Kite aerial photography for gully monitoring in sahelian landscapes

Irene Marzolff, Johannes B. Ries and Klaus-Dieter Albert
Department of Physical Geography, Johann Wolfgang Goethe University Frankfurt am Main, Senckenberganlage 36, D-60325 Frankfurt am Main

email: marzolff@em.uni-frankfurt.de / j.b.ries@em.uni-frankfurt.de / k.d.albert@em.uni-frankfurt.de

OFFPRINT
In: Proceedings of the Second Workshop of the EARSeL Special Interest Group on Remote Sensing for Developing Countries, 18-20 September 2002, Bonn, Germany, 2-13.

Keywords: Gully erosion, degradation monitoring, large-scale photography, high resolution, digital photogrammetry

Gully erosion is a common phenomenon in arid and semi-arid regions around the world. Although generally considered a major process of land degradation, the contribution of gullying to total soil loss by erosion has recently been subject of much discussion. The main reason for the shortage of quantitative data is the lack of adequate methods for the documentation and monitoring of gully development.

At Frankfurt University's Department of Physical Geography, a large-scale remote sensing system for aerial survey and image processing has been developed which meets the demands of spatial and temporal resolution required for gully monitoring. In the windswept savannahs of the Sahel of Burkina Faso, a kite system was employed for repeated aerial photographic surveys of several gully systems in 2000 and 2001. The system consists of a 6 m² rokkaku kite and a camera cradle with SLR camera which is suspended from a gondola running on the kite line. Camera orientation, tilt and trigger are remotely controlled, enabling to take vertical and oblique or horizontal photographs during the same flight. The kite can be positioned above the survey area very accurately when anchored to a motor vehicle.

The small format colour transparencies with image scales between approx. 1:500 and 1:5000 are transferred into digital format onto Kodak PhotoCD, yielding very high ground resolutions of 0.3 – 6 cm. Digital image processing and GIS software are used for rectification, georeferencing and mapping of gully extent and morphology. Digital change analyses of gully extent show considerable growth rates and enable detailed interpretation of patterns of gully headwall retreat for different gully types. Stereo photographs allow stereoscopic interpretation of gully morphology and erosion processes and can be employed for digital photogrammetric analysis, expanding the potential of the kite monitoring method from 2 to 3 dimensions.

1 INTRODUCTION

1.1 *Study area and research environment*

For the last 7 years, the authors and their work group have investigated processes of soil erosion as a major factor of land degradation in semi-arid landscapes. The work presented in this paper was carried out within the Deutsche Forschungsgemeinschaft's Collaborative Research Centre "West African Savannah" (SFB 268), in sub-project D5 on "Landscape evolution and actual morphodynamics in semi-arid regions of Burkina Faso". The study area is situated in the North-East of Burkina Faso at the southern rim of the Sahel (Fig. 1), where gully erosion can frequently be observed affecting both the widespread fixed dunes of late Pleistocene origin and the clayey-loamy sediments and soils of the flat peneplains. The region is under strong pressure by grazing and millet farming and after many centuries of land use today represents a severely degraded culivated landscape (Albert 2002; Albert, Hallier, Kahlheber & Pelzer 2001).

Field studies on actual soil erosion processes have involved quantification of site-specific infiltration capacity using single-ring infiltrometers according to Hills (1970) and Link (2000), measurement of site-specific runoff coefficients using a small jet-type rainfall simulator (according to Calvo, Gisbert, Palau & Romero 1988) and monitoring of linear gully erosion using large-scale multitemporal aerial photography (Pecho 2002; Albert, Müller, Ries & Marzolff 2002; Marzolff, Ries & Albert 2002; Albert 2002). The aim of this paper is to describe the method of large-scale remote sensing by kite and to present first results of the on-going study.

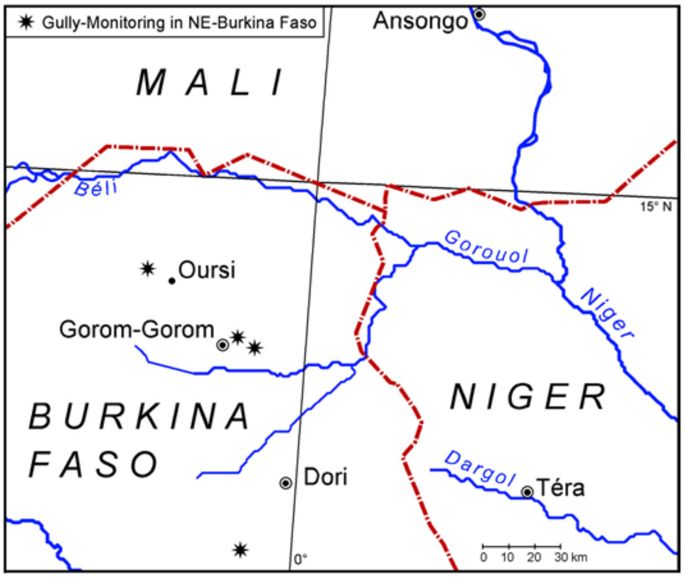

Fig. 1: Study area in North-East Burkina Faso, Westafrika.

