Geogr. Fis. Dinam. Quat.
39 (2016). 161-170, 7 figg.; 2 tabb.

DOI 10.4461/ GFDQ 2016.39.15

JAN KROPÁČEK (*,**), CALOGERO SCHILLACI (**,***), RICCARDO SALVINI (****)
& MICHAEL MÄRKER (*****,******)

ASSESSMENT OF GULLY EROSION IN THE UPPER AWASH, CENTRAL ETHIOPIAN HIGHLANDS BASED ON A COMPARISON OF ARCHIVED AERIAL PHOTOGRAPHS AND VERY HIGH RESOLUTION SATELLITE IMAGES

ABSTRACT: KROPÁČEK J., SCHILLACI C., SALVINI R. & MÄRKER M., *Assessment of gully erosion in the Upper Awash, Central Ethiopian Highlands based on a comparison of archived aerial photographs and very high resolution satellite images.* (IT ISSN 0391-9839, 2016)

Gully erosion is a burning problem in the Ethiopian Highlands leading to massive soil losses and sedimentation in reservoirs. In this study gully erosion in the Upper Awash River basin in the central part of the Ethiopian Highlands was studied using archived aerial photographs from 1965, 1971 and 1972 in combination with satellite images from Ikonos-2 and Pleiades acquired in 2006 and 2013 respectively. Gully length, areal extent and the accurate position of gully heads were mapped by means of visual interpretation. Elevation changes due to the gully incision were analysed by calculating the difference between two digital elevation models for the years 1972 and 2006 generated by means of terrain reconstruction using the Structure from Motion approach (SfM) and satellite photogrammetry. In the study area the total gully length increased three times in the period 1965-2013. The initial rapid gully headward extension rate slowed down after 1972. Especially after 2006 effects of remediation activities led even to a decrease in total gully length. However, dendritic gully complexes continue to propagate at an alarming rate. The identified trend of gully evolution in Upper Awash area over the studied period fits to the overall trend identified in northern Ethiopia. In future more attention should be paid to quickly growing gully complexes in order to prevent increasing soil loss and sedimentation in the Koka Reservoir. The presented study proved that the approach based on a combination of archived aerial photos and data from the new satellite systems is effective to monitor gully erosion in semi-arid regions.

KEY WORDS: Water erosion, Gully evolution, Process monitoring, Digital elevation model (DEM), Aerial photographs, Structure from motion (SfM), Very high resolution (VHR) Satellite imagery, Ethiopia, Upper Awash.

(*) *Katedra aplikované geoinformatiky a územního plánování, Fakulta životního prostředí, Česká zemědělská univerzita v Praze, Kamýcká 129, Praha, Česká Republika.*

(**) *Institut für Geographie, Eberhard Karls Universität Tübingen, Rümelinstr. 19-23, 72070 Tübingen, Germania.*

(***) *Dipartimento di Scienze Agrarie e Ambientali, Università degli Studi di Milano-Bicocca, Via Celoria 2, 20133 Milano, Italia.*

(****) *Dipartimento Scienze fisiche, della Terra e dell'ambiente e Centro di GeoTecnologia CGT, Università degli studi di Siena, Via Vetri Vecchi 34, 52027, San Giovanni Valdarno, Arezzo, Italia.*

(*****) *Heidelberger Akademie der Wissenschaften, Karlstr. 4, 6113 Heidelberg, Germania.*

(******) *Dipartimento Scienze della terra e dell`Ambiente, Università degli studi di Pavia, Via Ferrata 1, 27100 Pavia, Italia.*

This study was carried out within the framework of the German Science Foundation (DFG) project "Integrated assessment of geomorphological process dynamics on different spatio-temporal scales in the Ethiopian Highlands using remote sensing and advanced modelling approaches" (HO1840/11-1). The aerial photographs were provided by the Ethiopian Mapping Agency. Pléiades data was obtained from ESA through the Third Party Mission scheme (project code C1F13160). Ikonos-2 scenes were acquired within the framework of the European Community Culture 2000 project titled "From the past to the present in Ethiopian prehistory: an interactive museum for the archaeological park of the early Paleolithic site of Melka Kunture". AIGeo Grant that supported the participation at the VI young geomorphologist day- 29 September 2015 Cagliari. We thank Dr. Luigi Lombardo for language proofing and useful comments. We are also grateful to two anonymous reviewers who largely contributed to an improvement of the manuscript.

INTRODUCTION

Gully erosion especially in semi-arid areas is a burning problem as it leads to degradation of agricultural land (Daba & *alii*, 2003; Haregeweyn & *alii*, 2015; Märker & *alii*, 2001; Poesen & *alii*, 2003; Valentin & *alii*, 2005; Zakerinejad & Märker 2014). Additionally, gullies tend to evolve head ward thus, increasing the drainage density and accelerate desertification processes in the semi-arid zones (Valentin & *alii*, 2005). It was also shown that gully erosion is often a major contributor in reservoirs sedimentation, which is a serious problem especially in semiarid areas with pronounced seasonality in precipitation such as Ethiopia (Hamed & *alii*, 2002; Haregeweyn & *alii*, 2006; Tamene & *alii*, 2006). Usually, gully erosion is triggered or accelerated by land use change and/or by extreme climatic events (Valentin & *alii*, 2005). A better understanding of gully evolution is necessary for the development of management strategies to combat soil erosion. Therefore, numeric as well as stochastic modelling approaches have been applied for gullying and concentrated flow processes such as debris flows taking into account remotely sensed information on different levels (e.g. Sidorchuk 1999; Sidorchuk & *alii*, 2003, Lombardo & *alii*, 2016, Märker & *alii*, 2016,).

Gully erosion in the Ethiopian Highlands was studied by different authors. Billi & Dramis (2003) investigated the role of shear stress along developing channels of 16 gullies in two localities with different geo-environmental conditions in the Lakes Region in the Rift valley north of Shashamene and in the area of Mekele in Tigray. They distinguished discontinuous gullies and stream gullies based on different behaviour of shear stress and morphological properties of channels. Bewket & Sterk (2003) analysed two catchments in the northwest of Ethiopia using field surveying. Their results showed that in the studied catchments gullying contributes to the total sediment production by 70%. A photogrammetric approach was applied by Daba & *alii*, (2003) to analyse gully volume in eastern Ethiopia from aerial photographs taken in 1966 and 1996. The authors estimated a high soil loss of 1.7 tons/m^2 in the study catchment in Hararghe highlands in east Ethiopia. Furthermore, they showed that wetness index alone or a combination of the wetness index and the compound topographic index can be efficiently used for predicting hill-slope areas susceptible to further gullying. Nyssen & *alii*, (2006) document the development of gullies on three representative localities in Tigray, Ethiopia, which was initiated after 1965 and culminated between 1977 and 1990, with no further gully developed after 1995. Another study in Northern Ethiopia indicated the presence of gullies in the late 19th century and a strong channel incision phase starting in the 1960s while since the year 2000 a decrease in gully erosion rates were observed (Frankl & alii, (2011). The last evidence can be explained by an intensification of soil conservation practices and increasing vegetation cover (Nyssen & *alii*, 2015). Frankl & *alii*, (2012) analysed gully head retreat rates in a catchment in north Ethiopia in the rainy season in 2010. The linear retreat rate was 0.34 m/a while it reaches up to 1.93 m/a especially in areas of Vertisols affected by piping. Using archived terrestrial and aerial photographs the linear, areal and volumetric erosion rates were calculated as 3.8 m/a, 31.5 m^2/a, and 47.7 m^3/a in the medium to long-term time scale (Frankl & *alii*, 2012). Nyssen & *alii*, (2015) suggest, that the traditional agricultural system which is practiced also in the Upper Awash area is well adapted to the environment of the Ethiopian Highlands. However, the combination of overgrazing and agricultural intensification with precipitation seasonality and erosion prone soils represent a high potential for gully development in Ethiopia.

