Gully development and its spatio-temporal variability since the late 19th century in the northern Ethiopian Highlands[1]

Amaury Frankl

Department of Geography, Ghent University, Belgium

Scope and objective

Drylands are areas where evapotranspiration exceeds precipitation during part of or the whole year (Kassas, 1995). They cover 40% of the Earth's surface and house about 2.1 billion people in nearly 100 countries, including Ethiopia (UNEP-DDD, 2012). In terms of aridity, drylands are defined as regions where the ratio between long-term annual precipitation and potential evapotranspiration between 0.05 and 0.65. They include hyper-arid, arid, semi-arid and dry sub-humid zones (Thornthwaite, 1948; UNEP, 1994). For these zones, water availability and biomass production are restricted and mostly confined to a short rainy season. As a result, the carrying capacity of the ecosystems is rapidly exceeded by the human exploitation of natural resources, especially in poor countries with fast demographic expansion and deficient exploitation techniques (Kassas, 1995). Furthermore, the resilience of drylands is often reduced by the occurrence of recurring droughts and severe desertification, which threatens sustainable development in these fragile environments.

Gully erosion is acknowledged as a key erosion process whereby land degradation in dryland environments occurs (Figure 1). In a review, Poesen *et al.* (2002) conclude that gully erosion contributes to 50% to 80% of overall sediment production in drylands. Sediment yields are locally very variable, but may be as high as 12.1 ton ha^{-1} y^{-1} in Ethiopia, 3.4 ton ha^{-1} y^{-1} in Kenya, 32 ton ha^{-1} y^{-1} in Niger, 16.1 ton ha^{-1} y^{-1} in Portugal, 64.9 ton ha^{-1} y^{-1} in Spain and 36.8 ton ha^{-1} y^{-1} in the USA (Poesen *et al.*, 2003).

Understanding historical and present-day gully erosion is therefore essential when addressing the consequences of future land use and climate change scenarios (Poesen *et al.*, 2003; Valentin *et al.*, 2005). For instance, land managers need to foresee the effects

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of land use changes, infrastructure construction or urbanization on gully development. Without such projections, future developments may be unsustainable and yield much higher costs than originally budgeted for. In addition, soil losses may strongly increase, jeopardising in-situ and downstream agricultural production (Poesen *et al.*, 2003). Furthermore, the rapid expansion of gullies is related to shifts in the hydrological regime of landscapes (Knighton, 1998), by which runoff and soil water rapidly converges to gullies (Muhindo Sahani, 2011). This often results in flash floods of polluted water which threaten human health.

The main objective of this thesis was to understand gully development since the late 19th century at a regional scale in the Northern Ethiopian Highlands. In order to frame these developments within changes in the environmental controls, land use/cover changes and their relation to rainfall patterns were also analysed.

Figure 1: In the proximity of the 19th century capital of Tigray Hintalo, two gully heads occur on the historical photograph (black arrows), in land depleted from any vegetation. They seem to have re-activated recently before the photographing of the in-ruined capital (Markham, 1868) as the linear depressions that prolong them downstream display smooth walls that indicate stabilized gullies. In 2009, both gullies were active and the gully heads were branching, frequently incited by piping. The location of the gullies may not be the same as in 1868, suggesting that one or more cut and fill cycles took place. This is also indicated by the hummocky terrain and by a 50 year old local informant which states that the gully in the front on the repeat photograph initiated seven years ago after a heavy rainfall event. Hintalo has been declining since the 19th century, and, as it is away from the main road, it is even not a distinct capital anymore. In recent years however, impermealisation has increased as a consequence of building activities. The gully in the front was 6.60 m wide and 1.74 m deep in 2009 (at arrow location). The gully in the back (at arrow location) was 6.80 m wide and 2.81 m deep in 2009. (Original photograph 1868: Royal Engineers, KingsOwn Museum, Lancaster, U.K.; repeat photograph 2008: Jan Nyssen)

Materials and methods

Investigating historical and present-day gully erosion and land use/cover required to assemble a large dataset of terrestrial photographs, aerial photographs and satellite images. For each of these materials, appropriate methods of quantitative geomorphologic research were applied and fine-tuned with the aim of achieving the specific objectives. Key in this was the fieldwork which occurred during several campaigns in the period 2007-2011. The study mainly focused on eight catchments that are representative for the regional variability in environmental characteristics and which cover in total 123 km^2 (Figure 2).

