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Paolo Billi [(*)]

HYDRO-MORPHOLOGY OF DISCONTINUOUS GULLIES: AN ETHIOPIAN EXAMPLE

Abstract - P. Billi, *Hydro-morphology of discontinuous gullies: an Ethiopian example.*

Gully erosion is very common in Ehtiopia affecting large areas with different geomorphological, pedological and climatic characteristics. The amount of soil loss due to gullying has become a very serious problem in the recent decades leading to remarkable depletion of cultivated land. Field investigations on gully morphological development were carried out in two study areas of Ethiopia, the Lakes Region in the Main Ethiopian Rift Valley and the central highlands, representative of different geo-morphological and environmental conditions. Three main types of discontinuous gullies were identifies on the basis of their morphological characteristics. In order to investigate the main causes originating the different types of gullies, data on geomorphic parameters were collected in the field. From the analysis of field data hypotheses on the mechanisms responsible for gully development in the study areas were derived. The short- and mid-term gully expansion rate and the main processes involved are discussed as well.

Key words - discontinuous gullies, gully expansion, land degradation, dryland, Ethiopia

Riassunto - P. Billi, *Idromorfologia dei solchi d'erosione discontinui: un esempio Etiopico.*

L'erosione per solchi è molto comune in Etiopia e colpisce vaste aree con diverse caratteristiche geomorfologiche, pedologiche e climatiche. La quantità di suolo perso a causa di questo fenomeno erosivo è divenuto, nei decenni recenti, un problema molto grave che ha portato ad un marcato degrado del territorio. Ricerche di campagna sullo sviluppo morfologico dei solchi d'erosione sono stati condotti in due aree dell'Etiopia, la Regione dei Grandi Laghi nella Rift Valley centrale e l'altopiano centrale, rappresentative di differenti condizioni geomorfologiche ed ambientali. Sulla base delle loro caratteristiche morfologiche, sono stati identificati tre diversi tipi di solchi d'erosione. Allo scopo di identificare le principali cause che danno origine a questi differenti tipi di solchi d'erosione, dati dei loro parametri geomorfici sono stati misurati in campagna. L'analisi dei dati di campo ha permesso di formulare delle ipotesi su processi fisici responsabili della loro formazione. Inoltre vengono discussi anche il loro tasso di espansione a breve e medio termine ed i fattori di controllo.

Parole chiave - solchi d'erosione, idromorfologia, degradazione del suolo, zone aride, Etiopia

1. Introduction

Gullies are amongst the most important erosion processes that largely contribute to land degradation in many arid and semi-arid regions of the world. The development of gullies has many negative impacts as it normally implies the loss and (in some cases) the deposition of a great amount of soil. In many low-income countries, the loss of large soil quantities by gully erosion commonly stands for the depletion of a basic natural resource. Gullies are typically generated by soil water saturation and excess overland flow, but at the same time they can contribute to shortening the runoff lag time and to increase its volume.

Once a gully is formed, it tends to further enlarge and there are very few chances its expansion can be naturally inverted or, at list, halted. Every year in the world, very many hectares of cultivated land are definitively lost because of gullying. This results in a substantial loss of income which may deeply affect the economy of developing countries, where agriculture is normally the main economic resource. Gully erosion, therefore, may represent a significant constraint to the economic growth of rural communities. For their geomorphic and social significance, gullies have been investigated all over the world and a lot of efforts have been made by many scientists to understand the main factors and processes that originate them and to control their growth. In spite of that, what causes the formation and development of gullies is still a matter of animate debate.

Some authors suppose that gullies simply develop from rills (e.g. Ireland *et al.*, 1939, in Oostwoud Wijdenes & Gerits, 1994), but the latter have different geomorphic features (Oostwoud Wijdenes & Gerits, 1994). According to De Oliveira (1989), gullies can be formed by headward stream retreat affecting unincised slopes whereas Oostwoud Wijdenes & Gerits (1994) indicate soil tunneling as a common factor in triggering gully formation.

An important role is also played by man through disturbance to vegetation. In fact, a sparse vegetation cover results in a diminished boundary roughness and, hence, in a reduced resistance to overland flow (Trimble, 1974; De Ploey, 1990), whereas a deficit of organic matter in the soil decreases its aggregate stability.

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Though a few papers have investigated the stages of gullies growth after their formation (Thomas *et al.*, 2004; Vanwalleghem *et al.*, 2005; Nyssen *et al.*, 2006; Lankriet *et al.*, 2015), yet little information is available in the literature about their geomorphic characteristics and the way they reflect the relationships with and the effectiveness of the main controlling factors. After an embryo gully is formed, its development is controlled by the relationship between flow and flow resistance and by the soil properties which are responsible for the gully morphological features. The analysis of gullies geometry and its changes through time can therefore contribute to shed some light on the processes responsible for their growth and, possibly, to define efficient countermeasures.

Gullies are very common in Ethiopia and affect a very large proportion of the country. Despite a wide variability in climate, physiography, geomorphology and soil characteristics, gully erosion is an ubiquitous land degradation process which substantially hinder the agricultural and, hence, the economic development of the country. Though the human pressure on the land is having a patent negative impact in many areas (Billi, 1998), the effects of short term changes in the precipitation regime is still matter of discussion among scientists (Billi & Dramis, 2000).

In order to investigate the factors controlling the geomorphological development of gullies, three representative gullies with characteristics, distinctive of different typologies, size and geomorphological setting were selected and surveyed in the field. The study gullies are located in Ethiopia in two areas with different physiographic and climatic characteristics: the Lakes Region in the Ethiopian Rift Valley and the central highlands north of Addis Ababa.

