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Monitoring of gully erosion in the Central Ebro Basin by large-scale aerial photography taken from a remotely controlled blimp

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Abstract

Large deep gullies (Span. *barrancos*) are some of the most important sediment sources in the semi-arid environment of the Central Ebro Basin. They are incised into the Quaternary valley bottoms (Span. *vales*), which are characteristic landforms in this area. In the research project EPRODESERT (Evaluation of Processes Leading to Land Degradation and Desertification under Extensified Farming Systems), the development of a large *barranco* system is being investigated by different methods, including documentation and monitoring by aerial photography.

Geomorphological forms and processes, such as sheet wash, rill and gully erosion, cannot be documented sufficiently by conventional remote sensing methods. Spatial and temporal resolution of satellite sensors as well as of conventional aerial photography do not correspond to the scale and dynamics of geomorphological processes.

With a specially designed hot-air blimp as a sensor platform, large-scale aerial photographs were obtained from the Barranco de las Lenas specifically aimed at the scientific demands (very high spatial and temporal resolution). The development of the gully is documented and its dynamics are evaluated by a sequence of six aerial photographs taken between 1995 and 1998.

Keywords: Gully erosion; Monitoring; Large-scale aerial photography; Blimp system; Central Ebro Basin

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1. Introduction

1.1. Problems and questions

Gullies present the most conspicuous erosion forms in the Mediterranean region. Incising the Quaternary sediments of many valley bottoms, they frequently threaten agricultural fields and plantations. In Spain, gullies (Span. *barrancos*) are considered as the main sediment source responsible for the rapid siltation of reservoirs, which are of vital importance for supply with drinking and irrigation water. Poesen et al. (1996, pp. 257f) found a sediment rate of 9.7 m^3 ha^{-1} $year^{-1}$ and estimate that gully erosion contributes 80–83% of total sediment produced on rangelands in Southeast Spain (Poesen and Hooke, 1997, p. 172). Land use and land use change within the catchment have a clear impact on gully erosion, and almond groves have been shown to be the location of the most active gully heads (Oostwoud Wijdenes et al., 2000, p. 159).

In Northeast Spain, particularly in the almost completely cleared-out cultivated steppe land of the Inner Ebro Basin, gullying is a characteristic and widespread phenomenon, incising and dissecting the flat valley bottoms built up by Quaternary sediments which are characteristic landforms in this area (Pellicer Corellano and Echeverría Arnedo, 1989, pp. 119ff).

Since the beginning of the 1990s, set-aside programmes of arable land have been supported by subsidies of the EU with the result that the number of abandoned fields has increased. This young fallow land shows very complex fluvial–geomorphologic processes. Runoff is very high and erosion rates increase compared to those of arable land. When the former arable land is no longer ploughed, harrowed and rolled regularly, as was usual in the traditional dry farming system, soil crusts heavily reducing local infiltration capacity develop on the sandy silts to silty loams. Runoff coefficients between 20% and 89% are the result (Ries et al., 2000, p. 101). Runoff magnitudes like these strongly favour linear erosion forms like rills and gullies. The velocity of their development is generally accepted to be determined by the activity at the head cut, and retreat is mostly controlled by plunge pool undercutting and headwall break-off.

1.2. Aims of the study

Within the scope of the research project EPRODESERT (Evaluation of Processes Leading to Land Degradation and Desertification under Extensified Farming Systems in Northeast Spain, funded by the Deutsche Forschungsgemeinschaft), which investigates the interaction of vegetation succession, geomorphodynamics and land use, large-scale aerial photographic monitoring of such a gully head was carried out. In contrast to previous work by Soriano (1993), Barrón et al. (1994) and Vandaele et al. (1997), no conventional aerial photographs were used for this study, as their image scales would be too small. Changes at the gully head occur in magnitudes of tens of centimeters. They cannot be mapped from standard aerial photography like the *Vuelo Nacional de España* (1:20,000–30,000) with sufficient precision, nor can process dynamics be sufficiently monitored due to the low repeat cycle of these aerial surveys. Therefore, survey methods need to be developed enabling the detection and documentation of changes at the gully head. The aim of this paper is to present a remote sensing method using a remote controlled hot-air blimp as a platfrom for photographic cameras which was designed to meet the needs of spatial and temporal resolution for process monitoring. A detailed description of the survey system and techniques is followed by the example of an image series at a gully head, which was deliberately chosen for its little changes in order to show the high potential of this monitoring method.

1.3. Study area

In the Central Ebro Basin, the study area María de Huerva is located in the Val de las Lenas, an eastern tributary of the Huerva river, which flows into the Ebro at Zaragoza about 15 km north (Fig. 1). Flat-lying Miocene gypsum, marl and clay series with interbedded limestone and sandstone form the bedrock of the highly dissected slopes of the mesa Plana de Zaragoza (ITGE, 1998). The series between 400 and 500 m a.s.l., which are dominated by gypsum in the middle part, form an impressive erosion landscape with mostly straight to slightly convex upper and mid slopes and provide the silty material composing the Quaternary valley fillings. The slopes turn sharply into scree covered glacis which change smoothly into the plane valley bottom. The valley bottom fillings are mostly Holocene (Peña Monné et al., 1993; Sancho et al., 1991) but on the base partly Late Pleistocene (Andres et al., 2000). They are up to 20 m thick and consist of interbedded