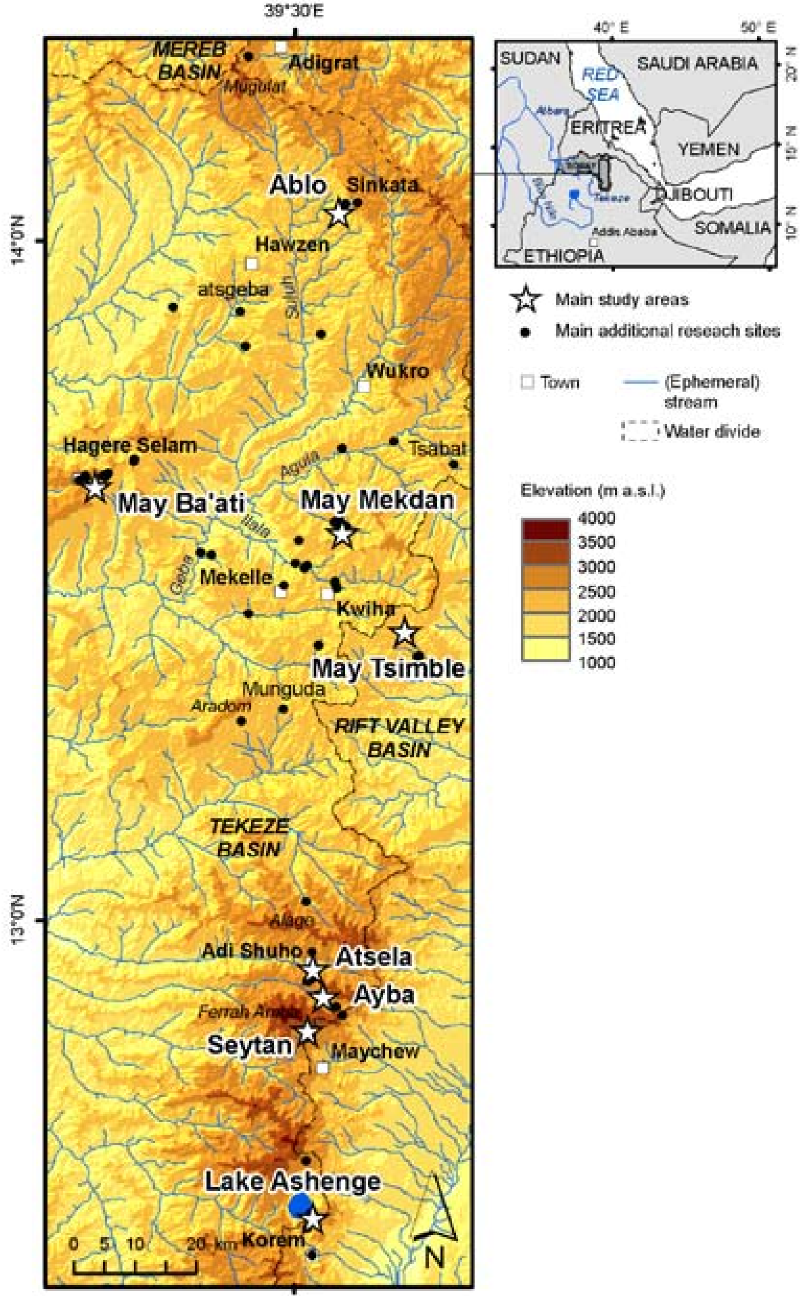

Figure 2: Northern Ethiopian Highlands (Eastern and Southern Tigray) and the main (additional) study areas

In order to compare the situation on the historical terrestrial photographs of the period 1868-1994 to the present, the photographs needed to be relocated in the field and repeated by the methods of repeat photography (e.g., Figure 1). Combining this with field measurements of gully morphology allowed us to quantify historical gully cross-sections (Frankl *et al.*, 2011). Repeat photography methods were used to quantify headcut retreat rates (Frankl *et al.*, 2012b). Accurate GPS measurements in the landscape portrayed by the terrestrial photographs allowed us to prepare land use/cover maps of the situation in the late 19th – early 20th centuries. The particularity of the historical terrestrial photographs is that they allowed us to observe the environment in historical times, similar to the way we perceive landscapes in the field. Thus, with a large dataset of photographs at hand covering the regional variability in environmental characteristics, repeat photography demonstrated to be a powerful tool for assessing environmental change and channel response in historical times (e.g., Figure 1).