2. Geographical setting and study areas

Two of the study gullies are located in the Rift Valley whereas the third one is in the central highlands close to the Afar Window (between Debre Birhane and Debre Sina) and to the rift margin divide separating the Awash watershed from the Blue Nile river system (Fig. 1). Both study areas are underlain by volcanic rocks but, while in the rift sites Tertiary to Quaternary basalt lavas and more acidic tuffs and ashes are found, in the highland site Tertiary basalts of the trap series prevail. Late Quaternary fluvio-lacustrine deposits cover a wide area of the Main Ethiopian Rift (MER) and witness the occurrence of a very large lake that occupied a major portion of the MER. The four lakes of today in the central sector of the MER (Ziway, Langano, Abiyata, Shala) are what remains of such ancient lacustrine basin (Benvenuti *et al.*, 2002). The MER floor is punctuated by young (Late Pliocene to Late Holocene) volcanoes and calderas, which erupted rhyolitic lava flows, pumice and ash. Obsidian flows are the final

Fig. 1 - Location map of the study gullies.

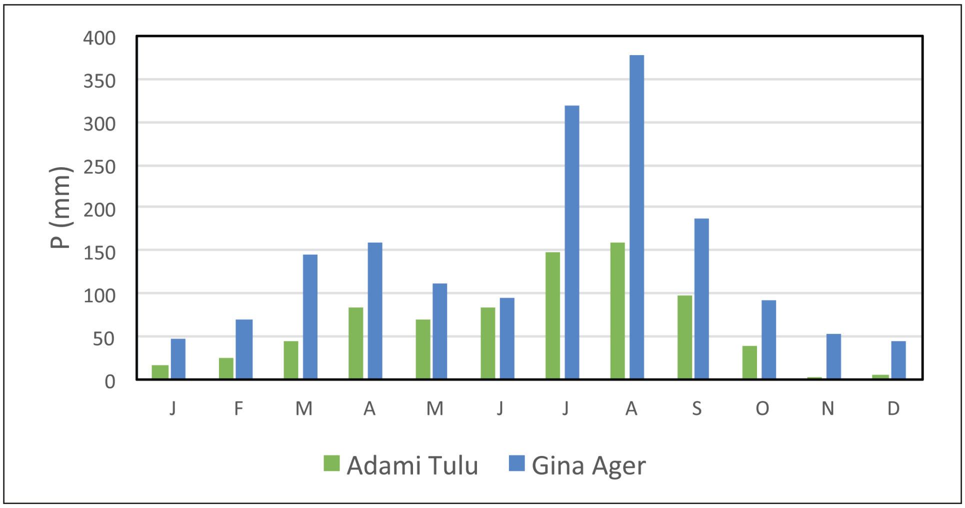
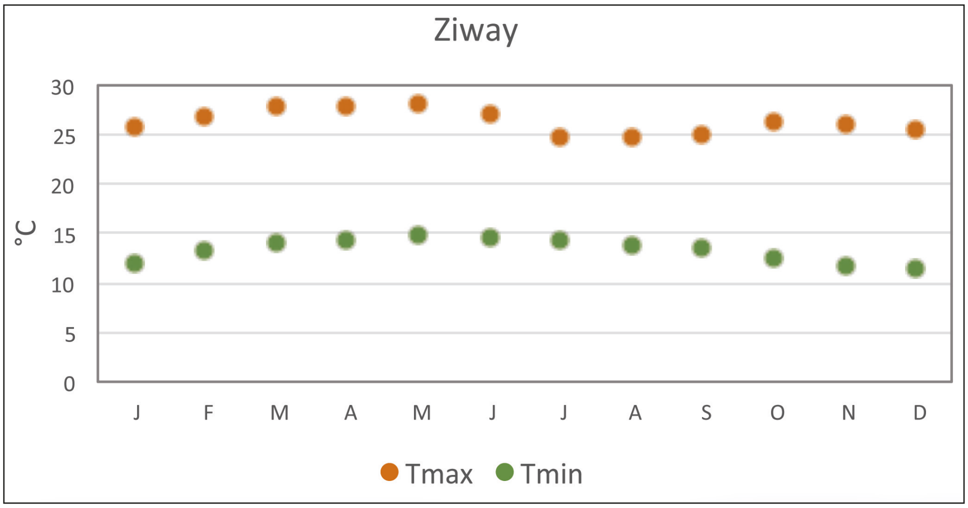
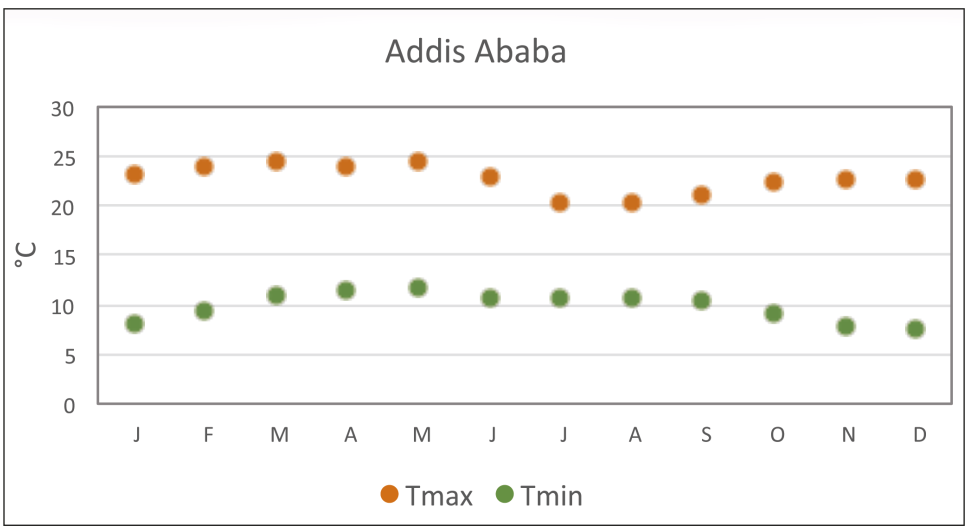


Fig. 2 - Mean monthly precipitation in Adami Tulu (Rift floor) and Gina Ager (central highlands eastern margin).



(a)



(b)

Fig. 3 - Mean monthly maximum and minimum temperature for: a) Ziway (Rift floor); b) Addis Ababa (central highlands).

product of the volcanic activity. Slope and colluvial deposits are very common on both foothills and escarpments (Benvenuti *et al.*, 2002).

