

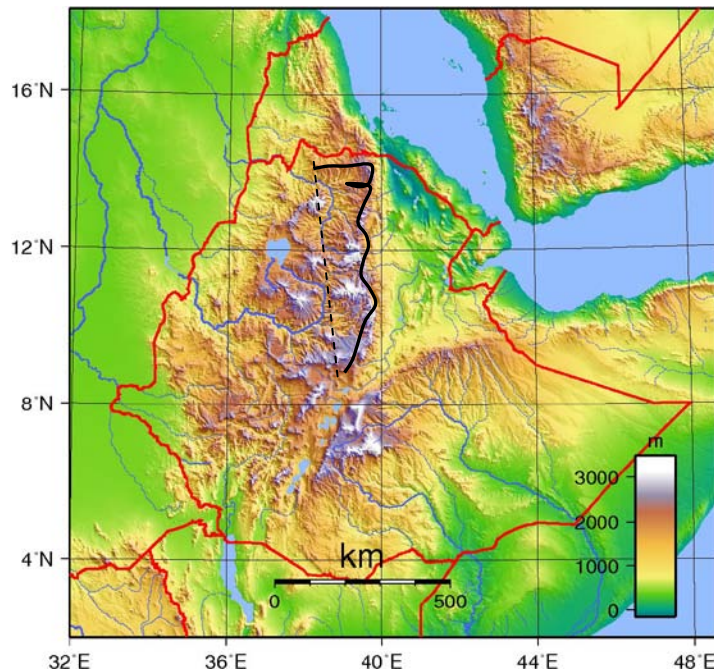
IAG REGIONAL CONFERENCE 2011

GEOMORPHOLOGY FOR HUMAN ADAPTATION TO CHANGING TROPICAL ENVIRONMENTS

ADDIS ABABA, ETHIOPIA FEBRUARY 18-22, 2011

ORGANIZED BY

EAG - ETHIOPIAN ASSOCIATION OF GEOMORPHOLOGISTS



**Post-conference excursion
Geomorphological hazards, land degradation and
resilience in the northern Ethiopian highlands
23 February – 2 March 2011**

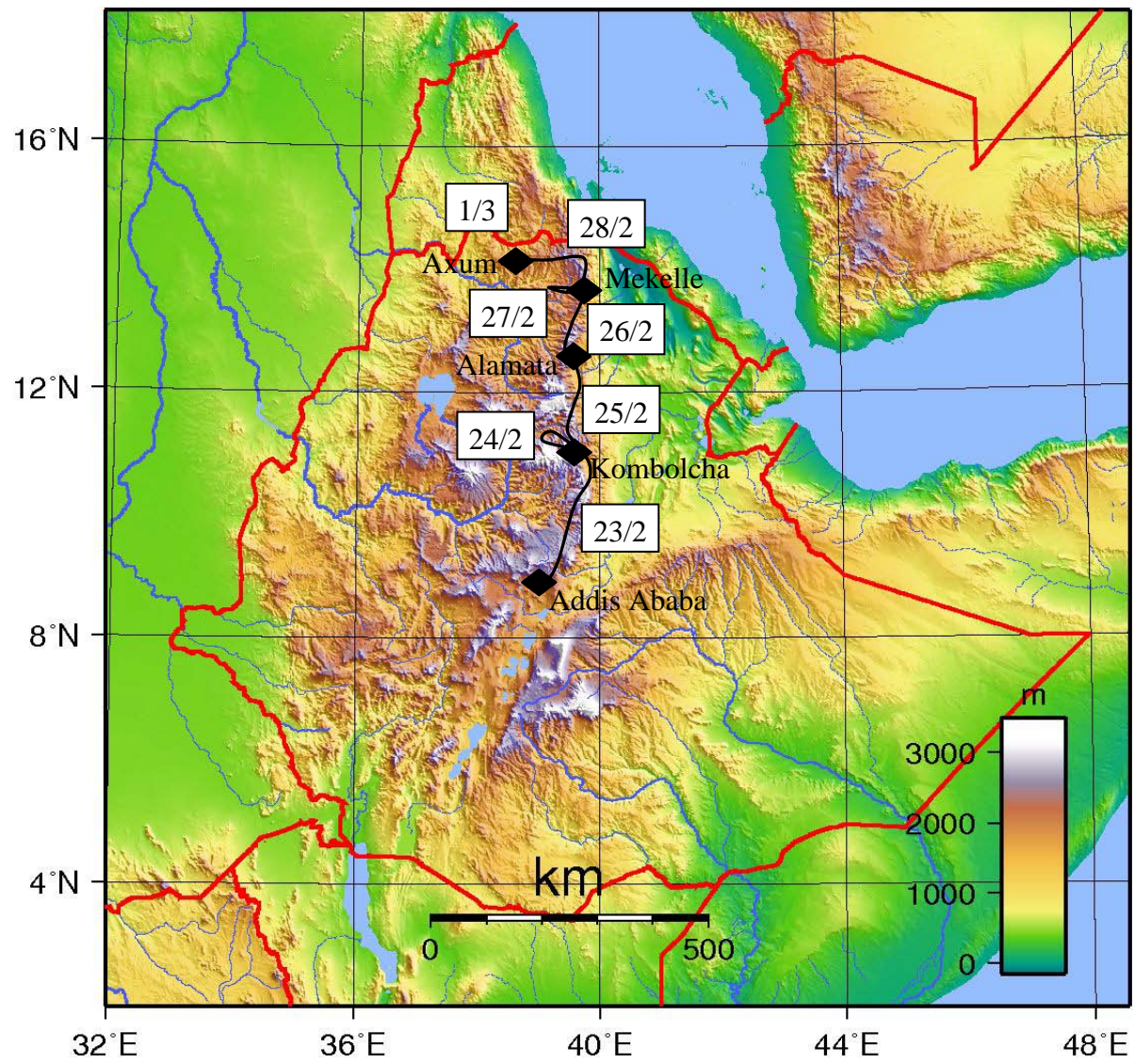
**Jan Nyssen, Asfawossen Asrat, Francesco
Dramis, Mohammed Umer (Eds.)**

Table of contents of the excursion guide

1. The western Rift Valley escarpment.....	4
2. Coseismic surface faulting in the Kara Kore area (Wollo) caused by the 1961 earthquake ..	5
3. Geomorphological evolution and present-day processes in the Dessie graben	8
4. Repeat photography for studies on environmental changes and geomorphological processes in northern Ethiopia	16
5. Land degradation and resilience in Wollo from the 1930s onwards, as derived from aerial and terrestrial photographs.....	22
6. Hydrogeomorphology in a marginal graben of the Rift Valley	30
7. Land use change and related changes in hydrogeomorphology of an ephemeral mountain stream at Gra Kahsu (Rift Valley escarpment)	36
8. Long-term gully and river channel dynamics in Tigray	39
9. Upper tree limit and land use on the upper slopes of Ferrah Amba, the peak of Tigray (3939 m a.s.l.).....	45
10. Geological and geomorphological framework of the Tigray Highlands	52
11. Geomorphology of the Mt. Amba Aradam south-eastern slope	61
12. Sediment transport in the Geba River system.....	65
13. Soil-landscape relationships in the basalt-dominated uplands of Tigray – example in May Leiba	72
14. Rainfall-triggered slope failures on shale hillslopes; the case of Amba Raesat	77
15. Using the sediment of Mayleba reservoir for land reclamation.....	83
16. The effect of soil and water conservation treatments on rainfall-runoff response and soil losses in the Northern Ethiopian Highlands: the case of May Leiba catchment	86
17. Apple tree introduction and adaptation in the Tigray highlands.....	93
18. Rural marketing in Tigray: the case of Hagere Selam market.....	97
19. Beekeeping innovation by farmers in Tigray for generating income and restoring natural vegetation	102

20. Livestock fodder development as an essential component of catchment management: case study in Mai Zeg-Zeg.....	104
21. Monitoring of the remobilisation of the May Ntebteb landslide near Hagere Selam	109
22. The sediment budget of May Zeg-zeg catchment and its components.....	114
23. Hydro(geo)logy and impact of soil and water conservation measures on the hydrological response in May Zeg-zeg catchment.....	121
24. Soil and water conservation through introduction of conservation agriculture in Dogua Tembien	128
25. Monitoring gully headcut retreat rates in May Bati.....	134
26. The travertine dammed sedimentary sequence of Mai Makden	136
27. The limestone caves of Tigray: their potential for speleothem palaeoclimate studies	141
28. Planation surfaces on the road from Mekelle to Adigat	143
29. Geology of the rock-hewn churches of Tigray	145
30. Glacial geomorphology: the paleozoic sedimentary successions of Northern Ethiopia.....	148
31. Rockfall shapes the <i>amba</i> landscape.....	153
32. Geology of the Negash area.....	158
33. Land use and land cover changes in Sinkata village.....	160
34. Impact of surface water reservoirs on ground water reserves in the highlands of Northern Ethiopia, Tigray region	165
35. Adwa phonolite plugs and the temple of Yeha.....	170
36. Geomorphology and geoarchaeology of the Axum archaeological area	172
MAPS	
Overview map of the excursion	3

MAP OF THE EXCURSION



1. The western Rift Valley escarpment

Location of the field presentations

(1) “Afar window” (locally known as 'Gemasa Gedel'): amazing view from the Rift shoulder extending to the Afar depression; the Afar window represents the major rift escarpment where the main fault plane (scarp) has a vertical throw of more than 700 m.

(2) Chira Meda, in the middle of the escarpment, with a nice view to both the Rift to the East and the plateau/escarpment to the West.

See the section on road geology between Addis Ababa and Maichew in:

Asrat, A., Demissie, M., Mogessie, A. (2009) Geo-tourism in Ethiopia. *SHAMA Books*, Addis Ababa, 186 pp.

2. Coseismic surface faulting in the Kara Kore area (Wollo) caused by the 1961 earthquake

(mostly taken from Gouin, 1979)

G. Fubelli & F. Dramis

Department of Geological Sciences, "Roma Tre" University, Rome, Italy

1. The 1961 Kara Kore Earthquake

In 1961, from the end of May to the end of September, over 3500 earthquake shocks were recorded from the Kara Kore area at the Geophysical Observatory in Addis Ababa. A first series of earthquake shocks, which began on 29 May, reached a maximum frequency of 150 per day; a second series began on 1 June with a peak frequency of 350 per day. Two shocks had a magnitude >6.4 and seven >5.0 . The felt area was estimated as about 300,000 km² and a relatively higher intensities were observed in the southeastern sector of the zone. The maximum intensity at the centre of the epicentral zone was estimated as VIII-IX on the Mercalli-Modified scale.

Cracks, fissures, and subsidence of up to 1 meter deep developed on the Addis Ababa - Mekelle highway: many culverts and retaining walls along the road had to be rebuilt. Gravitational movements were observed on steep escarpments slopes and a 15-20 km long fissure, in places 6-7 meters deep, formed in unconsolidated soil along the eastern scarp of the Borkena marginal graben (Fig. 1). There were no casualties.



Figure 1. Panoramic view of the Borkena graben in the Kara Kore area. Coseismic deformation affected the road on the right of the image during the 1961 earthquake.

The maximum damage was localized along the Addis Ababa – Mekelle highway between latitude N 10° and 11° and longitude E 39.7° and 37.9°. At these latitudes, the highway runs along the upper margin of the eastern escarpment of the Ethiopian Plateau, which is dissected longitudinally by the Borkena graben, and transversely by NE-SW faulting curving in from Afar. In the epicentral area, the village of Majete was completely destroyed while the village of Kara Kore was affected only in part, maybe because of the type of buildings. In Kara Kore only the masonry collapsed, while the tukuls (traditional houses) withstood the shocks very well. Along the highway, damage was spectacular. Large boulders from rockslides, some estimated to weigh 12 – 15 tons, blocked the road. Bridge pillars were fissured and parapets destroyed; cracks as

wide as 60 cm and as deep as 150 cm were opened in the road surface; heavy slumping and subsidences with a resulting difference of some 100 cm in the surface level rendered the road impassable. All the bridges and culverts between kilometre posts 240 and 255 from Addis Ababa had to be rebuilt. Heavy alterations in the landscape had been also recognized. In addition to the numerous landslides, a piedmont scarp in unconsolidated materials opened along the escarpment of the Borkena graben. This scarp could be followed over 12 – 15 km until it became obscured by rubble. In some places, the vertical differential displacement reached 2 m, the depth 5-7 m, and the width at the surface over 1 m.

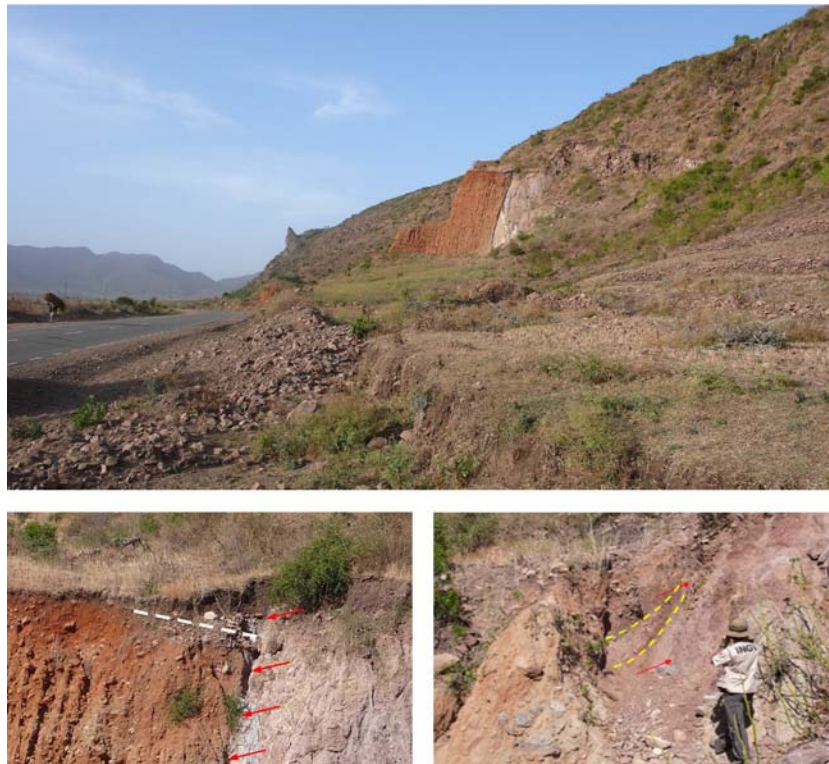


Figure 2. Upper photo: quarry in the Kara Kore area where the contact between the basalt and slope/alluvial deposits due to the fault activity is exposed. Lower photos: detail of the slope deposits (left) tilted towards the fault plane (the white dashed line marks the attitude of the deposits) and (right) dragged (as indicated by yellow dashed lines) along the fault plane (indicated by red arrows).

Excursion stops

Stop 1. Active fault on the Addis Ababa-Mekelle highway, south of Kara Kore

A gravel quarry excavated on the Addis Ababa-Mekelle highway, few kilometres south of Kara Kore, on the eastern bordering scarp of the Hora basin, a small tectonic depression located on the southern edge of the Borkena graben (Fig. 2), makes it possible to examine a north-south trending normal/strike slip fault that displaces Tertiary volcanics (footwall) and slope-alluvial deposits (hanging wall), referred to the Quaternary in the Geological Map of Ethiopia (Menghesa *et al.*, 1996). A trench running along the intersection of the fault with the ground indicates a very recent reactivation likely occurred during May 29, 1961 (Gouin, 1979).

The deep incision of the downthrown sediments indicates that the fault displacements have acted in connection with the strong uplift that affected the area in Pliocene-Quaternary times (Faure, 1975; Almond, 1986; Mohr, 1986).

Stop 2. Coseismic surface faulting at Kara Kore.

In this stop a showy surface fault produced in connection with the May 29, 1961 earthquake can be observed. At Kara Kore, on the eastern bordering slope of the Borkena graben, a piedmont scarp in unconsolidated materials is still visible. This scarp could be followed over 12 – 15 km with vertical displacement up to 2 m (Gouin, 1979). Considering that this displacement is very high in relation to the earthquake magnitude ($M=6.6$), it seems likely to explain it by the contribution of a strong gravity stress related to the high difference of relief between the Ethiopian Plateau and the Afar (Chorowitz *et al.* 1999).

Stop 3. Coseismic surface faulting at Majete.

Coseismic ground ruptures related to the 1961 earthquake are visible in the Majete area on the western side of the Borkena basin.

References

- Almond D.C., 1986. *Geological evolution of the Afro-Arabian dome*. Tectonophysics 131, 301–332.
- Chorowicz J., Collet B., Bonavia F. & Tesfaye Korme 1999. *Left-lateral strike-slip tectonics and gravity induced individualisation of wide continental blocks in the western Afar margin*. Eclogae Geol. Helv. 92, 149-158.
- Faure H., 1975. *Neotectonics in the Afar (Ethiopia, T.F.A.I.)*. In: Suggate R.P., Creswell M.M. (eds.), *Quaternary Studies*, R. Soc. New Zealand, Wellington, pp. 121-126.
- Gouin P., 1979. *Earthquake History of Ethiopia and the Horn of Africa*. International Development Research Center (IDRC), Ottawa.
- Mengesha Tefera, Tadiwos Chernet & Workineh Haro, 1996. *Explanation of the geological map of Ethiopia. Scale 1:2.000.000*. 2nd Edition, Ethiopian Institute of Geological Survey, 80 pp. 2nd ed. EIGS, Addis Ababa.
- Mohr P., 1986. *Sequential aspects of the tectonic evolution of Ethiopia*. Mem. Soc. Geol. It. 31, 447–461.

3. Geomorphological evolution and present-day processes in the Dessie graben

(reduced from Fubelli et al., 2008)

Fubelli G.

Department of Geological Sciences, "Roma Tre" University, Rome, Italy

Introduction

The Dessie basin (Fig. 1) is a small graben (ca. 7 km long and 3 km wide) located around 2600-2700 m a.s.l. on the western Afar margin. The basin is crossed by the Borkena River which flows to Kombolcha through a 300 m deep narrow gorge, locally named Doro Mezleya (*Chicken Jump*); its south-west sector is part of the Kelina River catchment (Fig. 2). A large part of the basin floor is occupied by Dessie Town, one of the main urban settlements of Ethiopia (200,000 inhabitants).



Figure 1. Panoramic view of the Dessie basin from the top of Doro Mezleya.

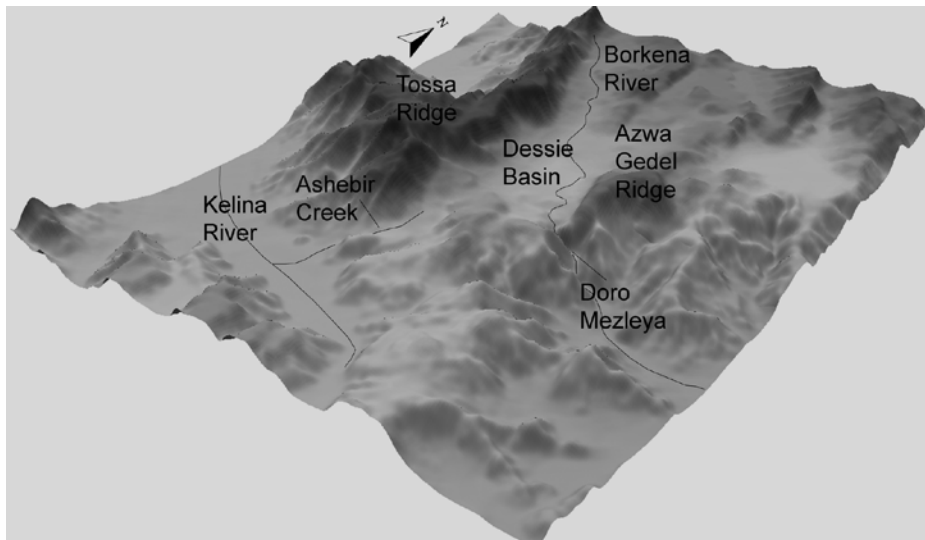


Figure 2. Digital Terrain Model of the study area showing the bordering ridges and location of the mentioned localities.

