and thus the increase in gully length. Other than this simple measure, which is most commonly used in gully monitoring research (Poesen *et al.*, 2011), the average linear retreat rate in all directions (R_l or R_l yr^{-1}) – as defined in Vandekerckhove *et al.* (2001) – also takes into account the widths on which headcut retreat occurs, and was calculated by dividing the area change by the length of the changed gully edge.

The details of the gully forms are easy to perceive in 3D view of the stereomodels, often appearing spectacularly realistic. Although mapping the gully extent initially seems simple and straightforward, there are several methodological issues that need standardized procedures and reproducible decisions when it comes to drawing a line in the actual sense of the word. The gully walls are rarely perfectly vertical, but usually more or less sloping or overhanging. Small area changes at the gully edge often do not involve loss of soil material along the full height of the wall (or depth of the gully). A realistic estimation of the mean depth of the lost volume of soil involves comparison with the earlier-date stereomodel and some interpretation using expert knowledge. Depending on the morphology and position, many change areas were not assigned the full gully depth at this position, but a realistic, lesser depth, when it was apparent that only the upper part of the wall had come off. Thus, the tendency to overestimate soil loss for gully retreat rates, which field studies using the full gully depth for volume calculation are inclined to, could be avoided in this study.

Regarding the distinction between headcut and sidewall, no universal definitions exist, although several authors do distinguish these two gully parts (e.g. Blong *et al.*, 1982; Bocco, 1991; Martínez-Casasnovas *et al.*, 2004). For the

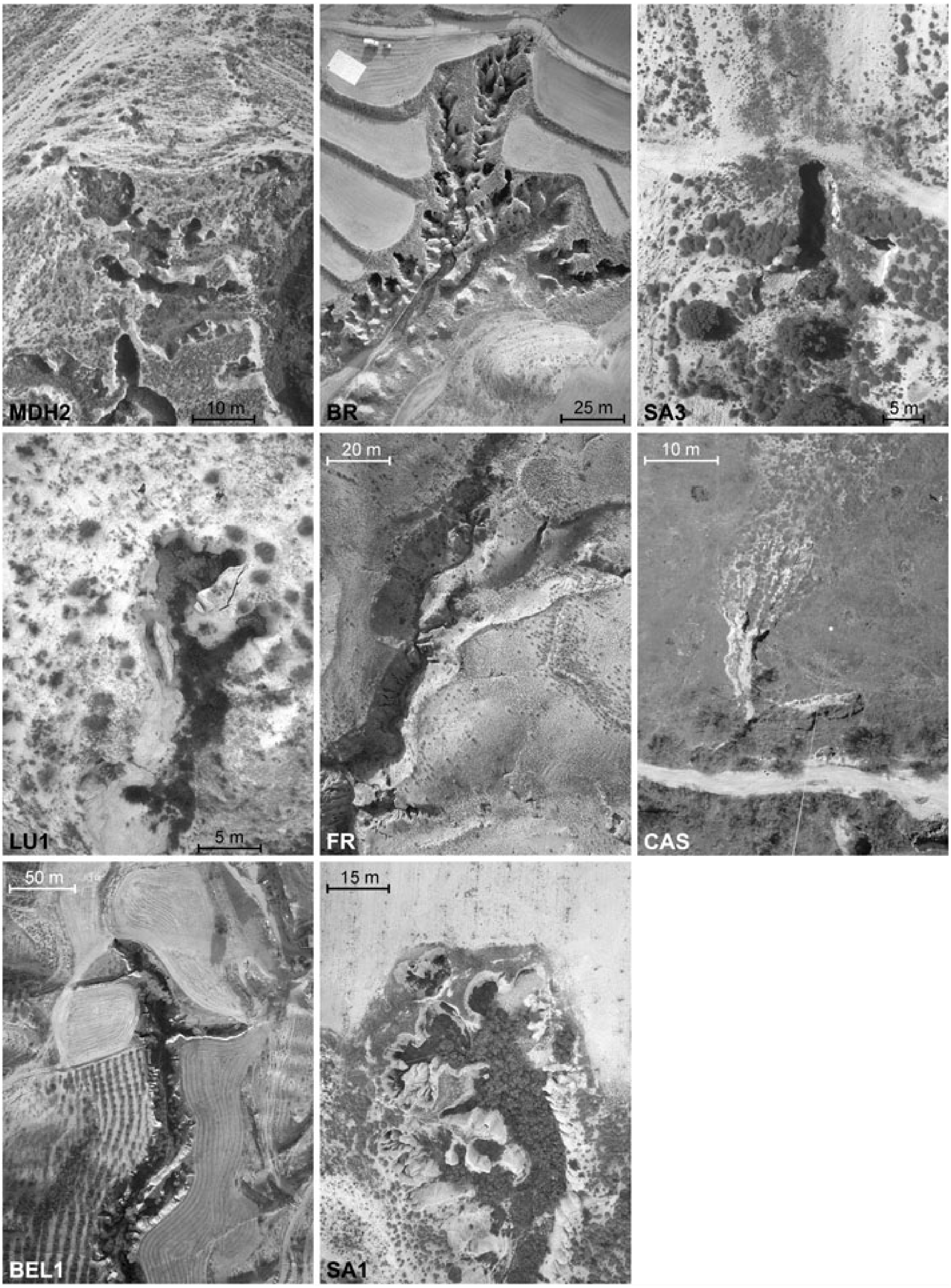


Figure 3. Large-scale aerial photographs of the gully sites taken from approximately 50–300 m height by hot-air blimp, kite or model airplane. MDH2, Barranco de las Lenas; BR, Barranco Rojo; SA3, Salada 3; LU1, Luchena 1; FR, Freila A and B; CAS, Casablanca; BEL1, Belerda 1; SA1, Salada 1 (state in 1998).

purpose of this study, "headcut" is defined as the upslope end of a gully branch, where the gully edge migrates backwards following a drainage line (i.e. smaller secondary headcuts may also appear at the sides of a dendritic system where the gully starts to branch off the main channel, following a slight or pronounced linear depression acting as drainage line; cf. Figure 4). The headcut section ends where the gully channel has reached its full width. Sidewalls are all other remaining channel edges. While a headcut receives more or less channelled surface runoff from the catchment, the sidewall usually does not and is thus much less subject to erosion by overland flow. The sidewall length measures, however, are affected by the definition of where a gully ends downslope: i.e. at the point where the gully channel runs out into a sediment fan, or in the case of a bank gully, where it joins the larger (river) channel or terrace bank. In this study, the gullies were monitored as far as there seemed to be a fair chance of gully sidewall activity; all but Casablanca and Freila B continue farther downslope in reality.

The headcuts of several gullies – Salada 1, Salada 3, Luchena 1 and Belerda 1 – had been monitored with field measurements using reference pins and measuring tapes in 1997, 1998 and 1999 (Vandekerckhove *et al.*, 2001). In these cases, the gully-head retreat data analysed from the aerial photographs since 1998 could be supplemented with earlier headcut volume data (included as period 1997–1998 in Figure 4). Belerda 1, where field measurements were taken in 1997 and 1998, but photo-monitoring began only in 2008, had additionally been documented regularly with terrestrial ground photographs since 1996. In order to extend the monitoring period back in time, these oblique ground photographs were registered with the aerial photographs by image-to-image rectification. Although the resolution and geometric quality of these warped images are limited, the large size and development speed of this gully allowed mapping of headcut retreat – albeit not as spatially detailed – between 1996–2006, thus supplementing the vertical airphoto maps of 2008–2009 (see Figure 4). The channel depth measurements for deriving the eroded volume between 1996–2006 were analysed retrospectively from the stereophotographs of 2009. Sidewall retreat was not analysed for Belerda 1 but can be regarded as insignificant over the period 1997–2009.

There are three types of possible errors involved in this method: the accuracy of the photogrammetric restitution, the accuracy of the gully-edge definition, and the accuracy of the depth measurements. The first is dependent on the image resolution, precision of ground control measurements and accuracy of camera calibration; it varies between the individual surveys (with a tendency towards improvement in later years due to optimization in survey design and camera models) and is typically between 2–3 cm for X/Y and 5–7 cm for Z (Marzolff and Poesen, 2009; Aber *et al.*, 2010). Both the accuracy of gully-edge delineation and depth measurements are affected by this photogrammetric error, but additionally depend on the precision with which the actual edge may be defined (high for sharp edges, lower for rounded edges) and the reliability of the actual change-depth judgement made by the interpreter as outlined earlier. For the edges, errors by uncertain locational definition were minimized by mapping the visibly changed parts of a gully only, relative to the existing outline of the earlier period. For depth measurements, the relative measurement accuracy is higher (usually 2–5 cm) than the absolute orientation accuracy, and as the depth of each lost soil lump is determined relative to the gully edge, the somewhat inferior absolute orientation of the stereomodel is of little consequence. Regarding the precision of depth assessment for those parts of the wall that have not failed along the full depth of the gully, but only in the upper portion, there is no possibility of independent validation, as it is based on stereo-interpretation, visual comparison with the previous period and process knowledge of the operator. However, the method employed must be judged more accurate than field measurements, as for the latter no possibility of direct comparison between the current and former state of the gully walls would exist, making it necessary to calculate with the complete local depth for each change area and thus risk an overestimation of soil loss.

Precipitation data analysis

Daily precipitation data from five rainfall stations were used for analysing the correlation of gully retreat to rainfall during the study period (Table II). For some later years, the data had to be complemented by other stations nearby. In three cases – until May 2007 for Barranco de las Lenas and Barranco Rojo, and until December 2006 for the Salada gullies – the rainfall stations are located close (1–4 km) to the gullies, in all other cases, the distance was between 7 and 20 km.

Following the results of rainfall threshold research conducted by various authors (Poesen *et al.*, 2003), it can be assumed that the total precipitation sum would be less correlated to gully volume change than the amount of higher-intensity rains within each period. Therefore, the total precipitation sum, the sum of precipitation > 10 mm per day, the sum of precipitation > 20 mm per day and the maximum precipitation per day occurring in the period was determined for each gully site and monitoring period. Linear regression was used to relate the total eroded volume (V_e) per period at both headcut and sidewall to these parameters with the aim to identify the factor that best explains gully retreat.