Annual rainfall is about 778 mm at Adami Tulu, in the Rift Valley, and 1702 mm at Gina Ager in the highland. The climate of both areas is characterised by two main rainy seasons, the first from March to May (the small rains) and the second from July to September (the big, monsoon type rains), which is followed by five months with negligible precipitation (Fig. 2). The big rains account for almost 60-70% of the annual precipitation.

Given the marked difference in elevation between the two study areas, i.e. around 1600-1700 m asl for the Rift gullies and about 3100 m asl for the highland site, the mean maximum monthly temperatures in Ziway (Rift Valley) and Addis Ababa (central highlands) are constantly higher and lower than 25 °C (Fig. 3), respectively. The range between maximum and minimum temperatures varies modestly through the year (with a minimum during the big rains) and it is almost the same, around 13 °C, for both meteo-stations (Fig. 3).

In the Rift, below the elevation of 1,800 m a.s.l., the vegetation consists of scanty grass and bush of acacias reflecting the lack of sufficient rainfall, which, combined with excess grazing, leaves 50% of the soil bare. Only a small portion of the land is cultivated and animal breeding prevails. In the highlands, the larger quantity of rainfall (Fig. 2) favors a much denser vegetation cover. Almost all the land is cropped, though animal husbandry is carried out as well. During the last decades, extensive deforestation and overgrazing occurred throughout Ethiopia and in the study areas as well.

3. Gully morphology and field methods

In Ethiopia, gullies occur in every region, no matter the climate, the top soil characteristics, the physiography and the lithology of the substratum. Their typical geomorphological settings include slopes, pediments, colluvial belts and alluvial fans on slope gradients ranging from 3 to 10 degrees, but straight scars can be observed also on very steep slopes with gradients exceeding 35-40 degrees.

Discontinuous gullies (Leopold *et al.*, 1964; Bull, 1997) are individual, isolated gullies that entirely develop within a single slope stretch. They originate at a highly variable distance from the divide (Heede, 1976) and reach their maximum depth at a variable distance from their downslope end. Width is not uniform (Poesen & Govers, 1990; Billi & Dramis, 2002), as it may either constantly increase downstream or reach a maximum around its mid length to decrease again to a relative minimum at the downstream end.

Three main types of representative discontinuous gullies were recognized in the field. They differ in size, geomorphological setting and slope gradient. The first gully (Gagna gully) is located on the external slope of a half collapsed caldera rim (Fig. 1 and 4) on the rift valley bottom at an elevation around 1700 m asl.

It is cut into thick colluvial deposits, it is by far longer (2030 m long) and larger than the other two (Table 1) and has the typical morphology of a box gully, i.e. it is very narrow (maximum and average top width 67 and 24 m, respectively) and deep (maximum and average depth 24 and 9.6 m, respectively) (Table 1) with almost vertical sides (Fig. 4a). The second gully (Langano gully) is a dynamic, small size gully (49-75 m long, 1.50-1.80 m wide and 0.61 m deep) in its early stage of development. It is incised into the colluvial deposit at the inner rim footslope of Langano lake northern caldera (Fig. 4b), at an elevation of about 1620 m asl. The geometry of this gully has been surveyed seven times across a nine years interval to analyse its geomorphological evolution and to quantify the amount of soil loss through time. The last gully (Andit Tid gully) is a straight scar originating close to the divide of a short and very steep slope at an elevation around 3100 m asl (Fig. 4c).

Table 1 - Main geomorphic characteristics of the study gullies.

	Gully		
	Gagna	**Langano**	**Andit Tid**
Total length (m)	2030.2	33.0 - 75.0*	50.0
Slope gradient (mm^{-1})	0.0414	0.076	0.648
Mean bottom gradient (mm^{-1})	0.0137	0.032 - -0.068*	0.648
Maximum top width (m)	67.6	3.14 - 4.16*	1.24
Mean top width (m)	23.8	1.52 - 1.80*	0.69
Maximum depth (m)	23.8	1.30 - 1.42*	1.41
Mean depth (m)	9.6	0.61 - 0.62*	0.51
Mean x-section shape factor	2.39	2.47 - 3.39*	1.35
Sinuosity	1.42	1.26 - 1.18*	1.00

* Extreme values measured during seven field survey campaigns throughout the 1997-2006 study period.

Fig. 4 - The three study gullies: a) Gagna box gully; b) Langano gully; c) Andit Tid steep gully.

Fig. 6 - The outwash deposits at the mouth of Gagna box gully.

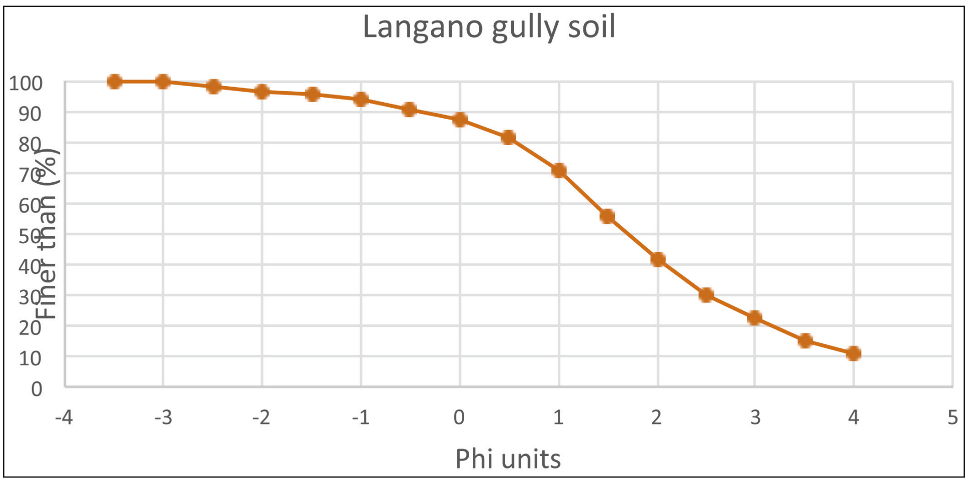


Fig. 5 - Grain size distribution of Langano gully soil.