The climate of Dessie is characterized by two distinct wet and dry seasons (Ethiopian Mapping Authority, 1988). Rainfall data recorded between 1974 and 2004 show that there is a bi-modal rainfall pattern with the heaviest rains occurring during the months of July and August with annual average reaching 1600 mm and that more than a third of the annual precipitation is concentrated in the same months (Fig. 3). The average annual temperature is 18.5°C.

In spite of the high yearly rainfall and the dense potential vegetation cover (Ethiopian Mapping Authority, 1988), the slopes bounding the basin are poorly vegetated, likely because of widespread anthropic deforestation. Slope processes and, most of all landslides, play an important role in the present geomorphological evolution of the Dessie basin (Lulseged & Vernier, 1999; Tenalem & Barbieri, 2005).

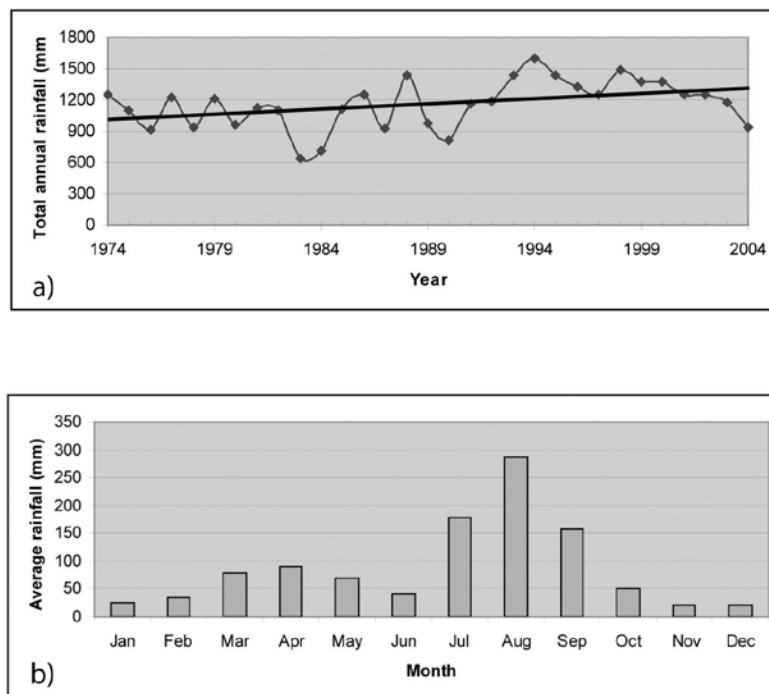


Figure 3. Dessie rain data for the hydrological years 1974-2004: a) total annual rainfall, with linear trendline; b) monthly average rainfall between 1974 and 2004.

The main triggering factor of slope movements is heavy rainfall (Lulseged & Vernier, 1999; Lulseged, 1999). Also the earthquakes which recurrently strike the area may be responsible for landslide triggering. Moreover, man-made activities, such as the construction of houses, roads, bridges or leakage of water from aqueducts and pipelines, may induce slope instability by adding weight to incipient landslides, modifying slope profiles or changing groundwater levels and flow. Landslides have a heavily impact on the Dessie basin interacting with people, settlements, infrastructures and farmlands. In particular, a large number of landslide events have repeatedly struck the urban area since long time ago, causing the loss of life and property (Tenalem & Barbieri, 2005). In 1977, two people were killed by a seismically induced landslide (Gouin, 1979) and in 1994, landslides triggered by heavy rainfall blocked a segment of the Main Dessie-Mekelle highway, destroyed a bridge and buckled the foundations of several houses.

Geological setting and morphotectonics

The Dessie basin is one of the numerous “hanging” tectonic depressions located along the western Afar margin (Fig. 4). It is bordered by two N-S striking normal faults: the Tossa fault to the west and the antithetic Azwa Gedel fault to the east. Both faults form high walls which bound the intermediate lowered sector crossed by the Borkena River and its tributaries. More to the east, the N-S trending faults of the Azwa Gedel horst, make a transition to the marginal basin of Kombolcha, located at around 1800 m a.s.l., 800 m below the Dessie basin. The SW-NE trending Doro Mezleya fault is apparently a transfer zone between the Dessie and Kombolcha grabens. Another SW-NE fault, with less geomorphic evidence, borders the basin to the north, separating it from the Seyo Kurkur depression. Other faults ranging in strike from NNW-SSE to NW-SE cross the area exerting a more or less direct control on the basin topography.

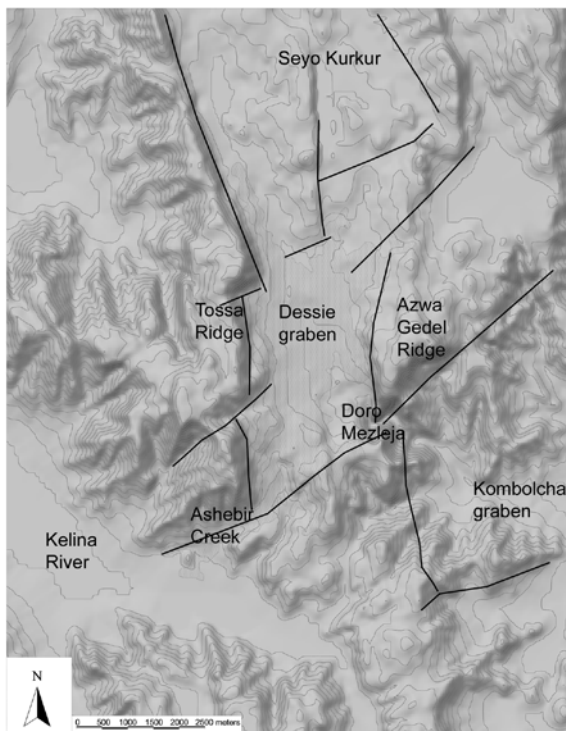


Figure 4. *Fault pattern of the Dessie basin.*

The bedrock consists of ignimbrites, volcanic agglomerates and basalt flow layers ranging in age between 30 and 25 Ma (Kazmin, 1979; Mengesha *et al.*, 1996). In particular two different units have been recognized: a) pre-rift flood basalt and b) the graben floor post-rift basalt post dating the main faulting. The first unit widely outcrops on the main fault escarpments and their top surfaces; the second unit is the most dominant rock type in the axial part of the Dessie graben and is exposed along the banks of the Borkena River. These rocks have undergone variable degrees of weathering and are often interbedded with reddish paleosols.

The graben floor filling sediments consist mainly of alluvial-swampy-lacustrine deposits, mostly made of yellow sands with gravelly levels, white diatomite beds, and scarce pyroclastic fragments, likely derived from volcanic products in the surrounding areas. These sediments were considered to be of Quaternary age by previous authors (Gregnanin *et al.*, 1978; Tenalem & Barbieri, 2005). Actually, notwithstanding the lack of chronological data, the relatively small

thickness of the deposits, their flat depositional surface constantly located at 2,520 m a.s.l., and the extremely rapid dynamics of the geomorphic processes affecting the area, seems to testify a very recent geological origin.

Main landform units and present-day geomorphic processes

From the geomorphological point of view, the Dessie graben can be divided into seven different landform units (Fig. 5):

- 1) *the fault escarpments and gently sloping summit surfaces;*
- 2) *the talus belts;*
- 3) *the fluvio-denudational slopes;*
- 4) *the hummocky graben floor;*
- 5) *the alluvial fans of the Borkena River tributary streams;*
- 6) *the Dessie terrace;*
- 7) *the river beds and terraces.*

The fault escarpments and gently sloping summit surfaces

The main N-S fault escarpments form imposing rocky walls over which the *basalts and ignimbrites of the continental flood basalt (Trap Series)* outcrop. The Tossa fault escarpment is up to 400 m high and up to 80° steep. It follows a rectilinear trend being only interrupted by the upper catchments of the two western tributaries of the Borkena River. The Azwa Gedel scarp is lower (ca. 200 m) and has a more rectilinear trend, without major stream incision. The two N-S bordering escarpments are topped by gently sloping surfaces, whose maximum elevation is ca. 2950 m on the Tossa side and 2720 m a.s.l. on the opposite Azwa Gedel side. It is probable that these surfaces were fragments of the ancient depositional top of the trap volcanics before the opening of the Dessie graben. All these escarpments are diffusely affected by rill wash and gullies as well as by different types of failures. Rock falls and topplings, generally of small size, are common on the Tossa escarpment. The Azwa Gedel escarpment is locally affected by rock slides which involve the outcropping pre-rift flood basalt unit.

The talus belts

A thick (up to 15 m) belt of open work and clast-supported talus deposits outcrops on both sides of the Dessie basin, at the foot of the Tossa and Azwa Gedel escarpments. Scattered blocks up to few metres large, emplaced by rock falls and topplings from the densely jointed stratoid basalt of the escarpments are locally found. Two buried soils likely referable to more humid and vegetation-rich phases of the early-mid Holocene (Dramis *et al.*, 2003; Coltorti *et al.*, 2009) are present in the upper part of the sequence.

The slope deposits are poorly compacted and are rapidly incised by running waters fed by the upslopes. Those at the foot of the Tossa escarpment are mobilized by translational debris slides along sandy-clayey levels or over the basalt floor, as in the case of the huge rock slide which affects the Tossa escarpment talus on the right side of the Ashebir Creek, south of Dessie. This movement is indicated by the occurrence of sub-rectangular box-shaped trenches, with outcropping basalt at their base.

The fluvio-denudational slopes

Relict fluvio-denudational slopes modelled on basalt bedrock are testified by the occurrence of wind gaps crossing the Azwa Gedel ridge. More recent slopes, carved by fluvial erosion, are those forming the upper catchments of the two tributaries of the Borkena River. These slopes are covered by a relatively thick eluvial-colluvial mantle which is affected by debris flows and debris slides during the rainy season.

The hummocky graben floor

A large part of the graben floor is characterized by an irregular hummocky topography, with low round-shaped hills separated by narrow flat-floored small valleys crossed by the Borkena River and its tributaries. The low, rounded hills clearly result from selective erosion of the volcanic ridges and cones on the graben floor. They are commonly deeply weathered and covered by eluvial-colluvial materials, at places including pyroclastic materials (Tenalem & Barbieri, 2005), likely erupted by Pliocene-Quaternary volcanoes in the nearby areas (Kazmin, 1975; Mengesha *et al.*, 1996). These materials are diffusely shifted downslope by soil-creep movements and tend to fill up small valleys and inter-hill depressions.

The Dessie terrace

A 75 to 100 m thick sedimentary sequence of alluvial-swampy-lacustrine facies, made of sands and clayey sands alternating with silty siliceous levees and less frequent gravelly levels, fills up the lower part of the Dessie depression. These deposits have been incised down to their base by the Borkena River forming a wide terrace, constantly 2,520 m a.s.l high from the Dessie Football field to the edge of the Borkena River gorge. Eastward, the same feature may be recognized up to the St. Michael Church, where its southward continuity is interrupted by rotational slides.

The eastern terrace sector is less developed, likely due to the reduced debris production from the Azwa Gedel escarpment, lower in altitude and relatively poor in the older escarpment rocks. The sequence overlays a sub-horizontal surface of vesicular basalt whose elevation is 2500 m a.s.l. on the Borkena River bed, close to the Doro Mezleya gorge, and 2525 m a.s.l. in the westernmost part of the Dessie terrace.

Widespread slope instability is induced in the deeply incised alluvial-swampy-lacustrine sequence by the lateral erosion of the Borkena River directly flowing over the more resistant basalt bedrock. As a consequence, the alluvial-swampy-lacustrine sediments are affected by numerous mass movements, mostly retrogressive rotational slides of different size, which are responsible for an extremely rapid retreat of the terrace edge. Moreover, small-scale debris slides affect the colluvial materials covering the river-cut escarpments.



Figure 5. *Main landform units of the Dessie Basin.*

The alluvial fans of the Borkena River tributary streams

The fluvial sediments transported from the Tossa escarpment to the Borkena River by the two tributary streams form wide alluvial fans over which sectors of the Dessie town are located. These features are deeply affected by the regressive erosion induced by the Borkena River deep incision.

The alluvial fan deposits are made of mainly partially rounded clast-supported basalt conglomerates alternating with sandy-clayey levels, more frequent in the distal sectors of the fan. The surface slope angles are around 15°-20° in the apical sectors and less than 13° in the distal parts. Their maximum thickness is ca. 30 m. The distal parts of the alluvial fans interfinger with the Dessie terrace. The apical sectors of the fans are fed by recurrent debris flows originating from the fluvio-denudational slopes of the upper catchments.

The top part of the sequence is made of blackish soil, sediments and debris, which indicate a recent period of widespread slope denudation (Coltorti *et al.*, 2009).

The river beds and terraces

The Borkena River with its tributaries, and the Ashebir Creek to the south-west, make up a network of narrow channels across the graben floor. The present channels are incised, up to 10 m, within an alluvial terrace made of clast-supported basalt cobbles and gravels with a sandy and silty matrix. The river-bed materials generally consist of basalt boulders, cobbles and gravels with a minor percentage of sand. The Borkena River terrace disappears as the river enters the Doro Mezleya gorge through a ca 60 m high waterfall,

Excursion stops

Stop 1. Detachment scar of the translational rock slide on the SW-NE trending Doro Mezleya fault escarpment and panoramic view of the Dessie basin. The rock slide moves along basalt cooling joints which, in this particular sector, are parallel to the slope.

Stop 2. Panoramic view of the Dessie basin from the top of Doro Mezleya. The Azwa Gede fault scarp is visible on the right. The deep incision of the Borkena River has induced rotational slides in the alluvial-colluvial and lacustrine deposits of the graben floor.

Stop 3. A landslide involving some houses in the Dessie Town.

References

Coltorti M., Cinque A., Fubelli G., Dramis F., Bekele Abebe & Asfawossen Asrat, 2009. *Late Holocene environmental changes and present-day geomorphic processes in the Wurgu catchment (Wollo, Ethiopia)*. Geogr. Fis. Dinam. Quat. 32, 129-134.

Dramis F., Mohammed Umer, Calderoni G. & Mitiku Haile, 2003. *Holocene climate phases from buried soils in Tigray (northern Ethiopia): Comparison with lake level fluctuations in the Main Ethiopian Rift*. Quaternary Res. 60, 274-283.

- Ethiopian Mapping Authority, 1988. *National Atlas of Ethiopia*, Addis Ababa.
- Fubelli G., Bekele Abebe, Dramis F. & Vinci S., 2008. *Geomorphological evolution and present-day processes in the Dessie Graben (Wollo, Ethiopia)*. Catena, 8-37.
- Gouin P., 1979. *Earthquake History of Ethiopia and the Horn of Africa*. International Development Research Center (IDRC), Ottawa.
- Gregnanin A., Piccirillo E.M., Abebaw Endeshaw, 1978. *The subdivision of volcanic series in the Ethiopian Plateau. New geologic interpretation of the Dessie area*. Technical Report. Unpublished, Rome, Italy.
- Kazmin V., 1975. *Explanation of the Geological Map of Ethiopia*. Geological Survey of Ethiopia Bull. 1, 14 pp.
- Lulseged Ayalew, 1999. *The effect of seasonal rainfall on landslides in the highlands of Ethiopia*. Bull. Engn. Geol. Envir. 58, 9-19.
- Lulseged Ayalew & Vernier, A., 1999. *Causes and mechanisms of slope instability in Dessie town, Ethiopia*. In: Yag N., Yamagami T. & Jang J.-C. (eds.), *Slope stability engineering*. A.A. Balkema, Rotterdam/Brookfield, pp. 1181-1186.
- Mengesha Tefera, Tadiwos Chernet & Workineh Haro, 1996. *Explanation of the geological map of Ethiopia*, 2nd ed. EIGS, Addis Ababa.
- Tenalem Ayenew & Barbieri G., 2005. *Inventory of landslides and susceptibility mapping in the Dessie area, Northern Ethiopia*. Engn. Geol. 77, 1-15.

4. Repeat photography for studies on environmental changes and geomorphological processes in northern Ethiopia

Jan Nyssen^{1,*}, Paolo Billi², R. Neil Munro³, Amaury Frankl¹, Mitiku Haile⁴, Jean Poesen⁵

¹ Department of Geography, Ghent University, Belgium

² Earth Sciences Institute, University Ferrara, Italy

³ Old Abbey Associates, Dirleton, Scotland, U.K.

⁴ Department of Land Resources Management and Environmental protection, Mekelle University, Ethiopia

⁵ Department of Earth and Environmental Sciences, K.U.Leuven, Belgium

* Corresponding author. Tel. ++32 9 264 46 23, email: jan.nyssen@ugent.be

The illustrative power of a set of repeat photographs is often stronger than that of other scientific output, but historical photographs are also a very useful research tool and object themselves (Fig. 1).



Fig. 1a. Dessie and Tossa Amaba around 1907 (Photo Vanini © Italian Military Geographical Institute, Firenze)

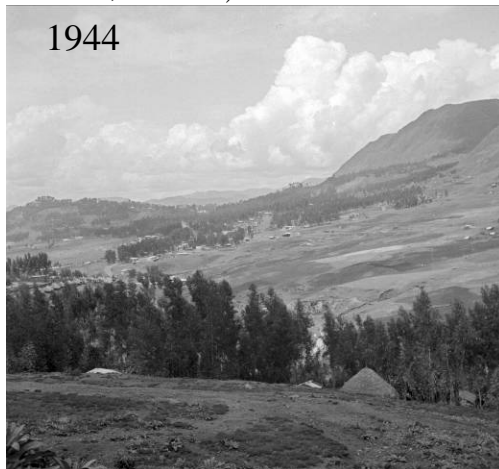


Fig. 51 - Dessiè ed i monti Tossà.

Fig. 1b. Dessie and Tossa Amaba around 1940. Left: 1944 (Photo D. Buxton); right 1937 (Gortani and Bianchi, 1973)

Among the digital archives with historical photographs of Ethiopia that we accessed, some hold fully digitised databases including downloadable photographs (of variable resolution); others show only part of the digital imagery available but have a possibility of ordering other photographs online; still others basically display a few photographs to give an idea about the collection and further clearly state procedures for on-site selection visits as well as ordering of scanned photographs (Nyssen *et al.*, 2010a).



Fig. 2. Map of the Abyssinian expedition (Nyssen *et al.*, 2009)

As the name implies, repeat photography means retaking photographs from the same spot and of the same subject several times; it requires precise repositioning of the camera and composition of the subject, typically the distant landscape (Nyssen *et al.*, 2010b). The relocation of historical photographs in Ethiopia was based on rough indications on some of the photographs, detailed scrutiny of maps with routes taken by the original photographers – for instance the “Abyssinian expedition” in 1868 (Fig. 2), knowledge of landscape forms induced by various lithologies, screening of the 3-dimensional landscape using Google Earth, and a fifteen-years long geomorphic research experience in the study area.

First, the approximate camera position was obtained by identification of unique landscape features such as mountain peaks, drainage ways and their relative position. Finally, the exact camera position and orientation was obtained by lining up near and distant objects in a triangulation system. However, not all photographs could be repeated; some particular problems concerned the absence of identifiable objects. In Ethiopia, repeated photographs have been used for qualitative analysis, such as the Simien mountains study (Nievergelt, 1998), to illustrate land use and cover changes that were identified using other techniques, or to verify some common perceptions, such as that of a 40% forest and vegetation cover in the northern highlands of Ethiopia in the early 20th century (Crummey, 1998, 2001). This perception has been challenged earlier on, on the basis of historical and stratigraphic evidence; however to challenge a perception, photographic evidence is

a strong argument (Fig. 3).

Though repeat photography is more commonly used in qualitative studies, it can also be used in a quantitative way, such as our studies that compared land degradation and a soil erosion assessment between 1975 and 2008 (Munro *et al.*, 2008; Nyssen *et al.*, 2008), changes in gully volumes (Frankl *et al.*, 2011) and historical land use mapping (de Mûelenaere *et al.*, 2011; Meire *et al.*, 2011).