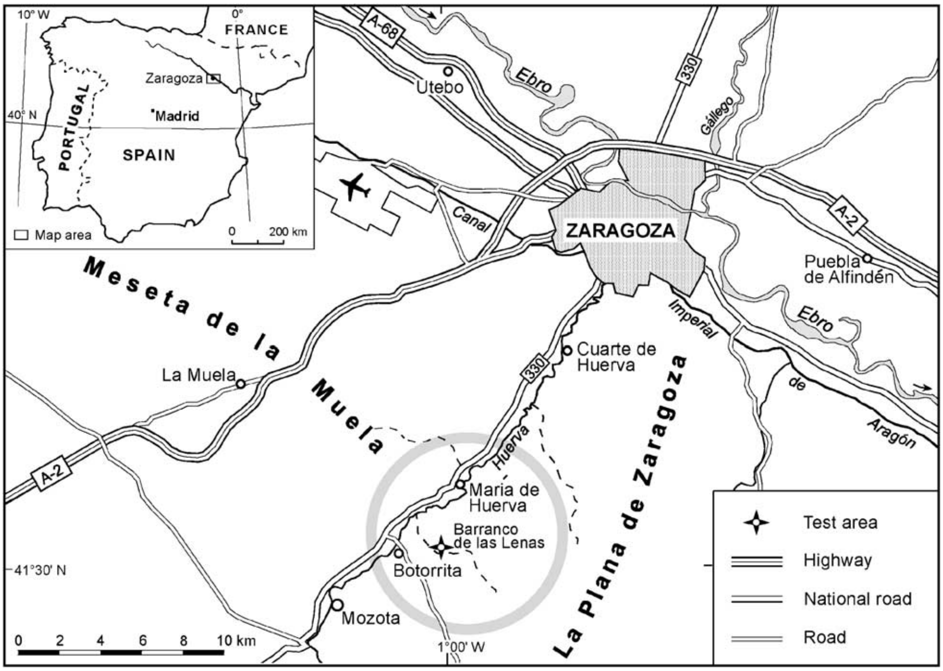

Fig. 1. Study area Val de las Lenas, María de Huerva, Central Inner Ebro Basin.

Table 1
Grain size distribution of the layers of the valley filling in the Val de las Lenas, María de Huerva, according to DIN (German Industry Norm) in AG BODEN, BODENKUNDLICHE KARTIERANLEITUNG (KA4) (1994, p. 134), no gypsum disaggregation

Situation below surface [cm]	Sand [%]	Silt [%]	Clay [%]	Solutes, mainly gypsum [%]
1 (crust)	12.9	80.2	6.9	30.0
28	33.1	58.8	8.1	35.6
52	12.1	79.9	8.0	25.2
76	12.4	76.8	10.8	26.0
85	17.4	70.3	12.3	39.0
150	5.5	86.9	7.6	27.0
310	21.5	70.4	8.1	26.6
380	23.9	67.2	8.9	28.5
420	7.5	88.2	4.3	31.5

layers, 20–60 cm thick, of silty loam, sandy loamy silt, sandy silt and argillaceous loam, interrupted by discontinuous stone and gravel layers with silty sandy matrix, which are 5–20 cm thick (Table 1). In the margins, coarser material often prevails as fanglomerates, which result from episodic removal from the slopes of the tributaries following intense precipitation.

The flat valley bottoms are used for agriculture and today show a large percentage of fallow land. On young fallow land, the slow vegetation succession with sparse therophyte vegetation (*Hordeum murinum*) provides only low cover owing to the semi-arid climate with 6 arid months and a total precipitation of 320 mm/year. After several years, the first dwarf shrubs (*Artemisia herba-alba*) start to grow, but a vegetation cover of over 50% can be observed only after 6–8 years (Marzolff, 1999, pp. 108ff). Elder fallow land, too, often shows a vegetation cover under 60% and is covered with sparse steppe grass vegetation (*Lygeum spartum*) and open shrub land (*Salsola vermiculata*, *Rosmarinus officinalis*, *Thymus vulgaris*). Between them crusts of lichens, which seal the surface, are developed. Although the pore volume is much higher than that of younger fallow land due to bioturbation in the edaphon, and although this results in an increase of the average infiltration rate and decrease of runoff and erosion rates, runoff coefficients of up to 76% were also found on elder fallow land. In particular, the terrace edges on old fallow land are starting points for incision and regressive erosion. Here, sheet wash basins and bank gullies can be observed which act as collector and pathway for overland flow towards the gully head.

2. The hot-air blimp monitoring method

Blimps and balloons as well as kites, model airplanes and helicopters have been used before by scientists as unmanned platforms for photographic and video cameras (see for example Batut, 1890; Bürkert et al., 1996; Palacio-Prieto and López-Blanco, 1994; Walker and de Vore, 1995). However, the combination of an open hot-air system with the shape of a zeppelin (Fig. 2) is unusual and has been specially designed in order to combine the advantages of both systems (Marzolff and Ries, 1997).