An analysis of archived aerial photographs proved to be a useful tool for the investigation of gully development as for instance the estimation of sediment production rates (Betts & DeRose 1999; Daba & *alii*, 2003; Martinez-Casasnovas & *alii*, 2003; Nachtergaele & Poesen 1999; Sidorchuk & *alii*, 2001). In Ethiopia some areas were covered by air photographs taken by the Italian military in the period 1935-1941 (Frankl & *alii*, 2015). A systematic aerial acquisitions of the Ethiopian territory by metric cameras started in the 1950s.

In this study, we analyse archive aerial photographs and very high resolution (VHR) satellite images to assess gully erosion dynamics in the Upper Awash area on the Ethiopian Highlands in the last decades. We analyse the extent of gullies in the 1960's at the beginning of a modern intensification of agriculture and in the last decade. Additionally, we demonstrate the usefulness of the archive aerial photographs for investigation of the landscape development.

This study is focused both regionally and methodologically. We aim at a regional assessment of gullying in the Upper Awash area and methodologically on an evaluation of the potential of archived aerial photographs for erosion processes investigations. Since the possibility to evaluate vertical changes based on the available aerial photographs was limited due to their scale and level of detail, we emphasize the regional implications of the results.

STUDY AREA

Our study area is located in the Upper Awash basin on the Ethiopian Highlands close to western escarpment of the main Ethiopian rift (Fig. 1). The main settlement is Melka Awash which is located on the Butijara Road approximately 30 km south-west from Addis Ababa. An important Palaeolithic site Melka Kunture, known for numerous early hominid remains is located near the settlement (Chavaillon & Berthelet 2004). Furthermore, Melka Kunture represents the earliest known example of obsidian utilization, which originates from numerous outcrops around the site (Piperno & *alii*, 2009). The area is characterized by a typical smooth relief of the plateau with slopes mainly up to 10°. The elevation range is 2000 to 2250 m a.s.l. The Awash River drains the study area towards the east and southeast. The river enters a gorge with a knickpoint south of Melka Awash caused by the propagation of headward erosion with a base level in the rift valley. The landscape development was driven by tectonic activity connected to rifting, mainly explosive volcanism, erosion and sedimentation (Salvini & *alii*, 2012). Multiple phases of volcanic activity were initiated 4 to 5 Ma BP (Raynal & Kieffer 2004). Extensive lava flows and layers of ignimbrites crop out in exposed scarps. The area is characterized by a horst and graben structure, which runs parallel to the structural rift pattern (Salvini & *alii*, 2012) denoted as semi-graben fault system by Gallotti & *alii* (2014). Morphological evidences of the tectonic structure can be identified in the Melka Kunture area (Raynal & Kieffer 2004; Salvini & *alii*, 2012). The so called 'Awash Sill' which is a border fault delimiting the graben from SE due to its periodic reactivation has controlled the cycle of sedimentation and erosion in the area (Raynal & Kieffer 2004). The main soil types of the area are Vertisols and Fluvisols (Berhanu Debele 1985). Vertic Umbrisols and Vertisols can be found on gentle slopes and flat areas, while flood plains are characterized by clay rich Fluvisols (Gleysols). The main feature of the Vertisols is that they desiccate and produce cracks more than 20 cm deep, which develop during the dry season. Nyssen & *alii*, (2000) showed that in

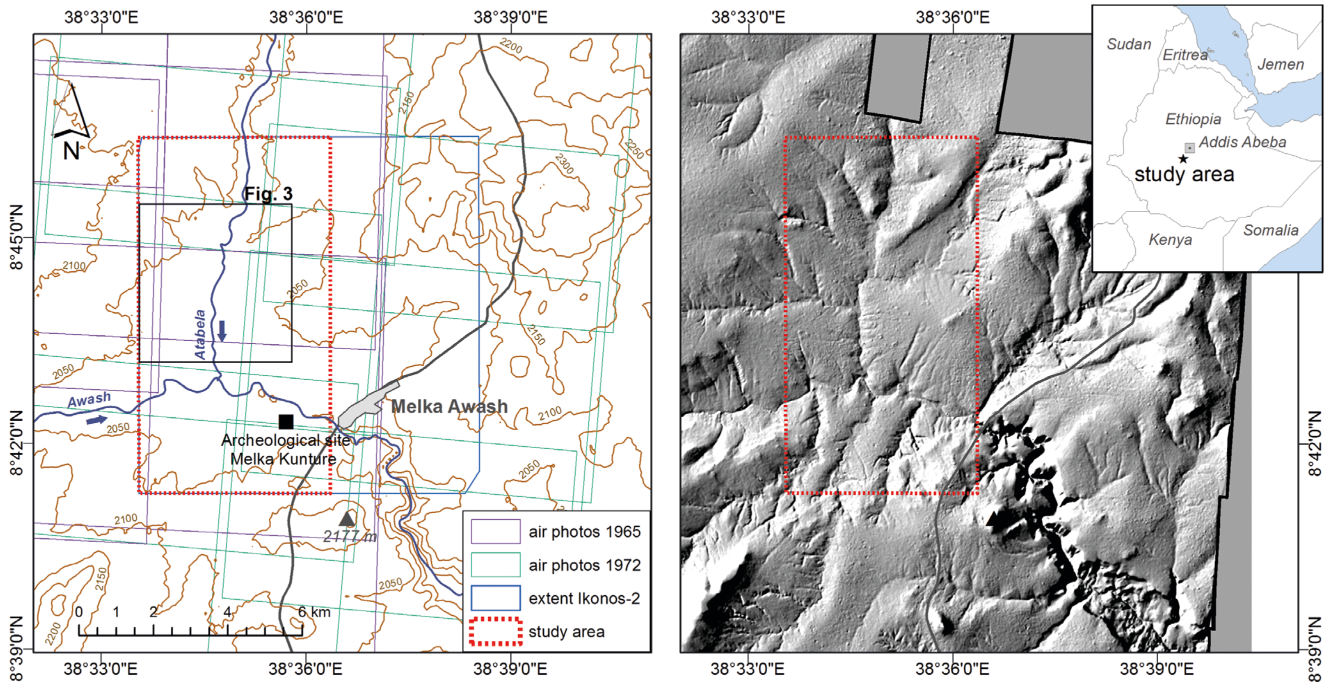

FIG. 1 - The study area south west from Addis Ababa in the surroundings of the archaeological site of Melka Kunture. The extents of the utilized datasets are shown as rectangles.