As an example, the methodology is presented that was applied to study environmental changes in the north Ethiopian highlands since the late 19th century. Landscape photographs taken during the “Abyssinia expedition” in 1868 were obtained from the Kings Own Museum. Thirteen landscapes photographed in early 1868 (dry season) were re-visited in the same season in 2008 and a new set of photographs prepared. They covered a north-south transect between the Red Sea coast and Maqadala (Fig. 2) and provided a fair representation of the 1868 landscape. The location of the interpreted landscapes was assumed to be random, insofar that the photographers

in 1868 could not foresee environmental changes that would take place in these areas, or had occurred before.

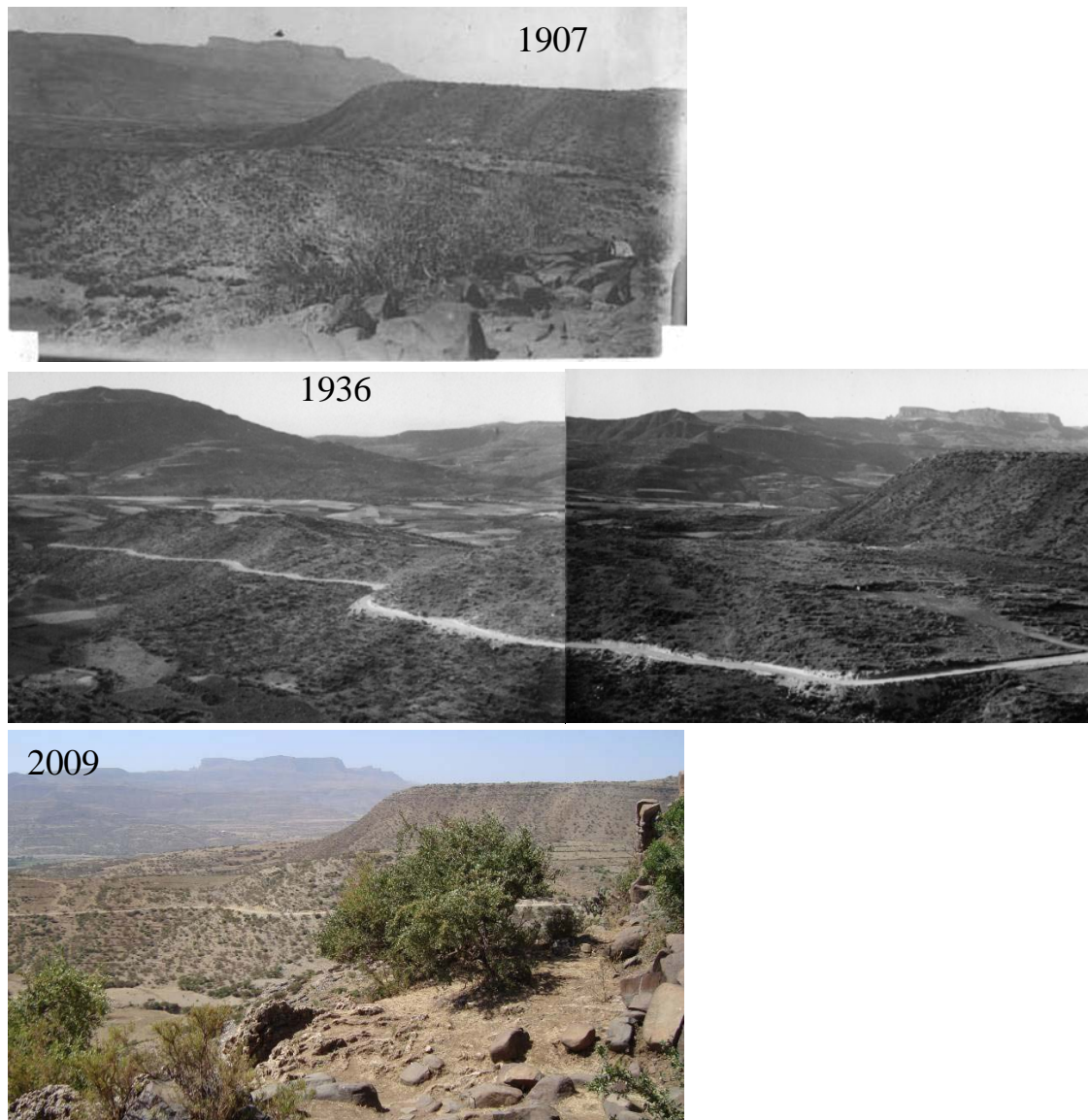


Fig. 3. Amba Aradom mountain seen from the North in 1907 (top), 1936 (middle, under a slightly different angle) and 2009 (bottom) (Nyssen et al., 2010a). These photographs are not exact matches, but are very useful in revealing changes through the years; it is called an “incidental time series”. The landscape portrayed on the 1907 and 1936 photographs is remarkably similar to the current one, a fact which appears on many of the historical photographs. Such photographs hopefully contribute to demythify common beliefs in the area that the shrubs which are currently visible evidence that ‘at the time of our grandfathers all this area was forest’. 1907 photograph Vanini © Italian Military Geographical Institute, Firenze; 1936 photograph A. Maugini © Istituto Agronomico per l’Oltremare, Firenze; 2009 photograph © Jan Nyssen.

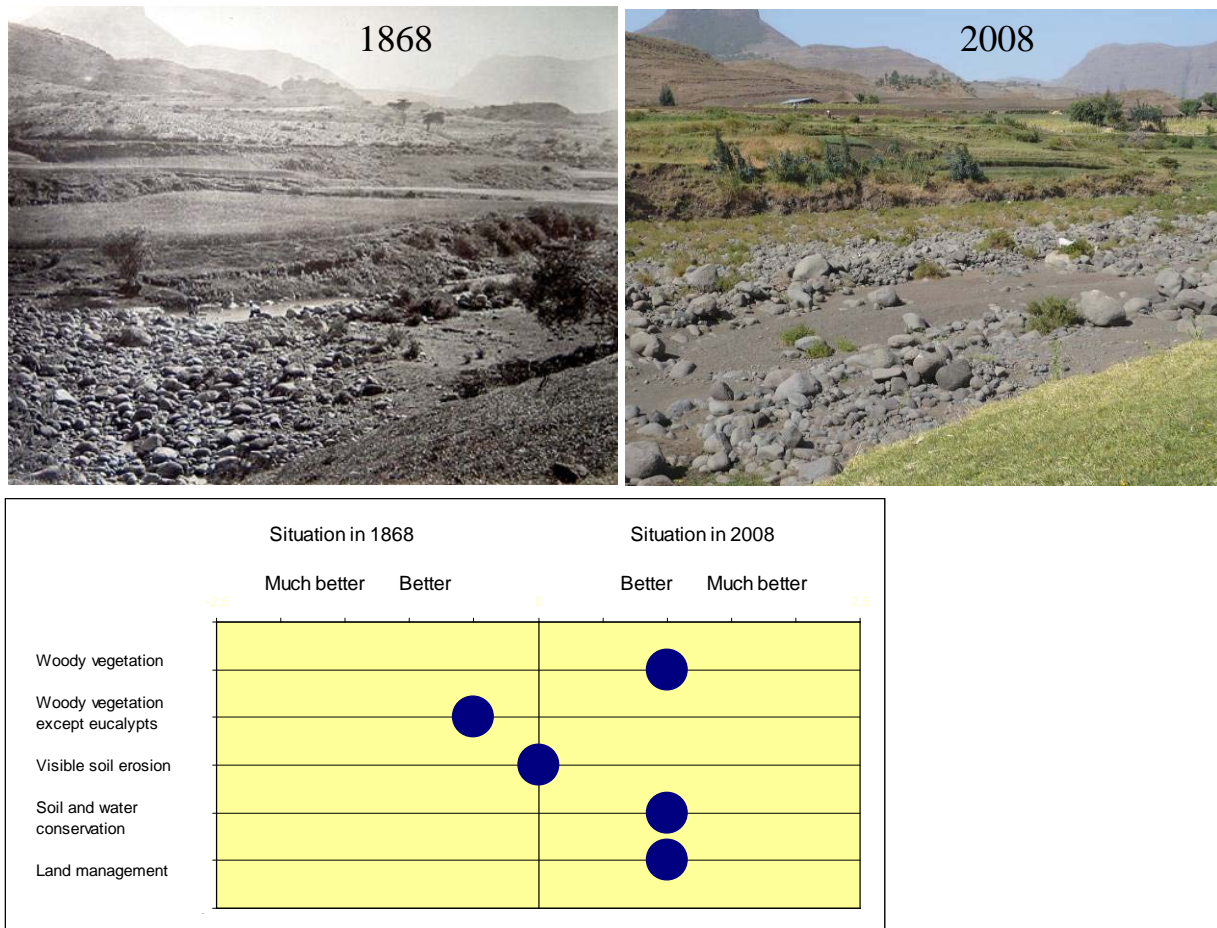


Fig. 4. The left photograph was taken in 1868 near the source of Tacazze River, one of the main rivers draining the Ethiopian highlands to the Nile. The river terrace in the centre of the 1868 photograph is cropped with wheat or barley which were commonly irrigated crops at that time (Markham, 1868), unlike nowadays when irrigation is mainly used for marketable vegetables. By 2008 (right photograph), the river terrace has completely been eroded away. More steep slopes are cultivated nowadays, which explains why there are more lynchets (cultivation terraces). The aspect of the slope in the middle of the photographs has completely changed because of these terracing practices. Furthermore, the land use did also change, from rangeland to cropland. The graph represents the medians of change evaluations by eight international experts (Nyssen *et al.*, 2009). 1868 photograph © King's Own Royal Regiment Museum; 2008 photograph © Jan Nyssen.

For that study (Nyssen *et al.*, 2009), the photographs (historical photographs and repeats) were shown to eight scientists with longstanding research experience on geomorphology and land management in Ethiopia and elsewhere. Only photocouples, taken at exactly the same place, in the same season and under the same angle were considered. The immediate foreground is dependent on the exact position of the photographer. To avoid bias, it was masked for the analysis, unless it had clear reference points.

The repeat photography analysis involved comparing on-the-ground conditions of 2008 (presented as black and white photographs) to photographs depicting the 1868 conditions,

whereby scores were assigned by the experts. Given that the scoring method used ordinal variables, the median score per indicator was calculated for every photo-couple, provided that at least four of the eight experts thought the indicator relevant for the photo-couple. Averages of the median scores were then calculated for each indicator, for the whole set of time-lapsed photographs. The deviation of the averages from zero (no change) was tested with the Wilcoxon signed-rank test. This study of landscape re-photography covering 140 years of change showed that the status of natural resources in northern Ethiopia was very degraded in 1868, and has since then either remained in a status that is similar (Fig. 4), or has improved, or has in some areas greatly improved (Nyssen et al., 2009).

To allow the participants to verify changes by themselves, historical photographs taken from a dozen different viewpoints of this excursion are included in the excursion guide as reference material (Fig. 5 and Table 1).



Fig. 5. Half way Dessie and Alamata in 1944. Photo D. Buxton. (Nyssen et al., 2010)

Table 1. Historical landscape photographs appearing further in the excursion guide

- Tita (1937; 1997), on p 24 and 25.
- Gra Kahsu (1939; 1975; 1991), on p. 36.
- Lake Ashenge (1939; 1975), on p. 40.
- Atsela pass to Ferrah Amba (1942), on p. 46.
- Atsela plain (1937; 1975), on p. 40.
- Amba Aradom (1868), on p. 64.
- May Makden, (1974; 1994), on p. 41.
- Wukro, near rock church (1937), on p. 146.
- Senkata (1975), on p. 160.
- Adwa volcanic plugs (1974), on p. 170.

References

- Crummey D. 1998. Deforestation in Wollo: process or illusion? *J. Ethiop. Stud.* 32, 1-41.
- Crummey D. 2001. Ambiente, carestia e non sviluppo in Etiopia in una prospettiva storica: il caso del Wollo. *Storia Urbana* XXV(95), 45-70.
- de Mûelenaere S, Frankl A, Mitiku Haile, Poesen J, Deckers J, Nyssen J. 2011. Calibration of Landsat land use/cover in the Ethiopian highlands using historical terrestrial photography. *Land Degradation & Development*, in preparation.
- Frankl A, Nyssen J, De Dapper M, Mitiku Haile, Billi P, Munro R N, Deckers J, Poesen J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (North Ethiopia). *Geomorphology*, in press.
- Gortani M, Bianchi A. 1973. Missione geologica dell'Azienda Generale Italiani Petroli (A.G.I.P.) nella Dancalia Meridionale e sugli altipiani Hararini (1936-1938). *Illustrazione Geologica*, I. Accademia Nazionale dei Lincei, Roma.
- Markham C R. 1868. Geographical Results of the Abyssinian Expedition. *Journal of the Royal Geographical Society of London* 38, 12-49.
- Meire E, Frankl A, De Wulf A, Mitiku Haile, Deckers J, Nyssen J., 2011. Mapping the 19th century landscape in Africa - Warped terrestrial photographs of North Ethiopia. *Regional Environmental Change*, in preparation.
- Munro R N, Deckers J, Grove A T, Mitiku Haile, Poesen J, Nyssen J. 2008. Soil and erosion features of the Central Plateau region of Tigray - Learning from photo monitoring with 30 years interval. *Catena* 75(1), 55-64.
- Nievergelt B. 1998. Long-term changes in the landscape and ecosystems of the Simen Mountains National Park. *Walia*, special issue, 8-23.
- Nyssen J, Frankl A, Munro R N, Billi P, Mitiku Haile. 2010a. Digital Photographic Archives for Environmental and Historical Studies: An Example from Ethiopia. *Scottish Geographical Journal* 126(3), 185 - 207.
- Nyssen J, Mitiku Haile, Munro R N, Poesen J, Grove A T, Deckers J. 2010b. Repeat photography challenges received wisdom on land degradation in the northern Ethiopian Highlands. In: R H Webb, D E Boyer, R M Turner (Eds.), *Repeat photography - methods and applications in natural sciences*. Island Press, Washington DC, pp. 186-196.
- Nyssen J, Mitiku Haile, Nauds J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009. Desertification? Northern Ethiopia re-photographed after 140 years. *Science of the Total Environment* 407, 2749-2755.
- Nyssen J, Poesen J, Descheemaeker K, Nigussie Haregeweyn, Mitiku Haile, Moeyersons J, Frankl A, Govers G, Munro R N, Deckers J. 2008. Effects of region-wide soil and water conservation in semi-arid areas: the case of northern Ethiopia. *Zeitschrift für Geomorphologie* 52, 291 - 315.

5. Land degradation and resilience in Wollo from the 1930s onwards, as derived from aerial and terrestrial photographs

Girmay Kassa¹, Donald Crummey², Katrien Descheemaeker³, Jan Nyssen⁴

¹ Ethiopian Mapping Authority, Addis Ababa, Ethiopia

² Illinois University, Champaign, USA

³ CSIRO, Australia

⁴ Ghent University, Belgium

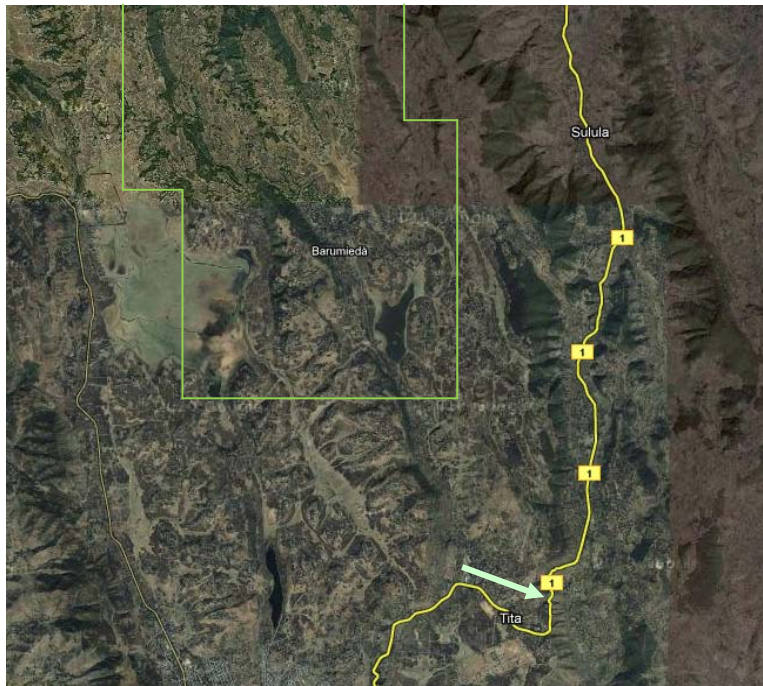


Fig 1. The study area North of Dessie (from Google Maps). Arrow indicates the excursion viewpoint. The approximate area covered by the 1936 aerial photographs is outlined.

Introduction

Popular perceptions in the North Ethiopian Highlands, including Wollo, are that there were many more trees in earlier times (i.e. 1935-1945), as shown in interviews with elders concerning overall changes in numbers of trees, realised in 1997 (Table 1).

Table 1. Perceived changes in numbers of trees, Wollo (after Crummey & Winter-Nelson, 2003)

Peasant Association cluster	More trees then	More trees now	No response	Total
Borru	5	6	4	15
Gerba	18	0	2	20
Gwobeya	4	3	9	16
Sulula	9	6	4	19
T'abisa	4	3	4*	11
T'is Aba Lima	5	0	2	7
TOTAL	45	18	25	88

* One of the T'abisa informants judged that there had been no overall change in tree numbers.
Source: Survey of elders

This study makes a multi-temporal and multi-disciplinary assessment of changes in vegetation cover over a period of 70 years, in South Wollo.

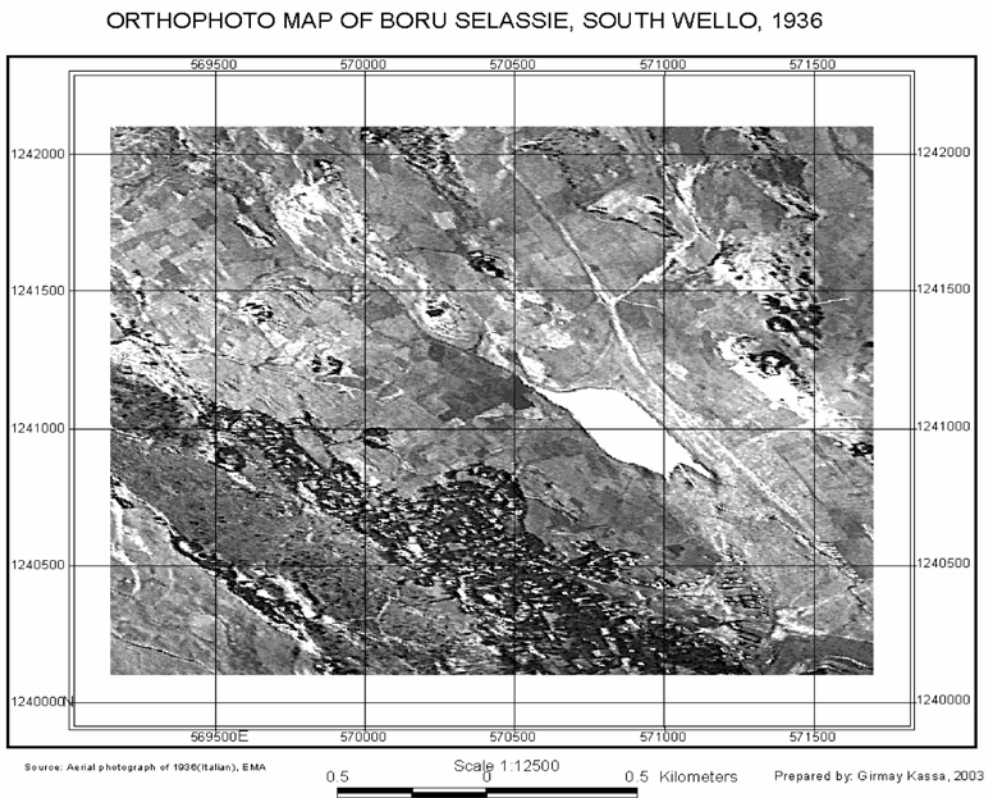
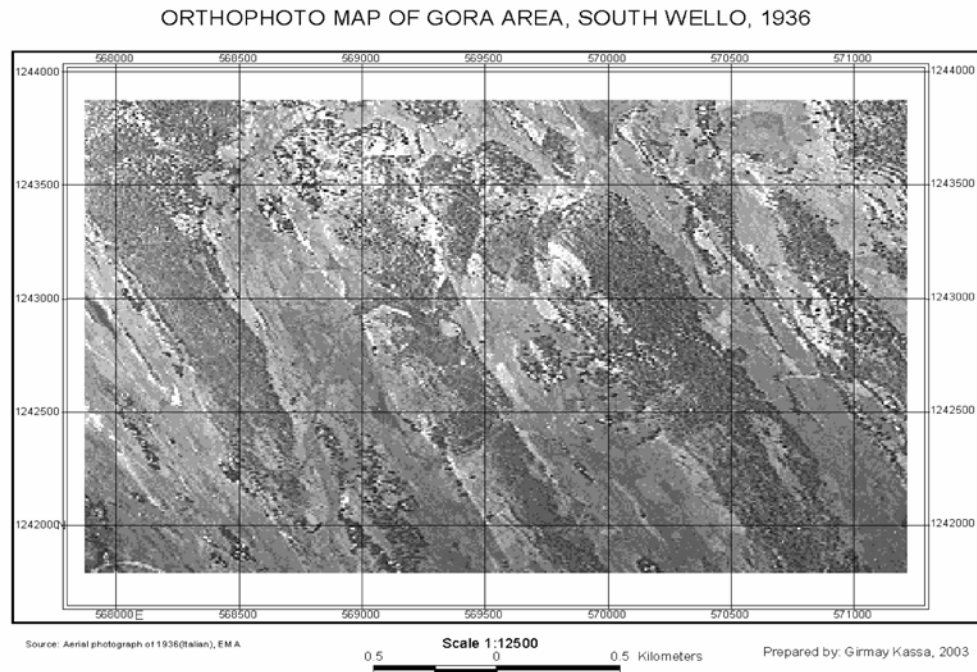


Fig. 2. Orthophotomaps of the study area, realised after Italian aerial photographs, held at the Ethiopian Mapping Agency (Girmay, 2003)

Methodology

Four research methodologies were used:

(1) Qualitative analysis of repeat photographs.