Results

A summary of gully erosion rates is given in Table III. It is immediately obvious that the dataset covers a wide range of erosion rates, with different magnitudes of area loss (factor 25) and volume loss (factor 200) for the studied gullies: while approximately 0·5 m^3

Table II. Rainfall stations used for the analysis of precipitation data at the gully sites

Gully site	Rainfall station	Distance to gully site	Data source
Barranco de las Lenas (MDH2)	Botorrita, supplemented by Zaragoza Aeropuerto since 5/2007	1·9 km (Botorrita) 17·5 km (Zaragoza)	Agencia Estatal de Meteorología de España (Botorrita) METEORED (Zaragoza)
Barranco Rojo (BR)	Botorrita, supplemented by Zaragoza Aeropuerto since 5/2007	2·3 km (Botorrita) 19·8 km (Zaragoza)	Agencia Estatal de Meteorología de España (Botorrita) METEORED (Zaragoza)
Salada 1 and 3 (SA1, SA3)	Zarcilla de Ramos, supplemented by Turilla la Paca since 1/2007	3·6 km (Zarcilla) 8·3 km (Turilla)	Agencia Estatal de Meteorología de España (Zarcilla) Ministerio de Agricultura, Pesca y Alimentación (SIAR system; Turilla)
Luchena 1 (LU1)	Zarcilla de Ramos, supplemented by Turilla la Paca since 1/2007	8·2 km (Zarcilla) 12 km (Turilla)	Agencia Estatal de Meteorología de España (Zarcilla) Ministerio de Agricultura, Pesca y Alimentación (SIAR system; Turilla)
Freila A and B (FR-A, FR-B)	Baza	11 km	Ministerio de Agricultura, Pesca y Alimentación (SIAR system)
Casablanca (CAS)	Guadix	15·5 km	Consejería de Agricultura y Pesca de la Junta de Andalucía and Consejería de Medio Ambiente (REDIAM system)
Belerda 1 (BEL1)	Diezma	7·4 km	Agencia Estatal de Meteorología de España

Table III. Summary of erosion parameters at the gully sites

Gully site	Monitoring period (yr)	D	$V_e\ a^{-1}$	$A_e\ a^{-1}$	$R_{max\ h}\ a^{-1}$	$R_{l\ h}\ a^{-1}$	H/S index
		(m)	(m³/yr)	(m²/yr)	(m/yr)	(m/yr)	
Barranco de las Lenas (MDH2)	13	1·2	1·41	1·10	0·088	0·016	0·5
Barranco Rojo (BR)	7	4·0	5·85	3·03	0·374	0·042	103·2
Salada 1 (SA1)	6/11[a]	10·0	108·41	21·75	0·516	0·262	58·1
Salada 3 (SA3)	11	4·4	7·26	2·07	0·151	0·059	0·5
Luchena 1 (LU1)	10	3·8	3·13	1·29	0·171	0·024	0·9
Freila A (FR-A)	7	2·1	2·90	2·97	0·615	0·097	12·9
Freila B (FR-B)	7	0·7	2·16	2·67	0·225	0·047	6·4
Casablanca (CAS)	7	1·5	0·49	0·84	0·074	0·016	1·1
Belerda 1 (BEL1)	1/13[b]	7·7	26·47[c]	3·51[c]	0·348	0·215[c]	—[c]

[a] Gully head infilled after six years; erosion parameters taken from the first six years.

[b] Aerial photomonitoring started in 2008; values of previous years estimated from terrestrial photographs and measurements.

[c] Headcut measurements only (sidewalls not measured).

D, mean gully depth in thalweg beneath main headcut (first monitoring date); $V_e\ a^{-1}$, eroded volume per year at both headcut and sidewalls; $A_e\ a^{-1}$, eroded area per year at both headcut and sidewalls; $R_{max\ h}\ a^{-1}$, maximum linear retreat per year at headcut; $R_{l\ h}\ a^{-1}$, mean linear retreat per year at headcut ; H/S index, ratio of volume headcut erosion to volume sidewall erosion.

of soil per year is eroded at Gully Casablanca, Gully Salada 1 grows by over 100 m^3 per year. Generally, deeper gullies show larger retreat rates than shallower gullies, and a positive exponential relation exists between mean linear headcut retreat rate per year ($R_{l\ h}\ a^{-1}$; in m/yr) and gully depth (D; in metres) at the headcut: $R_{l\ h}\ a^{-1} = 0{\cdot}0278\ e^{\,0{\cdot}2338\ D}$; $R^2 = 0{\cdot}53$; $n = 9$. Although D was measured in the gully thalweg beneath the main headcut, and depths along the channel banks of a gully differ continuously, it can still be used as a representative value for describing the general depth of each gully. Even higher ($R^2 = 0{\cdot}79$) is the correlation of mean annual eroded volume ($V_e\ a^{-1}$) with gully depth; however, because the depth at each changed gully section is involved in the calculation of V_e and not completely independent of general gully depth, this could be expected.

Spatial and temporal gully development

Results for the individual monitoring period at all gullies are shown in Figures 4 and 5. The spatial distribution of the changes documented in Figure 4 illustrates the different spatial growth behaviour of the individual gullies. Some tend to linear elongation with little or no sidewall erosion (Freila, Belerda), while others also grow considerably in width (Salada 3, Luchena). For Barranco de las Lenas and Casablanca, the changes are distributed rather evenly along the walls. Barranco Rojo grows less by linear headcut retreat but by widening of piping holes preceding the gully head (see later). Due to the varying depths and widths of the gullies, the mean linear retreat rates ($R_l\ a^{-1}$) may be rather similar in some cases even when the volume change differs considerably – compare, for example, Luchena 1 and Barranco Rojo (medium-term $R_l\ a^{-1}$ 0·033 m and 0·041 m, but medium-term $V_e\ a^{-1}$ 1·25 m³ and 5·8 m³). Salada 1 is not included in the maps because its peculiar evolution will be discussed later. The discrimination between headcut and sidewall is shown by the dashed line in the maps (Figure 4) and the stacked columns in the graphs (Figure 5); for the latter, additional headcut change values for the first periods at Salada 3, Luchena 1 and Salada 1 were taken from the research conducted by Vandekerckhove and Poesen (partly documented in Vandekerckhove *et al.*, 2001) as described earlier.

None of the gullies change in a regular fashion, and for some short-term periods, the differences with the medium-term average eroded volume – given as maximum above- and below-average percentage changes for headcut and sidewalls in the upper left corner of each graph in Figure 4, with respect to the medium-term average – is considerable. Negative deviations are as small as −100% (no sidewall changes at Gully Barranco Rojo and at Gully Freila B in 2002–2004 and 2008–2009 as well as no headcut changes at Gully Salada 3 in 2008–2009), and positive deviations are as large as +283% (headcut changes at Gully Salada 3 in 1997–1998). The largest sidewall change relative to the medium-term average (+249%) occurred along extensive stretches of the sidewalls of Salada 3 in 2004–2006, where whole parts of the nearly vertical or even overhanging wall have collapsed and accumulated in big soil lumps on the gully floor. With an $R_l\ a^{-1}$ of 0·13, this also corresponds to the by far highest mean linear sidewall retreat observed in the whole dataset. Looking at all gullies (Table IV), the above-average and below-average short-term fluctuations of headcut retreat are +66% or −52%, respectively, of sidewall retreat +63% and −57%, respectively: there is not much difference in variability of the two gully parts. For both headcuts and sidewalls, periods with above-average changes are rarer than periods with below-average changes, which conforms to the notion that high-erosion periods are associated with rather singular, heavy events.

The ratio between headcut and sidewall retreat rates (see H/S index in Table III and Figure 5) also varies significantly for the individual gullies. There is – apart from very small changes only visible in the map in Figure 4 – no sidewall change at one gully (Barranco Rojo) and less sidewall than headcut change for three gullies (Freila A and B, Salada 1; H/S indices 6·4–58·1). At Gully Casablanca, sidewall and headcut change are rather balanced with a H/S index of 1·1, but for further three gullies (Barranco de las Lenas, Salada 3 and Luchena 1), sidewall change is considerably higher than headcut change (H/S indices 0·5–0·7). In most cases where sidewall changes occur, they tend to decrease with larger distances from the headcut (Figure 4).

Role of precipitation

The relationship between precipitation and gully growth is shown in Figure 6. The sums of daily precipitations over 20 mm were found to correlate best with the total volumes eroded in the respective period – only in the case of Luchena 1 (the smallest catchment by far in the dataset) the total rainfall sum of all rain events yielded clearly better correlation coefficients. Here we can assume the highest runoff coefficients and because of the small catchment area also the highest sediment delivery ratio. With the exception of Luchena and Casablanca, headcut erosion shows a stronger dependency on rainfall, while the correlation of sidewall erosion with rainfall is usually weak or non-existent. No meaningful correlation with headcut change exists for Casablanca, and correlations for Belerda 1 and Barranco de las Lenas are very weak.

Role of catchment area

Among the many factors that control gully development, Vandekerckhove *et al.* (2000) demonstrated that the original catchment area – draining to the gully mouth – is the topographic parameter that correlates best with total gully volume. Consequently, the present drainage area at the headcut can be expected to correlate with annual headcut retreat. This

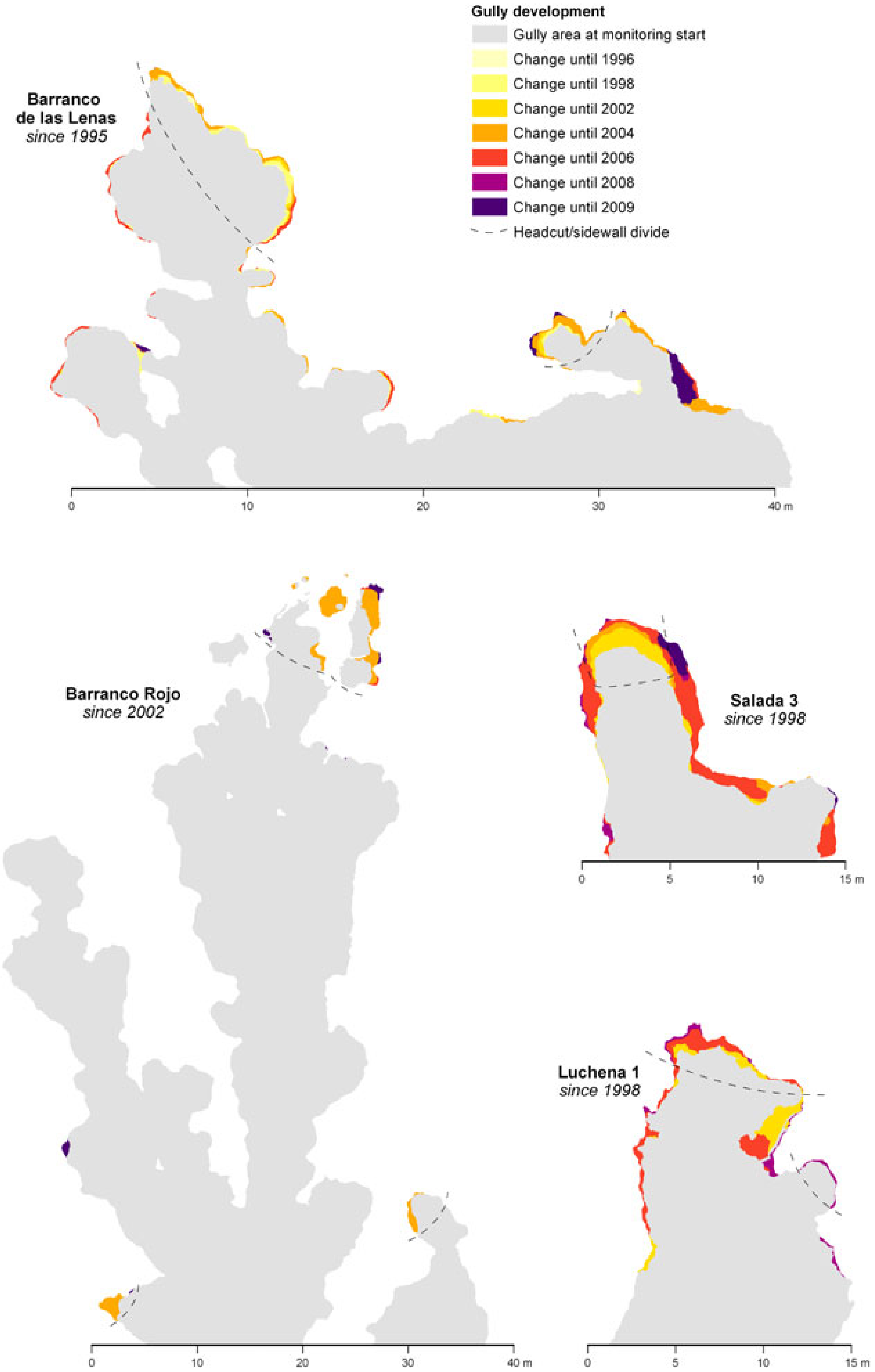


Figure 4. Gully development during the individual monitoring periods at gullies: (a) Barranco de las Lenas, Barranco Rojo, Salada 3 and Luchena 1 (note smaller scale of Barranco Rojo); (b) Freila A, Freila B, Casablanca and Belerda 1 (note smaller scale of Freila A and B).