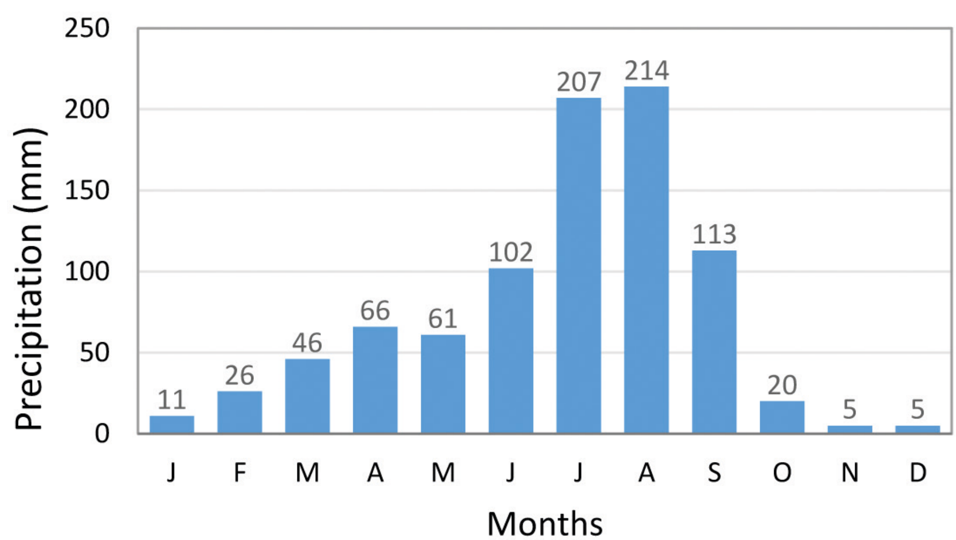

FIG. 2 - Monthly precipitation means calculated from daily measurements at Boneya station operated by the National Meteorology Agency. Monthly means are based on measurement records from the period 1974-2014. Boneya gauge is located about 5 km from the study area to the northeast at the elevation of 2251 m a.s.l.

northern Ethiopia Vertisols tend to physical and chemical destabilisation. The climate of the area is semi-arid with pronounced seasonality in precipitation. The mean annual precipitation measured at Boneya station is 982 mm. There is a main rainy season in July and August and small rainy season in April (Fig. 2) (Billi & Dramis 2003). During the period from April to September 68% of precipitation occur. The climate is rather dry in winter. During the late dry season (December - February) the tributaries of the Awash River often fall dry. The analysis of Boneya station records shows that the most intense rainfall event was registered at Awash-Melka Kunture Gauge with 73.4 mm/day, recorded on 4th September 1993, whilst the maximum monthly precipitation of 506 mm was registered in August 2011 (National Meteorology Agency of Ethiopia). Vast areas are covered by arable land cropped with cereals, mainly teff, durum, wheat and sorghum. Some smaller areas are left to fallow and used as pastures. In the vicinity of Melka Awash settlement there are two of many large green house areas appearing in recent years in the area around Addis Ababa. They are used for production of flowers for the international markets. There are no forest in the area but solitary trees scattered in the landscape. Some denudated or steep hillslopes are covered with sparse shrubs. Around the settlements, small eucalyptus plantations can be found. A rapid expansion of settlements in the area was identified by Salvi & *alii*, (2011) in the period 1972-2006. The extent of arable land, grazing on fallow land and concentrated precipitation leads to increasing erosion in the area, that results in high sediment transport by the Awash river. This represents a serious problem for the Koka Reservoir, which is located about 70 km downstream from the study area. The Koka Reservoir was constructed in the framework of hydropower development in Ethiopia in 1959 (Shahis 1993). In the period from 1961 to 1981 the total sediment deposit in this reservoir was estimated to 0.34 km^3 which corresponds to a general rise of the initial reservoir bed by 3 m (Shahis 1993). Paulos (1998) reports that 35 % of the storage capacity of Koka Reservoir is filled with sediment from the upstream highlands.

MATERIALS AND METHODS

Gullies are usually several meters wide and they are accompanied by smaller landforms, which can be distinguished only on remote sensing images with sufficient spatial resolution. Both traditional aerial photographs acquired by metric cameras and images taken by UAVs are suitable sources of information for gully features analysis. Furthermore, VHR satellite images with sub-meter resolution which are available since the launch of the first VHR commercial satellite Ikonos-2 in 1999 can provide a sufficient level of detail (Dial & *alii*, 2003). Declassified images acquired by the US reconnaissance satellite Corona are often used for environmental change detection studies (Altmaier & Kany 2002; Bolch & *alii*, 2008). Although gullies in the study area could be identified on Corona images from 3 November 1967, the spatial resolution did not allow their accurate mapping for the purpose of this study.

Archive Aerial Photographs and DEM for 1970's

We obtained eight softcopies of black and white aerial photographs of the study area acquired in 1971 and 1972 from the Ethiopian Mapping Agency (EMA), which provides the data for research purposes (Tab. 1). The photographs were acquired by a metric camera with a focal length of 152.57 mm. The scanning density of 1016 dpi resulted in a ground resolution of 1.0 m. The standard 60 % overlap allows photogrammetric processing. We derived a DEM (Air72 DEM) using the SfM technique (Westoby & *alii*, 2012) following the approach described in Kropáček & *alii* (2015). The three-dimensional model was reconstructed using stereo-matching algorithm implemented in Agisoft Photoscan version 1.0.4. The model was geo-referenced to UTM projection using 10 ground control points (GCPs). The resulting point cloud with a density of 0.2 points per m^2 was converted to a raster DEM with a resolution of 2.5 m (Fig. 3). It contains fine structured elements; however, it features some noise due to processing artifacts and surface structures such as trees and houses. Analytical hillshade was used to check the overall DEM quality in terms of relief features and for the noise detection (Schillaci C. & *alii*, 2015). Furthermore, six aerial photographs from 1965 were obtained for the study area from EMA. The scanning density of 1016 dpi and a higher flight height than in the case of the acquisitions from 1971 and 1972 resulted in a spatial resolution of 1.2 m. The processing in Agisoft using 11 GCPs resulted in a point cloud with a density of 0.1 points/m^2. The point cloud was converted to a raster DEM with a high amount of noise which unfortunately could not be used in this analysis. Furthermore, a good quality ortho-image with 2.5 m resolution was generated and further utilized for the mapping of the historical extent of gullies.

Very high resolution satellite images and DEM for 2006

To capture the recent situation in terms of relief we processed two pairs of Standard Stereo Ikonos-2 scenes acquired on 6 November 2006. The data were already used for the terrain reconstruction of the area for geological mapping (Salvini & *alii*, 2012). We derived a new DEM using eATE Erdas 2015 software package. Every point of the cloud, derived from satellite image processing, provided an elevation value and was classified either as building, vegetation or ground. The adopted strategy for the creation of the 3D point cloud included radiometric correlation methods, feature matching using segmentation (for edge detection and modelling the abrupt height changes), and multi-ray and multi-band image matching (for higher reliability and precision). Most of the residual spikes and blunders were eliminated through Principal Components Analysis (PCA) and RMSE (Root Mean Square Error) thresholds. The resulting point cloud containing on average 0.3 points per m^2 was converted to a raster DEM (Ikonos DEM) with spatial

TABLE 1 - Aerial photographs and VHR satellite images used in this study.