The morphology of the study gullies was surveyed in the field by means of a total station and through the measurement of several cross-sections spaced about 20 m of each other in the large gully (Gagna) and 1.0 m in the other two smaller gullies.

The cross-section spacing was decreased wherever an important change in the gully geometry was observed. The very upstream part of Gagna gully was not measured because of difficult access to the area. The field measurements included both the gully top and bottom width and mean depth for each cross-section, both the gully bottom and slope gradient, the gully total length and sinuosity. The mean gully bottom gradient was obtained simply as the ratio between the total difference in elevation between the uppermost and the lower most cross-section divided by the gully total length.

The colluvial deposits into which Gagna gully is cut are characterised by a stratification complexity of scour and fill sequences and, high variability of grain size. The soil on the steep slope of Andit Tid gully is very shallow and show a marked longitudinal variation in thickness and grain size characteristics. By contrast the soil of Langano gully is rather homogeneous and, therefore, only the soil of this gully was sampled for particle size analysis. This soil is rather coarse with about 4% of gravel, 86% sand and 10% silt and clay (Fig. 5). The upstream origin of the three study gullies is a head cut. It is very well developed in Langano gully, whereas it is not marked in Andit Tid., because of the steep gradient, and in Gagna gully as it starts in the thin and stony soil a few meters over the contact between the colluvial deposits and the caldera rim bedrock. However, as the gully enters the colluvium, it becomes very deep and almost inaccessible for the very dense vegetation and sub-vertical sides. In its most downstream part, Gagna gully enters an almost flat area and forms a thin and narrow fan shaped wash out deposit consisting of sand and cobbles (Fig. 6). Langano and Andit Tid gullies have instead, very small downstream deposits, likely because of their small size and steeper gradient.

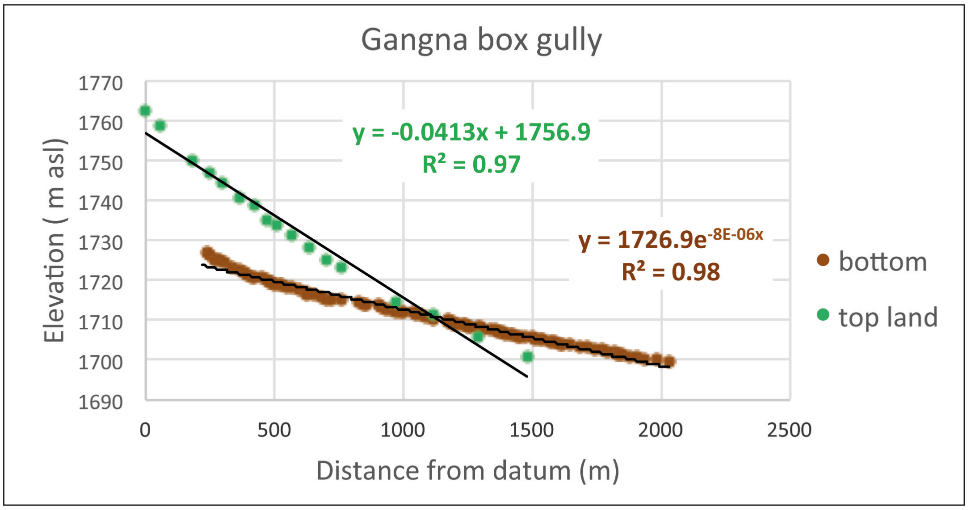


Fig. 7 - Longitudinal profile of the colluvial deposit surface slope and Gangna gully bottom.

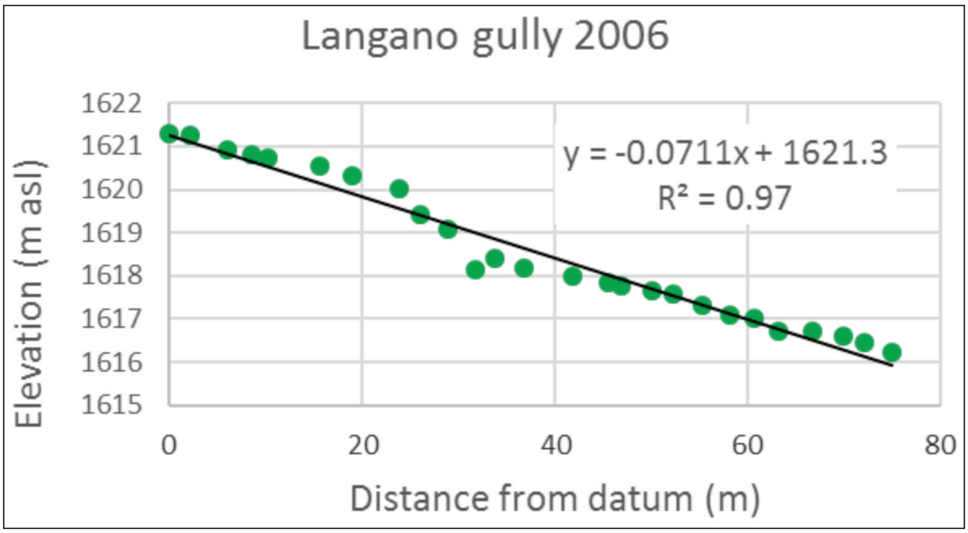


Fig. 8 - Longitudinal profile of Langano gully.