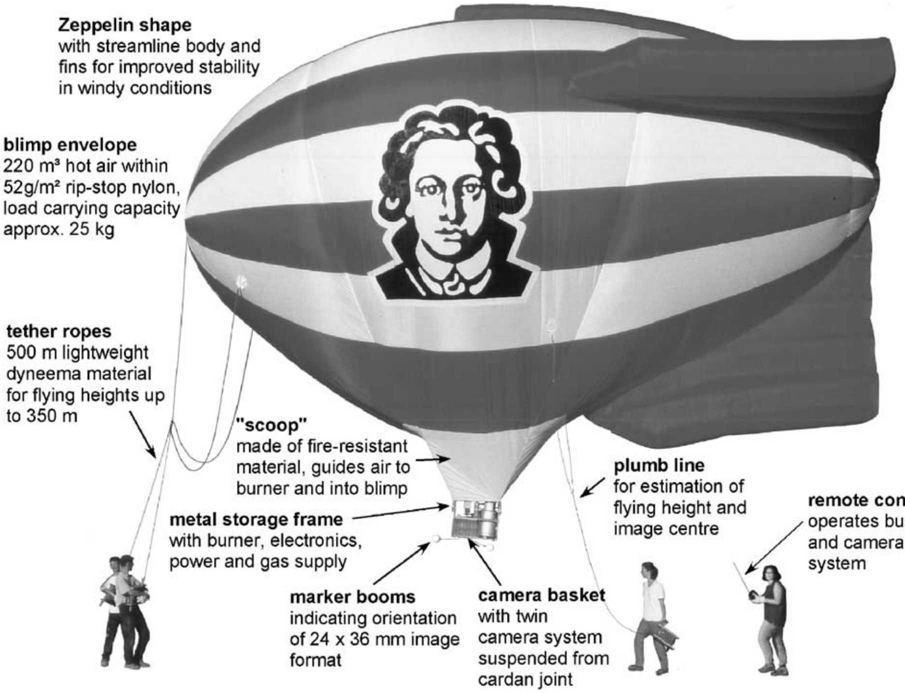

Fig. 2. The hot-air monitoring blimp of the Institute of Physical Geography of Frankfurt University.

2.1. Blimp envelope

The blimp body or envelope is made of rip-stop nylon and has a volume of 220 m^3. When inflated, it measures approximately 11 m in length; it is just over 8 m high and about 5 m wide. In contrast with conventional airships, the blimp body is not supported by a framework: the shape of the envelope is given by the pressure of hot air only. The blimp's three fins are supplied by an inflation system through a tunnel along the blimp's back, ensuring a good distribution of hot air pressure throughout the blimp body.

Where the envelope is open at the bottom, a scoop of fire-resistant material encloses the burner system from three sides and guides front breezes from the blimp's nose towards the burner and into the body, further increasing its inner stability.

2.2. Burner system

The burner system, electronic controls and cameras are stored in a metal storage frame suspended from steel cables. Four spiral burners are mounted on top of the frame so they are enclosed by the scoop from three sides. They are powered by liquid propane gas from an 8-l aluminium gas bottle. Propane is used in many countries as cooking gas and can be bought cheaply from gas supply stations.

With the help of a small pilot flame, the main burner is ignited when the remotely controlled electronical valves closing off the connection to the propane bottle are opened. The liquid gas provides an extremely powerful quadruple flame. A gas filter is installed between bottle and burner to prevent dirt and grit entering and blocking the valves.

2.3. Sensor system

The sensor system comprises two single-lens reflex cameras with motor drives, which are mounted against each other with parallel camera bases onto an aluminium frame. The cameras are suspended from a 360° electronic turntable by a damped cardan joint, which ensures a vertical optical axis at any time. With focal distance set at infinity and shutter speed set to 1/125 or faster, photographs are taken in automatic aperture mode using an electronic trigger connected to a remotely controlled switch.

The twin camera systems allows photographs to be taken simultaneously with different film types (normal or infrared colour) or with different focal lenghts (50 or 28 mm), respectively. KODAK EKTACHROME Elite 100 films for transparency slides with a skylight filter were used for the images appearing in this study. A wicker basket is used for storage and protection of the camera system. As the cameras are completely protected inside the basket and concealed from the view at the distance, two marker booms fixed to the camera system protrude from the basket, indicating the direction of the oblong image format to the blimp pilot on the ground.

The use of photographic cameras is, of course, not imperative, as any sensor could be attached which can be remotely controlled and is not (like scanners) dependent on specific flying velocities. The weight limit given by the blimp’s load carrying capacity is approximately 25 kg. With recent development in the field of digital photography, high-end digital cameras as well as video cameras are now offering increasingly high resolution and could in future provide a true alternative even to photographic films—particularly when further digital processing and analysis is intended.

2.4. Remote control and electronics

Burner system, camera trigger and turntable are controlled from the ground by a commercial remote control device. Separate channels are used to control electronic switches opening pilot flame and main burner valves, triggering electronic ignition and camera shutter and operating the camera turntable. A 12-V storage battery powers electronic ignition, main burner valve and camera turntable, a second 5.6-V storage battery supplies the receiver, pilot flame valve and camera trigger. High security is ensured by the use of a PCM fail-safe system which automatically sets all valves and other functions to OFF and thus cuts the gas supply in case of transmission faults.