Source	Acquisition date	Resolution (m)	Type	Focal length (mm)	Approximate scale
air photos	13-Nov-1965	1.2	BW	150.9	1 : 40,000
air photos	14-Dec-1971	1.0	BW	152.6	1 : 38,000
air photos	06-Dec-1972	1.0	BW	152.6	1 : 38,000
Ikonos-2	06-Nov-2006	1.0	multispectral	10,000	
Pléiades	21-Aug-2013	0.5	multispectral	13,000	

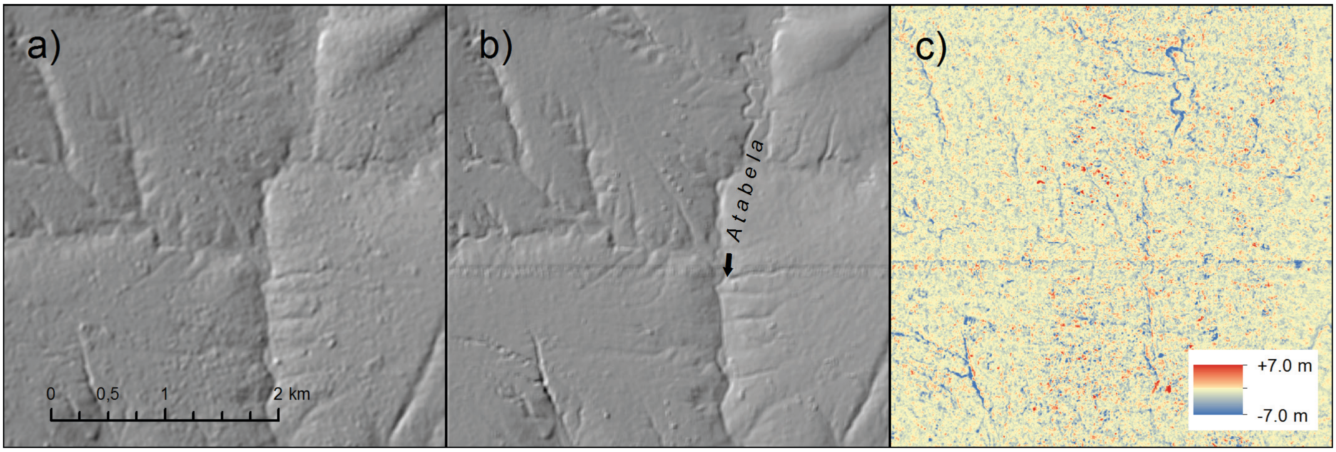

FIG. 3 - Shaded relief based on Air72 DEM (a), Ikonos DEM (b) and the difference image (c) for the central part of the study area. The extent of the depicted area is shown in Fig.1.

resolution of 1.0 m (Fig. 3). Additionally, an ortho-image with a resolution of 1.0 m was generated. The accuracy of the Ikonos DEM was assessed by a comparison with elevation data obtained by Differential Global Positioning System (DGPS) survey. The RMSE of Z values for 102 check points measured at the ground level with respect to the elevation of the raster DEM was 0.7 m. Additionally, we utilized VHR images from Pléiades, which is a French-Italian high resolution optical satellite system consisting of two satellites 1A and 1B launched in 2011 and 2012 respectively. Both satellites acquire data in one panchromatic and 4 multispectral bands with the resolution 0.5 and 2.0 m respectively in a 20 km wide swath. In the framework of the ESA's Third Party Mission scheme, we received a pan-sharpened ortho-image of the study area with a 0.5 m resolution from the 21th August 2013. The image was acquired in blue, green, red and near-infrared bands. This image was used for mapping of the current extent of gullies.

Estimation of elevation change

To derive the altitude difference in the gully systems we carried out an accurate co-registration of the two DEMs both in horizontal and vertical direction. As the landscape experienced significant changes over the period 1972-2006 (Salvi & *alii*, 2011) it was difficult to find homologous points in the ortho-images. Instead, we delineated the drainage network using a flow accumulation threshold for both DEMs. We identified manually 14 points representing main confluences in the drainage network, which were used to fit the Air72 DEM to the IK2 DEM by first order polynomial matching. The shape of the confluence was checked to avoid a bias in position due to fluvial dynamics. Subtraction of the two DEMs revealed a trend in the vertical differences across the image, which indicates a geometrical distortion of one of the DEMs. To assure a good interpretability of the difference image this trend had to be removed. First, vertical differences were extracted at a regular net of 1600 points with spacing of 250 m. Several points had to be discarded as they represented the gullies, noise or errors in the DEMs such as clouds (in total 35 points). Then a trend plane was fitted to the remaining points using a second order polynomial. To correct the image difference the plane was arithmetically subtracted. Certain striping could be still traced in the difference image, which probably results from some processing artifacts of one of the DEMs. An adaptive adjustment was additionally applied based on a local estimate of the vertical difference as median value in a floating window of 81x81 pixels. To preserve the studied features in the difference image, the window size has to exceed largely the size of the studied features. In our case, the size of the window exceeds the width of gullies approximately by factor of 10. This adjustment resulted in a difference image containing information on landform development in the period 1972-2016 (Fig. 3).

Mapping of gullies

To understand the extent and evolution of gullies in the Upper Awash area, gullies were mapped in a rectangular area of 49.3 km^2 delimited by the overlap of all four ortho-images. An automatic mapping of gullies represent a complex problem due to i) the variation of reflectance inside the gullies, ii) vegetation cover, iii) shadowing effects, iv) soil properties such as organic matter and v) moisture content (Mararakanye & Le Roux 2012). Gullies in the study area were mapped by means of visual interpretation based on characteristic features such as dendritic shape, size, shadows, and position in the landscape. We left out ephemeral gullies since farmers usually fill these. The shallow ephemeral gullies could be recognized as they do not feature a shadow. Non-active gullies covered with vegetation were also left out. The visual interpretation is a laborious and time-consuming process but on the other side it can result in a high accuracy of about 90%, depending on spectral contrast of the gullies to the surrounding areas (Mararakanye & Le Roux 2012). Taking into account the resolution of the ortho-imagery the level of detail of the resulting layers following (Tobler 1988) corresponds to the mapping scale of 1:1,000, 1:2,000, 1:2,000 and 1:2,400 in case of Plèiades, Ikonos-2, air photographs from 1972 and air photographs from 1965 respectively. The mapping was carried out at the scale of 1:3,000, occasionally if more detail was needed the background image was zoomed up to about 1:2,000. This ensured high accuracy necessary for the following analysis.

Field measurements

It was shown by Nachtergaele & Poesen (1999), for a site in Belgium, that a combination of aerial and field data leads to an effective identification of gullies. A field campaign was carried out in November 2014. We measured gully depth and width at 12 point near the archaeological site using Laser inclinometer TruPulse 360 Laser Rangefinder with integrated compass. The measurements were used for validation of the generated DEMs. Furthermore, a validation of the mapping effort was carried out during the field campaign.

RESULTS AND DISCUSSION

Our results outline that gullies developed more extensively on gentle slopes, which is in agreement with findings by Janeau & *alii*, (2003). The gentle food and midslopes have bigger contribution areas than the steep backslopes. Moreover, the lower sloping areas are often related to colluvial and thus, to material with higher erodibilities. Some gullies follow distinct lineaments, over 3.5 km in NE SW directions. This effect can be explained by the structural control exerted by fractures that lead to concentrate through-flow and eluviation of soil particles, which in turn results in surface lowering (Planchon & *alii*, 1987).