(2) Aerial photo interpretation, starting with historical Italian aerial photos taken in 1936 and kept at the Ethiopian Mapping Agency, and further aerial photos dating back to 1965, 1986 and 1994. The 1936 aerial photographs were interpreted for a 12 km² sample area at Boru Selassie and Gora and separately compared with the recent 1994 aerial photographs to evaluate land use land cover changes, land degradation and population distribution. The aerial photographs were scanned and geo-referenced, the land cover types identified and digitised. Due to high distortions on the edges, only the central part of the 1936 aerial photographs was used.

(3) Quantitative analysis of repeat photographs. Twenty-three landscapes of South Wollo, recorded on historical photographs in 1937, were rephotographed in 1997 and again in 2009; environmental changes apparent on the matched photographs are analysed through expert rating. Two sample sites, taken from a popular viewpoint in different directions, at different epochs are presented (Figs. 3 and 4) and may be re-photographed in the field by the excursionists.



Fig. 3. Tita in 1937 (top - photo A. Maugini, © Istituto Agronomico per l'Oltremare, Firenze) and in 1997 (bottom - photo D. Crummey) (Crummey, 1998)

(4) Historical analysis on the basis of field interviews with 88 informants in South Wollo who lived through the landscape changes documented in the repeat photos. Informants were selected on the basis of age (born about 1930) and residence in villages documented by the photos. The attempt at gender balance among informants fell short - 49 males and 39 females participated in structured but free-form interviews.



Fig. 54 - Valle che da Itacià scende a Combolcià
vista dalla strada Dessiè-lago Haic.



Fig. 4. View from Tita towards Kombolcha. Top: in 1937 (Gortani and Bianchi, 1973); bottom: in 1997 (Crummey, 1998).

Results and discussion

1. Land use and cover trends, as observed on repeat photographs

The land use and cover changes that can incidentally be observed in the field by comparison to historical photographs (Figs. 3 and 4) are under way of analysis through expert rating (cfr. Nyssen et al. 2009). General tendencies in landscape changes include an improved vegetation cover between 1937 and 1997 and again after 1997. Evidence of soil and water conservation follows a similar trend. Impacts on hydrology can be observed when comparing ephemeral streams on historical photographs (Fig. 3) with the current situation.

2. Changes to population density and land use since 1936

Observations by repeat photography are in line with results of aerial photo interpretation. Population density estimated from house counting in the sample area of Boru Sellassie was 298 persons/km² in 1936 and increased to 628 persons/km² in 1994 (Table 2). In the wider Boru-Metero area, a similar trend was observed (Fig. 5).

Table 2. Population density based on house count of the wider Boru-Metero area in 1965, 1986 and 1994, and for the Boru Sellassie and Gora sample areas in 1936 and 1994 (after Girmay, 2003).

Study area	Year	Assumed family size	Number of household	Interpolated population number	Cultivated land (ha)	Area of the study (ha)	Agricultural density	Population density (person/ km ²)
<i>Boru Meteo</i>	1965	4	1351	5404	1385.9	3088	389.93	175.00
	1986	5	1601	8050	1526	3088	527.52	260.68
	1994	4.5	2172	9774	1532	3088	637.99	316.52
<i>Boru Sellassie</i>	1936	4	382	1528	260.44	513	586.70	297.85
	1994	4.5	778	3501	329.5	513	1062.52	682.46
<i>Gora Area</i>	1936	4	79	316	267.35	717	118.20	44.07
	1994	4.5	580	2610	350.31	717	745.05	364.02

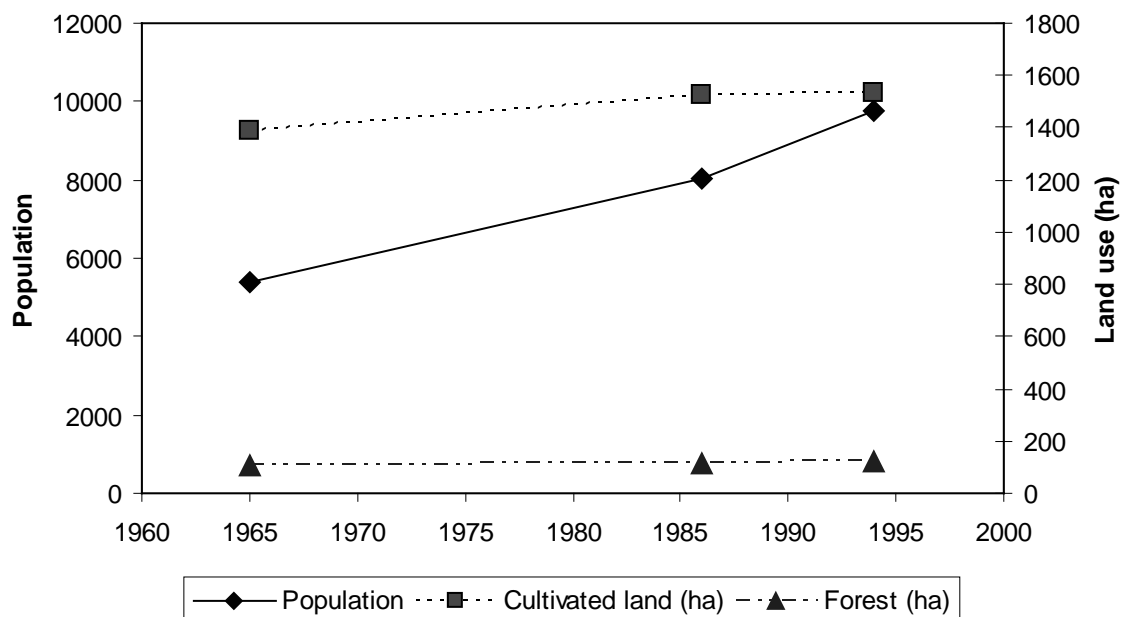


Fig. 5. Changes in population and major land use / land cover classes in the wider Boru-Metero area from 1965 to 1994 (after Girmay, 2003)

Since 1936, there has been an expansion of cultivated areas, essentially through the amendment and cultivation of marginal (bare) land and drainage of swampy areas. The area occupied by various types of permanent vegetation remained roughly the same until 1994, although a shift took place towards mixed forest and private woodlots.

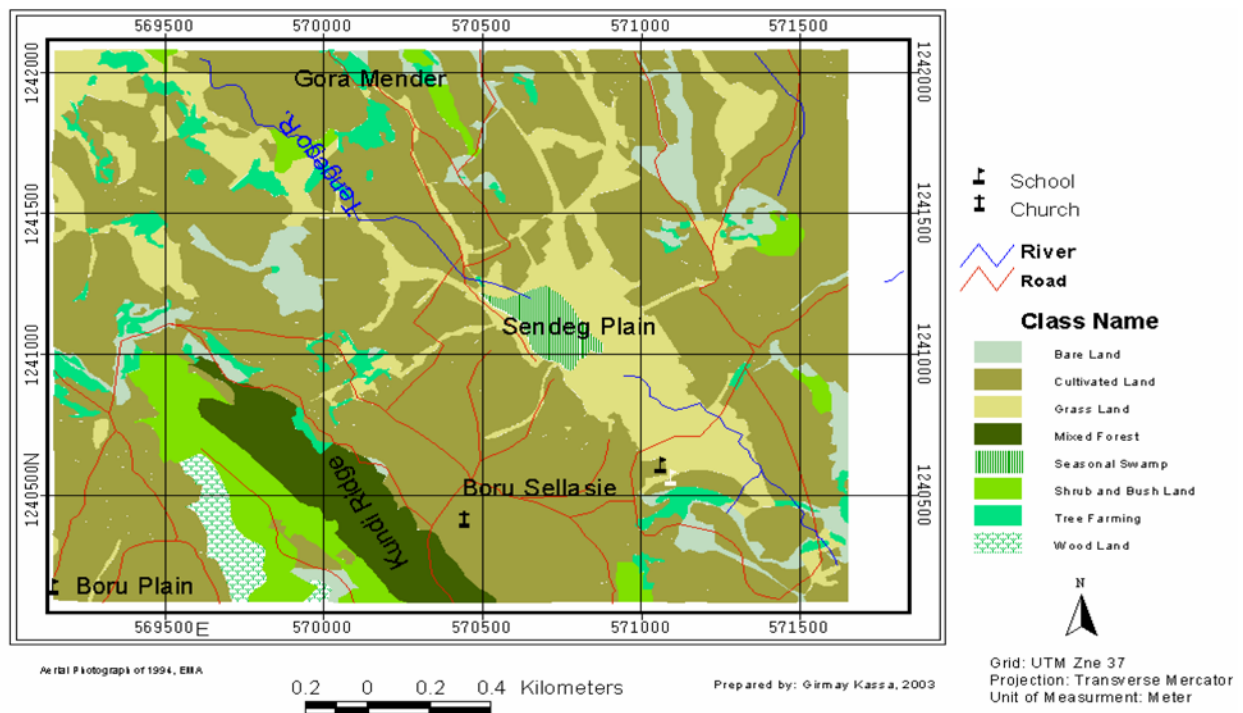
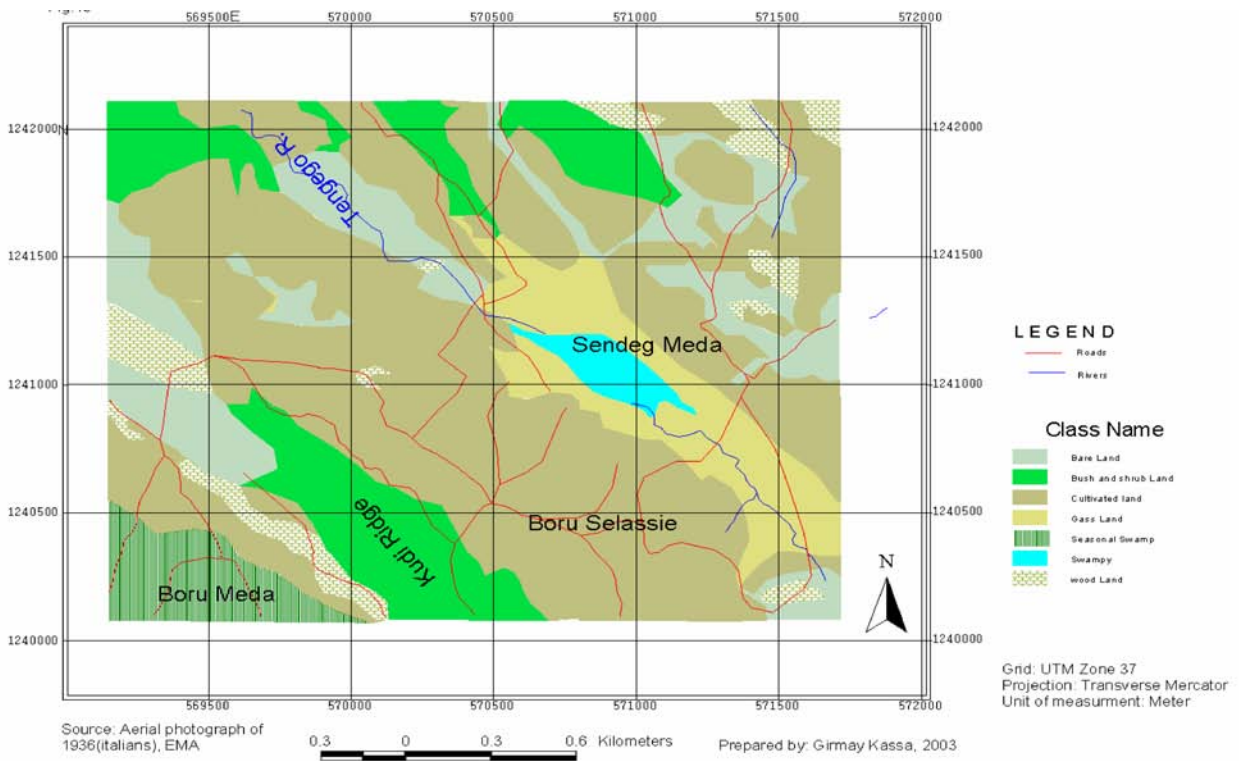


Fig. 6. Land use/cover in Boru Selassie sample area in 1936 (top) and 1994 (bottom) (after Girmay, 2003).

Table 3. Land use/cover changes in Boru Selassie sample area, between 1936 and 1994 (after Girmay, 2003).

Land use /Land cover type	Land use/Land cover area changes				Changes in land use/ Land cover (in ha)
	1936		1994		1936-1994 (ha)
	Area (ha)	%	Area (ha)	%	
Bare land	70.48	13.76	27.58	5.37	-42.9
Bush & shrub land	70.40	13.74	27.36	5.33	-43.04
Cultivated land	260.44	50.83	329.95	64.25	+69.51
Grass land	54.04	10.55	72.64	14.14	+18.6
Mixed forest	0	0	23.69	4.61	+23.69
Tree Farms	0	0	20.31	3.96	+20.31
Swampy area	7.95	1.55	0	0	-7.95
Temp. Grass land	22.53	4.40	5.51	1.07	-17.02
Wood Land	26.51	5.17	6.52	1.27	-19.99
Total	512.35	100	513.56	100	

The most significant land cover change was the increase of tree farming of Eucalyptus trees. In the wider Boru-Metero area, it covered only 1.6% in 1965 and increased to 4.7% in 1986 and 4.6% in 1994. This change was the result of afforestation and enclosure establishment in the 1980s, as well as the increase of financial income gained from sale of fuel wood and poles that initiated farmers to plant Eucalyptus trees around their homestead and on their farms.

3. Farmer resource management: capacity and constraints

In contrast to the view of a tradition-bound peasantry entrenched in unsustainable farm practices, survey data and farmers' narratives demonstrate that resource-poor peasant farmers are modifying and developing their production systems. The farmers of Wollo are not passively caught in a trap of increasing land scarcity, declining land quality and intensified poverty and hunger. Our results also indicate variation in their ability to innovate, despite the narrow band of resource differentiation. For example, woodcutting remains a source of livelihood for a handful of people with the most limited resources of land and capital, while the development of market gardens and tree plantations is dominated by the more successful, entrepreneurial farmers.

Overall we gained the impression that, poor and hard-pressed as they are, the farmers of northern Ethiopia are not desperate, nor have they forsaken sound farming practices. On the contrary, they have a truly astonishing range of knowledge of soils, seeds and seasons. Their sense of themselves, and of the value of their culture and institutions, was quite intact. They expressed themselves clearly, drawing on a rich store of metaphors. Their lives are stories of innovation, adaptation and adjustment, and, if the wider forces working on them are not always clear to them, they face those forces with resolve, a sense of irony and humour and an admirable capacity for work (after Crummey & Winter-Nelson, 2003)

Farmers have not been the only tree-planters in Wollo. Governments are also responsible for the increase in forest cover since 1937. The Derg closed hilltops and hillsides and embarked on huge tree-planting schemes. It implemented policies, which radically restricted, where they did not halt altogether, local exploitation of woods for grazing and fuel. The government which replaced the Derg has kept those policies in place and expanded them, involving local communities. But a

close observation of the landscape also reveals intricate patterns of tree-planting and tree nurture, which can only be attributed to local farmers (after Crummey & Winter-Nelson, 2003).

Conclusions

Increased vegetation cover in these mid-elevation areas is the result of farmer initiatives as of the 1930s and intense rehabilitation activities since the 1980s. The implementation of physical soil and water conservation follows the same trend. The positive changes that result from these conservation activities in the north Ethiopian highlands are an issue of global concern as they show that (1) in this study area direct human impact on the environment seems to be more important than potential effects of climate change and (2) population increase would not necessarily lead to severe land degradation.

Acknowledgements

The photograph of the 1937 landscape in the book by Gortani and Bianchi was provided by Paolo Billi. Fikir Alemayehu fostered linkages towards the collection of historical aerial photographs dating back to the 1930s, held by the Ethiopian Mapping Agency. Numerous farmers in South Wollo provided useful insights.

References

- Crummey D. 1998. Deforestation in Wollo: process or illusion? *J. Ethiop. Stud.* 32, 1-41.
- Crummey D. 2001. Ambiente, carestia e non sviluppo in Etiopia in una prospettiva storica: il caso del Wollo. *Storia Urbana* XXV(95), 45-70.
- Crummey, D., Winter-Nelson, A., 2003. Farmer tree-planting in Wällo. In: Bassett, T.J., Crummey, D. (eds.), *African savannas – global narratives and local knowledge of environmental change*. Oxford/Portsmouth NH: James Currey/Heinemann: 91-120.
- Girmay Kassa, 2003. GIS-based analysis of land use /land cover, land degradation and population changes - a study of Boru Metero area of South Wello, Amhara region. Unpublished MSc thesis, School of Graduate Studies, Addis Ababa University.
- Gortani M, Bianchi A. 1973. Missione geologica dell'Azienda Generale Italiani Petroli (A.G.I.P.) nella Dancalia Meridionale e sugli altipiani Hararini (1936-1938). *Illustrazione Geologica*, I. Accademia Nazionale dei Lincei, Roma.
- Nyssen J, Mitiku Haile, Nauds J, Munro N, Poesen J, Moeyersons J, Frankl A, Deckers J, Pankhurst R. 2009. Desertification? Northern Ethiopia re-photographed after 140 years. *Science of the Total Environment* 407, 2749-2755.
- Nyssen J, Frankl A, Munro R N, Billi P, Mitiku Haile. 2010. Digital Photographic Archives for Environmental and Historical Studies: An Example from Ethiopia. *Scottish Geographical Journal* 126(3), 185 - 207.

6. Hydrogeomorphology in a marginal graben of the Rift Valley

Paolo Billi

Department of Earth Sciences, University of Ferrara, Italy - bli@unife.it

1. Study area

The Kobo basin is an intermontane hollow located across the border between Welo and Tigray in northern Ethiopia (Fig. 1). It has a rectangular shape elongated in a north-south direction reflecting its structural origin associated with the development of the main rifting system of the area. Master faults, in fact, bound the margins of the basin and separate it from the main Ethiopian plateau to the west (highest peak 4008 m a.s.l.) while the Udaelwa-Asele Ridge (highest peak 2438 m a.s.l.) makes up an ultimate structural barrier before the Danakil depression to the east. The stratigraphy of the study area is known only approximately and refers mainly to the work of Merla et al. (1979). As a consequence of such physiographic asymmetry the largest rivers flow from the western margin to the centre of the basin where they form terminal distributary systems and dry up. Only the Golina R. crosses the Kobo basin and the Udaelwa-Asele Ridge, vanishing in the Afar-Danakil lowland (Fig 1).