2.5. Tether ropes

While burner and camera functions are remotely controlled, the blimp as a passive unmanned airship has to be steered with tether ropes from the ground. It is guided with the help of two special lightweight ropes (polyester coated dyneema, 2.5 mm) attached to the blimp's nose. As wind pressure against the rope and blimp as well as slant rope angles have to be taken into account, 500-m long tether ropes are required for a maximum flying height of approximately 350 m. A third rope, suspended from the rear of the blimp near the sensor system and marked in 5-m intervals, serves as a plumb line indicating ground position and flying height.

2.6. Photographic survey

The inflation process is the most critical phase in terms of risk for the blimp; at least three people are needed along the back of the blimp to fix the envelope to the ground and prevent it from drifting into the burner flames. The air inside the body is heated with long blasts from the main burner until the pressure is high enough for launching and keeping it aloft. When the camera system is attached to the storage frame, the survey can be started.

The altitude of the blimp is controlled by short intermittent blasts; depending on their frequency the airship will rise, float or sink, which requires some experience by the pilot. One gas bottle filling is usually enough for about 50–60 min flying time (including inflation); both films and gas bottles can be changed without deflating the blimp as the hot air keeps long enough to park the airship for several minutes.

While the maximum altitude of the blimp is limited by the length of the tether ropes, there is practically no lower limit to flying height. Depending on the altitude and focal length, the photographs vary in scale between approximately 1:200 and 1:10,000, covering areas from 35 m^2 up to 10 ha (Table 2). The blimp can be positioned with the tether ropes fairly precisely. Stereoscopic coverage can easily be accomplished by towing the blimp along a straight line across the area.

The complete system, when packed in aluminium boxes and canvas bags, weighs approximately 200 kg and can easily be transported by minivan. More details about the technique are given by Marzolff (1999, pp. 34–49).

The hot-air blimp employed for this study is a further development of a smaller version which belongs to the Institute of Physical Geography of Freiburg University (Marzolff and Ries, 1997). This smaller system of 100 m^3 could be carried by four people and has successfully been employed in little accessible high mountain regions. In respect to load carrying capacity and wind susceptibility, the size of this smaller blimp proves, however, to be at a critical lower limit. Both blimp envelopes were designed by the balloon factory Gefa-Flug (Aachen, Germany). As a direct result of field experience, earlier versions of the

Table 2
Image scales and areas covered depending on flying height and focal length

Flying height above ground (h_g) [m]	50-mm lens		28-mm lens	
	scale	area	scale	area
10	1:100	4.8 × 7.2 m (35 m^2)	1:357	8.6 × 12.9 m (111 m^2)
25	1:500	12 × 18 m (216 m^2)	1:890	21 × 32 m (0.7 ha)
50	1:1000	24 × 36 m (864 m^2)	1:1785	43 × 64 m (2.8 ha)
100	1:2000	48 × 72 m (0.4 ha)	1:3570	86 × 129 m (1.1 ha)
200	1:4000	96 × 144 m (1.4 ha)	1:7140	171 × 257 m (4.4 ha)
300	1:6000	144 × 216 m (3.1 ha)	1:10,700	257 × 386 m (9.9 ha)

control system were greatly improved by the staff of the technical workshop of the Faculty of Geosciences/Geography at Frankfurt University who constructed and assembled the burner system, electronic controls and metal storage frame.