During the filed campaign, we observed that piping is a common erosion accelerating process that characterize the head cuts of gullies in the study area (Fig. 4). The depth of the gullies changes depending on the hillslope inclination, substrate and degree of gully evolution, reaching the maximum depth of a few meters. We could find only rarely gullies deeper than 10 m during the field campaign. The gullies form characteristic V-shape transverse profiles during the active phase, which can change to trapezoid form if the bedrock is reached by the incision. Non-active gullies tend to a U-shape profile. A number of smaller gullies were filled (Fig. 5). This was observed especially between 2006 and 2013, which resulted in a decline of the total gully length in the period. At one place artificial steps for prevention of gully erosion were identified on the Pléiades image.

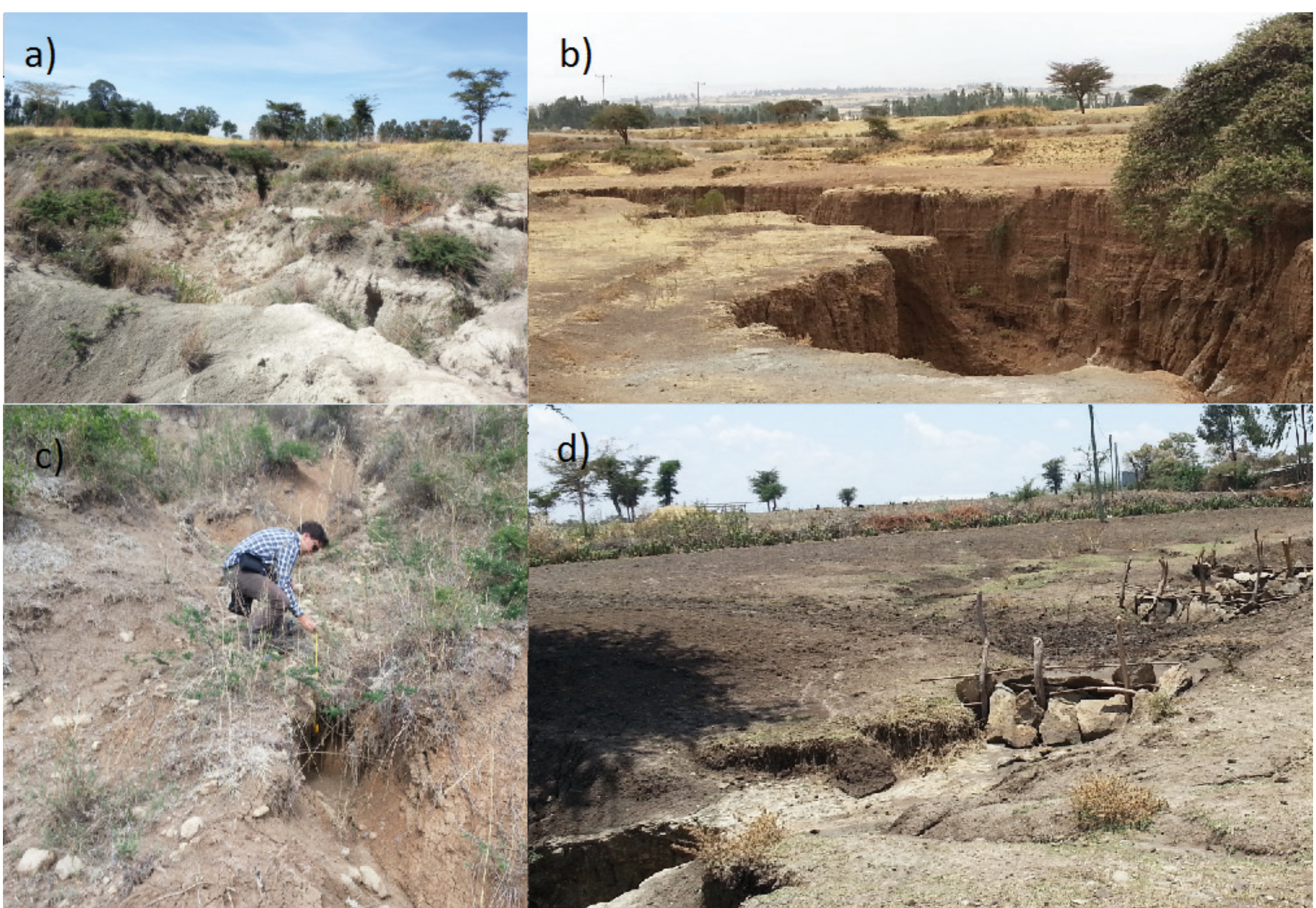

FIG. 4 - A gully incised in volcanic tuffs (a); an active gully several meters deep located north from Melka Awash (b); Piping at a gully head in the study area (c); sediment traps controlling the gully evolution (d).

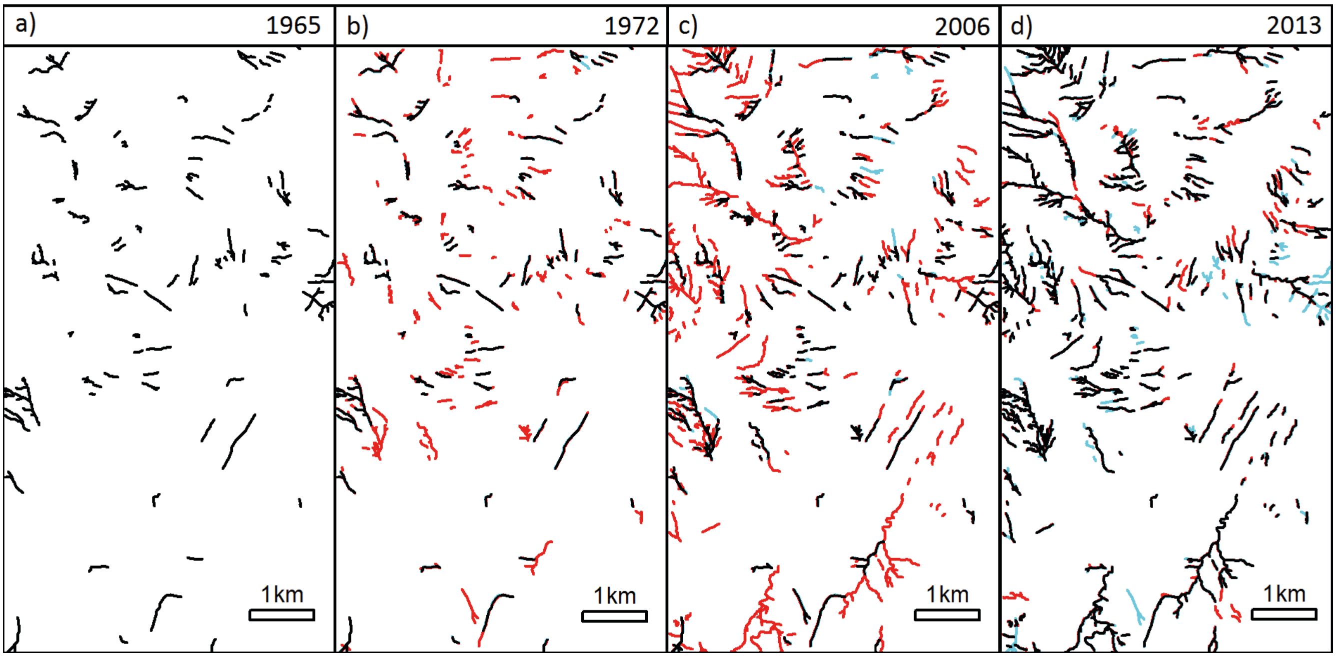

FIG. 5 - the changing extent of gullies in the study area in 1965 (a), 1972 (b), 2006 (c) and 2013 (d) shown as lines. New gullies with respect to the previous date are red, refilled gullies in cyan.