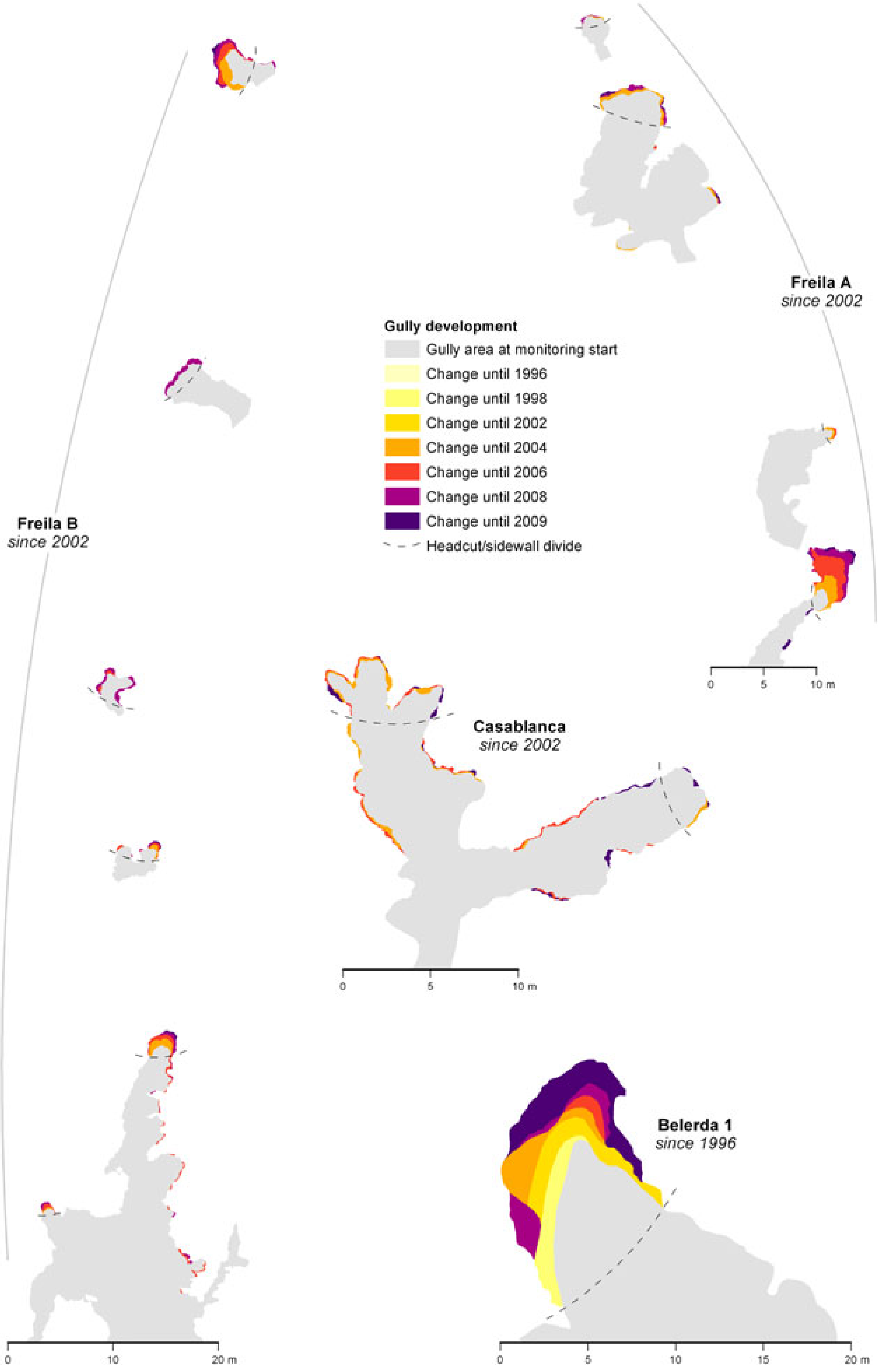


Figure 4 (*continued*)

was confirmed by Vandekerckhove *et al.* (2001, 2003) using short-term (two years) and medium-term (21–46 years) datasets of 46 or 21 gullies respectively in the Guadalentín and Guadix area. The increase of the coefficient of determination (R^2) they found for the short-term to the medium-term and long-term relationships were explained by the greater variability of the annual gully erosion rates measured over short periods, which is smoothed out over a gully's lifespan. Increasing the length of the observation period implies (1) a decreased variability in measured annual erosion rates as the effects of tension cracking, piping, gully wall collapse and spatially variable rainfall intensities average out in the longer term; and (2) an increased contribution of extreme rainfall events whereby the role of drainage basin in the erosion process becomes more pronounced, as runoff is then produced from the entire catchment and runoff transmission losses are much lower than at low intensity events (Vandekerckhove *et al.* 2003).

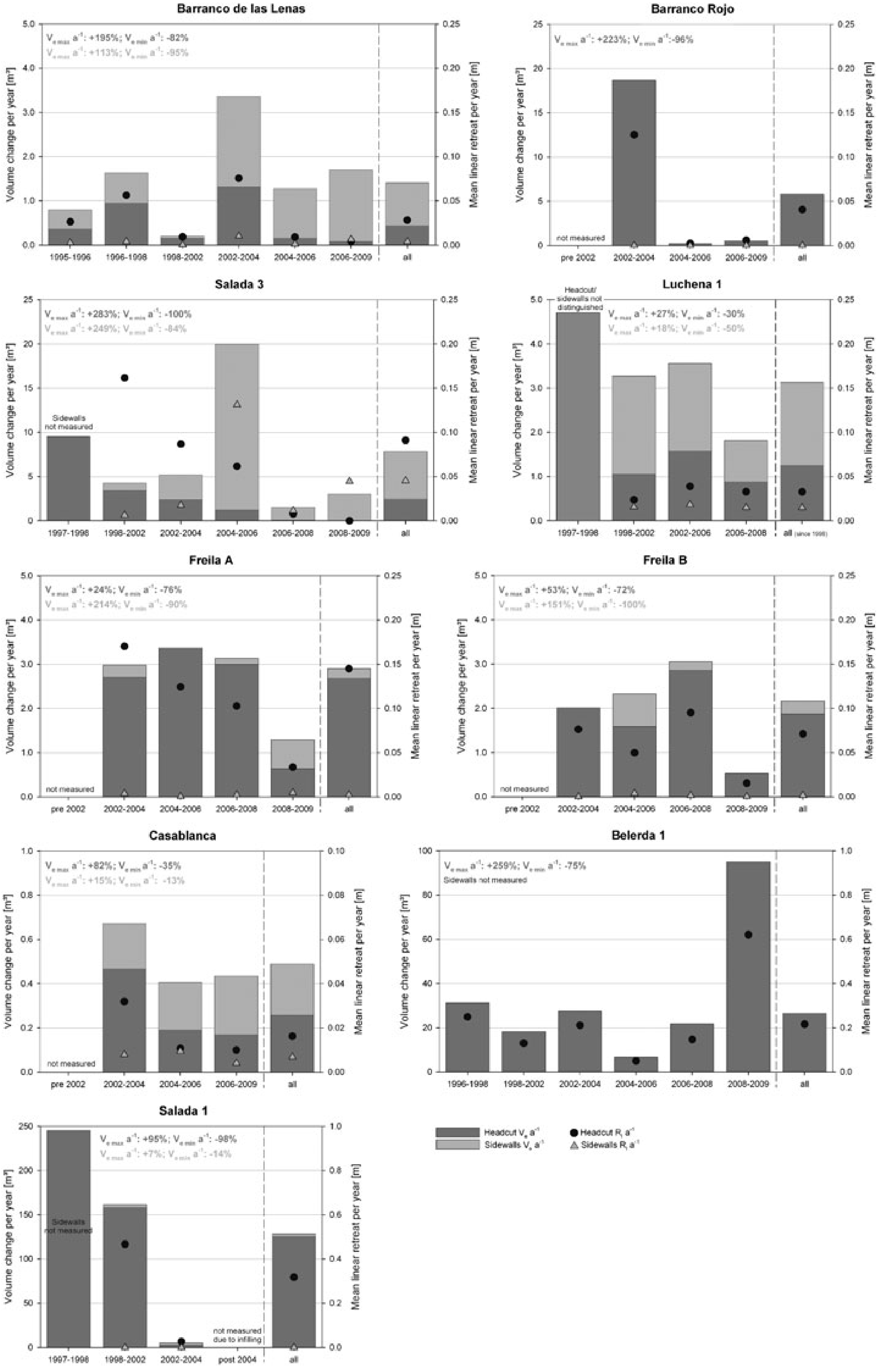


Figure 5. Gully volume change per year ($V_e\ a^{-1}$) and mean linear retreat rate per year ($R_l\ a^{-1}$) at headcut and active sidewalls for the individual monitoring periods (short-term) and averaged for the entire monitoring period (medium-term) at gullies Barranco de las Lenas, Barranco Rojo, Salada 3, Luchena 1, Freila A, Freila B, Casablanca, Belerda 1 and Salada 1 (1997–1998 values for Salada 1, Salada 3 and Luchena 1 taken from Vandekerckhove *et al.*, 2001). Note different scales on volume change axes. The maximum above- and below-average percentage changes ($V_{e\ max}\ a^{-1}$, $V_{e\ min}\ a^{-1}$; with respect to medium-term average) that occurred during the short-term periods for headcut and sidewalls are given in the upper left of each graph.