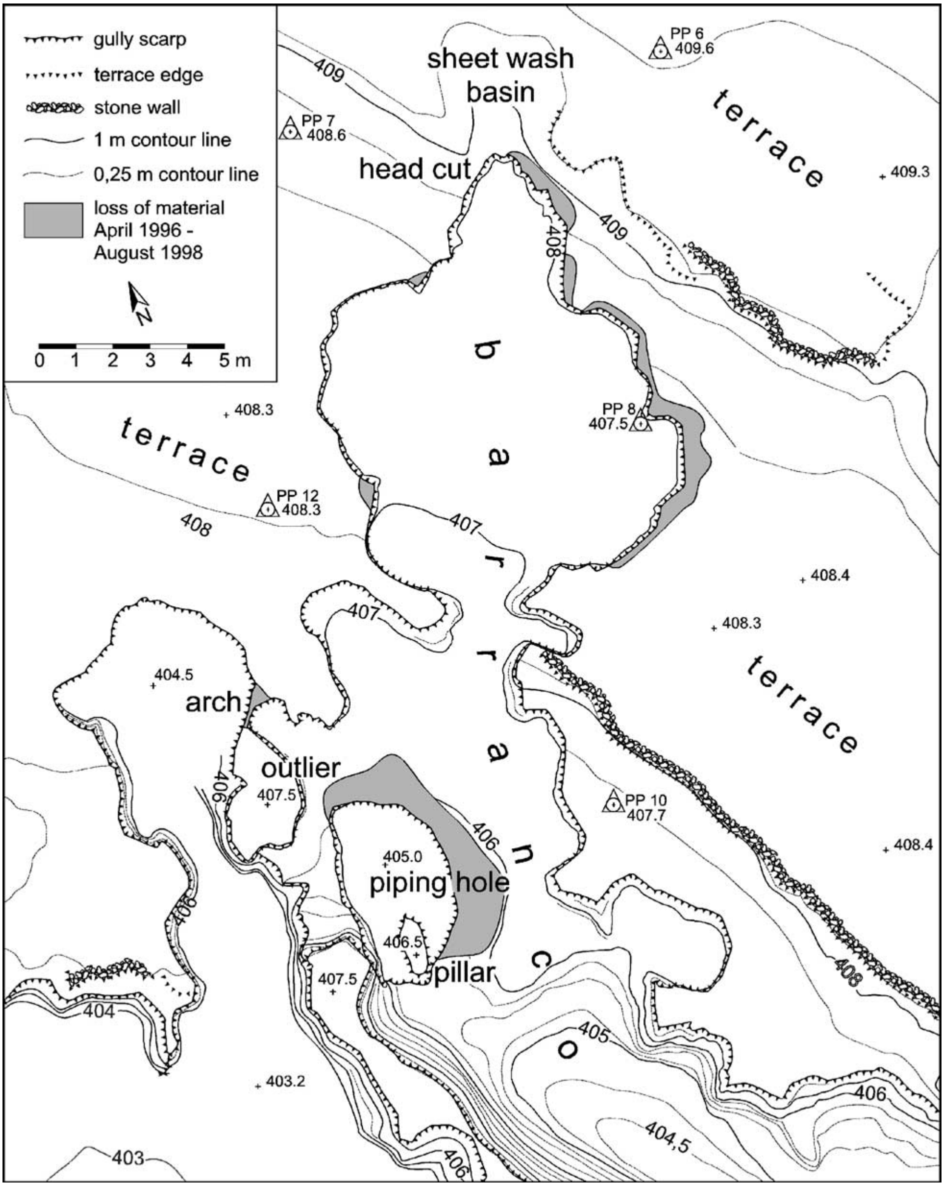

Fig. 3. Development of the gully head cut between April 1996 and August 1998. Large-scale topographic map derived from stereoscopic photography taken in April 1996 (Photogrammetric plotting: R. Thormann, Karlsruhe Polytechnic University 1997).

3. Results of gully monitoring at the Barranco de las Lenas head cut

The observed Barranco de las Lenas cuts into a terraced field abandoned approx. 60 years ago. The area covered by the photographs (Figs. 5–10) and map (Fig. 3) encompasses three terraces separated by low, partly disintegrated stone walls. A sheet wash basin is situated just upslope of the gully which guides overland flow from the terrace towards the head cut and onto the first gully level 70 cm below the terrace area. There are no signs of piping processes in the vicinity of the head cut which could indicate a potential direction of head cut retreat.

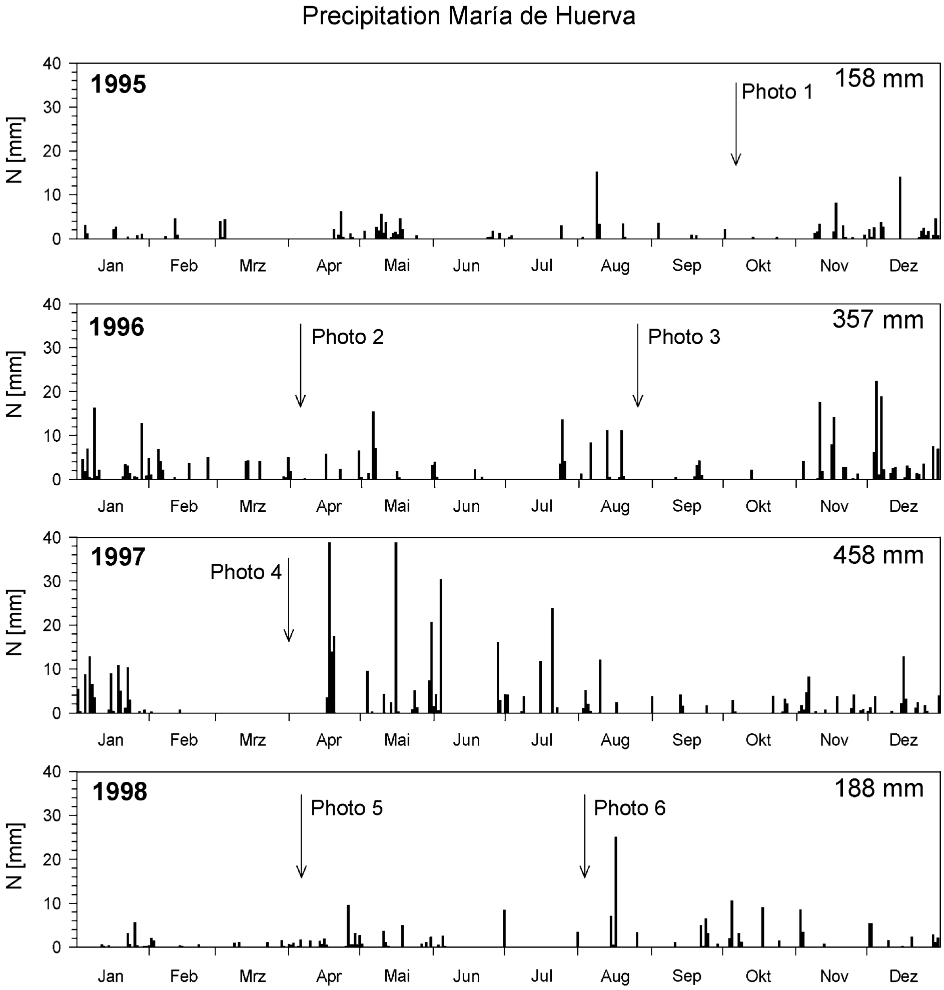

Fig. 4. Daily precipitation 1995–1998 at the weather station of Botorrita, 1.5 km west of the study area. Aerial photographic survey dates are marked with arrows.