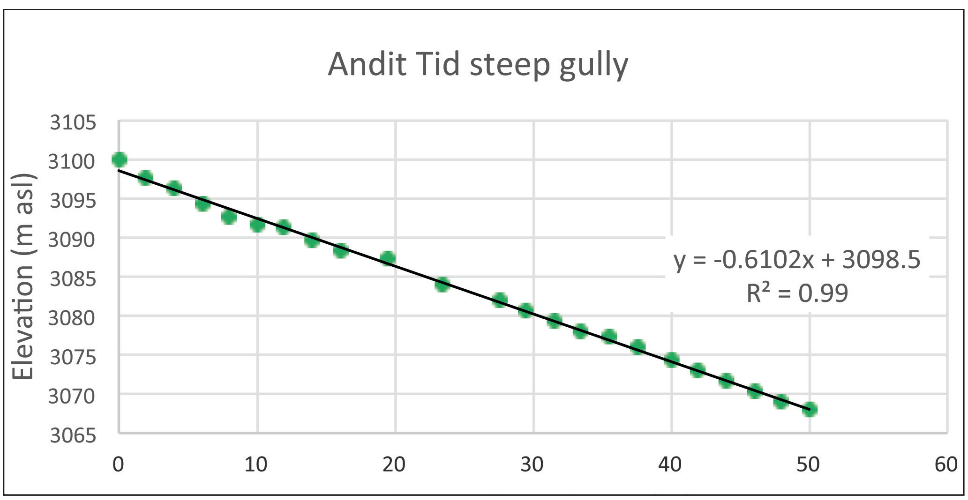


Fig. 9 - Longitudinal profile of Andit Tid steep gully.

4. Results

The main geomorphic data of the study gullies are reported in Table 1. Gagna is the longest gully (2030 m), whereas Andit Tid is the shortest (50 m). At the beginning of the study in 1997, Langano gully was only 33 m long, but its length was more than doubled by 2006 (75 m). Andit Tid has the steepest mean gully bottom gradient (0.648), whereas Langano and Gagna have much gentler mean bottom gradients of 0.032-0.068 (gradient changed during the 1997-2006 study interval) and 0.0137, respectively. In Langano (2006 data) and Andit Tid gullies, slope gradient and gully bottom gradient almost coincide. In Gagna box gully, instead, slope gradient is steeper than the gully bottom average gradient (Fig. 7). The longitudinal profile of Langano and Andit Tid is well interpolated by a straight line (R^2 = 0.97 and 0.99, respectively) (Figg. 8 and 9), whereas that of Gagna follows and exponential low (R^2 = 0.98) (Fig. 7).

Gagna and Langano gullies have a similar average shape factor close to 2.5, i.e. cross-section top width is about two and a half times mean depth. Andit Tid shape factor is instead smaller, about 1.35, likely because of the very steep gradient favouring a fast downstream transfer of the water mass and flow energy dissipation mainly on the gully bottom rather than on the banks. The downstream change of the shape factor follows an irregular pattern in all the three study gullies and shows no significant correlation with distance. This can be accounted for by the high variability of the gully width associated with bank failure, which locally may markedly widen the gully. This hypothesis is confirmed by the more regular pattern of gully depth. The longitudinal variation of depth is well explained by a linear regression for Gagna and Langano gullies (R^2 = 0.96 and 0.82-0.91, respectively) (Figg. 10 and 11), whereas the best interpolation for Andit Tid is a logarithm function with a lower determination coefficient (R^2 = 0.46) (Fig. 12), which explains also the poorest correlation between distance and shape factor of this gully.

Gagna gully has the most sinuous pattern with a sinuosity of 1.42 (Fig. 13) (similarly to rivers, sinuosity is the gully total length divided by the straight distance between the gully extremes measured as the slope line of maximum gradient parallel to the gully). Andit Tid sinuosity is practically equivalent to 1.00, whereas Langano has an intermediate value ranging from 1.18 to 1.26.

In order to anlayse the gully growth through time and, hence, the rate of soil loss, seven field surveys of Langano gully geomorphic features were repeated from January 1997 to January 2006 (Table 2).

In nine years, the gully volume increased by a factor 3.4, with an expansion from the initial 18.31 m^3 to 61.73 m^3 in 2006 (Fig. 14). This corresponds to an average annual soil loos of about 4.8 m^3yr^{-1}, which corresponds to an average annual expansion rate of 26% with respect to the initial volume of the gully. Such a marked increase in volume was achieved mainly through lateral expansion as top width increased about two times, though following and irregular pattern of change. Also bottom width follows an increasing trend, though with an even more irregular pattern. By contrast, gully depth did not change appreciably and remained almost constant within the range of 0.54-0.64 m (Table 2) (Fig. 15). The gully bottom gradient changed as well from the highest value of 0.087, measured in 1997, to the lowest value of 0.032 measured in July 2000 and ultimately to 0.068 in 2006.

Rainfall amount does not seem to have played an important role in Langano gully growth. In fact, though the minimum rainfall amounts is associated with the minimum soil loss, the maximum rainfall is associated only with the third lowest change in gully volume. Short and intense rains are likely more effective than total amounts in triggering erosion and, hence, in controlling the gully dynamics (Nachtergaele *et al.*, 2002; Tucker *et al.*, 2006).

Table 2 - Langano gully geomorphic parameters variation through time.

Survey dates	Volume	Top width	Bottom width	Depth	Bed gradient	Rainfall	D V	Days
	(m^3)	(m)	(m)	(m)	(mm^{-1})	(mm)	(m^3)	No.
15/01/1997	18.31	0.97	0.65	0.64	0.087			0
15/11/1998	24.07	0.84	1.34	0.64	0.049	1207	5.76	669
07/07/2000	28.10	1.52	0.80	0.61	0.032	1549	4.03	600
02/12/2000	28.47	1.62	1.15	0.58	0.039	390	0.37	148
12/07/2002	30.15	1.81	0.78	0.61	0.039	1135	1.68	587
11/07/2004	42.48	1.83	0.95	0.54	0.068	1299	12.33	730
16/01/2006	61.73	1.75	0.52	0.61	0.068	1342	19.25	554

Rainfall is the total amount of rain between two consecutive surveys; D V is the gully volume difference between two consecutive surveys; Days = number of days between two consecutive surveys.