To analyse the general trend of the medium-term changes of the gullies (average values from seven to 13 years), their headcut development was plotted against the catchment area draining to the headcut in Figure 7 (black dots and solid trend line). The relationship is significant at the 95% level with an R^2 of 0·37. This compares well to the medium-term as well as short-term relationships found by Vandekerckhove *et al.* (2003) for the larger datasets of 21 and 46 gullies in the same south Spanish regions (dotted lines). As Figure 5 indicates high temporal variability of short-term gully change at our sites, the trend lines for the periods with minimum and maximum volume change per year (using the lowest and highest $V_e\ a^{-1}$ values for each gully) were also computed and added to the graph in Figure 7 (dashed lines). This enables us to simulate what the relationship would have looked like if we had happened to pick a period with low erosion rates or high erosion rates during a short-term monitoring project.

Discussion

Gully erosion variability

The medium-term relationship between catchment area and gully-headcut volume change for our dataset shown in Figure 7 is very close to that reported by Vandekerckhove *et al.* (2003) (note that the logarithmic scaling of the graph over-emphasizes the small absolute differences in volume-change prediction for small catchments). Apparently, measuring over a period of seven to 13 years in this environment (this study) yields very similar results to those obtained by longer-term monitoring (i.e. 21–46 years; Vandekerckhove *et al.*, 2003). The similarity of the two relationships thus suggests that the nine gullies used in this study present a representative selection of gullies in semi-arid Spain and the chosen medium-term period is long enough for describing even longer-term gully evolution. The short-term trend reported by Vandekerckhove *et al.* (2003) plots clearly below the medium-term trend found in both studies but well above the minimum short-term trend of this study, which can be attributed to the different dataset sizes. As the former study as well as Figure 5 show, the variability between the erosional behaviour of different gullies in any single short-term period may be very high, especially when their spatial distribution is dispersed enough to ensure that they are subject to different spatial rainfall patterns. Also, the within-gully variability between different short-term periods was shown to be high for both studies. The 46 gullies on which the study by Vandekerckhove *et al.* (2003) is based can be expected to show a wide range of above-average to below-average retreat rates (with respect to their individual long-term retreat trend) within the two observation years, owing to the spatial and temporal difference of precipitation patterns involved. Consequently, the average short-term trend observed at many gullies should indeed come near to the average trend of a few gullies monitored for longer periods – such as our medium-term dataset.

The short-term minimum and maximum trend lines for our dataset in Figure 7 confirm the high variability between the monitoring periods documented in the change graphs of Figure 5. On average (median of all gullies), the maximum observed headcut change was 14·3 times higher than the minimum change (standard deviation 49·5; mean 39·3). The height of the curves reflect the different amounts of eroded volume for the short-term and medium-term trends, but the general relationship with the catchment area is valid independent of the length of the observation period. Looking closely, the slope (as well as R^2) is lowest for the short-term minimum trend and highest for the short-term maximum trend – this might be interpreted as the more important influence of catchment size in times of high erosion. Large headcut retreat rates are likely to be associated with singular heavy-rainfall events, during which the large runoff rates can be expected to improve the connectivity within a catchment, increasing the probability that the effective runoff contributing area actually equals the topographically defined catchment area. This effect would be less pronounced for smaller catchments, where connectivity is relatively higher and even small runoff volumes may reach the gully and be erosive (see example of Luchena 1 later). Thus, the increased weighting of larger catchments during high-erosion events will lead to steeper slopes in the relationship of catchment size with headcut volume change, as observed here. However, these assumptions need yet to be confirmed with larger and longer-term datasets.

As the size of the catchment area in the earlier analysis actually serves as a proxy for runoff as the dominant erosional agent, the relationships were recalculated using the total amount of potentially erosive precipitation that had fallen during each period within the catchment (Table V). The effect of increasing slope is present here as well, and the strengths of the relationships increase (note higher R^2 and lower p-values). This reinforces the conclusion by Vandekerckhove *et al.* (2003) that catchment area becomes even more important in controlling gully-headcut erosion rates during extreme rain events, as the runoff connectivity within the catchment is then highest.

For all trends analysed in Figure 7, the strength of the relationship ($R^2 = 0{\cdot}35$–$0{\cdot}45$) is less than the respective long-term trend of original catchment size with total gully volume ($R^2 = 0{\cdot}65$) reported by Vandekerckhove *et al.* (2000). In the case of the medium-term trend found in our study, the deviation of the individual gullies from the trend line (see black dot

Table IV. Positive and negative deviations of short-term headcut and sidewall changes from the medium-term average for all short-term observation periods

	Headcut above-average changes	Headcut below-average changes	Sidewalls above-average changes	Sidewalls below-average changes
Mean of all gullies over all periods, weighted according to individual period lengths	+66·22%	−52·27%	+62·78%	−57·47%
Number of periods[a]	17	21	11	16
Cumulative lengths of periods (total observed time)[a]	38·15 years	48·33 years	30·65 years	33·48 years
Percentage of cumulative period length (percentage of total observed time)	44%	56%	48%	52%

[a] The summed total number and lengths of the headcut and sidewall values are not the same, because for some years the gullies sidewall change was not measured.

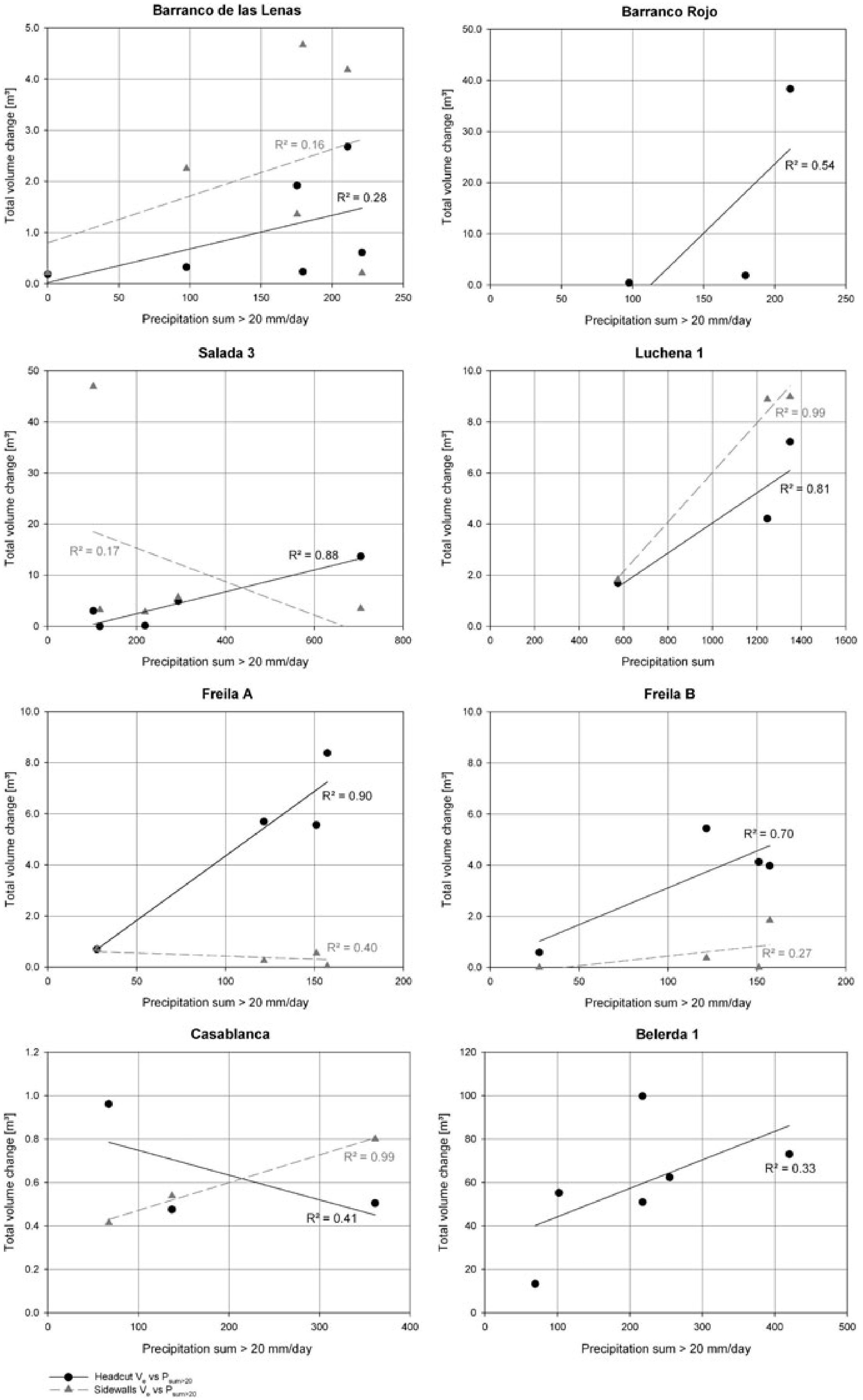


Figure 6. Linear regression of total gully volume change per year (V_e a^{-1}) versus precipitation sum for days with more than 20 mm precipitation ($P_{sum>20}$) (except for Luchena, where precipitation sum for all days was used) for the individual short-term monitoring periods at gullies Barranco de las Lenas, Barranco Rojo, Salada 3, Luchena 1, Freila A, Freila B, Casablanca and Belerda 1. Note different scales on *x*-axes and *y*-axes.

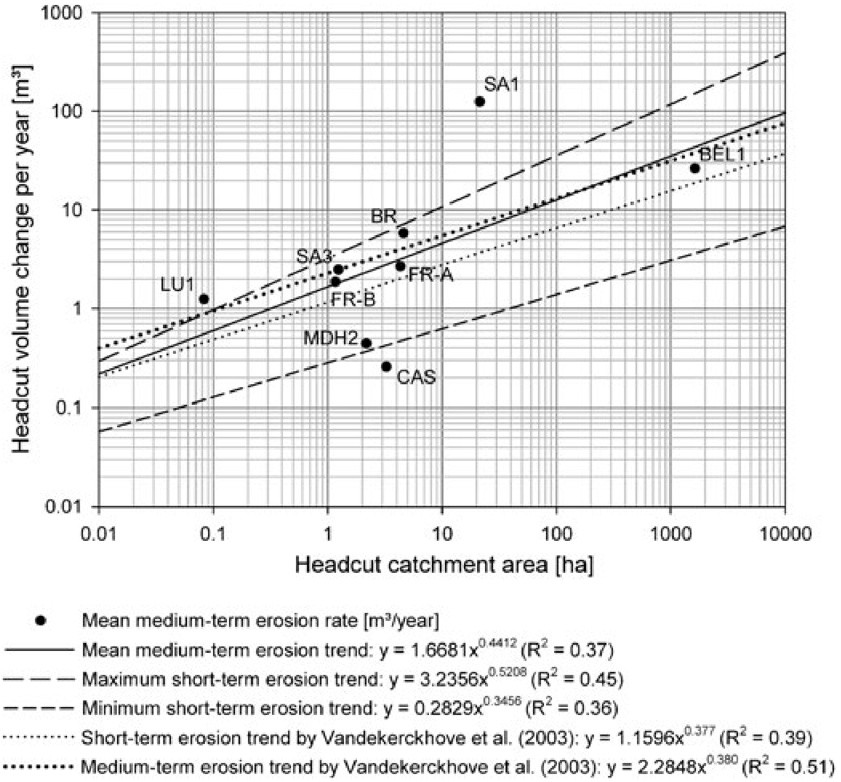


Figure 7. Non-linear regression of mean annual headcut volume change ($V_e\ a^{-1}$) versus headcut catchment area at all nine gullies as determined by medium-term monitoring (7–13) years), compared to short-term trends (1–3 years) as determined from periods with maximum and minimum volume change per year. The short-term erosion trend (two years; $n = 46$) and the medium-term erosion trend (21–46 years; $n = 21$) reported by Vandekerckhove *et al.* (2003; formulas converted to hectares) for southeast Spanish gullies is also plotted on this graph.

symbols in Figure 7) coincides with above- and below-average erosional behaviour that might be expected from their respective characteristics regarding local land use and human impact. Although not shown in Figure 7, similar positions of the individual gullies relative to the trend line were found for the relationship with potentially erosive precipitation analysed in Table V. In the following section, the individual gullies are discussed with reference to and in their order of appearance in Figures 4, 5 and 6.