1.2 *Gully erosion in semi-arid landscapes*

Gully erosion is a common phenomenon in arid and semi-arid regions around the world. Gullies are typical erosion forms without a permanent stream of water (Fig. 2); they have sharp edges and steep walls and are subject to periodic or episodic development. Other than smaller erosion rills, they cannot be eliminated by ploughing, and therefore cause permanent soil loss at the erosion site.

The activity at its uppermost headwall (headcut) controls the development of a gully (Fig. 3): Water running over the ground surface falls over the gully headwall, carving out undercuts and washing out fine material in plunge pools below. Where the wall is destabilized by undercuts and dessication or tension cracks, parts of the wall break off, are deposited within the gully and later washed out of the system. With progressing erosion, the headcut retreats upslope, continually enlarging the gully area.

Although generally considered a major process of land degradation, the contribution of gullying to total soil loss by erosion has recently been subject of much discussion. Some erosion researchers argue that in spite of being spectacular erosion forms, gullies only affect small areas mostly on unproductive land, while sheet and interrill erosion are the by far dominant factors for onsite impairment (Hudson 1995). However, recent works in the Mediterranean by Poesen et al. (1996, 2002) show that gullies play a central role for downslope sediment transport, causing massive offsite damage e.g. reservoir silting. The authors consider gullies as the most important sediment sources in drylands.

In order to get closer to an explanation of the processes involved in gully erosion and to an assessment of its contribution to total soil loss by erosion, more quantitative data on gully development are needed. The main reason for the shortage of quantitative data is the lack of adequate methods for the documentation and monitoring of gully development. Experiences from field work on gully erosion has shown that we need to improve or accomplish

- documentation of the complex forms with active and inactive parts
- identification and assessment of processes involved
- and above all detailed quantitative data of gully development both for area and volume.

For many of the issues involved in these questions, remote sensing and photogrammetry are an obvious choice of research method. However, the scale levels involved in gully erosion processes greatly restrict the choice of suitable remote sensing data.

Fig. 2: Gully erosion near Gorom-Gorom, Burkina Faso, July 2000.

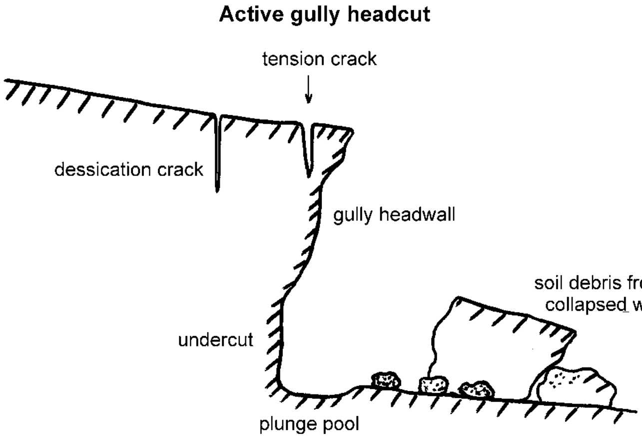

Fig. 3: Gully headcut development (adapted from Oostwoud Wijdenes et al. 2000)

2 LARGE-SCALE AERIAL PHOTOGRAPHY BY KITE

2.1 *Remote sensing system requirements*

Changes of gully extent can occur within hours or months, amounting from square centimetres to square metres. They cannot be mapped from standard aerial photography (IGB surveys in Burkina Faso: 1:50 000) with sufficient precision, nor can process dynamics be sufficiently monitored due to the low repeat cycle of these aerial surveys. Even very high resolution satellite imagery (IKONOS, QuickBird) does – apart from being extremely costly – not provide image resolutions appropriate to the research scale levels involved in gully development.

Several requirements for a system which would adapt to these scales of research can be identified:

- the spatial resolution has to correspond to the process magnitude (very large image scales, very high resolutions)
- the temporal resolution has to correspond to the dynamics of gullying (high and flexible repeat rates)
- the system needs to close the gap between terrestric vertical photography and conventional aerial photography (image scales 1:100 to 1:10 000, area coverage approx. 10 m² to 10 ha).

Other requirements were that the system was to be a low-cost system with good transportability, independence of difficult to control factors like availability of airstrips, fuel etc., and the resulting images were to be applicable for a wide range of image interpretation techniques.

2.2 *The kite system*

Blimps and balloons was well as kites, model airplanes and model helicopters have been used before by scientists as unmanned platforms for photographic and video cameras (see for example Batut 1890; Bürkert, Mahler & Marschner 1996; Walker & de Vore 1995) but rarely been employed for other than visual interpretation and hardly ever for erosion monitoring. Two of the authors have been working for several years with a hot-air blimp system for monitoring land degradation processes in Spain and Germany (Marzolff & Ries 1997, 2000; Marzolff 1999; Ries & Marzolff 2002). However, use of the blimp system is often limited by wind. For the frequently windy conditions in the Sahel regions, a kite system was developed as an alternative which is shown in Fig. 4.