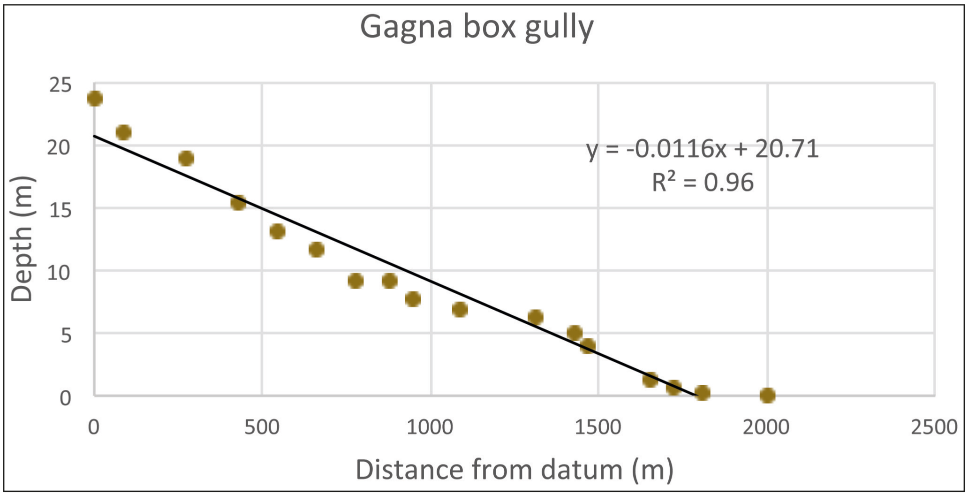


Fig. 10 - Longitudinal variation of depth in Gagna gully.

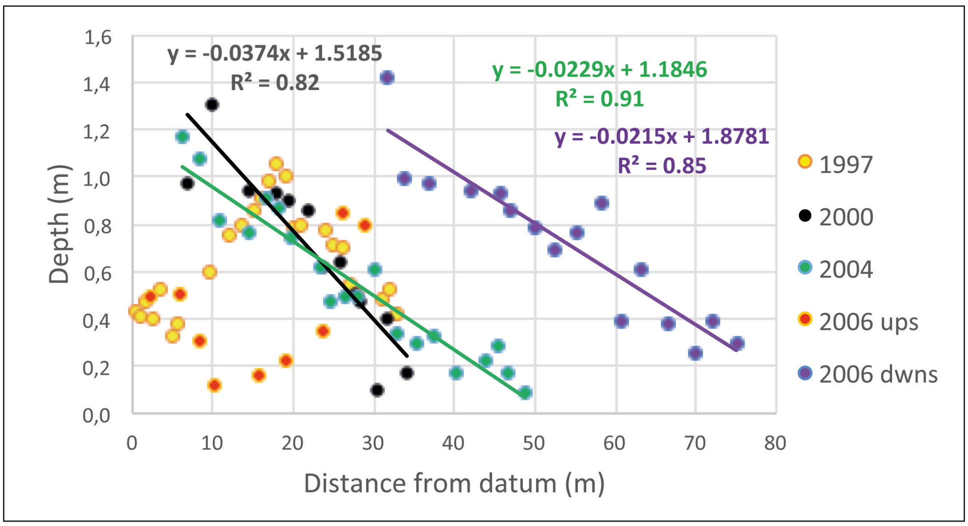


Fig. 11 - Langano gully longitudinal variation of depth as measured in different surveys.

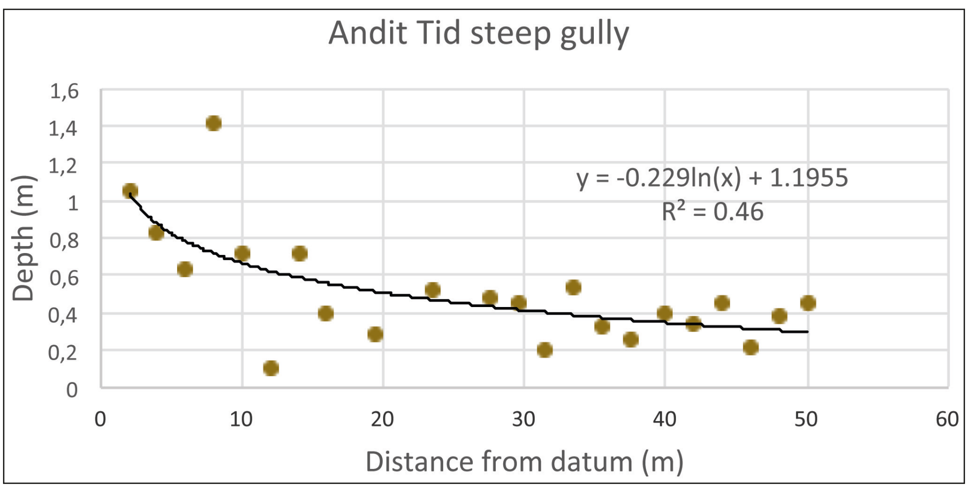


Fig. 12 - Longitudinal variation of depth in Andit Tid gully.

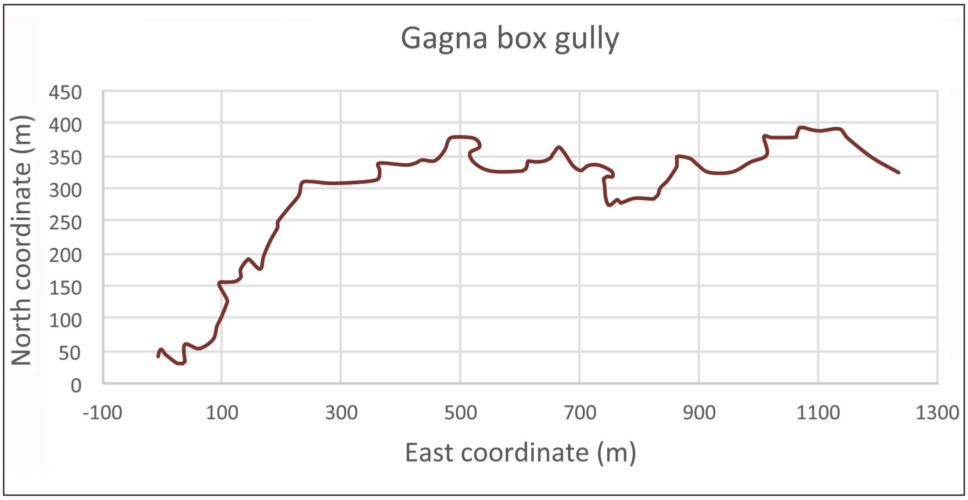


Fig. 13 - Planform pattern of Gagna gully. Notice the relatively high sinuosity.