Within the gully, the drainage line continues beyond a second 50-cm drop where the gully narrows at the terrace edge of the second terrace level. In this part of the gully bottom, several distinct features can be observed: A narrow arch connects a towering outlier to the terrace surface level and links the middle part of the gully to a deeper branch to the left. Further into the gully, another remnant of the former surface level is preserved as an island. To the right of these remnants, a piping hole is situated which is partly filled with sunken blocks. An isolated pillar remains in the lower right of the hole. Further downstream from the mapped area, the gully continues into a deep gorge with up to 20-m high walls which, together with various lateral gullies, forms a widely ramified system.

The large-scale aerial photographs (Figs. 5–10) were taken on October 6, 1995, April 6, 1996, August 18, 1996, April 2, 1997, April 8, 1998 and August 7, 1998, each between 7 and 9 a.m. The low sun casts long shadows from the upper right to the lower left in the photographs where northeast is up. The images are full-size reproductions (not cropped) of the uncorrected, i.e. relief-distorted original colour slides. Please note the similarity of image scale, area covered and orientation, which can be achieved with the blimp system and facilitates easy comparison of the individual dates. The following paragraphs will describe the changes at some prominent places (head cut, arch, piping hole and pillar) which were mapped from the aerial photographs.

The precipitation regime is characterised by high intra-annual and inter-annual variability; the bimodal precipitation distribution typical for the Western Mediterranean long-term climate (spring and autumn rainfalls with dry season in summer and a secondary minimum in late winter) is not distinctive in individual years. Annual rainfall ranges between 158 and 458 mm during the study period with daily sums reaching up to 40 mm. Potentially erosive precipitation events (days with more than 10 mm; Ries, 2000, p. 184ff) can be observed in all seasons (Fig. 4). The dates of the aerial photographic surveys are marked in Fig. 4; precipitation sums of the monitoring periods are given in Table 3.

3.1. October 1995–April 1996

The photograph taken in October 1995 shows the situation of gully incision into the former terraces fields (Fig. 5). While the lower and middle terraces exhibit a

Table 3
Summary of precipitation sum, potentially erosive precipitation, days with minimum temperature below 0 °C, gully retreat and piping hole enlargement during the monitoring period

Monitoring period	Precipitation [mm]	Potentially erosive precipitation [mm]	Days with minimum temperature below 0 °C	Gully retreat [m^2]	Piping hole enlargement [m^2]
Oct. 1995–Apr. 1996	162	43	16	0.72	2.5
Apr. 1996–Aug. 1996	94	40	0	0.38	–
Aug. 1996–Apr. 1997	245	118	16	1.32	4.0
Apr. 1997–Apr. 1998	396	236	18	0.76	–
Apr. 1998–Aug. 1998	52	–	0	–	–
Total	949	437	50	3.18	6.5

Source of climate data: Instituto Nacional de Meteorología.

Fig. 5. Head cut of the Barranco de las Lenas, October 1995.

medium to dense coverage with *L. spartum* and lichens, the upper terrace (transversed diagonally by a sheep track) has very low cover due to heavy overgrazing. Within the sheet wash basins retreating into this upper terrace, the slightly more dense vegetation of dwarfed bushes and grass has been favoured by moister conditions. The actual head cut is located 30 cm below the terrace wall and shows all typical characteristics with vertical wall, undercut and small plunge pool. Below the head wall of the gully, a broken bath tub dumped here some time earlier can be recognized. To the right, the gully scarp shows small coves and bites.

Between October 1995 and April 1996 (Fig. 6), 162 mm of precipitation were recorded, of which 43 mm were potentially erosive. The bath tub below the head wall was partly filled with material broken off the wall to the right of the head cut. Further to the right, gully scarp retreat of up to 30 cm can be recognized by the fresh coarse material crumbled onto the grasses at the gully bottom. Total changes at the head wall amount to 0.72 m^2. The piping hole has widened by approximately 2.5 m^2 towards the upper left where its edge, overgrown with *L. spartum*, has broken off due to undercutting. Fresh material has piled up on the older sunken blocks within the hole.

The detailed topographic map shown in Fig. 3 was compiled from stereoscopic photographs taken at this stage of April 1996.

3.2. April 1996–August 1996

Until August 1996, 94 mm of precipitation fell (40 mm potentially erosive) (Table 3). The bath tub is now all but concealed by 0.38 m^2 of material broken off the right head wall (Fig. 7). Apart from this, no changes can be observed at the head cut, and the left