As a camera platform, a 6 m² rokkaku kite is used which has to be secured to a car or ground anchor as it will pull up to 400 kg in good wind. The camera is suspended from a sledge-like gondola running on the kite line; it can be pulled up by a second line which runs through a pulley fixed to the kite line about 10 m below the kite. Using this camera sledge rather than attatching the camera suspension directly to the kite line makes launching of the kite more secure and enables changing films or lenses without having to take down the kite.

The camera cradle suspended from the sledge holds a 35-mm single lens reflex camera with motor drive and 50 mm or 28 mm lenses (Fig. 5). With focal distance set at infinity and shutter speed set at 1/500 sec or faster, photographs (KODAK EKTA-

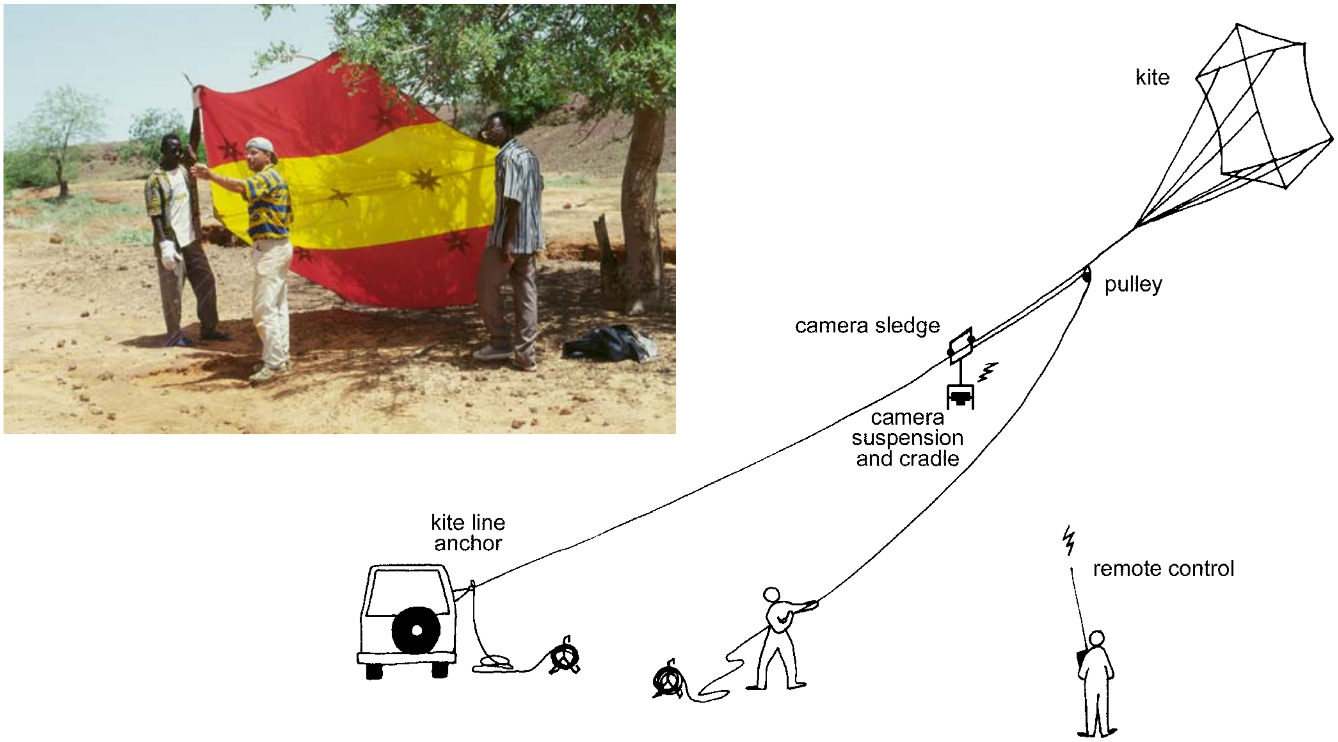

Fig. 4: Kite system comprising rokkaku kite and camera suspension

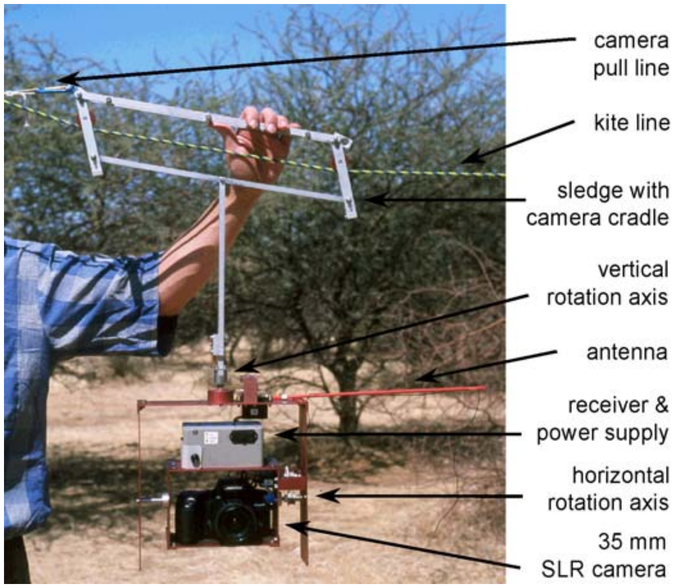

Fig. 5: Kite camera system with sledge and cradle

CHROME Elite 100 colour transparency film) are taken in automatic aperture mode using an electronic trigger connected to a remotely controlled switch. The cradle can be rotated horizontally and vertically by remote control to facilitate capture of both vertical and oblique photographs.

2.3 *Survey conduction and resulting images*

For the photographic survey, 10-30 control points are marked on the ground with paint or red cardboard. XYZ coordinates of the GCPs are measured with a total station to centimetre accuracy to enable georeferencing of images and stereo models later.

The survey is conducted with various heights and scales in order to give detailed photographs as well as overviews. While flying height is a function of line length, kite angle, wind velocity and distance from the site, the position of the camera can be adjusted by pulling the suspension sledge along the kite line, by moving the anchoring car or (in less strong wind) by redirecting the kite line with a pulley, walking sideways from the anchor on the ground. Stereoscopic coverage is possible by taking advantage of the swaying of the kite or by repositioning the kite. Oblique photographs were also taken as they provide an excellent illustration of the gullies' situation in the surrounding flat landscape.

An overview of scales, areas and resolutions for varying flying heights using standard or wide angle lenses is given in Table 1. The photographs vary in scale between approx. 1:500 and 1:7000, covering areas from 200 mm² to 4.5 ha. When digitized onto Kodak PhotoCD with 2200 dpi, they will yield ground resolutions between 0.5 and 8 cm.