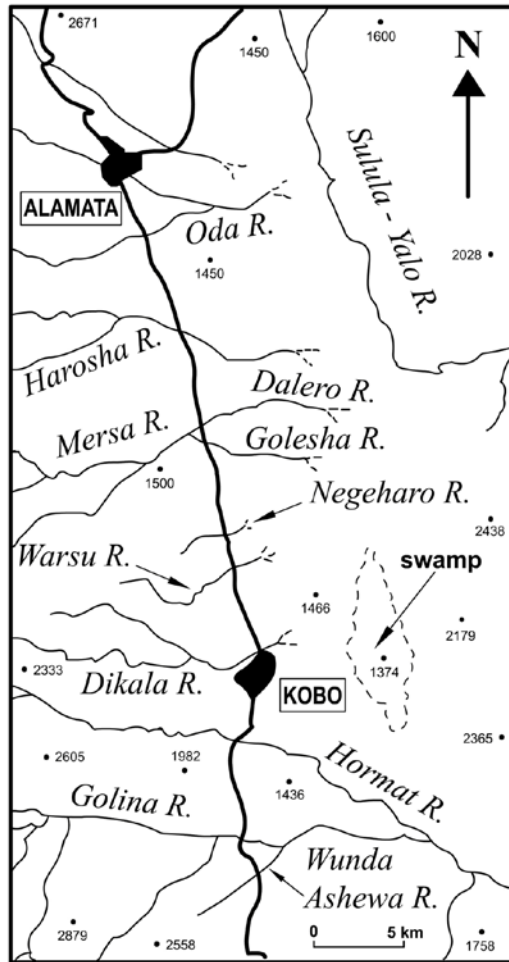
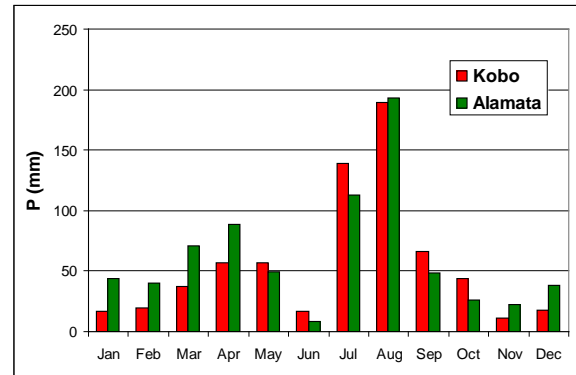
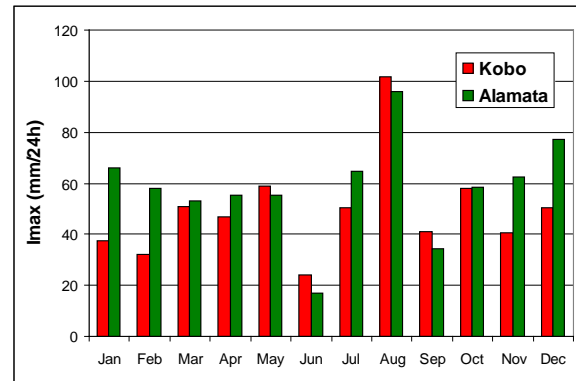


Fig. 1. Study area



(a)



(b)

Fig. 2. Monthly rainfall distribution (a) and (b) monthly maximum rainfall intensity in 24 hours for both Kobo and Alamata rain gauges

In the study area no river flow data is available while there are only two meteorological stations, Kobo and Alamata respectively (Fig 1 and 2) (Billi, 2007; 2008). Average annual rainfall is 726 and 768 mm for Kobo and Alamata, respectively, while potential evapotranspiration, calculated by Thornthwaite's method, is 931 mm yr^{-1} . Though the annual amount is relatively large, precipitation consists mainly of few, very intense, isolated rainstorms that are more frequent during the monsoon type summer rainy season. Given such rainfall pattern, the streambed of the rivers in the Kobo basin are completely dry for most of the time and water flows only when rainfall yields a sufficient volume of runoff.

3. The Golina River

The Golina R. is a sandy boulder bed river (Fig. 3). The study reach is located 2 km downstream of the bridge on the Woldya –Alamata road. Here the Golina R. the streambed morphology consists of a few surfaces with different elevation resulting from the overlapping of horizontal, tabular gravel sheets 0.5-1.5 m thick (Fig. 4). The highest surfaces are at an elevation close to the lower river banks fringe (Fig. 4 b) and have a rhomboidal shape resembling that of longitudinal and laterals bars of braided rivers in more humid environments (Bluck, 1979). Neither riffle and pool sequences, nor bar downstream accretionary front and downstream sediment segregation are present.

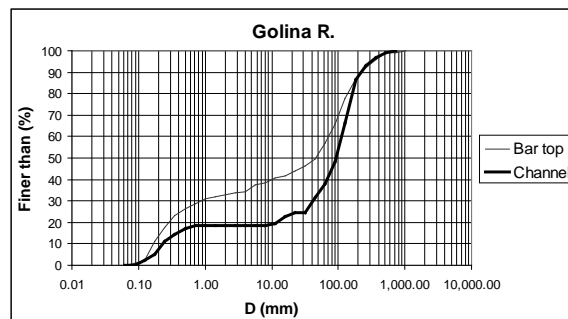


Fig. 3. Representative grain size distribution of the Golina R. (Billi, 2011a)

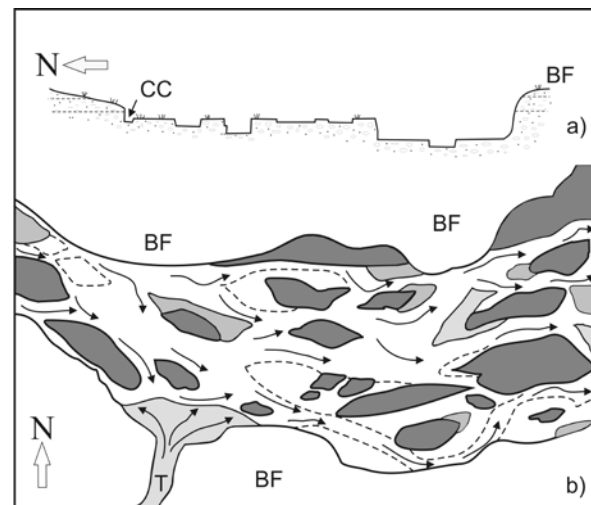


Fig. 4. Sketch map of the study reach (not in scale): a) conceptual, representative cross-section; b) conceptual plan view: dark grey = higher bar top; light grey = intermediate surfaces; white = less elevated surfaces. CC = chute channel; BF = basin fill top; T = tributary (Billi, 2011a).

The streambed deposits are very homogeneous and monotonous throughout the study reach with poorly defined bedding, ungraded, poorly sorted and well imbricated particles prevailing on reversely graded beds, whereas normally graded beds are practically absent if we do not include in this category the gravel beds capped by a sand drape, deposited by the waning flows. The Golina deposits characteristics suggest that bed material is transported en masse and that some vertical sorting is possible, with the larger particles (as much as 1 m in size) pushed towards the

surface by buoyancy and dispersive forces (Billi, 2011a). The overall sedimentological characteristics, in association with morphological peculiarities such as the lack of riffle and pool sequences, lead to interpret the study reach streambed deposits as resulting from the freezing of bedload sheets (Whiting et al., 1988) and the braided channel morphology as originated by the combination of bedload sheets emplacements and subsequent dissection during the waning flood flow. The lack of an evident stratification may be due to the merging of individual sheets as observed by Whiting et al. (1988) and also by the specific role played by sand during the sheet formation and migration. The infilling of the finer sediment contributes to reduce the frictional resistance of the coarser particles and likely to increase the buoyancy forces that keep the largest boulders on top of the deposit. In order to verify this hypothesis the threshold of entrainment for large particles the critical shear stress formulas of Milhous (1973), Costa (1983) and Williams (1983) were used. According to the predictions of these criteria, a flow depth of 1 m is capable to entrain boulders ranging in size from 860 to 1500 mm, confirming the field observations (Billi, 2011a). Ephemeral streams floods are flashy, their hydrographs are very peaked and the fast approaching bore results in a very high rate of flow energy transfer to the streambed such that the whole bed, including the largest particles, is entrained and transported en mass. Bedload transport can be very high and any alteration of the flow-bed interaction can lead to bed scouring and infrastructure damage (Fig. 5).



Fig. 5. The Golina R. bridge on the Woldya-Alamata road in 2006 (left) and after the ultimate collapse in 2008 (right) (Billi, 2011b).

4. Sandbed rivers and distributary systems

The sandbed rivers of the Kobo basin are typically ephemeral, have a simple morphology and well match the ideal model proposed by Schumm (1977) since they are composed of three portions: 1) the headwater; 2) the main trunk channel and 3) the terminal distributary system.

Channel width expands rapidly just beyond the headwater gorge, reaches its maximum value a few hundreds of meters downstream of the gorge and tends to be constant along the main stem (with the exception of local broadenings due to particularly severe bank collapse) as far as its most downstream reach where widths tends to decrease in response of transmission losses as observed by Dunkerley (1992) and Tooth (2000) for Australian ephemeral streams. The terminal distributary systems of the study area can be grouped in two main categories, “bird-foot” and lobate type. Bird-foot type distributary systems are by far the most common. They consist of a few (two or three), primary distributary channels departing from the trunk channel and arranged

in a radial pattern. The radial structure of the distributary systems encompasses angles ranging from 20 to 90 degrees. Five reach units, with specific morphological characteristics were identified (Billi, 2007). In a downstream direction, they are (Fig. 6):

1. Main feeder channel
2. Primary distributary reach
3. Flow expansion reach
4. Accretionary front
5. Run out channel

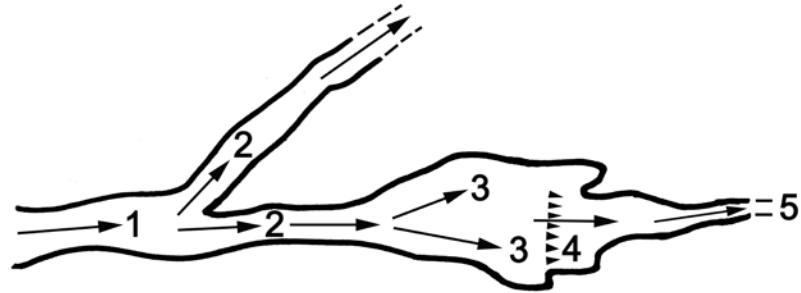


Fig. 6. Main channel units of distributary systems (Billi, 2007)

The feeder channel is the main river stem, just upstream of the first bifurcation from which the distributary system initiates. The feeder channel is characterised by large width/depth ratios (Tab. I), is slightly entrenched, though some transmission loss may occur, it generally carries a discharge greater than any other channel and represent the dynamic axis of the river system. The primary distributary reach has an arroyo-like morphology very similar to that of the river main trunk and at the bifurcation point their widths are. Further downstream the primary distributary channel may bifurcate into narrower, higher order distributary reaches. These then widen, get very shallow with only a few decimetres high banks and further downstream the flow becomes unconfined forming the flow expansion reach. Here, a notable volume of water infiltrates, flow loses much of its transport capacity and the largest proportion of the sediment load is deposited in flat, wedge-shaped bodies that commonly take up the whole reach and form an accretionary slip face in their downstream side. In the accretionary front the coarsest bed material of the whole alluvial system is found. This sediment accumulation is then partially reworked by low energy flows that wash out the finer material while part of the water that infiltrated upstream may re-emerge from the accretionary front contributing to locally increase the transport capacity. Downstream of the expansion reach, flow decreases at a very high rate and is conveyed to the run out, distal channel where discharge can be less than one tenth of that in the main stem or in the primary distributary channels.

5. Deposits characteristics and sediment transport processes

Bed material consists mostly of medium to coarse sand and, subordinately, of fine gravelly sand with pebbles and boulders scattered on a flat bed devoid of macro bedforms such as depositional bars. In the study rivers, horizontal bedding is ubiquitous and by far the most common sedimentary structure. A typical internal bed arrangement, consisting of four main divisions is found (Billi, 2008). A schematic model is presented; from bottom to top it consists of: 1) the basal reversely graded or massive, fine-grained division; 2) the core coarse division; 3) the horizontally laminated sandy and grainy division and 4) the receding flood flow mud and sandy mud drape (Billi, 2008) (Fig. 7).

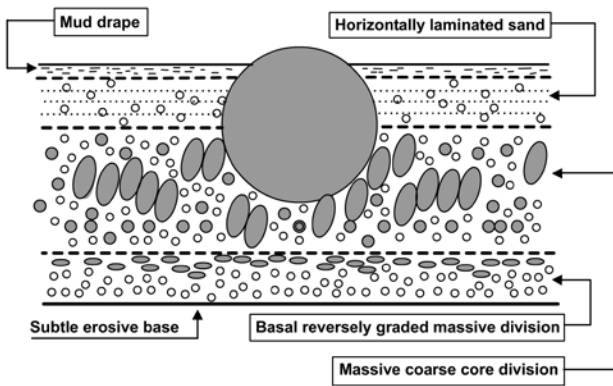


Fig. 7. Schematic model of typical division arrangement within an individual layer stream bed.

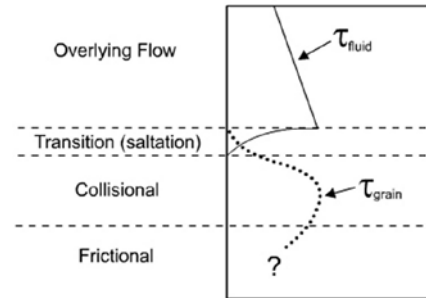


Fig. 8. Vertical distribution of shear stress (modified from Sohn, 1997).

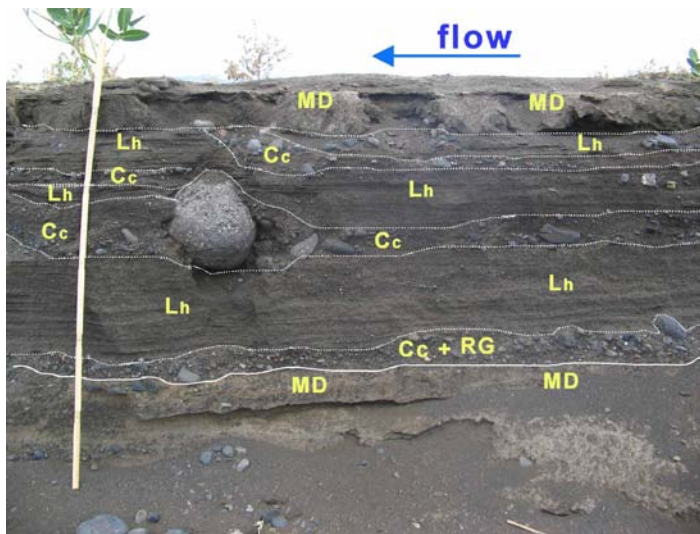


Fig. 9. Stratigraphic log from a modern streambed cut bank. Horizontally laminated and massive sand in the vicinity of larger particles typically do not show flow perturbation features nor scour holes or lee side fine grained wake. Division notation: Cc = coarse core division; Lh = horizontal lamination; MD = mud drape; RG = reverse grading. The stick ruler for scale is 1.2 m long.

The division association presented here seems to conform very well to the vertical shear stress distribution postulated by Sohn (1997) within his collisional zone (Fig. 8) rather than to a variation in the grain size of the supplied sediment proposed by the same author. In fact, the coarse core division can be associated with the highest shears stress of the collision zone, the lower massive or reversely graded division with lower shear stress at the transition between the collisional and frictional zone (though sediment features indicating the presence of a frictional zone were not observed), whereas the upper, horizontally laminated division forms in the upper part of the collisional zone where, according to Sohn (1997), shear stress decreases again and thin traction layers of bedload move, though a decrease in downward flux of grains, as advocated by this author, is not necessary, given a decrease in shear stress and particle concentration in this zone. These considerations and the prevailing geometry and upward fining of the horizontal laminae (Fig. 14) suggest these bedforms are to be interpreted as thin bedload sheets (Fig. 9) rather than as generated by the migration of low amplitude bed waves as postulated by Best and Bridge (1992).

References

- Best, J., Bridge, J., 1992, The morphology and dynamics of low amplitude bedwaves upon upper stage plane beds and the preservation of planar laminae, *Sedimentology*, 39, 737-752.
- Billi, P., 2007, Morphology and sediment dynamics of ephemeral stream terminal distributary systems in the Kobo basin (northern Welo, Ethiopia), *Geomorphology*, 85, 98-113.
- Billi, P., 2008, Flash floods, sediment transport and bedforms in the ephemeral streams of Kobo basin, northern Ethiopia, *Catena*, 75 (1), 5-17.
- Billi, P., Cecili, A., Cinnirella, A., 2011a, Sediment and channel processes in a boulder-bed ephemeral stream, submitted to *Sedimentary Geology*.
- Billi, 2011b, Dryland river processes and hazards: examples from the Horn of Africa. In Malet, J.P., Glade, T., Casagli, N. (eds.), *Mountain Risks: Bringing Science to Society*, CERG Editions, Strasbourg, 165-170.
- Bluck, B.J., 1979. Structure of coarse-grained braided stream alluvium, *Trans. Roy. Soc. Edinb.*, 70, 182-221.
- Costa, J.E., 1983. Paleohydraulics reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geol. Soc. Am. Bull.*, 94, 986-1004.
- Dunkerley, D.L., 1992, Channel geometry, bed material and inferred flow conditions in ephemeral stream systems, Barrier Range, Western N.S.W. Australia. *Hydrol. Processes*, Vol. 6, pp. 417-433.
- Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Canuti, P., Fazzuoli, M., Sagri, M., Tacconi, P., 1979. A geological map of Ethiopia and Somalia. Consiglio Nazionale delle Ricerche, Firenze.
- Milhous, R.T., 1973. Sediment transport in a gravel-bottomed stream. Ph.D. Thesis, Oregon State University, Corvallis, 232 pp.
- Sohn, Y.K., 1997, On traction-carpet sedimentation, *Jour. Sedim. Res.*, 67 (3), 502-509.
- Tooth, S. 2000, Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews*, 51, 67–107.
- Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G, Shreve, R.L., 1988. Bedload sheets in heterogeneous sediment. *Geology*, 16, 105-108.
- Williams, G.P., 1983. Paleohydrological methods and some examples from Swedish fluvial environment, I - cobble and boulder deposits. *Geogr. Ann.*, 65 A, 227-243.