In terms of retreat rates, **Barranco de las Lenas** gully is the slowest but one (Casablanca) in the dataset, and plots much lower than the average medium-term trend in Figure 7. From the map in Figure 4 it can be seen that over the complete observation period, all headcut rims are affected by a relatively regular retreat, although the spatial distribution and the amount of volume as well as mean linear retreat rate in all directions ($V_e\ a^{-1}$, $R_l\ a^{-1}$ in Figure 5) vary between the periods. Overall, however, headcut change is significantly smaller than sidewall change, the latter being mostly attributable to the collapse of a large part of tension-cracked sidewall before 2004 and 2009 (Figure 4). Rainfall analysis shows that there is no clear correlation between gully retreat and potentially erosive precipitation (Figure 6). The below-average position of this gully in Figure 7 is owing to the fact that the actual runoff-contributing catchment area may be much smaller during most times than the "topographically" delineated catchment due to a dirt track running across the catchment some 60 m upslope of the headcut. Regular levelling of this dirt road tends to create little dams of piled-up soil material along its margins. Thus, water flow from the road towards the gully may be prevented or, contrarily, be guided towards the gully through "dam breaches". As a result, the actual size of the gully catchment varies over time (Marzolff and Ries, 2007).

More than all other gullies, **Barranco Rojo** gully is subject to processes of subsurface erosion dominated by piping. Aerial photographs (Figure 3 BR) and detailed maps (Marzolff and Ries, 2007, Figure 4) reveal the evolution of the gully from a series of interconnected piping holes that have grown together by collapsing "interfluves". The occurrence and amount of piping involved in this gully's development may well be related to the

Table V. Results for the non-linear regression ($Y = aX^b$; $n = 9$) of annual gully headcut volume change ($V_e\ a^{-1}$) for the complete observation period (mean MT), the period with maximum change (max ST) and the period with minimum change (min ST) with headcut catchment area (CA; in hectares) and annual precipitation volume for rains > 20 mm/day ($P_{sum>20} \times$ CA; in litres × 1·00E + 04). R^2, coefficient of determination; *p*, *p*-value (probability of observation)

Relationship (*Y* versus *X*)	*a*	*b*	R^2	*p*
$V_e\ a^{-1}$ mean MT versus CA	1·6681	0·4412	0·37	0·0804
$V_e\ a^{-1}$ max ST versus CA	3·2356	0·5208	0·45	0·0466
$V_e\ a^{-1}$ min MT versus CA	0·2829	0·3456	0·36	0·0889
$V_e\ a^{-1}$ mean MT versus $P_{sum>20} \times$ CA	0·1349	0·5208	0·48	0·0380
$V_e\ a^{-1}$ max ST versus $P_{sum>20} \times$ CA	0·2172	0·5634	0·58	0·0168
$V_e\ a^{-1}$ min MT versus $P_{sum>20} \times$ CA	0·0475	0·4015	0·40	0·0655

land-levelling activities undertaken for the creation of the surrounding agricultural terraces: Piping holes and breaches of terrace banks can be observed at many places in the immediate vicinity. The volume change quantified for the "headcut" piping holes in Figure 5 most probably underestimates the real erosion rates, as the amount of subsurface erosion continuing within and between the piping holes cannot be estimated by the aerial photographs. Alternating use of the surrounding fields for cereal cultivation and fallow land results in repeated change of runoff conditions and highly variable runoff coefficients (Seeger *et al.*, 2009), which might contribute to the attenuation of the headcut retreat–rainfall relationship. The sidewalls at this gully are very stable and have not changed apart from very small sections (Figure 4).

Like Barranco Rojo, **Salada 3** gully performs slightly above-average in the medium-term trend analysis (Figure 7), and like Barranco Rojo, its surroundings are dominated by fallow land and cereal fields with varying, sometimes extremely high runoff rates up to 79% (as measured with rainfall simulation). However, piping processes are not involved in this gully's development – scour and plunge-pool erosion, undercutting and fluting at the headcut and desiccation and tension cracking at the sidewalls are dominating gully growth here (see also Vandekerckhove *et al.*, 2001). The difference of the processes involved in headcut and sidewall retreat are reflected by the rainfall analysis: correlation of headcut change with potentially erosive precipitation sums is high (Figure 6), indicating a strong dependency of surface runoff, but sidewall erosion is independent of precipitation. The failure of large parts of the gully sidewall between 2004 and 2006, which is recorded by the remarkable magnitude of change observed in Figure 5, may be connected with the unusual dry year 2005, which had received only 149 mm – less than half of the long-term average precipitation. The resulting desiccation of the walls may have encouraged shrinking and tension cracks. In the 2006 aerial photographs, large lumps of soil are visible on the gully floor; the sharp angularity of the lumps and lack of splash and flow marks suggest that the wall collapse has occurred not long before the aerial survey. In the 2009 photographs, water falling from the right, curving side of the gully edge (see Figure 4) has washed away most of the remaining soil lumps, leaving fresh flowmarks in a broad and still damp drainage line at the gully floor. The gully sidewall above, over which the water must have streamed, shows some retreat during the 2008–2009 period, for the first time since 1998. The water erosion of the gully floor – which is not recorded in the map and volume quantification – can be related to the heavy thunderstorms of mid and end September 2009 that affected all of southeast Spain, filling the daily news with reports of catastrophic inundations in Murcia, Alicante and the Balearic Islands (e.g. *El País*, 2009). Precipitation sums of 45 mm on 13 and 14 September and again 39 mm on 27 and 28 September were recorded in Zarcilla de Ramos, 4 km northeast of gully Salada 3; much of this precipitation having probably fallen in a very short time.

These same events have not been able to take effect at the Salada 3 headcut for a reason also documented by the 2009 aerial photographs: a small dam of soil material, not yet present on a field visit on 9 September, had been ploughed up by the farmer around the headcut, preventing overland flow from entering the gully in this part. Its immediate effectiveness during the following rainfall events is reflected by the below-average headcut erosion rate documented in Figures 4 and 7. The dam does, however, divert the flow to the right side, where it enters the gully as described earlier via the sidewall at a location up to then not reached by surface runoff.

Luchena 1 gully has a very small catchment (0·08 ha), but plots rather high on headcut development in Figure 7 because of the high erodibility of the dispersive marls in which this bank gully developed, but also because of high runoff discharges due to the sparse degraded matorral cover and heavy soil crusting in its catchment. This confirms observations made by Oostwoud Wijdenes *et al.* (2000) and de Luna Armenteros *et al.* (2004) who demonstrated that gully erosion rates in marls were among the highest observed in southeast-Spain. Evidence of rill erosion and strong sheet wash, including vegetation mounds rising above the eroded surface, can be found all over the catchment. Sidewall erosion is high owing to the failure of a large, tension-crack isolated block collapsing piecemeal until 2006. With only three periods correlated to precipitation, rainfall analysis has to be interpreted with caution, and the very high correlation of sidewall volume change with precipitation sums in these periods (Figure 6) may be incidental, as the position of this soil block should prevent its being influenced by surface runoff. The likewise very high correlation of headcut retreat, however, could be expected for such a small, runoff-prone catchment. In terms of short-term variability, this is the least variable of all gullies (see Figure 5): as a very small catchment, it shows the most direct response to what is happening in the contributing area and in this case little has changed in its catchment during the monitoring period.

The **Freila** gullies, which both comprise a series of headcuts along the same thalweg each, show much higher headcut retreat than sidewall change (Figure 5). The latter is mostly due to crumbling edges in the upper parts of the sidewalls and shows little or no correlation with precipitation (the Freila A correlation is even slightly negative; Figure 6), while headcut volume change appears to be related to rainfall in both cases. The headcuts have a certain tendency to broadening owing to the flatness of the sheet-wash areas they incise. Here, too, the catchments are rather small and vegetation cover is sparse: runoff coefficients reach 40–70% on most surfaces in the catchment. It is an interesting aspect of these gullies that their existence is based on human action in two respects: the shallow valley fillings, which they incise, were accumulated in historic times behind small stonewalls built by farmers as "sediment harvesting" measures in order to build up flat terraces and improve cereal cultivation in the small depressions between the degraded hillslopes. The sediment is silty-loamy sand, which forms rather stable walls but is easily eroded at the headcut by undercutting. The lower erosion rates of the sidewalls at the Freila gullies as compared to the other gullies may be related to compaction of the artificial historical fills by agricultural use – especially densification by draught animals – and homogenization in the plough horizons. With the continuous sedimentation of new material, the surface kept rising and the compacted horizons were buried.

After abandonment of these fields in the late 1960s, the stonewalls were not tended any more and started to decline. All of the gully headcuts of Freila A and Freila B (see Figure 4) have developed at the edges of former terrace walls, initiated by stonewall collapse or piping processes. They are now emptying the man-made sediment sinks once created to better exploit the agricultural potential of this landscape. Similar observations on the destruction of larger terraces by piping and gullying were made by Romero Díaz *et al.* (2007) and Lesschen *et al.* (2008), who conclude that terracing – originally intended as conservation practice – actually enhances erosion in abandoned areas in the Mediterranean.

Casablanca gully, which plots lowest in Figure 7, has a medium-sized catchment of rangeland with rather dense grass cover and reforested slopes. The precipitation sums increase from one period to the next, and they correlate well with sidewall erosion but negatively with headcut change (Figure 6). The spatial distribution of gully change is much more regular for this gully than for the others (see Figure 4), indicating that the gully retreat processes do not differ very much here between individual gully parts, probably due to the runoff-preventing grass cover. However, headcut change was significantly higher in the first period (Figure 5) and drops to less than half the annual amount in the following periods. This development may be attributed to the water harvesting measures introduced in the upper part of the catchment in 2004, where small terracettes were constructed on the footslopes of the hill for pine-tree afforestation. Evidently, these water harvesting measures have led to a reduction in surface flow and linear runoff in the thalweg running towards the headcut. In spite of the nearly three-fold precipitation total in the last period, headcut erosion has hardly increased – which is why this results in a negative correlation.