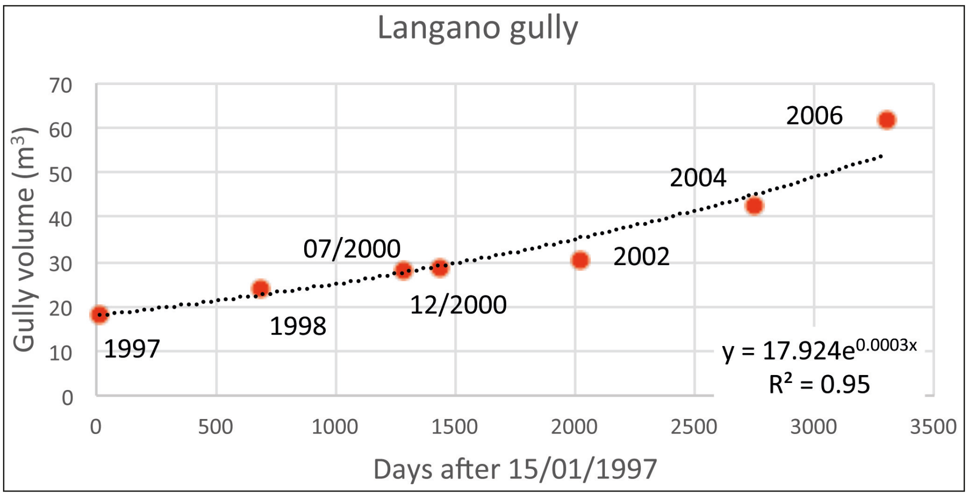


Fig. 14 - Langano gully expansion from January 1997 to January 2006.

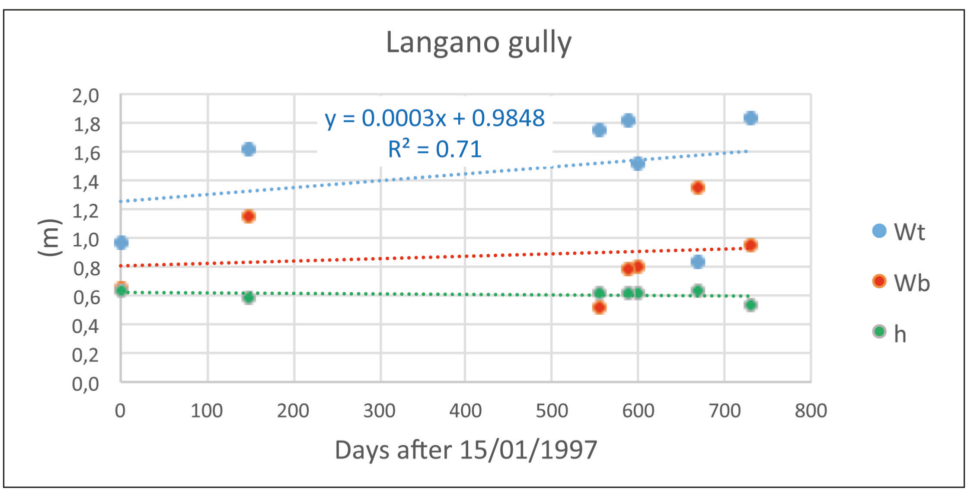


Fig. 15 - Variation through time of average top width (Wt), bottom width (Wb) and depth (h) in Langano gully, from January 1997 to January 2006.

The meteo-station, with a long data record, nearest (about 15 km) to Langano gully is Adami Tulu (Fig. 2) but, unfortunately, only daily rainfall data are available and a more detailed investigation on the role of rainfall intensity could not be carried out.

5. Discussion

Langano is a gully in its early stage of development and it is very dynamic. During the period of observation, this gully enlarged remarkably and its geomorphic evolution occurred through three main phases: 1) initially, the gully grew substantially by increasing its width; 2) in the second phase, it started to grow upstream, by head cut retreat, and downstream, by a short progradation; 3) in the last phase, both upstream and downstream expansion continued to the point that the gully joined a small gully, originally located 20 m downslope, and, given the increase in length, its volume increased considerably. This pattern is well reflected by the gully profile of 2006 (Fig. 8) in which three main portions can be distinguished. A break point in the profile is evident around the horizontal coordinate of 30 m. It clearly corresponds to the deep headcut of the first survey in 1997. A second break point can be seen around the horizontal coordinate of 65 m. This corresponds to the headcut scour of the downstream gully, which was incorporated by the downstream propagation of the main gully body. It is less pronounced than the main one because the downstream gully was smaller and, likely, it was partially filled with sediment yielded by the upstream main portion of the gully.

The upper portion of the profile results from the upslope migration of the gully headcut. In 2006 this process was still in progress and an equilibrium profile was not yet achieved as also indicated by longitudinal profile best fitted by a straight line. Such a complex geomorphological evolution is witnessed also by the variation of gully depth with distance (Fig. 11) especially as regards the different patterns of the upstream and downstream portions of the gully. Figure 11 also shows that Langano gully development consists of an alternation of instability conditions followed by an attempt to progressively reach a new geomorphic equilibrium. This situation of ongoing processes acting in a continuous attempt to reach a steady state of equilibrium is likely one of the main reasons for the linear interpolation of its longitudinal profile and diversify Langano from Gagna gully, which is instead characterized by a concave upward profile, well described by an exponential low (Fig. 7) (Rengers & Tucker, 2014). Gagna, in fact, is a big gully and the cut and fill sequences present in the colluvium into which the gully is incised indicate it likely started to form in the early to middle Holocene (Benvenuti *et al.*, 2005). Gagna gully, therefore, is older and had time enough to reach a river type concave profile (Morris & Williams, 1999: Tucker *et al.*, 2006). This conclusion is supported also by the higher sinuosity of Gagna (Fig. 11) compared to the other gullies.