7. Land use change and related changes in hydrogeomorphology of an ephemeral mountain stream at Gra Kahu (Rift Valley escarpment)

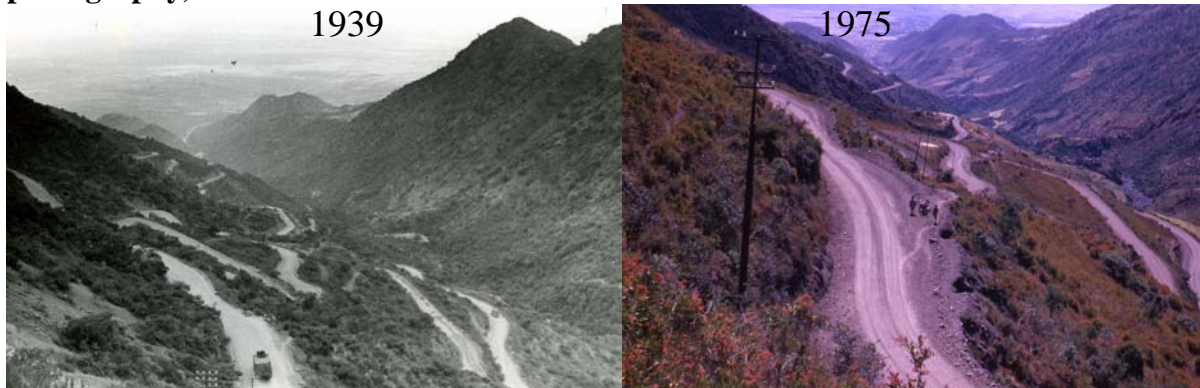
Jan Nyssen¹, Tigist Araya², Paolo Billi³

¹Ghent University, Department of Geography, Gent, Belgium

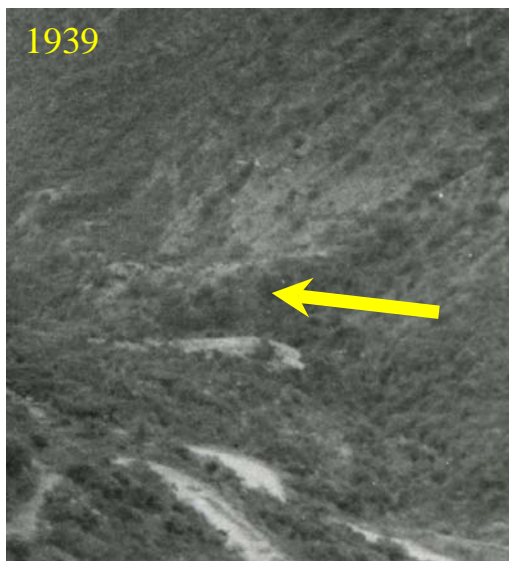
²Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia

³Department of Earth Sciences, University of Ferrara, Italy

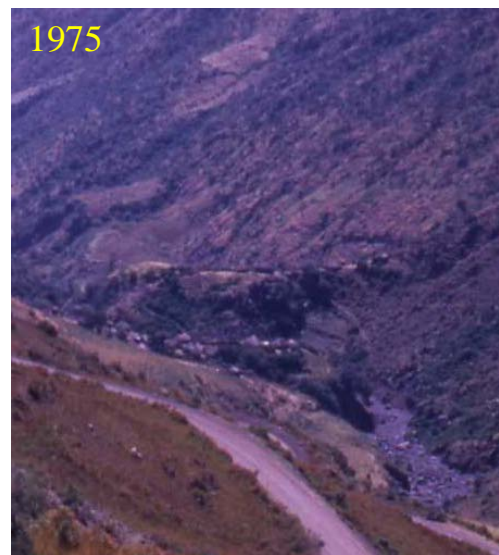
1. Land use changes and hydrogeomorphological response (field observations and repeat photography)



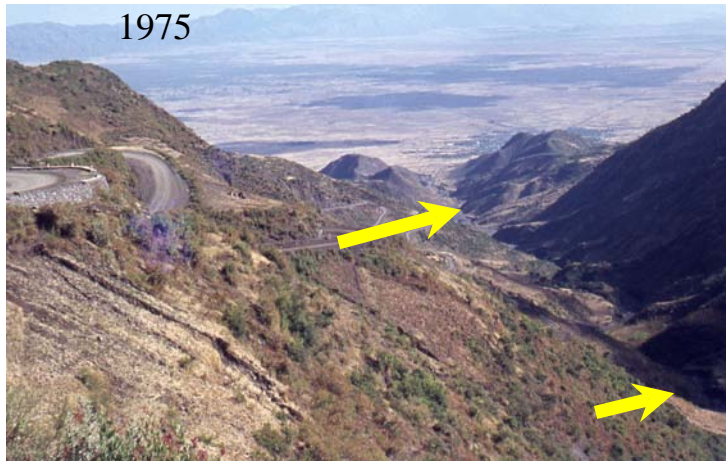
Gra Kahu. Left, in 1939: bushes are present in most places, but on the left hand, land clearance has started. Photo A. Maugini © Istituto Agronomico per l'Oltremare, Firenze. Right, in 1975. Photo R.N. Munro (Munro et al., 2008).



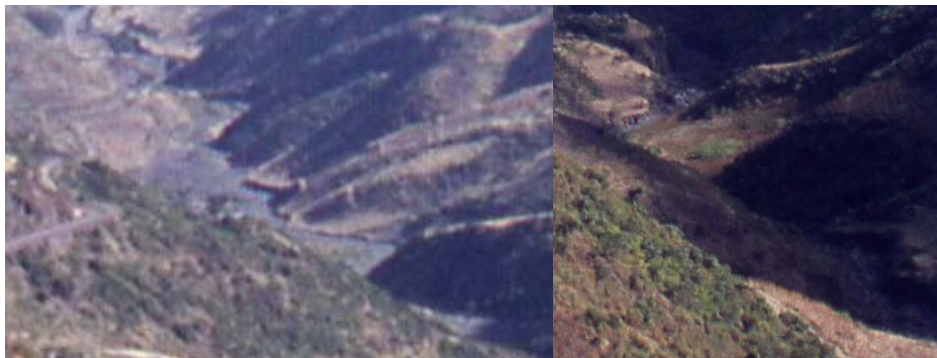
In 1939, a small village exists on a ridge in the middle of the valley, and slopes around it are cultivated. The river bed seems aggrading and filled with alluvial material (Photo A. Maugini).



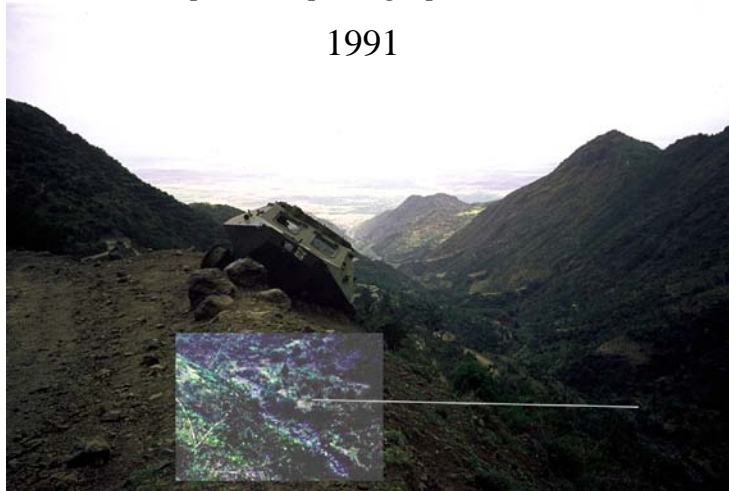
1975. The village has expanded, steep slopes are cultivated; close view of the river bed (Photo R.N. Munro)



In 1975, the slopes were widely cultivated (Photo R.N. Munro) (Munro et al., 2008)



The river bed was dynamic and large boulders were transported in 1975 (location indicated by arrows on the previous photograph) (Photo R.N. Munro)



In September 1991, the forest has started to grow, but abandoned farmlands are still clearly visible. The river incises its boulder bed (see lower right of photograph). The armoured vehicle, witness of the civil war that was just over, is still present on the site, though nowadays overgrown with vegetation (Photo André Crismer).

2. *Daget* (cultivation terraces or lynchets) are evidence of earlier cultivation

While crossing the Gra Kahu valley, evidence of old cultivation terraces is observed. Between the cultivated fields in the highlands of Tigray, one finds generally, besides the recently introduced stone bunds, many lynchets with heights of 0.3-3 m. Grasses occupy the riser and a strip on the shoulder. Traditionally, farmers established an untilled strip up to 2 m wide at the lower plot limit. The grass strip reduces runoff velocity, allows water to infiltrate and traps sediment transported by water and tillage erosion. Year after year, these lynchets, locally called *daget* continued to grow. When present in areas with semi-natural vegetation, *daget* witness of previous cultivation activities in that particular area (Nyssen *et al.*, 2000).



Figure 3. Lynchet with subvertical, retreating riser in Amba Gwasot, a hamlet of Duerere (September 1997). Figure 5. The presence of historical plough furrows (arrows) shows the importance of colluviation in the *daget*.

3. Upcoming research

Analysis of the dynamics of mountain streams is an appropriate method to disentangle human impact and climatic variability, because:

- Mountain streams strongly react to changes in their environment.
- Measurements can be done on sediment deposits, which avoids costly and unreliable permanent monitoring
- As the drainage areas are mostly marginal lands, land use changes occur rather homogeneously over wider areas (deforestation/reforestation), which allows to better analyse impacts, as compared to more level land where land use and cover changes are of patchy nature

Particularly, with regard to hydrogeomorphology, we will analyse the current transport capacity of the river and analyse changes in transport capacity over time through analysis of older deposits.

References

Munro R N, Deckers J, Grove A T, Mitiku Haile, Poesen J, Nyssen J. 2008. Soil and erosion features of the Central Plateau region of Tigray - Learning from photo monitoring with 30 years interval. *Catena* 75(1), 55-64.

Nyssen J, Mitiku Haile, Moeyersons J, Poesen J, Deckers J. 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional *daget* technique and its integration with introduced techniques. *Land Degradation and Development* 11, 199-208.

8. Long-term gully and river channel dynamics in Tigray

(Based on Frankl et al., 2011)

Amaury Frankl^{a,*}, Jan Nyssen^a, Morgan De Dapper^a, Mitiku Haile^b, Paolo Billi^{a,c}, R. Neil Munro^d, Jozef Deckers^e, Jean Poesen^e

^a Department of Geography, Ghent University, Krijgslaan 281 (S8), B-9000 Ghent, Belgium.

^b Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia.

^c Department of Earth Sciences, University of Ferrara, I-44100 Ferrara, Italy.

^d Old Abbey Associates, Dirleton, Scotland, EH39 5DX, U.K.

^e Department of Earth and Environmental Sciences, K.U.Leuven, B-3000 Leuven, Belgium.

* Corresponding author. Tel.: +32 92644694; amaury.frankl@ugent.be

In the Highlands of Northern Ethiopia gully occurrence is linked to poverty-driven unsustainable use of the land in a vulnerable semi-arid and mountainous environment, where intensive rainfall challenges the physical integrity of the landscape. Trends in gully and river channel erosion, and their relation to triggering environmental changes can proffer valuable insights into sustainable development in Northern Ethiopia.

In order to assess the region-wide change in gully and river channel morphology over 140 years, a set of 57 historical photographs taken in Tigray, and clearly displaying gully cross-sections, were precisely repeated from 2006 till 2009. Ninety-two percent of the gully and river sections ($n = 38$) increased in cross-sectional area during the studied period, after 1975. Two repeatedly photographed catchments of Lake Ashenge (**Fig. 1**) and Atsela (**Fig. 2**) allowed a detailed study of gully development from 1936 until 2009. Repeat photography was also used to study the gully and the gully network at May Mekdan (**Figs. 3 to 7**).

A conceptual hydrogeomorphic model was devised for these catchments and validated for the Northern Ethiopian Highlands (**Fig. 8**). Three major phases can be distinguished in the hydrological regime of the catchments. In the first phase, between 1868 (or earlier) and ca. 1965, the relatively stable channels showed an oversized morphology inherited from a previous period when external forcing in environmental conditions had caused the channels to shape. In the second phase (ca. 1965 – ca. 2000), increased aridity and continued vegetation clearance accelerated the channel dynamics of the gully and river system. The third phase (ca. 2000 – present) started after the large-scale implementation of soil and water conservation measures. In 2009, 23% of the gully and river sections were stabilizing. This paper validates previous research indicating severe land degradation in the second half of the 20th century. Additionally, it demonstrates that the recent erosive cycle started around 1965 and, that at the present time, improved land management stabilizes headwater streams.

Excursion stops

Stop 1. Development of a gully in a small catchment draining to Lake Ashenge (p. 40).

Stop 2. Panoramic view of the Atsela valley bottom, with Amba Alaje at the back. Here the gully network expanded throughout the 20th century and is now shrinking (p. 40).

Stop 3. In the field walk around Hagere Selam many gullies will be visited, and particular attention given to headcut retreat around May Ba'ati village (p. 134).

Stop 4. At May Makden, the gully will be visited from nearby and its dimensions and characteristics compared to historical photographs (p. 41).

Lake Ashenge (12°33'N, 39°31'E)

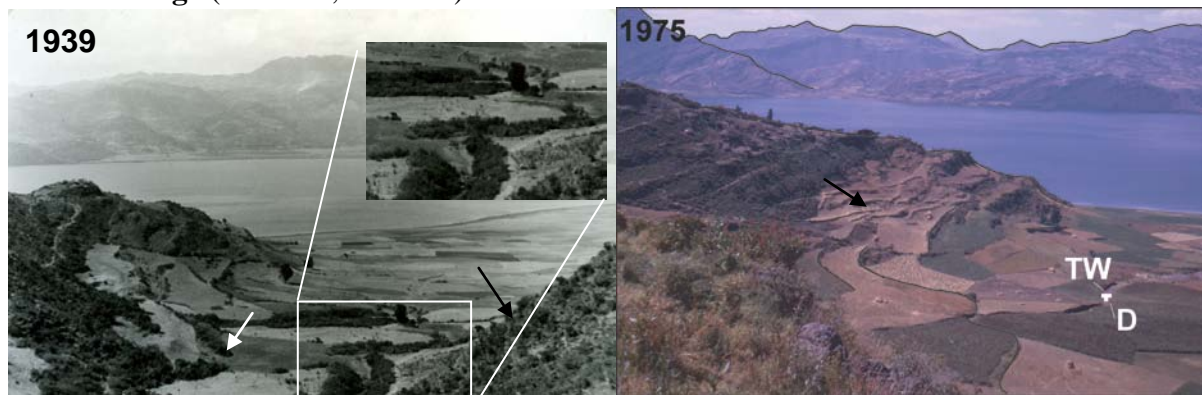


Fig. 1. Left: This photograph was taken in 1939 by A. Maugini (© Istituto Agronomico per l'Oltremare, Firenze, I) at Lake Ashenge, shortly after the construction of the road towards Addis Ababa. It shows that wood harvesting and agricultural exploitation severely affected the environment, but that shrub cover on the land (white arrow) and on the surrounding hills (black arrow) remained relatively high. The gully draining the valley is dormant and has been partially converted to cropland (enlargement). By 2009, the gully had extended downstream by 294 m (Frankl et al., 2011). It is now freshly incised and remains active despite the recent soil and water conservation efforts. **Right:** While surveying soil erosion in North Ethiopia in 1975, Neil Munro (Tigray Rural Development Study) incidentally photographed the same valley and gully previously recorded in 1939. The gully in 1975 appears freshly incised. Agricultural expansion was ongoing and is evidenced by recent terracing on the hillside (arrow). Cross-section properties could be calculated using repeat photography (Frankl et al., 2011) and were in 1975: Top Width (TW)= 5.00 m, Depth (D)= 1.73 m. In 2009 TW increased to 11.60 m and D to 3.80 m.

Atsela (12°54'N, 39°31'E)

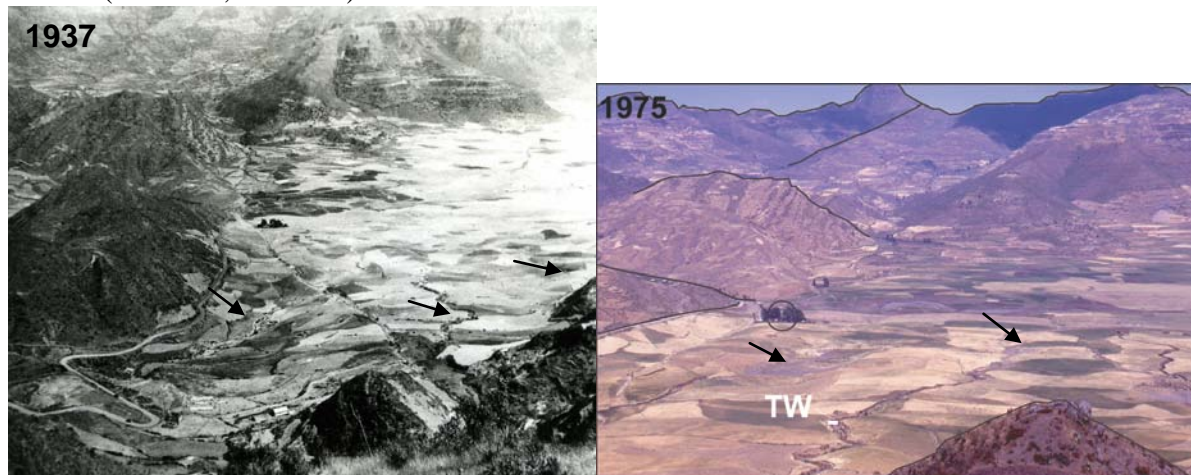


Fig. 2. Left: First pictured in 1937 by A. Maugini (© Istituto Agronomico per l'Oltremare, Firenze, I), the Atsela catchment was poorly managed and bore the signs of intensive agricultural exploitation. Farmland extended beyond its 2009 area to the lower steep mountain slopes, where terracing was absent. The three gullies (arrows) that nowadays cut through the valley

floor were already present in the early 20th century. However, their lower ends were located higher in the valley bottom at approximately 2490 m a.s.l. **Right:** This photograph taken by Neil Munro in 1975 shows that the overuse of the land continued and that the erosive activity of the gullies strongly increased. The channels appear re-incised and prolonged downstream by a total length of 1663 m, ending in large debris cones (arrows). At present, some of the stabilizing gully sections were converted into cropland because risk of flooding is decreased. The Top Width (TW) of the central gully could be calculated (Frankl et al., 2011) and was 6.35 m in 1975. At present the gully TW is 8.20 m (Frankl et al., 2011).

May Mekdan (13°34'N, 39°34'E)

Gullying in the Vertisols around May Mekdan is not recent as old citizens can remember the presence of a gully which could be crossed fairly easy by foot some 50 years ago. Photographs of 1974-1975 (**Fig. 3**), indicate that the gullies in the catchment of May Mekdan were active, having steep walls and carrying coarse bed load. The gully section west of May Mekdan was then some 9.27 m wide and 4.08 m deep (Frankl et al., 2011). Between 1974-1975 and 2009 the gully width and maximum depth doubled. Most of the cross-section change was already accomplished by 1994 (**Fig. 4**), after which the gully incised by a mean of 1.32 m. Despite the implementation of soil and water conservation measures on the hillsides that started in 1995, gullying remains very active (**Fig. 5**), as important flash floods still occur and gully networks expand through piping (**Fig. 6**). First order streams which have a strong link to the surrounding hillsides are de-activating (**Fig. 7**).



Fig. 3. The gully west of the town of May Mekdan drains an area of ca. 50 km².



Fig. 4. The gap in the gully bank in 1994 indicates the occurrence of large slab failures (arrow). Note the increase in shrub cover after 1994 on the slope in the background.



Fig. 5. Gully sidewall erosion by a large slab failure was caused by undercutting and the development of tension cracks parallel to the gully wall. Photographs by A. Frankl before (left) and after (right) an important rainfall event in the summer of 2010, when flood marks rose up to 3.5 m in the main gully (Fig. 6).



Fig. 6. *Left:* Flood marks were recorded up to a height of 3.5 m in the gully draining the May Mekdan valley, after three successive rainstorms stroke the area in 2010. **Right:** Bank gullies linked to piping in the Vertisols are frequent.