The gullies identified in the study area can be divided in large quickly progressing gully complexes with dendritic shape, linear gullies often following paths and angular gullies predisposed by filed borders and shallow ephemeral gullies on gentle slopes. The gully complexes represent the most severe thread to the soil cover as they tend to become deep and not easy to be filled (Fig. 6). There is one gully complex in the south of the Melka Kunture archaeological site, which was well developed but inactive in 1965. This

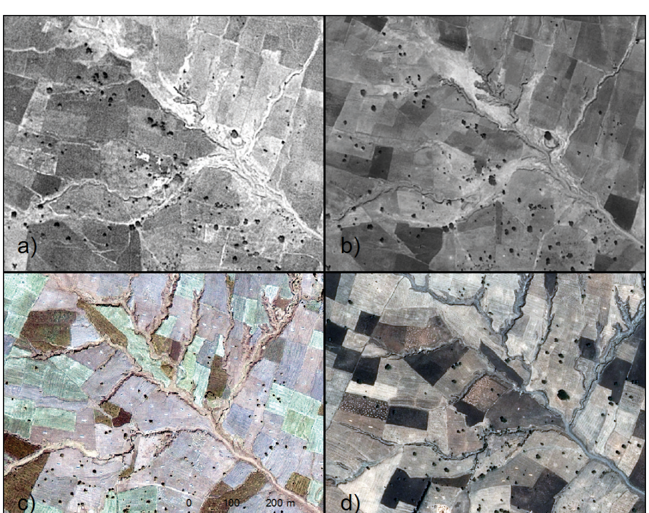

FIG. 6 - Evolution of a gully complex shown in the NW corner of the study area on the ortho-images for the years 1965 (a), 1972 (b), 2006 (c) and 2013 (d). A shift in land use from grassland to cropped fields during the study period can be seen. Solitary trees can be recognized in each of the images.

is evidenced by the vegetation cover on the aerial images from 1965 and 1972. This gully complex became re-activated during the studied period. Both the linear and angular gullies were in many cases filled. The same applies also to the ephemeral shallow gullies. It was observed that the gullies developed in some instances from discontinuous to continuous.

Changes in the geometry of gullies

During the time span between the aerial acquisition in 1964 and the Pléiades data take in 2013 the total length of gullies increased from 30.5 to 91.6 km (Tab. 2). This represents a triple increase in length during 49 years. During the same period, the average gully density increased from 0.6 to 1.9 km/km^2. The mean annual length increase was the highest in the period 1964-1972. It decreased considerably in the period 1972-2006 and it became negative in the period 2006-2013. Such initial high rate of gully expansion was described i.e. by Thomas & *alii*, (2004). Especially the fast increase in length which is followed by an increase in area and then by volume is typical for the initial phase of gully evolution as shown by (Kosov & alii, 1978) cited in Sidorchuk (1999) and (Sidorchuk & *alii*, 2003). The decrease in the period 2006-2013 is obviously due to an introduction of remediation measures. This trend of gully evolution over the studied period fits to the overall trend identified by Frankl & *alii*, (2011); Nyssen & *alii*, (2015). The progression of gully heads (Tab. 2) shows a similar pattern although, for this variable, the last period (2006-2013) shows larger values than for the second period. As progression of gully heads in contrast to the 'change in total length' does not take into account the disappeared

TABLE 2 - Changes in geometry of gullies in the study area in terms of total length, length increase/decrease, progression of gully heads and density of the gullies.

Year	Source	Total length (km)	Change in total length (km/a)	Gully density (km/km^2)	Mean progression of gully heads ± σ (m/a)
1965	air photo	30.5	-	0.61	-
1971-72	air photo	48.6	2.8	0.97	7.0 ± 4.1
2006	Ikonos-2	89.1	1.2	1.78	2.2 ± 1.4
2013	Pléiades	91.6	0.4	1.83	4.9 ± 3.8

gullies and gullies with no progression it shows continuing high dynamics of the gully development. It has to be noticed that the gully progression in general is quite intense compared to the findings of Frankl & *alii*, (2012) for north Ethiopia. However, this might be due to differences in the measurement approach.

Generally, semi-arid environments experience a strong inter-annual and seasonal variability in precipitation, which in turn affects erosion/deposition dynamics of the gully systems. Remote sensing images represent an instantaneous measurement, which may be influenced by specific conditions of the season or by an extreme precipitation event before one of the acquisitions. Moreover, the data acquisition frequency may be too low to account properly for the effects of extreme events. However, we can take the number of heavy rainy days per year (measured at Boneya station) as a proxy of the occurrence of extreme events. On average, there are 23.3 heavy rain days (rainfall > 10 mm). Even if there is a high variation in the number of heavy rain days per year (sigma = 15.3) we observe a relatively uniform distribution of extreme rainfall events over the last decades.

The images were acquired under different conditions in terms of seasonality concerning precipitation and phenology. The Pléiades image was taken during the rainy season whereas the aerial photographs during the dry season. Nevertheless, the monitored gully systems were active throughout the entire study period. Consequently, due to geomorphic dynamics and intensive grazing there is no or very scarce vegetation cover in the gully systems itself. Hence, vegetation effects has only marginal impact on the delineation of gully morphology. Finally, we observe a clear growth tendency of gully systems indicating that deposition processes are not prevalent.

The map of elevation differences between 1972 and 2006 (Fig. 3, 7) allows for the detection of depth changes of gullies in the study area. As the approach is sensitive to all fine scale changes in morphology, further processes such as lateral erosion of rivers could be detected. However, both DEMs contain a considerable level of noise, which affects the accuracy of the difference image. The extracted differences in elevation was not validated directly. However, we measured gully depth in the field in 2014 and compared it to the Ikonos DEM from 2006. Such comparison on 12 points resulted in an RMSE of 2.4 m, which confirms the high impact of noise. Furthermore, we generated 50 random points over the difference image and excluded the points overlapped by gullies. Then, root mean square difference on resulting 42 points was calculated as 0.6 m, showing a good performance of the DEM co-registration. Still, due to the processing artifacts and noise present in the DEM difference image, the volume change and sediment transport cannot be reasonably estimated. Nonetheless, several areas of high incision activity were highlighted in the difference image (Fig. 7).