Studying gully development from aerial photographs of the period 1963-1994 first required the creation of orthophotographs. As it concerns aerial photographs of relatively poor quality (out of focus, low contrast) that cover a landscape which has undergone important changes and therefore difficult to survey, the geometric rectification of some aerial photographs was done by co-registration. With scales varying between 1: 35 000 and 1: 60 000, direct quantifications of the morphology of the gully were not possible. Only the gully networks could be delineated with sufficient accuracy. By establishing relations between the length of gully networks and their volume from field measurements, gully volumes from networks that were mapped on historical aerial photographs could be quantified (Frankl *et al.*, 2012d). Such volume-length relations needed to account for the catchment lithology, varying proportions of high- and low-active gullies through time, and the implementation of check dams after 1994. Alternatively, the relationship between gully volume and catchment area and its average slope gradient was also explored. High-resolution satellite images available on Google Earth completed the time-series of aerial photographs for the most recent situation (Frankl *et al.*, 2012e).

Low-resolution satellite images were found suitable to study land use/cover changes at a regional scale (de Mûelenaere *et al.*, 2012). Land use/cover change analyses were performed from a conventional supervised classification of Landsat imagery of 1972, 1984/1986 and 2000. The use of historical terrestrial photographs to calibrate the images was also explored and yielded better results than the conventional methods (e.g., image differencing). As the different images had specific shortcomings and as they were recorded with different sensors, the images were subjected to an important pre-processing. NOAA Rainfall Estimates raster maps that are derived from low-resolution satellite images were used to understand spatiotemporal variations in cropping systems (Frankl *et al.*, 2012a).

Fieldwork was an important component of this research, not only as essential part of the above mentioned methods, but also to characterize gullies and the environment. About two month-long field campaigns were organized in the dry season of 2007 and in the rainy seasons of 2008, 2009 and 2010. Additionally, shorter visits occurred in 2011.

Assessing the present-day variability in gully morphology and morphometry was done through measurements of 811 cross-sections (Frankl *et al.*, 2012d). In addition, 57 photograph locations were visited in order to analyse historical changes in gully cross-sections (Frankl *et al.*, 2011). Gully network maps were validated and updated for recent changes. Furthermore, 24 headcuts were monitored during the rainy season of 2010 in the study area of May Ba'ati and an additional 18 headcuts were studied for long-term changes (Frankl *et al.*, 2012b). In order to understand the spatiotemporal variability of gully morphology and changes therein, local environmental characteristics were studied in the field. Important was the characterization of the semi-natural vegetation and of the cropping systems (Frankl *et al.*, 2012a). As farmers have good knowledge of past conditions, semi-structured interviews were organized with key informants. In total, about 170 local respondents were involved in this study.

Key conclusions

Regarding the development of gully erosion, the main conclusion of this work is that over the past 140 years, three marked periods of gully activity could be distinguished. In a first period, from 1868 until ca. 1965, gullies were generally low active. Most gullies on historical photographs of that period show smooth and vegetated cross-sections. As their size and morphology suggest, the gullies were not in equilibrium with the prevailing conditions; rather, this was inherited from a previous period when external forcing of environmental conditions caused significant geomorphic change (Frankl *et al.*, 2011).

Quantifying gully networks and volumes from aerial photographs (Frankl *et al.*, 2012c) of 1963-1965 indicated that the total gully drainage density (D_{total}) was 1.86 km km^{-2} and the area specific gully volume (V_a) 32.23 10^3 m^3 km^{-2}. 48% of the gully network was high-active.

In the second period, from ca. 1965 until ca. 2000, gully erosion was very severe. Quantifying gully networks and volumes from aerial photographs of 1974, 1986 and 1994 indicated that D_{total} and V_a increase subsequently. By 1994 D_{total} was 2.52 km km^{-2} and V_a 59.59 10 m^3 km^{-2}, with 93% of the gully network being high-active. The terrestrial photographs of that period also show gullies which are very active, having clear-cut walls and transporting important amounts of debris. At the upper gully margins, headcuts incised upslope, while at the lower ends, debris fans were deposited and incised subsequently. Long- to medium-term linear headcut retreat rates (R_l) were on average 3.8±4.7 m y^{-1} (Frankl *et al.*, 2012b).

Since ca. 2000, gully networks shrunk and decreased in volume, especially through the stabilization of first order gullies. From 2008-2010 D_{total} was 2.20 km km^{-2} and V_a 48.96 10^3 m^3 km^{-2}; 25% of the network was high-active (Frankl *et al.*, 2012c). Present-day short-term headcut retreat rates decreased to an average R_l of 0.34± 0.49 m y^{-1}, with especially gullies in Vertisols remaining particularly active and calling for specific measures (Frankl *et al.*, 2012b).