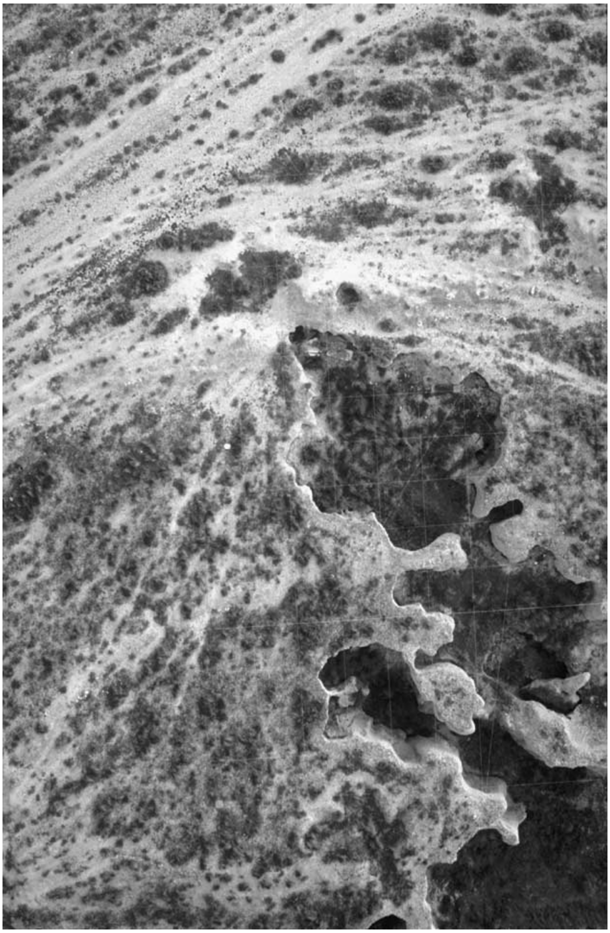

Fig. 6. Head cut of the Barranco de las Lenas, April 1996.

part below is now overgrown by vegetation, which indicates head cut inactivity during this last period. The arch as well as the pillar still remain as remnants of the former terrace surface, and the size of the piping hole is unchanged.

3.3. August 1996–April 1997

While the bath tub now completely covered by material from the face of the wall, the head cut itself remains unchanged (Fig. 8). The right gully wall has retreated approximately 20 cm near the ground control point PP8 (see Fig. 3). The former outlier has become an island by the disintegration of the arch which once connected it to the terrace surface. Altogether, 1.32 m^2 of surface was lost to the gully, the largest retreat recorded during the study period. Precipitation during these 8 months amounts to 245 mm of which 118 were potentially erosive.

Fig. 7. Head cut of the Barranco de las Lenas, August 1996.

The piping hole has widened by approximately 4 m^2 towards the left and upper right, and the tip of the pillar has collapsed into the hole where it came to a rest on the material accumulated here earlier.

3.4. April 1997–April 1998

The next 12 months show the highest precipitation sum (396 mm) and highest amount of potentially erosive rain (236 mm). For the first time, the uppermost head cut has retreated some centimetres and thus shows recurring activity (Fig. 9). To the right, the head wall shows small changes as well: a protruding block of material has fallen off the wall, and some centimetres of scarp retreat towards the eastern sheet wash basin can be observed further to the right. The fallen tip of the pillar has broken apart. However, total

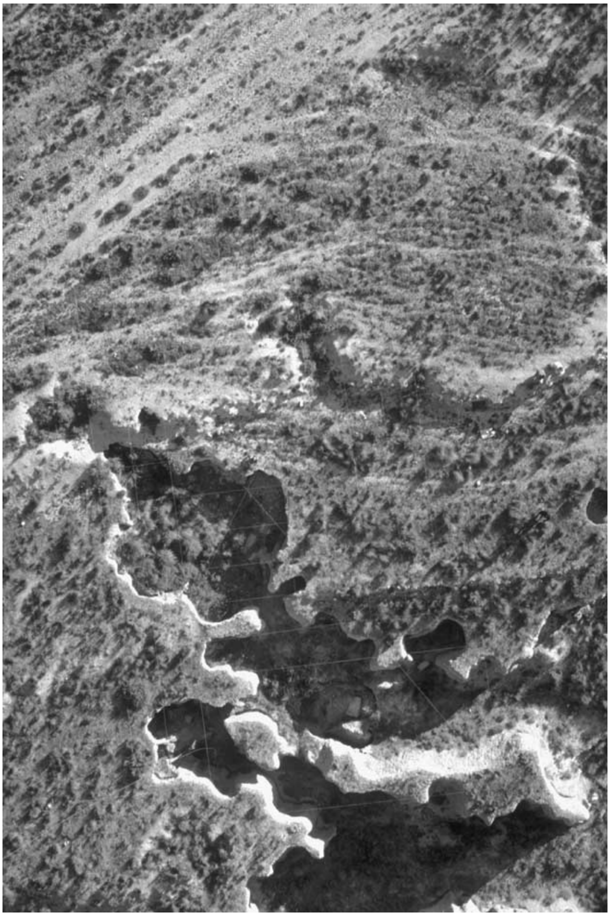

Fig. 8. Head cut of the Barranco de las Lenas, April 1997.

gully retreat adds up to only 0.76 m^2 and no changes could be observed at the piping hole.

3.5. April 1998–August 1998

There are no further changes to be observed until August 1998: head cut and wall remain unchanged and are inactive again in this period (Fig. 10). As no signs of flow marks exist and even the material deposited during the last period shows no signs of sheet wash, overland flow across the head cut and gully scarp can be excluded. A precipitation of 52 mm, none of which is potentially erosive, was recorded.

During the monitoring period of 34 months, changes at the head cut and head wall add up to 3.18 m^2, and a noticeable amount of material has broken off the face of the wall

Fig. 9. Head cut of the Barranco de las Lenas, April 1998.