The early stage of Langano gully is confirmed also by its grow rate following a positive exponential low (Fig. 14). This result of erosion acceleration was found also by Tarekegn (2012) in his study on four gullies in the Ethiopian highlands of Blue Nile Basin, 140 km south of Bahir Dar, at an elevation between 2500 and 2630 m asl and an annual precipitation of 1300 mm. In one rainy season, he found an average gully expansion rate of 20%, whereas the long term gully erosion measured by means of the AGERTIM (Assessment of Gully Erosion Rates through Interviews and Measurements) developed by Nyssen *et al.* (2006) resulted of 48 t $ha^{-1}yr^{-1}$, that is virtually a value much lower than that of 476 t $ha^{-1}yr^{-1}$, calculated for Langano gully. Other authors, such as Thomas *et al.* (2204), Nachtergaele *et al.* (2006) and Nyssen *et al.* (2006), instead, found that the volume of their study gullies in USA, Belgium and Ethiopia, respectively, increases with time following a negative exponential relation. The gullies studied by these authors, however, are much larger than Langano (and likely older) since range in volume from 240 to 140,000 m^3. The early stage of development of Langano gully is also confirmed by the lack of any correlation between top width and depth as instead observed by Nyssen *et al.* (2006) and Frankl (2012) for a large number of gullies in Ethiopia.

The average volume expansion of Langano gully is about 4.8 m^3 per year. On the base of data collected by Vandekerkhove *et al.* (2001) on 46 gullies in southeast Spain, Poesen *et al.* (2002) calculated for that area an average gully expansion of about 16 m^3yr^{-1}. The size of these gullies is highly variable from 10 to 2,000 m^3, but the study of Vandekerkhove *et al.* lasted only two years during which 85% of their gullies received an amount of rainfall about 48% and 21%, in the first and second year respectively, higher than the average annual precipitation of 276 mm.

In the north-eastern margin of the Ethiopian Rift, Daba *et al.* (2003) measured the change in volume of a very large and morphologically well developed gully across a time span of 31 years (1965-1996) using a photogrammetric method. They found an average gully expansion rate of 2259 m^3yr^{-1}. In absolute terms this is a very high rate of soil loss compared to that Langano gully, but in relative terms it corresponds to only 1% of the original volume, i.e., a much lower average unit soil loss, notwithstanding the higher annual precipitation of 827 mm (778 mm in Langano area) and elevation (2000 m asl).

The repeated surveys on Langano gully revealed that headcut retreat is not the only or main process responsible for this gully expansion as reported by many authors (e.g., Vandekerkhove *et al.*, 2001; Belyaev, 2004; Prasad, 2008; Shit *et al.*, 2013; Torri & Poesen, 2014). This gully, in fact, was observed to grow also in a downstream direction. Langano gully formed on a gently inclined slope of colluvial deposits and, during the nine years of observation, it never reached any stable base level. The downstream expansion of gullies is poorly reported in the literature as the upstream retreat of the headcut is a more dramatic and fast process that attracted the attention of many scientists. In this study, however, an initial phase of lateral expansion was followed by both upstream and downstream migration. The downstream progradation of the gully let it to join a downslope gully that, on its turn, was migrating upstream. Billi & Dramis (2000) have shown that the lower half of a gully is generally more stable than the upstream portion. Here, in fact, bank failure is rather common because of excess flow energy expenditure through scouring of the gully bottom results in high, unstable banks. On the other hand, the very fast emptying of the gully alters the pressure balance on the banks that are undermined by the flashy, shallower outwashing flow during the receding phases of the gully flooding. In the downstream portion sedimentation prevails contributing to bank stability. Nevertheless, as the gully increases in volume for the headacut retreat, a larger volume of water is conveyed through the gully and, during deep runoff events, even in the downstream portion of the gully the flow can exert a high shear stress capable to incise a loose substratum (Fig. 5) such as that of Langano gully.

Gagna is a large box gully and its planform pattern has a high sinuosity of 1.42, substantially higher than the other two study gullies. This gully has high and almost vertical walls that, mainly for this reason, are prone to failure (Fig 16). When a bank portion collapses, the fallen material can obstruct the gully bottom thus forcing the flow laterally to undermine the opposite side. The high sinuosity can be favoured also by bank incision of tributary gullies coming from opposite sides.

Fig. 16 - A sinuous stretch of Gagna box gully.

6. Conclusions

Gullies severely affect large areas of Ethiopia and every year a huge quantity of soil is lost with remarkable negative repercussions on an already suffering agricultural sector. Gully are commonly an irreversible process and only through the understanding of the factors controlling their development, it will be possible to design appropriate countermeasures. This study attempted to investigate the main geomorphic characteristics of three different types of gullies: 1) a large, well developed box gully; 2) a small gully in its early stage of development and 3) a very steep gully. The main results of this study include:

a) The older and larger box gully has a lower gradient than the topographic surface into which it is incised. Moreover, its longitudinal profile is concave upward and it is well interpolated by an exponential low. The small and steep gullies profile is instead rectilinear.
b) Both the box and small gully have an average cross-section shape factor of 2.5 (SF = top width divided by depth), whereas in the steep gully SF is only 1.35.
c) No correlation was found between top width and depth as instead reported by other authors.
d) The longitudinal variation of depth in both the box and small gullies is well described by a linear model, whereas a less significant logarithmic correlation was found for the steep gully.
e) The long term (nine years) monitoring of the small gully morphology indicates that gullies in their early stage of development can be very dynamic. The average rate of expansion of this gully is 4.8 m^3 per year, which corresponds to 26% of the initial gully volume and to a soil loss of about 467 $t\ ha^{-1} yr^{-1}$.
f) The small gully expanded in both upstream and downstream direction. Upstream migration was by headcut retreat, whereas the downstream expansion occurred simply by gully lengthening and merging with a downslope, already existing gully.

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