Fig. 6 gives an example for a photograph taken from about 40 m (original image scale 1:800) of a wide and flat gully system near Gorom Gorom. Below the sharp edges of the gully, soil debris broken off the wall is clearly visible as well as the flowpath covered with finer material on the gully bottom. The same gully is seen in Fig. 7 in an overview taken with a 28 mm lens from 130 m height (original image scale approx. 1:5000). It reveals a very large dendritic system with many individual headcuts cutting into the flat glacis area. Where separately developing branches converge by retreating headcut erosion, island-like remnants may remain in some places, but will eventually been eroded by fluvial processes within the gully. Even trees will not hamper erosion processes for long once the gully has reached them.

3 IMAGE PROCESSING AND INTERPRETATION

3.1 *Image processing techniques*

The image processing and interpretation techniques used on the kite photographs can be grouped in 2D and 3D processing steps:

Until recently the images were only used for 2D interpretation, i.e. for area mapping and quantification (Marzolff 1999; Marzolff, Ries & Albert 2002). Geometric correction is done by using ground control points for 2nd order image transformation and mosaiking with ERDAS Imagine image processing software; multitemporal images were also georeferenced by image to image rectification. A GIS (ArcView 3.2) was then employed for mapping of gully extent and morphology and for time series analysis resulting in quantification of area change. In some cases, monoscopic on-screen digitizing was aided by visual interpretation of prints with a stereoscope.

	50 mm lens			**28 mm lens**		
flying height	**scale**	**area**	**resolution (2200 dpi)**	**scale**	**area**	**resolution (2200 dpi)**
25 m	1 : 500	12 m ∗ 18 m	0.6 cm	1 : 890	21 m ∗ 32 m	1.1 cm
100 m	1 : 2000	48 m ∗ 72 m	2.3 cm	1 : 3570	86 m ∗ 129 m	4.1 cm
200 m	1 : 4000	96 m ∗ 144 m	4.6 cm	1 : 7140	172 m ∗ 258 m	8.3 cm

Table 1: Image scales, areas covered and ground resolutions for different focal lengths at varying flying heights

Fig. 6: Kite aerial photography of Gully Gorom, Burkina Faso, December 2001. Image width approx. 25 m.

Very recently, the monitoring potential was expanded by photogrammetric techniques for 3D mapping: With digital photogrammetry software (ERDAS Orthobase/StereoAnalyst), stereoscopic images even from non-metric cameras can be employed for photogrammetric block and digital stereo model creation. This allows on-screen stereo mapping of 3D-features like gully scarps and contour lines. The 3D data can then be used to compute digital raster elevation models or vector TINs for quantification and monitoring of gully volume.

3.2 *Gully monitoring at the Oursi test site*

During three field campaigns in 2000 and 2001, approx. 2000 photographs of five different types of gullies were taken in the study area in Burkina Faso. In the following chapter, one example of gully monitoring with first results also for 3D interpretation will be presented.