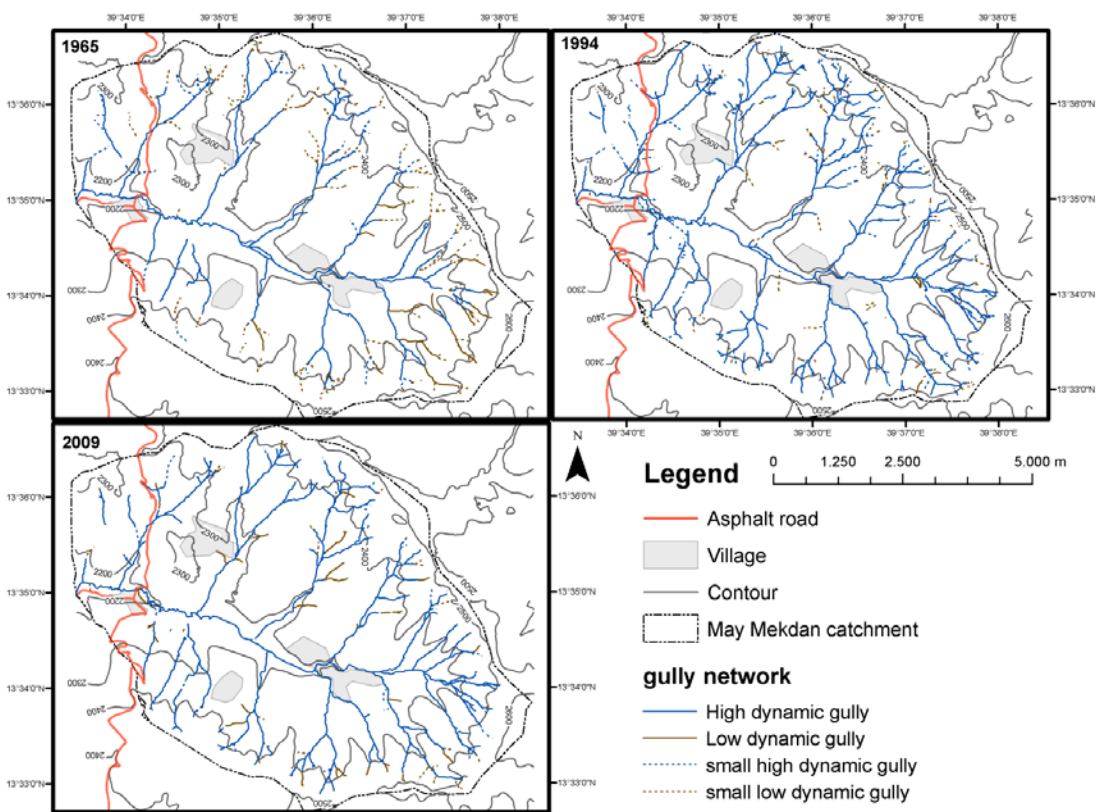


Fig. 7. Gully network development between 1965 and 2009 in the May Mekdan catchment (Scholiers, 2009). The area visited during the excursion is located at the lower (western) part of the main gully.

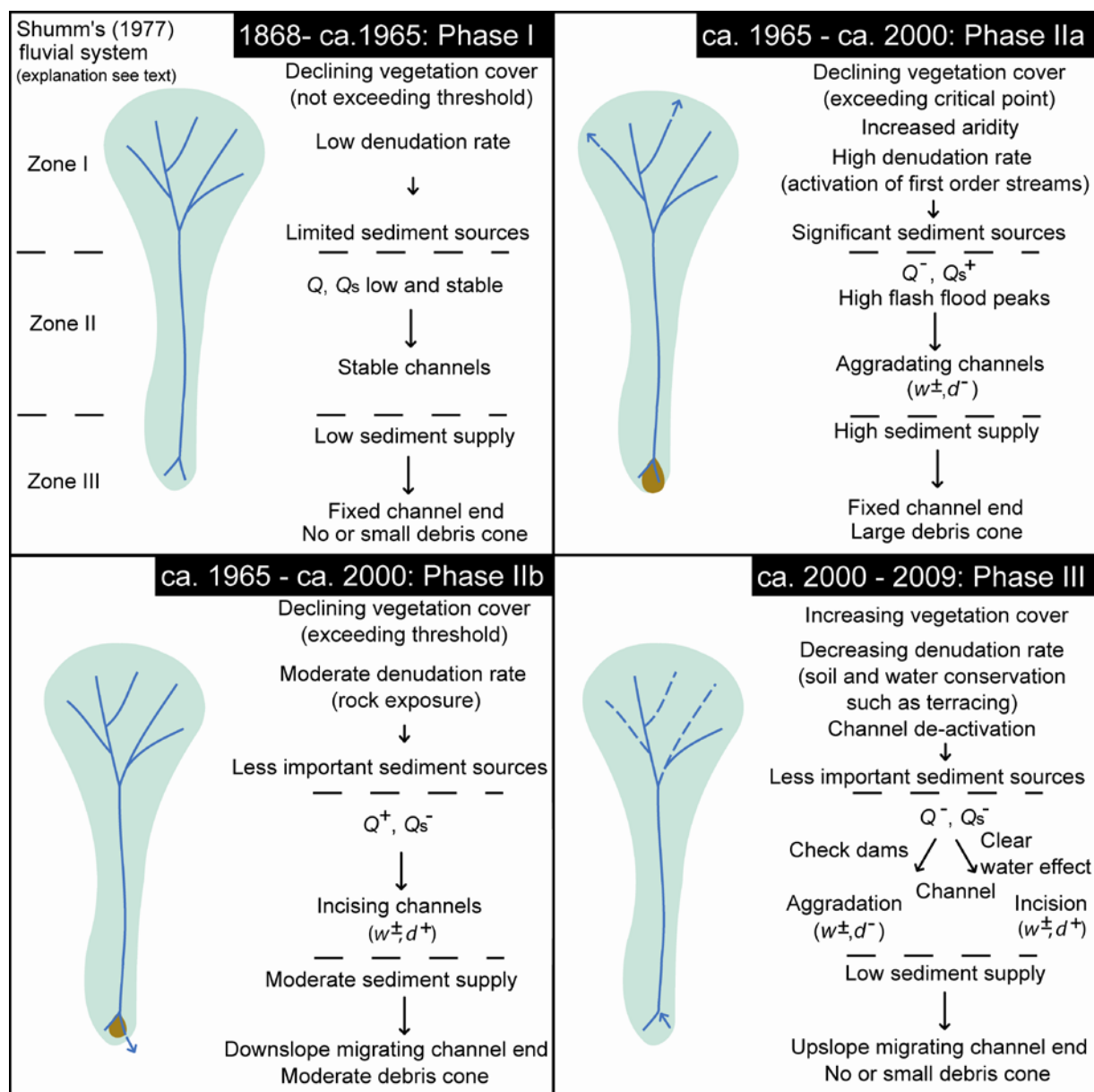


Fig. 8. Conceptual model of changes in the hydrogeomorphology of the Northern Ethiopian highlands based on Schumm's (1977) fluvial system. The threshold refers to a critical reduction in vegetation cover resulting in runoff conditions triggering gully incision or network expansion (After Frankl et al., 2011).

References

- Frankl, A., Nyssen, J., De Dapper, M., Mitiku Haile, Billi, P., Munro, N., Deckers, J., Poesen, J. 2011. Linking long-term gully and river channel dynamics to environmental change using repeat photography (Northern Ethiopia). *Geomorphology*, in press.
- Scholiers, N. 2009. Development of gully networks and volumes since 1965 in the May Mekdan catchment (North Ethiopian highlands). Unpubl. MSc. Thesis. Geography Department, Ghent University, Ghent, Belgium.
- Schumm, S.A., 1977. *The Fluvial System*. John Wiley & Sons, New York.

9. Upper tree limit and land use on the upper slopes of Ferrah Amba, the peak of Tigray (3939 m a.s.l.)

Nyssen, J.¹, Frankl, A.¹, Etafa Guyassa², Gidey Yirga³, Jacob, M.¹, Poesen, J.⁴, Mitiku Haile²

¹Ghent University, Department of Geography, Gent, Belgium

²Mekelle University, Department of Land Resources Management and Environmental Protection, Mekelle, Ethiopia

³Mekelle University, Department of Biology, Mekelle, Ethiopia

⁴K.U.Leuven, Department of Earth and Environment Sciences, Leuven, Belgium

1. Research question

The links between decreasing size and volume of the glaciers in East Africa's tropical mountains and the position of climatic belts on the one hand and global warming on the other have led to various interpretations on the occurrence of global warming and its magnitude and impacts in this part of the world. Here, we investigate the existence of temperature changes, its interaction with anthropogenic and zoogenic activity and their impacts in high mountain regions by analyzing the position of the upper *Erica* limit in northern Ethiopia and compare it to nearby massifs (Fig.1).

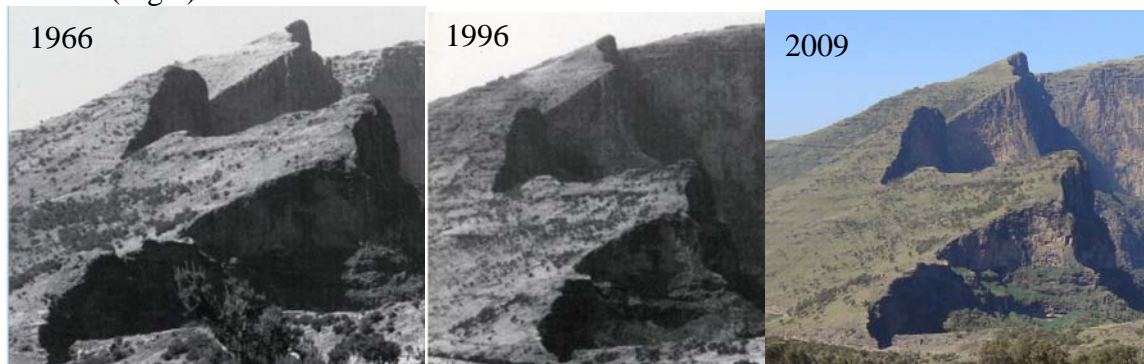


Fig. 1. Upward movement of the upper *Erica* limit in Simien mountains National Park, between 1966, 1996 (Nievergelt, 1998) and 2009 (own observations), at elevations of 3790, 3840 and 3900 m a.s.l. Such upward movement could not be observed on Ferrah Amba.

Beyond the Ayba valley there is another transverse range-that of Ferrah, also named after a mountain mass rising up on the right of the road. This Amba-Ferrah is a succession of grand precipices - a glorious mass of rock, not terminating in a peak like Alaji, but in angular walls of rock, with bright green steeps and ledges intersecting them. It rises up immediately on the right of the pass, which winds up the shelving hills down which a bright stream flows into the Ayba valley. The hills are covered with juniper bushes, and the hollows are golden with a pretty St.-John's-wort, which here first makes its appearance. On this pass, too, the kosoo tree was first seen. Large boulders covered with moss are scattered over the grass, and here and there thickets of wild roses scent the air, growing with a bright purple indigo and a crotalaria. The gigantic thistle rises above all, and on the higher slopes there is a heath with a white flower.

Notes (JN): St.-John's-Wort = *Hypericum*; Kosso = *Hagenia*

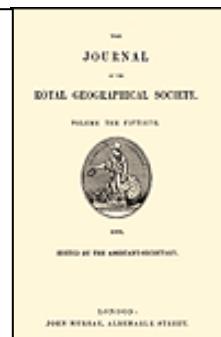


Fig. 2. First description of Ferrah Amba and its vegetation (Markham, 1868)

2. Study area

Ferrah Amba (“Mountain of Fears”) (12°52’N, 39°30’E, 3939 m a.s.l.) is the highest peak of Tigray; its first geographical description was made during the British military expedition to Ethiopia in 1868 (Fig. 2, Fig. 3).

3. Upper *Erica* limit and physiognomic treeline

Following concepts of (Holtmeier, 2009; Van Bogaert, 2010) we defined “Upper Erica limit” and “Physiognomic treeline”.



Fig. 3. Ferrah Amba in 1942. Photo D. Buxton (Meire et al., 2011).

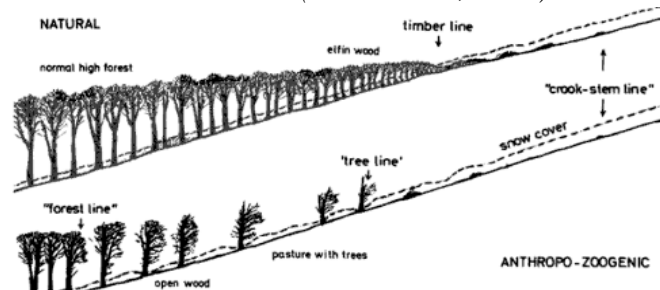


Fig. 4. Difference between natural and anthropo-zoogenic treeline in European mountains (after Ellenberg, 2009).



Fig. 5. *Erica arborea* grows from 3560 to 3840 m.a.s.l. The maximum height observed was 4 m and diameter 5 cm. Arrow indicates approximate location of excursion stop, at the foot of the hill in the middle plan.



Fig. 6. Some of the uppermost, isolated *Erica* specimen (upper Erica limit) at 3826 m a.s.l. Trees are not young, as witnessed by 1-2 cm thick stems. Neither here, nor in the forest downslope, regrowth could be observed. Note the clearly marked physiognomic treeline, at 3720 m.

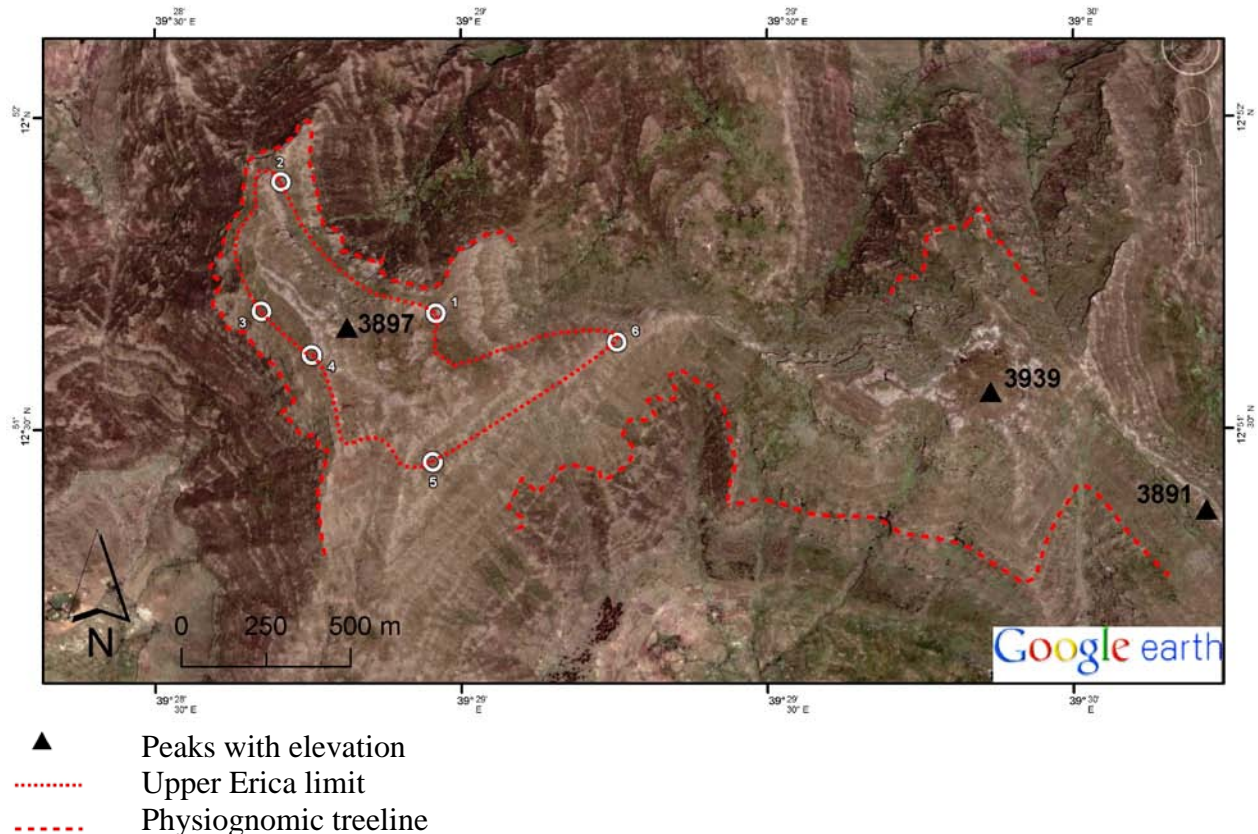


Fig. 7. Based on field observations (February 2010), interpretation of Google Earth image, and of aerial photographs (1994). 1-6 are highest Erica specimen observed (3829-3862 m a.s.l.). For these upper limits, no changes could be found between the situations in 1994 and 2010.

4. Changes in cropping system



Fig. 8. Google Earth image of part of the northern slope of Ferrah Amba with terraces evidencing cultivation at 3450-3500 m a.s.l. Locally some cultivation takes place. Though this resembled at first to abandonment of agriculture, it is simply part of the cropping system in which land is only cultivated once in two years.



Fig. 9. In 2009, for the first time, wheat has been cultivated by a few farmers around Dogu'a village (here at 3380 m a.s.l.) assuming that with warmer climate it could grow – and it did! Neighbouring farmers were making plans to grow wheat at these elevations as of June 2010.

5. Changes in climate

Mekelle airport (2257 m): average monthly temperature

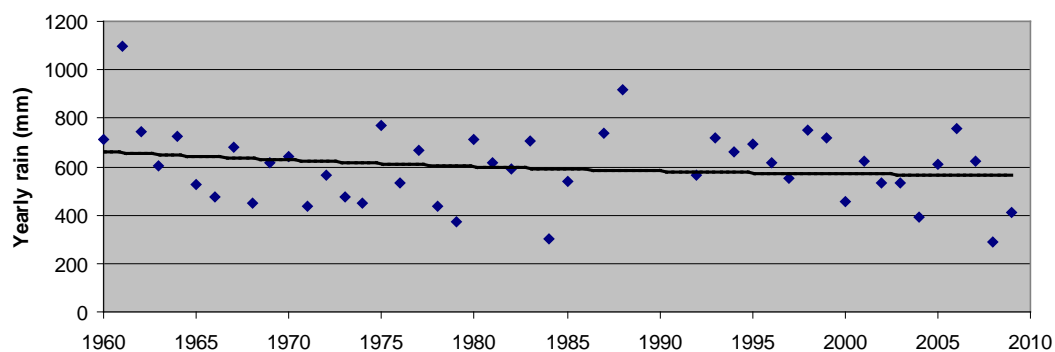
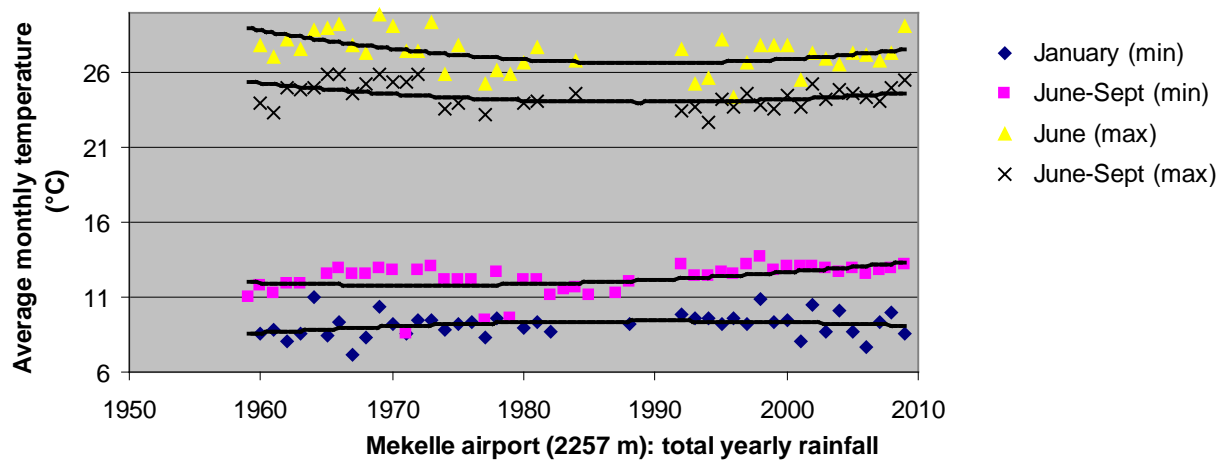
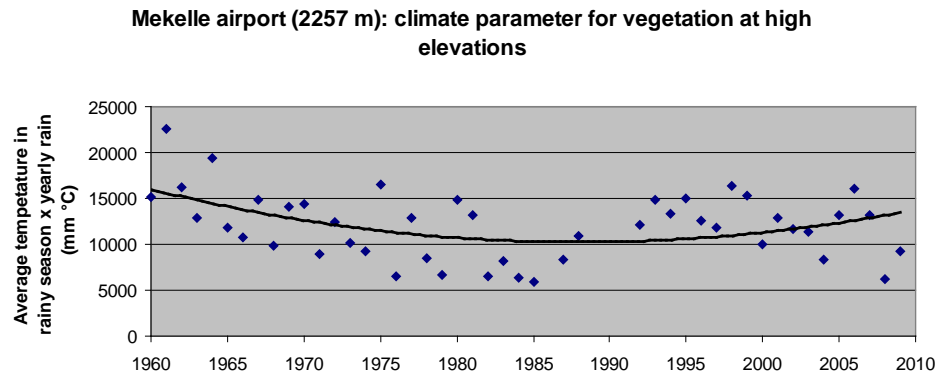


Fig. 10. Climate tendencies for Mekelle Airport (2257 m a.s.l. – data from NMSA), 80 km to the North. More nearby stations have only short time series, and all stations are located at least 1500 m lower than the peaks. Main tendencies are slight decrease in rainfall, as well as rising temperatures since the mid 1980s.