By far the largest catchment in the dataset is the one draining to gully **Belerda 1** (1622 ha), where an average 26·5 m^3/yr of headcut volume change could be observed between 1996–2009 (Figure 5). Although this headcut retreat does not correlate very well with rainfall (Figure 6), the exceptional annual value of the last period (95 m^3 in one year) is obviously related to the heavy rainfall events of September 2009 mentioned earlier. During the field visit in October 2009, considerable damage in the adjoining olive plantations gave evidence of the large amounts of surface runoff that must have occurred during these events. The heavy precipitation, also confirmed by a local farmer, was not, however, recorded at the weather station in Diezma nor at the new station at Benalúa de Guadix. It may be concluded that the distance of these stations (7·4 km and 8 km) is too far for registering local events such as these heavy thunderstorms. Consequently, the rather low correlation between headcut retreat and potentially erosive precipitation is most probably due to the lack of representative rainfall data and possibly due to changing connectivity of surface flow in this large catchment (see discussion of Figure 7 and Table V earlier). In the case of Belerda 1, the percentage of the topographically defined catchment area that actually contributes to surface runoff is especially difficult to assess owing to the abundance of bench terraces, tracks and other infrastructure elements influencing local runoff connectivity.

Aerial photographs of the area taken in 1956 show an agricultural landscape devoid of olive and almond plantations. Between this date and the start of the monitoring in 1996, the gully headcut advanced by 35 m – a mean long-term linear headcut retreat rate of 87 cm/yr, or 2·5 times the maximum annual rate that was observed in the following 13 years (see $R_{\max}$ in Table III). As the land-use change from small dry-farming fields to larger olive plantations has occurred sometime between 1956 and 1996 – most probably spurred by Spain's European Union (EU) entry – it may be assumed that the higher average retreat rate in this period is attributable to land-levelling measures and vegetation cover changes. It may also be assumed that within these 40 years, the headcut retreat rate was clearly lower prior to the conversion of the landscape and much higher afterwards, but the low temporal resolution of the data does not allow this distinction to be made. The role of land-use change towards tree plantations is even clearer in the example of another gully (Salada 1) that will be discussed in more detail later.

Headcut/sidewalls contribution to gully erosion

It was already observed (see Table III and Figure 4) that the proportion of gully headcut and sidewall changes differs greatly between the individual gullies, and that sidewall changes tend to occur with greater spatial and temporal frequency at the upslope gully parts, closer to the headcut. Given that the retreat of a headcut continuously generates new sidewalls in these upslope parts, the greater susceptibility to tension cracking, soil toppling, soil fall and gully-wall erosion processes such as fluting can be expected during the "adolescence" of these recently exposed soil volumes. Likewise, we would expect an increasing stability of the gully walls with advanced age and thus with increasing distance from the headcut. This assumption is supported by the well-developed flow crusts that may often be observed at gully walls (Ries, 1999), which are an indicator as well as a cause for the increased stability of these walls. It could be argued that, consequently, faster retreating gullies should show higher sidewall activity than slower retreating gullies – but this is not the case for our dataset: there is no correlation between the linear retreat parameters ($R_{\max}$, R_l) and the *H*/*S* index. The two fastest gullies – Salada 1 and Belerda 1 – do indeed show very little or no sidewall retreat (Belerda 1 sidewalls were not measured, but have changed insubstantially according to the aerial photographs).

The extent of sidewall activity documented in Figure 4 also illustrates that sidewalls contribute to total gully erosion not only in the early days after their exposure, but remain active for many years: the gully lengths at which sidewall changes were mapped are very large compared to the mean linear retreat rates observed during our medium-term period of 7–13 years, indicating that the gullies are still widening at walls already many decades to several hundred years old.

Gully erosion and precipitation variability

Looking at the relationship between gully erosion rates and precipitation depth, documented in Figure 6, and summarizing the findings from the discussion of the individual gullies, the following observations can be made. The highest correlations of headcut retreat rates with precipitation depth occur for small and medium-sized catchments with high-runoff surface conditions (Luchena 1, Salada 3, Freila). Correlations are lower in "disturbed" catchments such as Barranco de las Lenas (dirt track leading to changing runoff connectivity), Barranco Rojo (terracing with crop/fallow-land rotation) and Belerda (very large agriculturally used catchment with many potentially disconnectivity inducing terraces, irrigation canals and tracks). The relationship with potentially erosive rainfall is generally lower to non-existent for the gully sidewalls because they are less, not, or even inversely influenced by rainfall: soil fall and toppling induced by tension and desiccation cracking are the dominant processes here. However, owing to the dominant role of intense rainfall events associated with thunderstorms, precipitation data clearly are less meaningful with increasing distance from the gully. As none of the rainfall data was taken in the immediate vicinity of the selected gullies, and thunderstorms are known to cause considerable erosion damage in these regions, all correlations with headcut retreat are potentially under-estimating the role of precipitation and must be interpreted with caution.

The exemplary case of Salada 1 gully

The preceding discussion has repeatedly identified the role of human activities for increasing the temporal variability of runoff conditions and connectivity both in the headcut vicinity and gully catchment area. This is best illustrated by the special case of Salada 1, whose recent evolution demonstrates human interference in many ways.

Figure 8. Aerial photographs of gully Salada 1 (circled in white) and part of its catchment in 1957 and 1981. © Ejercito del Aire and Instituto Geográfico Nacional de España.

Salada 1 gully is situated at the lower end of a flat valley oriented to the east, which drains into the Rambla Salada. The standard aerial photograph of 1957 (Figure 8) shows cereal cultivation on the valley bottom, which is partitioned into 20 flat bench terraces and bordered by matorral-covered slopes to the south. By 1981 (Figure 8), the landscape has been remodelled for agricultural expansion: the valley footslopes were levelled (note the lighter colours where the upper soil horizon has been removed with bulldozers), the valley-bottom terraces were enlarged and new terraces constructed on the upper parts of the adjoining ridge. Cereal is now being cultivated on these slopes as well; fields north of the road have been enlarged and expanded into the matorral zone. The reason for the land-use change and terrace diminution, which is typical for the region (Oñate and Peco, 2005; Bellin *et al.*, 2009), is the mechanization taking place in this period, which is supported by the availability of large roadwork machinery for land-levelling.

Further historic photographs exist of 1946 and 1993, and the photograph series reveals that the gully headcut was originally limited by a terrace border but has not changed much between 1946 and 1993: the only enlargement visible at these scales (1:30 000–1:40 000) is a small piping hole starting to develop sometime before 1981 just upslope of the main headcut, behind an earthen dam that has been ploughed up around the gully. By 1993, the area east of the gully has been converted to almond plantations, owing to the subsidizing of the almond production after Spain's entry into the EU.

These almond trees were replaced by new trees in late 1996. The old earth dam around the gully head is still visible in 1998 on the first large-scale aerial photographs taken during this study. By then, the piping hole had grown to 127 m^2 and continues to grow to 183 m^2 until 2004 (see Figures 5 and 9). In 2005, the upper part of the gully was completely infilled with building rubble, covered in topsoil to restore a field area that cannot have existed since before the 1940s and bordered by a new earth dam. From there, the filling slopes down into the gully bottom. The material deposited here amounts to approximately 7000 m^3 (as quantified from stereophoto analysis) – this is about eight times as much as the net volume loss observed between 1997 and 2004, and thus sets the clock back to long before the situation in 1946.

In 2008, a fresh flow path through a breach in the new low earth dam led into the partial infilling, creating a piping-hole outlet through the base of the former finger-shaped peninsula into the main gully bottom (coordinate −45/35 in Figure 9). In September 2009, the heavy rainfall events already mentioned earlier resulted in terrace breaches, intense sheet wash, and ephemeral gully erosion in the upslope almond plantation. The last aerial photograph was taken shortly after (Figure 9), when a small pond retained by the earth dam had only just drained after another dam breach. While we were taking the photographs, the farmer tried to repair the breached dam with fieldstones collected in the plantation (see tractor in Figure 9). Obviously, his aim was to stop the further development of the

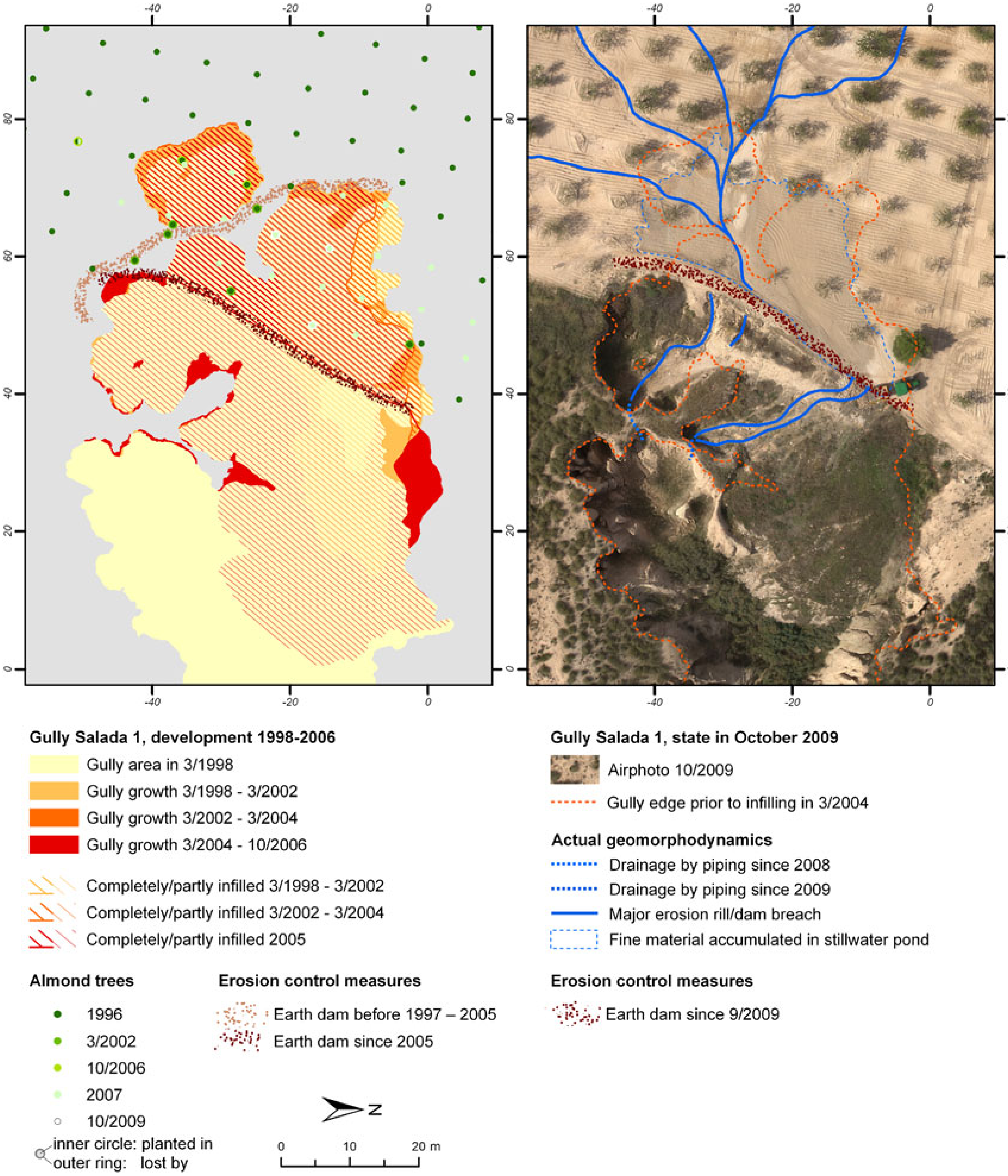
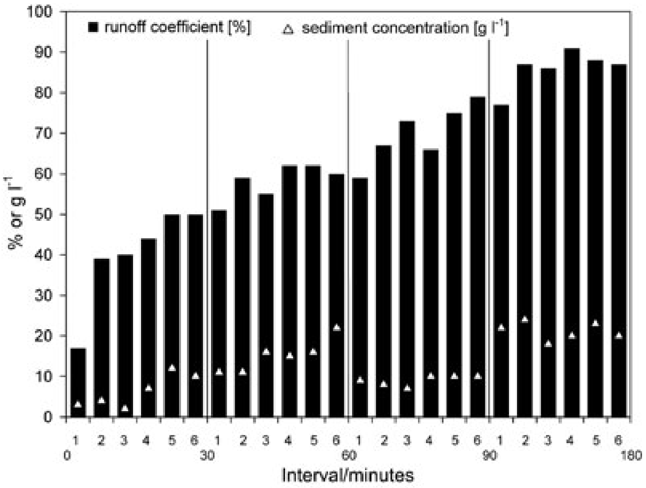