Fig. 8 shows a group of gullies cutting into Pleistocene dune deposits covered with settlement debris of medieval origin near the village of Oursi. The gullies are situated between several settlement mounds which are well visible until today as mounds of pottery shards and stones. These settlement mounds have extremely high runoff rates of up to 90%, as measured by rainfall simulation, and very limited infiltration capacity, thus encouraging linear

.

Fig. 7: Kite aerial photography of Gully Gorom, Burkina Faso, December 2001. Image width approx. 160 m. Rectangle indicates area covered by Fig. 6.

Fig. 8: Gully erosion between medieval settlement mounds (West African Iron Age) at the Oursi Dunes, Burkina Faso. Oblique kite aerial photography, July 2000.

erosion in the sandy deposits downslope. The gullies are now already cutting into the archaeological layers and it is of high interest to both geomorphologists and archaeologists in the research project if the hilly surface relief seen today does actually represent the historical settlements or if it has developed by erosion only fairly recently (Albert 2002).

It is easily imagined that field measurements of gullies like these are very cumbersome and difficult. Prior to introducing the kite aerial photography surveys, measurements in the fields were taken from the uppermost parts of one of the Oursi gullies. By using trees as fixed reference points, distances to the gully headcuts and gully width were measured. From these tables of data, a coarse sketch could be drawn up (Fig. 9), roughly depicting the development between July 1998 and July 1999 – however, only linear retreat and width increase can be deducted from such measurements, not area or volume.

From kite aerial photography taken in July 2000, July 2001 and December 2001, the complete gully area could be mapped with much more detail (Fig. 10). Although the retreating headcut is continually reducing its own catchment area, the gully grows up to 5 m in a single rainy season. The main branch (between reference points A and B) which advances fastest has split within the monitoring period and also unioned with the neighbouring branch to the west leaving an island with a tree in the middle. The eastern branches have advanced slower, probably due to changes in the catchment area which is being taken over by the western branch. The gully area shown totals 295.5 m² in July 2000; changes amount to 49,9 m² in the rainy season of 2000 and 39,6 m² in the rainy season of 2001. The majority of this soil loss is adding to the length of the gully rather than the width, testifying of the linear nature of this type of gully.

The western twin branch of the gully (stretching upslope from reference point E between B and G) has in December 2001 an area of 234 m². For this branch, first tests with stereocopic mapping and quantification have been made using digital stereo models created from a block of 5 kite photographs. The gully scarps, 20-cm contour lines and height points were mapped with ERDAS StereoAnalyst. The resulting detailed topographic map in Fig. 11a reveals that this erosion form is not only a complex dendritic system in its outlines but especially rough and uneven within the gully, with terraces, overhanging walls and even bridges which can not be properly surveyed with field methods.

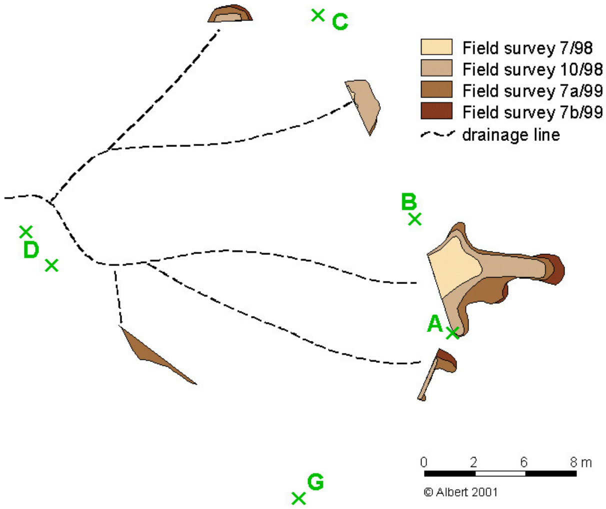

Fig. 9: Sketch compiled from field measurements of gully width and headcut retreat in 1998 and 1999, Gully Oursi, Burkina Faso.

For a first attempt of volume calculation, a TIN model of the December 2001 state was computed using ArcView 3D Analyst (Fig. 11b). By reconstructing presumable contour lines before gully incision over the digital stereo model, a second TIN of the alleged former surface could be computed. Subtraction of both TIN models result in a volume of 214 m³ for the depicted gully branch of 234 m² which has developed in probably less than 8 years.

As an absolute figure, this volume quantification does no yet provide sufficient information regarding the magnitude and role of gully erosion in the study area. It will during further research have to be related to precipitation data, infiltration and runoff measurements, soil substrate analyses and relief parameters of the catchment area. However, given this first appraisal of the area change and volume quantification of Gully Oursi, it has to be considered that this gully certainly is comparatively little active because it has not much catchment area (only 3500 m²) and expansion possibilites left – the watershed is almost reached. In comparison, the gully at Gorom Gorom shown in Figs. 6 and 7 which is not deep but very much wider, advances about 20 m a year and might produce much larger amounts of sediment.