Ideally, the DEMs used for the change detection by a direct numerical subtraction should originate from image data acquired by the same sensor under the same geometry. If a combination of two different systems is used, the reliability of difference image may be hampered by differences of vertical resolution of the two DEMs, which is dictated mainly by the base-to-height (B/H) ratio of the stereo-pairs. The B/H ratio of Ikonos-2 is 0.6 and higher, which is comparable to B/H ratio used in aerial photography (Neigh & *alii*, 2014). We calculated the B/H ratio of the 1972 photographs as 0.6 and B/H ratio of our Ikonos stereo-pair from incidence angles of both scenes as 0.8, which means that their vertical resolution is comparable. It has to be noted however, that the quality of a DEM generated from a VHR stereo-pair also depends on geometric processing parameters such as initial orientation, matching strategy and availability of GCPs, sun elevation and cloud cover (Poli & Caravaggi 2012). As a result, the DEMs used in the subtraction procedure contained different levels of noise and processing artifacts. Clearly, the airphoto 72 DEM required more smoothing for noise suppression, which affected the accuracy of the resulting difference image. The difference image thus, contains artifacts such as

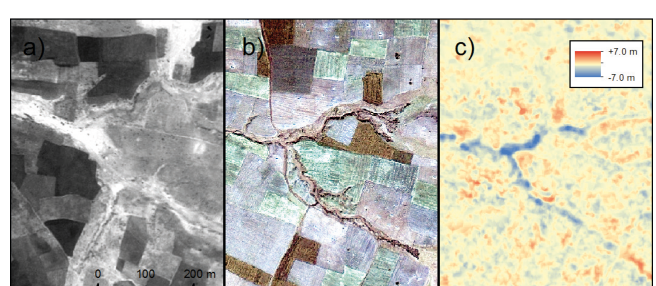

FIG. 7 - The detail view of development of a gully shown on the aerial photograph from 1972 (a), Ikonos image (b) and a difference image (c) calculated from DEMs representing the years 1972 and 2006.

patches of positive values in flat interfluves, which have no relation to any surface processes. Input data quality in terms of contrast and level of detail is therefore a limiting factor for the accuracy of the difference image, which has to be interpreted cautiously. Even though there are limitations due to noise and artifacts in the depth estimates of gullies we would like point out that the gully systems itself can be clearly mapped in terms of their surficial extend and their spatial distribution.

CONCLUSIONS

The analysis of archive aerial photographs and VHR satellite images showed a high gully erosion activity during the period of observation from 1965 to 2013 in the semi-arid Upper Awash River catchment (Ethiopia). The initial rapid gully head development slowed down after 1972. Especially after 2006 the effects of remediation activities, which led to a decrease in total gully length, was observed. The remediation is effective for shallow ephemeral gullies. However, dendritic gully complexes continue to propagate at an alarming rate. In one place a reactivation of a large old dendritic gully system could be traced. In general, the trend of gully evolution in the Upper Awash area over the studied period fits to the overall trend identified in northern Ethiopia. In the future more attention should be paid to quickly growing gully complexes in order to prevent increasing soil loss and its consequent sedimentation in the Koka Reservoir.

The presented study proved that the approach based on a combination of archived aerial photos and data from new satellite systems is effective for the analysis of erosion. The black and white photographs allow for an identification and mapping of the historical extents of gullies. However, to distinguish between active and inactive gullies or mapping in areas of low contrast or over-saturation appear to be a challenge for future research. The modern multispectral satellite systems with sub-meter resolution ensure a better confidence in gully identification especially in the exact delineation of gully areas. Additionally, the multispectral information allows for a better differentiation between temporarily active and non-active gullies using vegetation cover as an indication. The difference image calculated from two DEMs for 1972 and 2013 is biased by a high level of noise. A quantification of eroded material was thus not possible. Still, we identified a high incision activity in the active parts of gullies. In general, we proved that a difference image calculated from two DEMs contains relevant information for an assessment of erosion in semi-arid areas. However, a lack of details necessary for 3D reconstruction and a rather low radiometrical resolution of aerial photographs acquired primarily for topographical surveying poses constrains to such analysis.

REFERENCES

Altmaier A. & Kany C. (2002) - *Digital surface model generation from CORONA satellite images.* ISPRS Journal of Photogrammetry and Remote Sensing, 56, 221-235.

Betts H.D. & DeRose R.C. (1999) - *Digital elevation models as a tool for monitoring and measuring gully erosion.* International Journal of Applied Earth Observation and Geoinformation, 1, 91-101.

Bewket W. & Sterk G. (2003) - *Assessment of soil erosion in cultivated fields using a survey methodology for rills in the Chemoga watershed, Ethiopia.* Agriculture, Ecosystems and Environment, 81-93.

Billi P. & Dramis F. (2003) - *Geomorphological investigation on gully erosion in the Rift Valley and the northern highlands of Ethiopia.* Catena, 50, 353-368.

Bolch T., Buchroithner M., Pieczonka T. & Kunert A. (2008) - *Planimetric and volumetric glacier changes in the Khumbu Himal, Nepal, since 1962 using Corona, Landsat TM and ASTER data.* Journal of Glaciology, 54, 592-600.

Chavaillon J. & Berthelet A. (2004) - *The archaeological sites of Melka Kunture. Studies on the Early Paleolithic site of Melka Kunture, Ethiopia.* Origines, Firenze, 25-80.

d'Oleire-Oltmanns S., Marzolff I., Peter K.D. & Ries J.B. (2012) - *Unmanned Aerial Vehicle (UAV) for monitoring soil erosion in Morocco.* Remote Sensing, 4, 3390-3416.

Daba S., Rieger W. & Strauss P. (2003) - *Assessment of gully erosion in eastern Ethiopia using photogrammetric techniques.* Catena, 50, 273-291.

Dial G., Bowen H., Gerlach F., Grodecki J. & Oleszczuk R. (2003) - *IKONOS satellite, imagery, and products.* Remote Sensing of Environment, 88, 23-36.

Frankl A., Nyssen J., De Dapper M., Haile M., Billi P., Munro R.N., Deckers J. & Poesen J. (2011) - *Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia).* Geomorphology, 129, 238-251.

Frankl A., Poesen J., Deckers J., Haile M. & Nyssen J. (2012) - *Gully head retreat rates in the semi-arid highlands of Northern Ethiopia.* Geomorphology, 173, 185-195.

Frankl A., Seghers V., Stal C., De Maeyer P., Petrie G. & Nyssen J. (2015) - *Using image-based modelling (SfM–MVS) to produce a 1935 ortho-mosaic of the Ethiopian highlands.* International Journal of Digital Earth, 8, 421-430.

Hamed Y., Albergel J., Pépin Y., Asseline J., Nasri S., Zante P., Berndtsson R., El-Niazy M. & Balah, M. (2002) - *Comparison between rainfall simulator erosion and observed reservoir sedimentation in an erosion-sensitive semiarid catchment.* Catena, 50, 1-16.

Haregeweyn N., Poesen J., Nyssen J., De Wit J., Haile M., Govers G. & Deckers S. (2006) - *Reservoirs in Tigray (Northern Ethiopia): characteristics and sediment deposition problems.* Land Degradation & Development, 17, 211-230.

Haregeweyn N., Tsunekawa A., Nyssen J., Poesen J., Tsubo M., Meshesha D.T., Schütt B., Adgo E. & Tegegne F. (2015) - *Soil erosion and conservation in Ethiopia a review.* Progress in Physical Geography, 39, 750-774.

Hugenholtz C.H., Whitehead K., Brown O.W., Barchyn T.E., Moorman B.J., LeClair A., Riddell K. & Hamilton T. (2013) - *Geomorphological mapping with a small unmanned aircraft system (sUAS): feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model.* Geomorphology, 194, 16-24.