Regarding the most recent observations, the analysis of gully cross-sections in the field indicated that the median values for gully top width, depth and cross-sectional area were 6.34 m, 2.15 m and 10.1 m^2 respectively (Frankl *et al.*, 2012c). Important factors that determined gully cross-sectional shape and size where the presence of check dams, gully activity and lithology (Frankl *et al.*, 2012c). Gullies with check dams or which were low active had cross-sections that were 33.5% smaller than active gullies or gullies without check dams. Considering the effect of the lithology, median cross-sectional size increased from volcanics, sandstone to shale catchments. For the latter, the presence of incised travertine dams was considered as determent.

From these developments, the gully system appeared to experience a cut-and-fill cycle (Frankl *et al.*, 2011, 2012c). Rapid gully development occurred between ca. 1965 and ca. 2000, while after ca. 2000, net gully infilling occurred. Expressed soil loss by gullying, soil loss rates of 17.6 ton ha^{-1} y^{-1} occurred between 1963-1965 and 1994. Between 1994 and 2008-2010, a net infilling of 8.3 ton ha^{-1} y^{-1} occurred (Frankl *et al.*, 2012c). Large differences occurred between areas having contrasting lithologies, with soil losses by gullying in shales being about two times larger than in volcanics.

The gully erosion developments could be related to changes in land management (check dams, stone bunds), land use/cover and rainfall characteristics and were hence combined into a hydrogeomorphic model (Frankl *et al.*, 2011). In the first phase, from 1868 or earlier to ca. 1965, the predominance of low-active gullies was linked to an environment where the runoff response of the land was still low enough to prevent large-scale channel extension and degradation from occurring. Vegetation cover was however by no means abundant. The analysis of historical terrestrial photographs of ca. 12 km^2 revealed that only 5% of the surface was covered by forests and that many slopes were under degraded shrubland (Meire *et al.*, 2012). After ca. 1965, the continued decline in vegetation cover resulted in a strong runoff response leading to high denudation rates on the hillsides and upslope migration of gully heads. Probably the marked arid surges of the 1970s and 1980s triggered the widespread activation of gully networks. During such droughts, biomass production was altered, vegetation was under increased grazing pressure and the surface cover by cropland moved to steep and marginal areas. In 1984/1986 the categories bare ground and cropland accounted for 52% of the surface in the Northern Ethiopian Highlands (de Mûelenaere *et al.*, 2012). Moreover, during dry years, farmers will generally apply cropping systems with reduced cropping seasons (Frankl *et al.*, 2012a). As this increases the duration of the period for which fallow land occurs in the early rainy season, the vulnerability of the land to occasional rainfall events increases during dry years. Since ca. 2000, environmental rehabilitation programs stated to yield positive effects on the stabilization of gullies (Frankl *et al.*, 2011; 2012; 2012). Since the 1980s and especially the 1990s, widespread establishment of exclosures, introduction of stone bunds and building of gully check dams occurred. Surface cover by bare ground and cropland meanwhile decreased to 40%. A good example of how successful environmental rehabilitation can be, was found in the study area of Atsela, where a gully was transformed into a green oasis in the landscape as a result of well though land management.

This study validates previous research and indicates important land degradation by gullying in the second half of the 20th century in the Northern Ethiopian Highlands. In recent decades, local communities have however proven that with proper land management, this trend can be reversed. At a regional scale, gully networks are increasingly being stabilized and the landscape is greening. These developments have to be understood within a socio-economic environment of strong population growth and a low level of technological development, where most people rely on land resources for their livelihood, and where the fragility of the country's economy is frequently being emphasized, for example when climatic shocks such as drought cause severe food shortages and famine. Socio-economical developments and their relation to land degradation should therefore be monitored closely. With an annual population growth rate of 2.37% (period 2000-2010, CSA, 2008) and a population size which is likely to double by 2050, the country faces immense challenges. Key is to rehabilitate land as a resource base for food security and ecosystem services, and to strengthen and diversify the rural economy in order to make local communities less dependent on land resources. Such challenges are embraced by many local, national and international programs, and should remain high on the agenda.

As to other dryland environments, this study emphasizes that fast land degradation may occur when improper land management is applied. Most dramatic is the development of extensive and deep gully networks, which export large quantities of sediment through the ephemeral gully and river system and therefore jeopardize *in situ* agricultural production. Moreover, decreased agricultural production in the proximity of gullies can be expected as a result of the depressed water tables. With fast network expansion occurring, infrastructures may be damaged and costs related to future planning may be much higher than originally budgeted for. Downstream effects are also important. Water pollution caused by sediment and urban wastewater threatens human health and decreases agricultural production. As a result of a stronger flash flood regime, rivers – even those that are located many km downstream of the gullies – may respond strongly and geomorphic changes may cause infrastructures to be damaged (e.g., Billi, 2008).

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