The TIN model, in spite of being a first test with some deficiencies regarding its quality, already gives

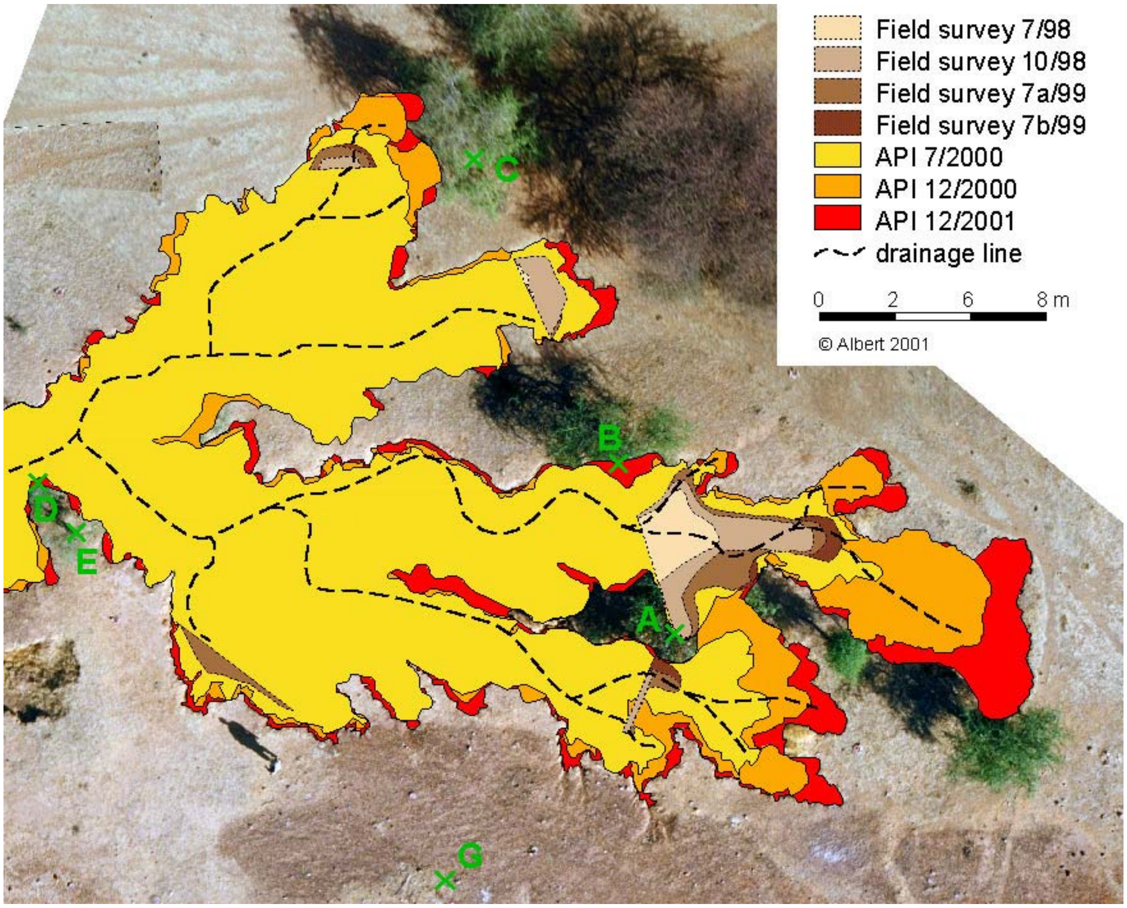

Fig. 10: Field measurements of gully width and headcut retreat 1998-1999 and gully area in 2000 and 2001 mapped by aerial photo interpretation from georeferenced airphoto mosaics, Gully Oursi, Burkina Faso.

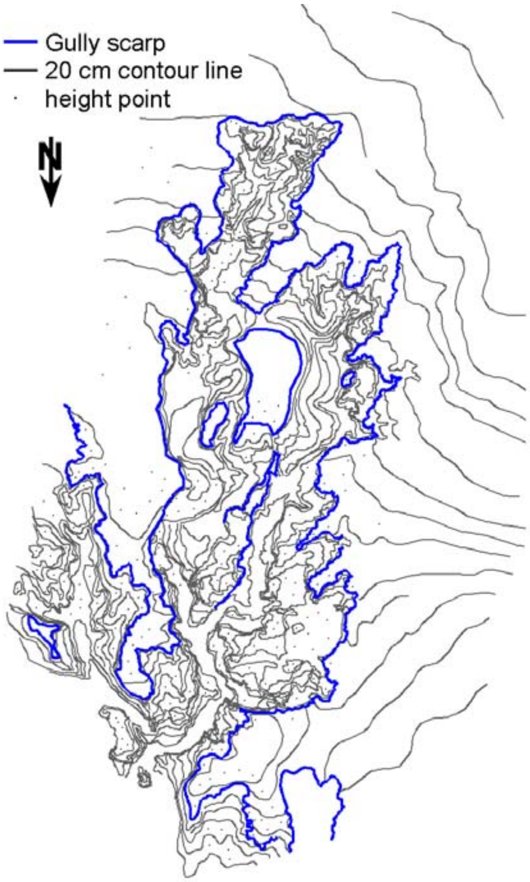

Fig. 11a: Topographic map of western branch of Gully Oursi, Burkina Faso, December 2001.