Figure 9. Evolution of gully Salada 1 during the monitoring period (1996–2009) with indication of gully erosion, rilling and piping, erosion control measures and almond tree plantings.

new rills and drainage lines that are visible on the image and which are now not only enlarging the already existing left piping outlet, but have already created another one through the peninsula base at the right (coordinate −35/33, Figure 9). In spite of the infilling and subsequent levelling of the almond plantation, the present drainage lines on the field may still serve to explain much of the shape and development of the former piping hole and gully (see 2004 outlines in Figure 9) by the spatial pattern of overland flow concentration.

Thus, the history of gully Salada 1 is one of alternating erosion and infilling strongly influenced by human activities and shows that even more variability-introducing parameters exist in gully development than discussed before. The gully was set in a dry-farming environment until the 1980s, and had until then remained nearly unchanged for at least 40 years. This is due to the runoff-preventing techniques of dry farming and terracing employed for cereal cultivation, which improve rainfall infiltration by repeated ploughing and small, flat terrace



runoff	sediment	solutes	sediment conc.	solutes conc.
15 l - 64 %	156 g - 558 g/m²	1.3 g - 5 g/m²	11 g/l	0.09 g/l

Figure 10. Runoff coefficient and sediment concentration measured at five minute intervals during four consecutive rainfall experiments (intensity is 40 mm/hour) at almond plantation within Salada 1 gully catchment in October 2006.

surfaces while further minimizing runoff by careful maintenance of vegetated terrace banks. Following the removal of the matorral on the slopes and the conversion of the area to almond plantations, the gully expanded rapidly, mostly via the piping hole behind the artificial earth dam. The largest volume change (245 m^3; see Figure 5) in the whole dataset was observed here in 1997–1998, immediately after the replanting of the almonds, suggesting that the land-use change had brought about a considerable change in runoff and infiltration behaviour. Simulated rainfall experiments (jet simulator; 40 mm/hour; measurement intervals of five minutes; 0·28 m^2 bounded microplot; see Ries and Langer, 2000) show that the almond plantation adjoining the gully, which is kept weed-free all year, produces extremely high runoff rates and sediment concentrations (Figure 10). A 10 minute-rainfall applied to the freshly ploughed surface already yields a runoff coefficient of nearly 40%. This increases to 60% after one hour and continues to rise to around 90% towards the end of the second hour. At the same time, the sediment concentration increases from initially below 5 g/l to a very high 23 g/l. In conjunction, these extremely high runoff coefficients and sediment concentrations, which are among the highest observed during 450 rainfall experiments conducted by Ries *et al*. (in preparation) in semi-arid environments, strongly encourage surface sealing and runoff production in the contributing area draining to Salada 1 gully. Its rapid and significant development rate following the land-use change to almond plantations is reflected in Figure 7, where it ranks by far highest among the gullies considered in this study. The future of the unconsolidated material filled into the piping hole and main gully remains to be observed. These observations corroborate earlier findings by Oostwoud Wijdenes *et al*. (2000) in this part of Spain indicating that the combination of gully heads formed in erodible sandy loams and almond orchards in the corresponding catchment results in rapidly retreating gully heads.

Conclusions

In this study, the detailed monitoring of nine Spanish gullies all formed in erodible materials has indicated a high variability of annual gully retreat rates both between individual gullies and between observation periods. Gully area loss varies by a factor of 25 and gully volume loss by a factor of 200. The important role of catchment area for controlling gully-headcut erosion rates, which was already reported by Vandekerckhove *et al.* (2003) for a larger number of gullies in southeast Spain, was confirmed in our study. The strength of the relationship could be shown to increase when potentially erosive precipitation depth is included in the analysis, reinforcing their conclusion that catchment area becomes even more important during extreme rain events, as the runoff connectivity within the catchment is then highest.

When comparing the actual gully volume change with the aforementioned medium-term trend, their above- or below-average behaviour may be ascribed to the varying influence of land use and human activities – erosion aggravating as well as erosion mitigating – in the catchment. Although material properties such as grain-size distribution, bulk density, shear strength and physio-chemical properties of the soil can also be expected to contribute to the high variability of gully retreat rates, land cover and land management appear to play a dominant role in our study. Many authors have shown that the extensive land-use and land-management changes instigated by the EU in the Mediterranean exacerbate erosion risk and accelerate erosion processes (e.g. Faulkner, 1995; Boellstorff and Benito, 2005; Oñate and Peco, 2005; García-Ruiz, 2010). This was confirmed in our study by the observations made at gully Salada 1, where a formerly near-stabilized gully was re-activated by the change from cereal dry-farming to almond plantations. Remodelling of the landscape, including infilling of gullies and levelling of badlands, is another phenomenon associated with agricultural intensification (e.g. Borselli *et al.*, 2006). When tracing back a gully's evolution over long time spans, for example by using historic imagery, one must be aware that interim infillings and land levelling might be a factor resulting in underestimating the net volume loss, especially in intensively used agricultural landscapes. This is also important for the estimation of gully-erosion rates in small and medium-size catchments using conventional aerial photographs and for their correlation with the suspended sediment data of gauging stations.

Beyond this large-scale impact, this study has shown that agricultural management also has effects on a much smaller temporal and spatial scale that result in an increase of gully-erosion variability. Not only the general crop change of cereal to almonds matters, but also the replanting of almonds; not only general land-management practices are relevant, but also small events and local human interventions such as creating a temporal disconnectivity by ploughing up small earth dams, or by maintenance of infrastructure (terrace banks, dirt roads). The examples of Salada 1 and 3 have shown that local erosion control at the headcut may be effective on a short-term timescale. However, if the problem of runoff generation in the contributing catchment area pertains, gully activity is only postponed for some time or shifted in space. Because of the transitory nature of these conditions, short-term monitoring (especially if not contiguous in space) may capture a phase or gully part of relative activity or inactivity not representative for medium- to long-term development. Consequently, the short-term periods analysed in this study show very high variability: on average (median of all gullies), the maximum headcut change observed in 7–13 years was 14·3 times higher than the minimum change, but the degree of fluctuation varies strongly between the gullies.

Not much difference in variability could be found for the two gully parts considered in this study (headcut and sidewalls), although they clearly are subject to different erosional processes. Sidewall changes show much less or no dependency on precipitation, and tension and desiccation cracking is responsible for the largest changes. Judging from the spatial distribution of gully-edge changes and the mean linear gully retreat rates we have determined (0·02–0·26 m/yr), sidewalls may remain active for decades if not centuries. For some gullies, the ratio of headcut to sidewall volume change is as low as 0·5, indicating that sidewall erosion is a gullying process not to be neglected.

Small-format aerial photography has proved a valuable tool in this study for documenting and analysing gully development in much more spatial detail than traditional aerial photographs or field methods based on tape or global positioning system (GPS) measurements would allow. Particularly, the spatially continuous documentation of the complete gully enables to capture and interpret changes in all parts – not only the headcut section and those sidewall parts judged active (and worthwhile measuring) during a field visit. None of the changes observed during the short-term periods could have been reliably quantified by standard aerial photography or satellite images due to their lower resolution of > 0·5 m. Even on the medium-term time scale of seven to 13 years, only Belerda 1 changes substantially enough to have yielded comparable results for areal change – but hardly for volumetric change – from such imagery.

In conclusion, this study confirms that short-term data are not representative of long-term gully development, and that medium- to long-term monitoring of both headcut and sidewalls is necessary for describing the development of a gully independently of short-term climatic and anthropogenic influences. However, short-term monitoring periods within longer-term monitoring are still necessary for capturing and explaining the immediate effects of rare heavy-rainfall events, of sudden land-use changes or of *ad hoc* erosion control measures by farmers. Human activity and its positive or negative effects on runoff production and connectivity needs to be taken into account in gully erosion research; in particular for the estimation of gully erosion rates from conventional aerial photographs.

Our findings have implications for extrapolating retreat rates into the past and future, and thus for modelling gully age and development over longer time spans and landscapes. Besides topographical, lithological and climatic factors, land management and land use – including its history and change – need to be considered at all spatial and temporal scales.

Acknowledgements—This study includes research funded by the Deutsche Forschungsgemeinschaft DFG under EPRODESERT (RI 835/1-3) and MoGul (MA2549/1-1 and RI 835/2-1) and was additionally supported by the Vereinigung von Freunden und Förderern der Johann Wolfgang Goethe-Universität Frankfurt am Main and the Frithjof Voss Stiftung – Stiftung für Geographie. Part of the gully monitoring was initiated during the EU-funded MEDALUS project and continued with the support of the European Commission funded RECONDES project and the Integrated Project DESIRE (Desertification mitigation and remediation of land – a global approach for local solutions; FP6, sub-priority 1.1.6.3. Global Change and Ecosystems, Contract no 037046). Of the numerous post-doctorate researchers, graduate and undergraduate students of Frankfurt, Trier, Leuven and Freiburg universities, whose contribution to fieldwork is gratefully acknowledged, we would especially like to thank Thomas Iserloh (Trier University) for providing Figure 10 and other rainfall simulation data discussed in the text.