Janeau J.-L., BricquetJ.-P., Planchon O. & Valentin C. (2003) - *Soil crusting and infiltration on steep slopes in northern Thailand.* European Journal of Soil Science, 54, 543-554.

Kosov B., Nikol'skaya I. & Zorina Y.F. (1978) - *Eksperimental'nyye issledovaniya ovragoobrazovaniya.* Eksperimental'naya Geomorfologiya, 3, 113-140.

Kropáček J., Vařilová Z., Baroň I., Bhattacharya A., Eberle J. & Hochschild V. (2015) - *Remote Sensing for Characterisation and Kinematic Analysis of Large Slope Failures: Debre Sina Landslide, Main Ethiopian Rift Escarpment.* Remote Sensing, 7, 16183-16203.

Lombardo L., Bachofer F., Cama M., Märker M., & Rotigliano E.(2016) - *Exploiting Maximum Entropy method and ASTER data for assessing debris flow and debris slide susceptibility for the Giampilieri catchment (north-eastern Sicily, Italy).* Earth Surface Processes and Landforms, 41 (12), 1776-1789.

Mararakanye N. & Le Roux J. (2012) - *Gully location mapping at a national scale for South Africa.* South African Geographical Journal, 94, 208-218.

Märker M., Moretti S. & Rodolfi G. (2001) - *Assessment of water erosion processes and dynamics in semiarid regions of southern Africa (KwaZulu/Natal RSA; Swaziland) using the Erosion Response Units concept (ERU).* Geografia Fisica Dinamica Quaternaria, 24, 71-83.

Märker M., Hochschild V., Maca V. & Vilímek V. (2016) - *Stochastic assessment of landslides and debris flows in the Jemma basin, Blue Nile, Central Ethiopia.* Geografia Fisica Dinamica Quaternaria, 39, 51-58.

Martinez-Casasnovas J., Antón-Fernández C. & Ramos M. (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, 443-456.

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, 693-706.

Neigh C.S., Masek J.G., Bourget P., Cook B., Huang C., Rishmawi K. & Zhao F. (2014) - *Deciphering the precision of stereo IKONOS canopy height models for US forests with G-LiHT airborne lidar.* Remote Sensing, 6, 1762-1782.

Nyssen J., Frankl A., Zenebe A., Deckers J. & Poesen J. (2015) - *Land management in the northern Ethiopian highlands: local and global perspectives; past, present and future.* Land Degradation & Development 26, 759–764.

Nyssen J., Moeyersons J., Deckers J.A., Haile M. & Poesen J. (2000) - *Vertic movements and the development of stone covers and gullies, Tigray Highlands, Ethiopia.* Zeitschrift fur Geomorphologie, 44, 145-164.

Nyssen J., Poesen J., Veyret-Picot M., Moeyersons J., Haile M., Deckers J., Dewit J., Naudts J., Teka K. & Gover G. (2006) - *Assessment of gully erosion rates through interviews and measurements: a case study from Northern Ethiopia.* Earth Surface Processes and Landforms, 31, 167-185.

Paulos S. (1998) - *Establishing Water Release Rules for Koka Reservoir for Wet Seasons.* Master Thesis Addis Ababa University, Ethiopia, Department of Civil Engineering, 121pp.

Piperno M., Collina C., Gallotti R., Raynal J.-P., Kieffer G., Le Bourdonnec F.-X., Poupeau G. & Geraads D. (2009) - *Obsidian exploitation and utilization during the Oldowan at Melka Kunture (Ethiopia)* - Interdisciplinary approaches to the Oldowan. Springer, 111-128.

Planchon O., Fritsch E. & Valentin C. (1987) - *Rill development in a wet savannah environment.* Catena Supplement, 55-70.

Poesen J., Nachtergaele J., Verstraeten G. & Valentin C. (2003) - *Gully erosion and environmental change: importance and research needs.* Catena, 50, 91-133.

Poli D., & Caravaggi I. (2012) - *3D modelling of large urban areas with stereo VHR satellite imagery for risk and damage assessment-lessons learned.* Natutal Hazards 68 (1), 53-78.

Raynal J.-P. & Kieffer G. (2004) - *Lithology, dynamism and volcanic successions at Melka Kunture (Upper Awash, Ethiopia)* - In: Jean Chavaillon and Marcello Piperno (Eds.) - *Studies on the Early Paleolithic site of Melka Kunture, Ethiopia.* Istituto Italiano di Preistoria e Protostoria, 111-135.

Salvi M.C., Salvini R., Cartocci A., Kozciak S., Gallotti R. & Piperno M. (2011) - *Multitemporal analysis for preservation of obsidian sources from Melka Kunture (Ethiopia): integration of fieldwork activities, digital aerial photogrammetry and multispectral stereo-IKONOS II analysis.* Journal of Archaeological Science, 38, 2017-2023.

Salvini R., Riccucci S. & Francioni M. (2012) - *Topographic and geological mapping in the prehistoric area of Melka Kunture (Ethiopia).* Journal of Maps, 8, 169-*175.*

Shahis M. (1993) - *An overview of reservoir sedimentation in some African river basins.* In: Sediment problems: Strategies for monitoring, prediction and control. Proceedings of the Yokohama Symposium, 93-100.

Schillaci C., Braun A. & Kropáček J. (2015) - *Terrain analysis and landforms recognition.* In: L.E. Clarke, & J.M. Nield (Eds.) *Geomorphological Techniques* (Online Edition) - London, UK: British Society for Geomorphology.

Sidorchuk A. (1999) - *Dynamic and static models of gully erosion.* Catena, 37, 401-414.

Sidorchuk A., Märker M., Moretti S. & Rodolfi G. (2001) - *Soil erosion modelling in the Mbuluzi river catchment (Swaziland, South Africa)* - Geografia Fisica e Dinamica Quaternaria, 24, 177-187.

Sidorchuk A., Märker M., Moretti S. & Rodolfi G. (2003) - *Gully erosion modelling and landscape response in the Mbuluzi River catchment of Swaziland.* Catena, 50, 507-525.

Tamene L., Park S., Dikau R. & Vlek P. (2006) - *Analysis of factors determining sediment yield variability in the highlands of northern Ethiopia.* Geomorphology, 76, 76-91.

Thomas J.T., Iverson N.R., Burkart M.R. & Kramer L.A. (2004) - *Long-term growth of a valley-bottom gully, western Iowa.* Earth Surface Processes and Landforms, 29, 995-1009.

Tobler W. (1988) - *Resolution, resampling, and all that.* Building Databases for Global Science, 12, 9-137.

Valentin C., Poesen J. & Li Y. (2005) - *Gully erosion: Impacts, factors and control.* Catena, 63, 132-153.

Westoby M.J., Brasington J., Glasser N.F., Hambrey M.J. & Reynolds J.M. (2012) - *'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications.* Geomorphology, 179, 300-314.

Zakerinejad R. & Märker M. (2014) - *Prediction of Gully erosion susceptibilities using detailed terrain analysis and maximum entropy modeling: a case study in the Mazayejan Plain, Southwest Iran.* Geografia Fisica Dinamica Quaternaria, 37, 67-76.

(Ms. received 1 June 2016; accepted 30 November 2016)