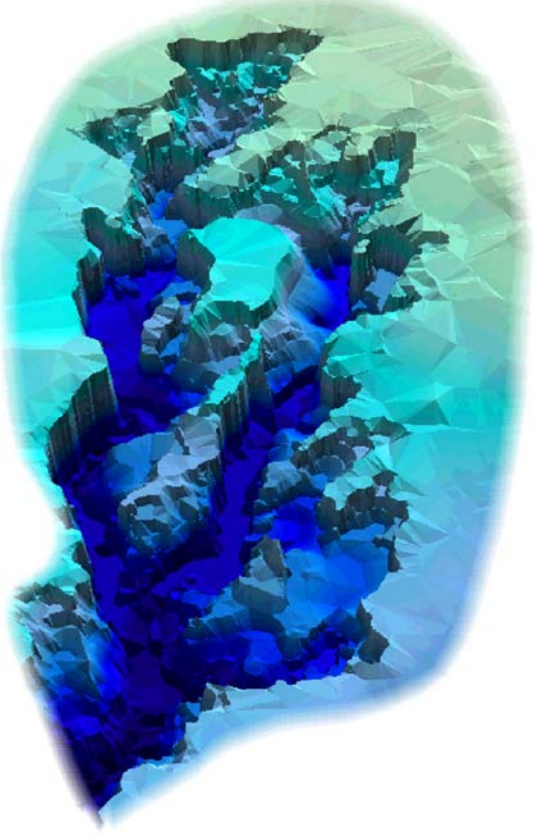

Fig. 11b: TIN surface model computed from 3D data shown in Fig. 11a, vertical exaggeration factor 1.5.

an excellent description of the different forms present in the gully system, indicating that TIN surface models might possibly give the better representation of gully morphology as compared to a raster DEM which tends to smooth out sharp edges.

3.3 *Monitoring accuracies*

Other than field measurements, the remote sensing and photogrammetry methods presented in this paper allow detailed monitoring of both area and volume of gullies. The digital base images used for the gully monitoring studies have resolutions of 1.5-4 cm, granting a potentially very high mapping precision. Using common geometric correction methods (2nd order polynomial equations computed from ground control point coordinates), RMS errors of 2-8 cm depending on image scale were achieved. It has to be mentioned that these RMS error apply to the surface area around the gully – due to central projection properites, relief distortions within the gully are rather large without the use of DEMs for orthophoto correction. However, this is not relevant for mapping of the gully edges.

Experiences so far have shown that slight geometric discrepancies originating from inaccuracies in geometric corrections for multitemporal images result in mean mapping errors of 5-8% of gully growth area, a figure which can be considered as well within an acceptable range of accuracy. Better yet results for the area quantification are expected when employing the photogrammetric software for 3D mapping and true orthophoto correction rather than monoscopic 2D mapping from images corrected with XY GCP coordinates only.

Regarding 3D processing and block creation, mean RMS errors for GCPs amount to approx. 2 cm in horizontal and 9 cm in vertical direction; consequences of these errors for volume accuracy remain to be estimated. Here also, higher accuracies are expected when incorporating camera calibration reports: all cameras used for further gully monitoring will in the future be upgraded with fiducial marks and calibrated for interior orientation values.

4 SUMMARY AND CONCLUSIONS

Background for the study presented in this paper was the shortage of quantitative data on gully development and the lack of adequate methods for the documentation and monitoring of these complex erosion forms. A method was needed for complete and detailed coverage of gully area to allow quantitative and qualitative change analysis.

Results show that 2D mapping from large-scale kite aerial photography allows area quantification in high detail and accuracy, while 3D photogrammetric mapping allows additional volume quantification and estimation of actual soil loss. First evaluations show accuracies to be in very satisfactory ranges regarding the research question of gully erosion. Results also suggest that 3-dimensional models might be differently suitable for the representation of morphological forms and processes of gully erosion and further research is needed on the possibilities arising from photogrammetric gully monitoring.

ACKNOWLEGDEMENTS

The authors would like to thank Michael Pecho, Axel Bernhard and Annika Wachsmuth, all diploma candidates at the Department of Physical Geography, as well as Mounkayla Yakouba, Houseini Alpha, Hamadou Idrissa and Boureima Abdoulaye from Gorom-Gorom for valuable assistance in the field. The tireless efforts made by the staff of the faculty of geoscience's technical workshop on constructing and improving the kite camera system are very gratefully acknowledged. We are very grateful for funding of this research by the Deutsche Forschungsgemeinschaft.

REFERENCES

Albert, K.-D. (2002 in prep.): Die Altdünenlandschaft im Sahel Nordost-Burkina Fasos – Geomorphogenese und Geomorphodynamik einer semi-ariden Kulturlandschaft. – PhD Thesis, Faculty of Geosciences and Geography, Johann Wolfgang Goethe University Frankfurt am Main.