References

Aber JS, Marzolff I, Ries JB. 2010. *Small-format Aerial Photography: Principles, Techniques and Geoscience Applications.* Elsevier Science: Amsterdam.

Bellin N, van Wesemael B, Meerkerk A, Vanacker V, Barbera GG. 2009. Abandonment of soil and water conservation structures in Mediterranean ecosystems. A case study from south east Spain. *Catena* **76**(2): 114–121. DOI. 10.1016/j.catena.2008.10.002

Bennett HH. 1960. Soil erosion in Spain. *Geographical Review* **50**(1): 59–72.

Betts HD, Trustrum NA, Derose RC. 2003. Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms* **28**(10): 1043–1058. DOI. 10.1002/esp.500

Blong RJ, Graham OP, Veness JA. 1982. The role of sidewall processes in gully development; some NSW examples. *Earth Surface Processes and Landforms* **7**(4): 381–385. DOI. 10.1002/esp.3290070409

Bocco G. 1991. Gully erosion: processes and models. *Progress in Physical Geography* **15**(4): 392–406.

Boellstorff D, Benito G. 2005. Impacts of set-aside policy on the risk of soil erosion in central Spain. *Agriculture, Ecosystems and Envorinment* **107**(2–3): 231–243. DOI. 10.1016/j.agee.2004.11.002

Borselli L, Torri D, Øygarden L, Alba S de, Martínez-Casasnovas JA, Bazzoffi P, Jakab G. 2006. Land Levelling. In *Soil Erosion in Europe*, Boardman J, Poesen J (eds). Wiley: Chichester; 643–658.

Brooks AP, Shellberg JG, Knight J, Spencer J. 2009. Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia. *Earth Surface Processes and Landforms* **34**(14): 1951–1969. DOI. 10.1002/esp.1883

Campo MA, Álvarez-Mozos J, Casalí J, De Santisteban LM, Giménez R, Martínez-Casasnovas JA. 2006. Long term evolution assessment of the permanent gully network in Las Bardenas Reales area (Navarre, Spain) influenced by land use change. In *Soil and Water Conservation Under Changing Land Use*, Martínez-Casasnovas JA, Pla Sentís I, Ramos Martín MC, Balasch Solanes JC (eds). Edicions de la Universitat de Lleida: Lleida; 147–150.

El País. 2009. El temporal de lluvia mantiene a 11 comunidades en alerta. *El País* 29 September. http://www.elpais.com/articulo/espana/temporal/lluvia/mantiene/comunidades/alerta/elpeputec/20090929elpepunac_3/Tes [3 January 2011].

Faulkner H. 1995. Gully erosion associated with the expansion of unterraced almond cultivation in the coastal Sierra de Lújar, S. Spain. *Land Degradation & Rehabilitation* **6**(3): 179–200. DOI. 10.1002/ldr.3400060306

García-Ruiz JM. 2010. The effects of land uses on soil erosion in Spain: a review. *Catena* **81**(1): 1–11. DOI. 10.1016/j.catena.2010.01.001

Hu G, Wu Y, Liu B, Yu Z, You Z, Zhang Y. 2007. Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. *Catena* **71**: 321–329. DOI. 10.1016/j.catena.2007.02.004

Lesschen JP, Cammeraat E, Nieman T. 2008. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. *Earth Surface Processes and Landforms* **33**(10): 1574–1584. DOI. 10.1002/esp.1676

de Luna Armenteros E, Laguna Luna A, Poesen J, Giráldez Ververa JV. 2004. Evolución de un sistema de cárcavas activas en el sureste Español. *Ingeniería del Agua* **11**(1): 65–73.

Martínez-Casasnovas JA, Antón-Fernándes C, Ramos MC. 2003. Sediment production in large gullies of the mediterranean area (NE Spain) from high-resolution digital elevation models and geographical information systems analysis. *Earth Surface Processes and Landforms* **28**(5): 443–456. DOI. 10.1002/esp.451

Martínez-Casasnovas JA, Ramos MC, Poesen J. 2004. Assessment of sidewall erosion in large gullies using multi-temporal DEMs and logistic regression analysis. *Geomorphology* **58**(1–4): 305–321. DOI. 10.1016/j.geomorph.2003.08.005

Martínez-Casasnovas JA, Concepción Ramos M, García-Hernández D. 2009. Effects of land-use changes in vegetation cover and sidewall erosion in a gully head of the Penedès region (northeast Spain). *Earth Surface Processes and Landforms* **34**(14): 1927–1937. DOI. 10.1002/esp.1870

Marzolff I, Poesen J. 2009. The potential of 3D gully monitoring with GIS using high-resolution aerial photography and a digital photogrammetry system. *Geomorphology* **111**(1–2): 48–60. DOI. 10.1016/j.geomorph.2008.05.047

Marzolff I, Ries JB. 2007. Gully monitoring in semi-arid landscapes. *Zeitschrift für Geomorphologie N. F.* **51**(4): 405–425. DOI. 10.1127/0372-8854/2007/0051-0405

Nachtergaele J, Poesen J. 1999. Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) aerial photographs. *Earth*

Surface Processes and Landforms **24**(8): 693–706. DOI. 10.1002/(SICI)1096-9837(199908)24:8<693::AID-ESP992>3.0.CO;2–7

Oñate JJ, Peco B. 2005. Policy impact on desertification: stakeholders perceptions in southeast Spain. *Land Use Policy* **22**(2): 103–114. DOI. 10.1016/j.landusepol.2004.01.002

Oostwoud Wijdenes D, Bryan RB. 2001. Gully-head erosion processes on a semi-arid valley floor in Kenya. *Earth Surface Processes and Landforms* **26**(9): 911–933. DOI. 10.1002/esp.225

Oostwoud Wijdenes D, Poesen J, Vandekerckhove L, Ghesquiere M. 2000. Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. *Catena* **39**(3): 147–167. DOI. 10.1016/S0341-8162(99)00092-2

Poesen J, Hooke JM. 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe. *Progress in Physical Geography* **21**(2): 157–199.

Poesen J, Nachtergaele J, Verstraeten G, Valentin C. 2003. Gully erosion and environmental change: importance and research needs. *Catena* **50**(2–4): 91–133. DOI. 10.1016/S0341-8162(02)00143-1

Poesen J, Vanwalleghem T, de Vente J, Knapen A, Verstraeten G, Martínez-Casasnovas JA. 2006. Gully erosion in Europe. In *Soil Erosion in Europe*, Boardman J, Poesen J (eds). Wiley: Chichester; 515–536.

Poesen J, Torri D, Vanwalleghem T. 2011. Gully erosion: procedures to adopt when modelling soil erosion in landscapes affected by gullying. In *Handbook of Erosion Modelling*, Morgan RPC, Nearing MA (eds). Blackwell-Wiley: Oxford; chapter 19.

Ries JB. 1999. Schluchterosion im Ebrobecken – Großmaßstäbiges Luftbildmonitoring am Barranco de las Lenas und mikromorphologische Beobachtungen an Barranco-Wänden. In *Geomorphologie und Paläoökologie. Frankfurter Geowissenschaftliche Arbeiten, Serie D 25*, Dittmann A, Wunderlich J (eds). Frankfurter geowiss: Frankfurt am Main; 177–195.

Ries JB, Langer M. 2000. Experimental investigations on water and wind erosion on abandoned fields and arable land in the Central Ebro Basin, Aragón/Spain. *Zeitschrift für Geomorphologie N. F. Suppl.-Bd.* **121**: 91–108.

Ries JB, Marzolff I. 2003. Monitoring of gully erosion in the central Ebro Basin by large-scale aerial photography from a remotely controlled blimp. *Catena* **50**(2–4): 309–328. DOI. 10.1016/S0341-8162(02)00133-9

Rodzik J, Furtak T, Zglobicki W. 2009. The impact of snowmelt and heavy rainfall runoff on erosion rates in a gully system, Lublin Upland, Poland. *Earth Surface Processes and Landforms* **34**(14): 1938–1950. DOI. 10.1002/esp.1882

Romero Díaz A, Marín Sanleandro P, Sánchez Soriano A, Belmonte Serrato F, Faulkner H. 2007. The causes of piping in a set of abandoned agricultural terraces in southeast Spain. *Catena* **69**(3): 282–293. DOI. 10.1016/j.catena.2006.07.008

Sala M. 1991. *Soil Erosion Studies in Spain*. Geoforma Ediciones: Logroño.

Seeger M, Marzolff I, Ries JB. 2009. Identification of gully-development processes in semi-arid NE-Spain. *Zeitschrift für Geomorphologie N. F.* **53**(4): 417–431. DOI. 10.1127/0372-8854/2009/0053-0417

Solé Benet A. 2006. Spain. In *Soil Erosion in Europe*, Boardman J, Poesen J (eds). Wiley: Chichester; 311–346.

Thornes JB. 1976. *Semi-arid Erosional Systems: Case Studies from Spain*, Geographical Papers No. 7. London School of Economics and Political Science: London.

Vandekerckhove L, Poesen J, Oostwoud Wijdenes D, Gyssels G, Beuselinck L, de Luna E. 2000. Characteristics and controlling factors of bank gullies in two semi-arid Mediterranean environments. *Geomorphology* **33**(1–2): 37–58. DOI. 10.1016/S0169-555X(99)00109-9

Vandekerckhove L, Poesen J, Oostwoud Wijdenes D, Gyssels G. 2001. Short-term gully retreat rates in Mediterranean environments. *Catena* **44**(2): 133–161. DOI. 10.1016/S0341-8162(00)00152-1

Vandekerckhove L, Poesen J, Govers G. 2003. Medium-term gully headcut retreat rates in southeast Spain determined from aerial photographs and ground measurements. *Catena* **50**(2–4): 329–352. DOI. 10.1016/S0341-8162(02)00132-7

Vanwalleghem T, Bork H, Poesen J, Schmidtchen G, Dotterweich M, Nachtergaele J, Bork H, Deckers J, Brüsch B, Bungeneers J, De Bie M. 2005a. Rapid development and infilling of a buried gully under cropland, central Belgium. *Catena* **63**(2–3): 221–243. DOI. 10.1016/j.catena.2005.06.005

Vanwalleghem T, Poesen J, Van Den Eeckhaut M, Nachtergaele J, Deckers J. 2005b. Reconstructing rainfall and land use conditions leading to the development of old gullies. *The Holocene* **15**(3): 378–386. DOI. 10.1191/0959683605hl807rp

Wu Y, Zheng Q, Zhang Y, Liu B, Cheng H, Wang Y. 2008. Development of gullies and sediment production in the black soil region of northeastern China. *Geomorphology* **101**(4): 683–691. DOI. 10.1016/j.geomorph.2008.03.008