Fig. 10. Head cut of the Barranco de las Lenas, August 1998.

itself. This figure represents the total gully enlargement, however, the actual head cut retreat does not contribute substantially to the gully development. At the gully bottom, the piping hole expanded by 6.5 m^2 at the same time (see Fig. 3).

4. Discussion

The study presented here shows that large-scale aerial surveys with the hot-air blimp as camera platform enable detailed monitoring of changes occurring at gully head cuts and walls. The system provides an extremely stable and vibration-free platform for photographic surveys. This stands in contrast to other large-scale remote sensing systems, which are usually less inert due to their dependence on motors (model airplanes and helicopters) or wind (kites). Apart from the necessity of study areas being accessible on foot and largely devoid of trees, power lines or other objects which could provoke conflicts with the tether ropes, the use of the blimp is not bound to specific launching places. A serious problem is wind; although the zeppelin shape ensures a fair stability even in windy conditions, anything more than a slight breeze will hamper inflation, and with more than approximately 3 Beaufort, blimp navigation is not feasible. It should also be understood that the system is not suitable for covering larger areas in a magnitude of square kilometres with adjacent images.

The blimp system has proven to meet the demands regarding documentation for spatially and temporally highly differentiated processes: head cut retreat as small as centimetres can be recognized, effects of sheet wash discerned and loss of material from the face of the wall can be verified by the presence of sediment deposits beneath even where the gully scarp remains unchanged. Transport of material at the gully bottom can be observed even in areas overcast by shadow from the wall owing to the good contrasts and high resolution of the photographs. This is of considerable importance with respect to the usually shaded gully bottoms. The temporal flexibility of the system allows high repeat rates for the survey and, in the present case, enables to distinguish between phases of head cut activity and inactive periods.

Although the cameras used for this study are small format, non-metric models and do not have defined photogrammetric properties, they proved to be suitable for the compilation of precise topographic maps (Fig. 3). Photogrammetric accuracy was considerably improved by the use of the values of inner orientation, which were defined by camera calibration at the Institute of Photogrammetry and Cartography of Karlsruhe Polytechnic University (Thormann, 1997). Ground control points, which were marked with red cardboard signals prior to the surveys and had their coordinates measured with a total station, enable absolute orientation of stereo pairs as well as geometrical correction of image time series. This also provides the prerequisite for further digital image processing, the construction of digital elevation models of various test areas and GIS analysis (Marzolff, 1999, pp. 76ff, 92ff, 103ff).

During the individual monitoring periods, no significant retreat due to linear flow at the actual gully head cut could be observed even with above average precipitation amounts of which up to 60% were potentially erosive. Instead, gravitative processes dominate at the head wall. Tension cracks, drying or frost cracks might be considered as a cause, and higher soil moisture can favour these gravitative processes. In particular, the terrace southeast of the right head wall—where overland flow from the sheet wash basin upslope (best seen in the centre of Fig. 8) infiltrates during precipitation events like those recorded in the study period—is well moistened. Here, the gully scarp retreats towards the east and is bound to tap into the direct flow path from the sheet wash basin in the near future. Thus, apart from episodic flow at the head cut, periodic gravitative break-offs at the gully walls have to be considered as an important factor for the velocity and bearing of the gully development. However, retreat rates cannot be easily correlated to precipitation amount, as can be seen from the data summarized in Table 3: Although periods with little precipitation show the smallest retreats, the peak retreat did not occur during the wettest period. The fact that the three highest retreat values always occurred during a winter period suggests that frost dynamics might be a major cause in material as silty as was found in this area.

No evidence of piping as a precursor for gully development could be found during the study period.

Based on the observed retreat rate of 3.18 m^2 in 34 months, an average annual retreat rate in the order of 1 m^2 $year^{-1}$ can be estimated for the 60 m^2 of the upper head cut area (above the lower terrace edge) since abandonment 60 years ago. Taking field measurements of gully depth into account, an average sediment yield of 26.7 kg m^{-2} $year^{-1}$ can be calculated, giving evidence of the high sediment contribution of the gully.

These figures do not include material loss within the gully due to piping processes: within the gully, piping processes play the dominant role for material transport (Table 3). The loss of material at the edge of the piping hole affects a noticeably larger area than could be observed at the gully scarp.

From the exemplary study of gully head development presented here, it must be deduced that sheet wash basins typically developing at terrace edges can be considered predecessors of the actual gully head cut. The shape of the upper part of the gully head suggests that it once originated from a similar situation: the narrowing at the edge of the middle terrace testifies the location of a former sheet wash basin until today. Disregarding the general similarity of gully development processes, gully shape and its development thus are subject to specific conditions in terraced terrain.

5. Conclusion

With the hot-air blimp system, a survey tool for detailed monitoring with high spatial and temporal resolution was developed. The authors feel that this study demonstrates the as yet little exploited potential of large-scale aerial monitoring for geomorphological process research. This method allows investigators to close the gap between terrestrial photography and conventional aerial photographs.

Changes at the scarp of the observed Barranco de las Lenas are manifold and highly variable. During the study period, they occurred mostly as lateral enlargement at the walls due to break-offs. Although changes amount to only 3.18 m^2 at the surface, this represents a remarkable loss of material. However, the most important changes were observed at the gully bottom as a result of piping processes.

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