Albert, K.-D.; Hallier, M.; Kahlheber, S. & Pelzer, C. (2001): Montée et Abandon des Collines d'Occupation de l'Age de Fer au Nord du Burkina Faso. – Ber. des Sonderforschungsbereichs 268, 14, 335-351.

Albert, K.-D., Müller, J., Ries, J. B. & Marzolff, I. (2002 in print): Aktuelle Landdegradation in der Sahelzone (Burkina Faso). – Albert, K.-D., Löhr, D. & Neumann, K. (Eds.): Mensch und Natur in Westafrika. Ergebnisse aus dem Sonderforschungsbereich 268 "Kulturentwicklung und Sprachgeschichte im Naturraum Westafrikanische Savanne", Wiley VCH.

Batut, A. (1890): La photographie aérienne par cerf-volant. – Facsimile in: Autha, D.; Nègre, S.; Beauffort, G. de & Fosset, R. (1988): Labrugière – berceau de l'aérophotographie par cerf-volant/birthplace of kite aerophotography. Arthur Batut 1846-1918, 95-155.

Bürkert, A., Mahler, F. & Marschner, H. (1996): Soil productivity management and plant growth in the Sahel: potential of an aerial monitoring technique. – Plant & Soil 180 (1), 29-38.

Calvo, A., Gisbert, J.M., Palau, E. & Romero, M. (1988): Un simulador de lluvia portátil de fácil construc-ción. – In: SALA, M. & GALLART, F. [eds.]: Métodos y Técnicas para la Medición en el Campo de Procesos Geomorfológicos. Sociedad Española de Geomorfología, Monografía No. 1; Barcelona, p. 6-15.

Hills, R. C. (1970): The Determination of the Infiltration Capacity of Field Soils Using the Cylinder Infiltrometer. – British Geomorphological Research Group, Technical Bulletin; Kent, 24 pp.

Hudson, N. (1995^3): Soil Conservation. – London, 391 pp.

Link, M. (2000): Das Einring-Infiltrometer mit schwimmgeregelter Überstauhöhe. Ein neues Gerät zur Messung von Infiltrationsraten in Böden. – Geoöko, XXI: 121-132.

Marzolff, I. (1999): Großmaßstäbige Fernerkundung mit einem unbemannten Heißluftzeppelin für GIS-gestütztes Monitoring von Vegetationsentwicklung und Geomorphodynamik in Aragón (Spanien). Freiburger Geogr. H. 57, 226 pp. + 99 pp. map appendix.

Marzolff, I., Albert, K.-D. & Ries, J. B. (2002): Fernerkundung vom Fesseldrachen. Luftbild-Monitoring gibt Aufschluss über Schluchterosion in der Sahelzone. – Forschung Frankfurt, 3/2002, S. 16-22.

Marzolff, I. & Ries J. B. (1997): 35-mm photography taken from a hot-air blimp. – In: Proceedings of the First North American Symposium on Small Format Aerial Photography, Cloquet, Minnesota, USA, 14-17 October 1997, S. 91-101.

Marzolff, I. & Ries, J. B. (2000): Großmaßstäbiges Luftbildmonitoring mit einem ferngesteuerten Heißluftzeppelin. – Petermanns Geographische Mitteilungen, 144 (6), 4-5.

Ries, J. B. & Marzolff, I. (2002): Monitoring of gully erosion in the Central Ebro Basin by large scale aerial photography taken from a remotely controlled blimp. – Catena 50 (2-4), 309-328.

Oostwoud Wijdenes, D., Poesen, J. Vanderkerckhove, L. & Ghesquiere, M. (2000): Spatial distribution of gully head activity and sediment supply along an ephemeral channel in a Mediterranean environment. – Catena, 39, S. 147-167.

Pecho, M. (2002 in prep): Oberflächenabfluss und Sedimentaustrag in verschiedenen Landschaftseinheiten der Sahelzone Burkina Fasos. – Unpublished Diploma Thesis, Department of Physical Geography, Faculty of Geosciences and Geography, Johann Wolfgang Goethe University Frankfurt am Main.

Poesen, J., Vandaele, K. & Van Wesemael, B. (1996): Contribution of gully erosion to sediment production on cultivated lands and rangelands. – In: Walling, D. E. & Webb, B. W. [eds.]: Erosion and Sediment Yield. Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996). IAHS Publ., 236: 251-266.

Poesen, J., Vanderkerckhove, L., Nachtergaele, J., Oostwoud Wijdenes, D., Verstraeten, G. & van Wesemael, B. (2002): Gully Erosion in Dryland Environments. – In: Bull, L.J. & Kirkby, M.J.: Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels. 229-262.

Walker, J. W. & De Vore, S. L. (1995): Low Altitude Large Scale Reconnaissance: A Method of Obtaining High Resolution Vertical Photographs for Small Areas. Denver, 161 pp.