*Fig. 11. Climate parameter (average minimum temperature in the rainy season * total yearly rain), showing improved conditions for vegetation growth since the mid-1980s.*

6. Effects of deforestation on downstream areas



Fig. 12. The uppermost Juniperus procera at 3500 m. a.s.l., in an inaccessible place, evidences the previous existence of a forest, as also confirmed by local farmers.



Figure 13. Uprooting of Erica stumps destroys regeneration from the tree roots (inset)



Fig. 14. Hundreds of sheep are brought daily to the slopes of the mountain, here at 3700 m a.s.l. Livestock browsing impedes regeneration of Erica and other trees of the sub-alpine biome.

Besides the negative effects of deforestation on biodiversity and ecology, the inhabitants spontaneously pointed to us that the removal of the vegetation (hence decreased infiltration) has led to a strong decrease of the discharge of downstream springs (Fig. 15), which in its turn led to a decrease of the irrigated area. This is the reverse of what happens on Mt. Bela (near Sokota) where strong vegetation regrowth took place (due to protection of the mountain) and large irrigation areas were developed using the strongly developed discharges of the downslope springs (Nyssen et al., 2009a).



Fig. 15. The lower part of Dogu'a village (at around 3000 m a.s.l.). View on Monkocies Abdera church forest dominated by Juniperus procera. The surroundings of the hamlet are irrigated. Spring discharges (and hence the irrigated area) are however decreasing due to continuous deforestation in the upslope areas.

7. Discussion and conclusions

Climate change is evidenced by introduction of wheat at high elevations.

At high elevations, anthropogenic-zoogenic impact (grazing, woodcutting, earlier use of fire) seems to override effects of (warming) climate on upper species limit and physiognomic treeline.

In areas that have become recently protected (such as national park establishment in Simien), trees that have started growing more upward may also be ascribed to the protected status, and to regulations that prevent farmers from expanding farmlands upwards, even if climatic and topographic conditions would allow to do so.

Implications for land management: indiscriminate harvesting of wood for fire and other domestic purposes, and absence of seedling establishment and destruction of coppiced *Erica* by browsing, will easily result in the further degradation of the last sub-alpine forest of Tigray, as well as the afro-alpine vegetation.

Unlike nearby mountain areas, the territory of the villages established on the flanks of Ferrah Amba extend from the top of the mountain to its foot. Downslope resettlement seems possible, as conflicts between villages may be largely avoided. Spontaneously, some villagers have already moved downslope to use the irrigation water (Figure 15). The overall vision for natural resource and agricultural development of this area be

- (1) to protect the afro-alpine and sub-alpine vegetation: protection of biodiversity and enhanced infiltration
- (2) subsequent development of springs in the downstream area enhances the downslope movement of inhabitants
- (3) development of community-based tourism will generate additional income. The big opportunity is that this area is easily accessible from the main road; a weakness should however be overcome that is to first allow the regeneration of the afro-alpine and subalpine vegetation and wildlife.

References

- Ellenberg, H., 2009. *Vegetation ecology of central Europe*. Cambridge University Press, Cambridge, 756 pp.
- Holtmeier, F.-K., 2009. *Mountain Timberlines: Ecology, Patchiness and Dynamics*. Springer, 437 pp.
- Markham, C.R., 1868. Geographical Results of the Abyssinian Expedition. *Journal of the Royal Geographical Society of London*, 38: 12-49.
- Meire E, Frankl A, De Wulf A, Mitiku Haile, Deckers J, Nyssen J., 2011. Mapping the 19th century landscape in Africa - Warped terrestrial photographs of North Ethiopia. *Regional Environmental Change*, in preparation.
- Nievergelt, B., 1998. Long-term changes in the landscape and ecosystems of the Simen Mountains National Park. *Walia*, special issue: 8-23.
- Nyssen, J., Getachew Simegn, Nurhussen Taha, 2009a. A permanent upland farming system under mutation: drivers of land use change in Bela-Welleh catchment (Wag, northern Ethiopian highlands). *Soil and Tillage Research*, 103: 231-238.
- Nyssen, J., Mitiku Haile, Naudts, J., Munro, R.N., Poesen, J., Moeyersons, J., Frankl, A., Deckers, J., Pankhurst, R., 2009b. Desertification? Northern Ethiopia re-photographed after 140 years. *Science of the Total Environment*, 407: 2749-2755.
- Van Bogaert, R., 2010. Recent treeline dynamics in sub-Arctic Sweden: a multidisciplinary landscape assessment. PhD thesis, Department of Geography, Ghent University, Gent.

10. Geological and geomorphological framework of the Tigray Highlands

Dramis F.¹, Coltorti M.² and Pieruccini P.²

¹ Department of Geological Sciences, “Roma Tre” University, Rome, Italy

² Department of Earth Sciences, University of Siena, Italy

The northern Ethiopian Highlands is a region of high plateaux, normally exceeding the altitude of 2000 m a.s.l. with isolated residual hills and volcanic ridges up to 4620 m a.s.l. high (Mt. Ras Dashen, the highest peak of Ethiopia). This region stretches about N-S and is bordered by stepped escarpments which make transition to the contiguous lowlands of the Afar to the east, and the Sudan to the west.

The Highlands are deeply incised by the main rivers (Takeze River, Giba River, Abay River) which flow westward making part of the Nile drainage network; only minor streams flow to the east to the Danakil depression. More or less flat summit surfaces and rocky terraces, either structural or erosional in their origin, are present in the area. The slopes frequently show step-like profiles, due to selective erosion; also the river channels have a stepped long profile with gently sloping segments and deep gorges with waterfalls at their head.

The excursion area (Fig. 1) includes the Mekelle Plateau (geologically known as Mekelle Oulier) and the Tigre Plateaus. The first is a wide (about 8000 km²) gently rolling region with a mean elevation of 2000-2200 m a.s.l., raising southwards to more than 3000 m a.s.l. (Amba Alagi volcanic range). To the north, the elevations exceed 3000 m a.s.l. in the Atsbi and Adi Shoha highlands and decline westward to about 1500 m.

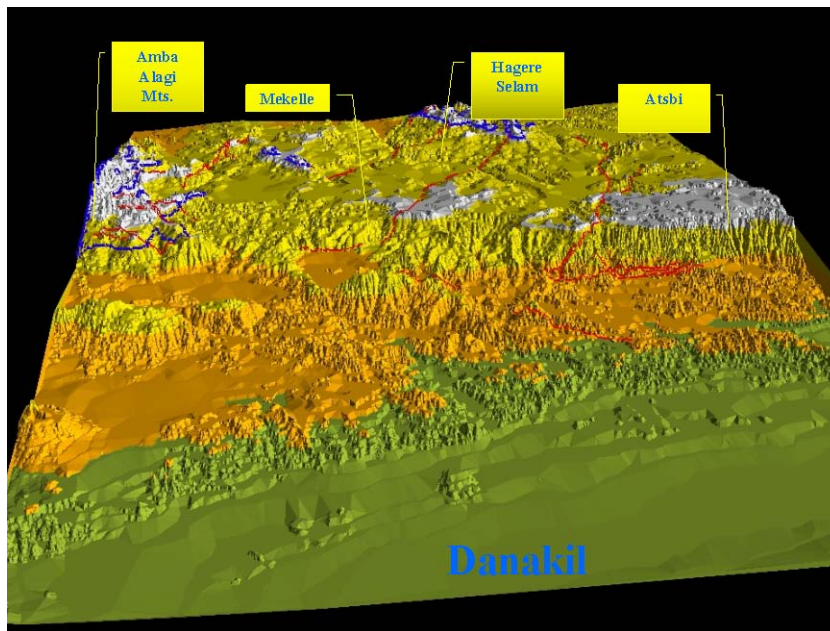


Figure 1. DTM of the excursion area (view from north-east).

The Mekelle Plateau is separated westward from the Tambien lower lands by high escarpments due to selective erosion following the Pliocene-Quaternary uplift (Almond, 1986; Mohr, 1986). Also the retreated fault-line escarpment that makes transition eastward to the Danakil depression

is mostly related to selective erosion. The Tigre Plateau is located northwards and is divided by the Mekelle Outlier by a set of fault scarps, up to some hundred metres high.

Geology

The geological setting of the northern Ethiopian Highlands is the result of complex geodynamic processes which have involved the Horn of Africa since the Precambrian (Blandford, 1869 and 1870; Merla & Minucci, 1938; Mohr, 1962; Levitte, 1970; Arkin *et al.*, 1971; Beyth, 1971; Kazmin, 1975; Garland, 1980). In the eastern portion of the Tigray highlands a Palaeozoic - Mesozoic sedimentary sequence (sandstones, tillites, limestones and shales) overlays the Pre-Cambrian metamorphic basement, locally intruded by huge igneous bodies of Late Pre-Cambrian/Early Palaeozoic age (Garland, 1980). South and west of Mekelle and around Adigrat Tertiary volcanics cover the Mesozoic sediments.

The Precambrian basement

The Precambrian basement here made of low grade metavolcanics (*Tsaliet Metavolcanics*) and metasediments (*Tembien Group*) dated to the upper Precambrian extensively outcrops north and west of the Mekelle Outlier (Arkin *et al.*, 1971; Beyth, 1971; Aklilu *et al.*, 1991; Russo *et al.*, 1996). The *Tsaliet metavolcanics* include pyroclastic levels and rhyolitic lavas alternating with marine sediments over a visible thickness of more than 1500 m. The *Tembien Group* metasediments unconformably overlie the previous unit. The above mentioned formations make part of the “*Upper Complex*” which in turn overlies the highly metamorphosed “*Lower Complex*” (Archean) outcropping in southern Ethiopia.

Both metavolcanics and metasediment are strongly deformed by tectonics (Levitte, 1970; Beyth, 1971). In the Tigre Plateau the structural setting of the basement rocks is characterized by high angle reverse faults and *en échelon* synclinoria trending NNE-NNW (Aklilu *et al.*, 1991). These structures make part of two main orogenic belts: the “*Mozambique Belt*” and the “*Red Sea Belt*” (Kazmin, 1971). At places, as for example east of Adigrat, post-orogenic granitic-dioritic batholites (*Mareb Granite*, *Forstaga Diorite*) cross the basement rocks, mainly along fold axes and shear zones. The age of these intrusions is Late Precambrian/Early Palaeozoic, according to the dates of 600 Myr obtained by Garland (1980) for the pink granite outcropping between Wukro and Hauzien. A comparable date (550 Myr) has been provided by another granitic body around Axum (Tadesse *et al.*, 2000). Other intrusions of doleritic, porphyric, aplitic and pegmatitic composition, also affecting the previous igneous bodies, are locally present (Arkin *et al.*, 1971; Tesfaye & Gebretsadik, 1978; Russo *et al.*, 1996).

The Early Palaeozoic deposits

In the Early Palaeozoic widespread denudational processes affected the Pre-Cambrian orogenic relief, generating a wide planated surface (Coltorti *et al.*, 2007) over which continental sandstones of alluvial facies (*Enticho Sandstone Formation*; Arkin *et al.*, 1971) and tillites (*Edaga Arbi Glacials*; Beyth, 1971), with a total thickness of few hundred meters were deposited. Based on paleontological data, Saxena & Getaneh Assefa (1983), referred the age of these deposits to the Middle-Upper Ordovician.

The *Enticho Sandstone* unconformably overlies the basement, locally infilling narrow valleys cut in the planated surface. The middle and upper part of the formation includes tillite lenses and layers with isolated decametric granite blocks, up to more than 0.5 m in diameter (*Edaga Arbi Glacials*) deposited by a wide glacial cover in a littoral environment (Dow *et al.*, 1971; Beyth,

1971; Morton, 1976; Garland, 1980). Paleomagnetic data confirm that during the Ordovician-Silurian the South Pole was located in North Africa so that the Ethiopian glacial cover could have the extension of a continental ice-sheet.

The Adigrat Sandstone

The first Mesozoic sediments (Triassic-Callovian) in the study area are represented by the *Adigrat Sandstone* (Blandford, 1870; Merla & Minucci, 1938), extensively outcropping all around the Mekelle Plateau and in the eastern Escarpement (Arkin *et al.*, 1971; Russo *et al.*, 1996). This formation unconformably overlies the previous deposits or, directly, the planated basement. According to most authors (Mohr, 1962; Kazmin, 1975; Garland, 1980; Bosellini, 1992; Russo *et al.*, 1994) their depositional environment is fluvial, as testified by the wide occurrence of cross bedding and point-bar sequences, weathered levels and fossil wood (Russo *et al.*, 1994). The sandstone deposition likely occurred over several million years over a vast pedimentary area. The maximum thickness is about 700 m at Abi Adi and progressively decreases west and north of the Mekelle Plateau (Beyth, 1972).

At a regional scale, the thickness of the *Adigrat Sandstone*, as well as that of the following sedimentary sequence, strongly increases eastward towards the Danakil Depression and the Red Sea (to more than 1,700 m at Ras Andadda, on the Eritrean coast, then decreases again up to disappearing east of the Red Sea coast (Geukens, 1966). A possible explanation for these differences in thickness is the occurrence of an early rift in the Danakil – Red Sea area (Russo *et al.*, 1994; Bosellini *et al.*, 1997).

The transition to the following Jurassic sequence is represented by a 20-30 m thick shaly level with shallow water, marine fossils and intercalated calcarenitic and arenitic intercalations. The occurrence of lateritic soils and hard grounds within the sequence indicates that the early stages of the Jurassic marine transgression were characterized by frequent minor ingressions-regressions cycles (Bosellini *et al.*, 1997). Basing on micropaleontological data, the age of the shales is Upper Callovian?-Lower Oxfordian (Bosellini *et al.*, 1997). Around Adigrat and in Eritrea the *Adigrat Sandstone* reliefs are covered by a thick lateritic crust (Abul-Haggag, 1961).

The Antalo Supersequence

The Antalo Supersequence (Upper Oxfordian - Kimmeridgian) is a marly-carbonatic shallow water marine succession, laying over a very low (1°-2°) angle homoclinal ramp on the eastern side of the African craton (Bosellini *et al.*, 1995). It largely outcrops in the Mekelle Outlier and, at a lesser extent, around Adigrat (Garland, 1980) and in the Danakil Alps (Abul-Haggag, 1961). As for the Adigrat Sandstone, the deposits become thinner westward with a high energy sedimentary facies; the maximum thickness in the study area is over 700 m around Shiket, south-east of Mekelle. The Antalo Supersequence also outcrops in other parts of Ethiopia such as in the Blue Nile Valley, in the Harar Plateau as well as in the area surrounding Dire Dawa and Chercher Mts. (Getaneh, 1991).

The lower part of the Antalo Supersequence, corresponding to the *Antalo Limestone Formation Auct.* (Blandford, 1870; Merla & Minucci, 1938; Levitte, 1970; Arkin *et al.*, 1971) is made of four depositional units, consisting of parasequences with systematic vertical and lateral changes which testify the incidence of several ingressions-regressions during the Jurassic transgression (Bosellini *et al.*, 1995).

The upper part of the Supersequence, corresponding to the *Agula Shales Formation Auct.* (Levitte, 1970), mainly consists of shales alternating with marls, coquina limestones, quartz-

arenites and gypsum which, on the whole, a general phase of marine regression (Bosellini *et al.*, 1995). In the Mekelle – Adi Goudum area, the original stratigraphic succession is locally dismembered by a net of doleritic sills and dykes, up to 300 m thick, emplaced during the Tertiary (Merla & Minucci, 1938).

The Amba Aradam Formation

The *Amba Aradam Formation* (Beyth, 1972) consists of a 100-200 m thick silicoclastic sandstone sequence of continental facies with quartz conglomerate, shaly and laterite levels. The formation unconformably covers the underlying units, visibly truncated by a wide planation surface which seals the Mekelle Fault (Arkin *et al.*, 1971; Russo *et al.*, 1996; Bosellini *et al.*, 1997; Coltorti *et al.*, 2007).

The *Amba Aradam Formation* outcrops locally south and east of Mekelle (Arkin *et al.*, 1971, Russo *et al.*, 1996); comparable deposits also outcrop in central and southeastern Ethiopia (Aklilu, 1991; Russo *et al.*, 1994) and in Eritrea (Hutchinson & Engels, 1970).

Due to the absence of fossils in the *Amba Aradam Formation* of Tigray, the only possible reference data are provided by a calcareous level within the “*Upper Sandstone*” of Harar, Chercher and Arussi, whose paleontological content gave an Aptian-Albian age (Silvestri, 1973).

The upper part of the formation is often deeply weathered by a reddish-violet lateritic horizon which testifies a prolonged exposure to the atmospheric agents in tropical conditions.

The Trap Volcanics

The Trap Volcanics consist of stratified basalt up to more than 2000 m thick, overlying the deeply weathered surface of Mesozoic, Palaeozoic and Pre-Palaeozoic formations (Blandford, 1869). At Lake Ashangi (12°45'N 39°35'E), the basalt sequence is divided in two main groups, separated by an angular unconformity (Blandford, 1869): the lower group (Ashangi Group – Early Eocene to Oligocene), composed almost entirely of basalts, and the upper one (Magdala Group - Miocene), which includes several sialic intercalations. According to Zanettin & Justin-Visentin (1973), the upper group is divided into the following formations: Aiba Basalts (Oligocene *p.p.*-Miocene *p.p.*); Alagi Rhyolites (Miocene *p.p.*- Pliocene *p.p.*); Termaber Basalts (Pliocene *p.p.*), Salale Mts. Phonolytes and Bishoftu Basalts (Pliocene *p.p.* - Holocene). Probably, the Magdala Group corresponds to the Aiba Basalts the Alagi Rhyolites (Zanettin & Justin-Visentin, 1973), both of fissural origin (Trap *s.s.*); the Termaber Basalts derive from central effusions while the Salale Mts. Phonolites and the Bishoftu Basalts are only found at Salale Mts., about 50 km north-west of Addis Ababa.

Around Mekelle the Trap volcanics outcrops only locally (e.g. at Hagere Selam and in the Amba Alagi Highlands). Here a relatively shallow (down to few meters) sequence of stratified olivine basalts and tuffs with scattered lacustrine intercalations overlays the *Amba Aradam Formation*.

In the Amba Alagi highlands the previous sequence is conformably topped by alternating alkaline rhyolites and basalts (Alagi Rhyolites, varicoloured acidic tuffs and thin layers of trachyte).

Based on Ar/Ar datings and magnetostratigraphy, the volcanic eruptions responsible of Trap emplacement started between 30.5 and 29.5 Ma (lower Oligocene-upper Oligocene) (Hofmann *et al.*, 1997; Rochette *et al.*, 1998). Detailed stratigraphic studies suggest that most of the sequence has been formed in less than 1 Myr; more recent ages (28-26 Ma) are found for the higher units and may correspond to minor volcanic inputs (Rochette *et al.*, 1998). The Termaber basalts are dated 22-20.5 Ma (lower Miocene) (Pik *et al.*, 1998).

The Mekelle Dolerite

In the area between Mekelle and Samre a large number of doleritic dykes and sills of different dimension and shape, often perfectly conformable with the layering of the intruded rocks, are found within the Antalo Supersequence, especially within the *Agula Shales* (Merla & Minucci, 1938; Justin-Visentin, 1974; Tesfaye & Gebretsadik, 1982). These sills are prevailingly found within the *Agula Shales* around Mekelle and are apparently connected with the Trap Volcanics. The K/Ar dating of a sample collected at Enda Jesus (east of Mekelle) gave an age of 32.8 Ma (Justin-Visentin, 1974).

Tectonics

The sedimentary rocks of the Mekelle Outlier and the Pre-Palaeozoic metamorphic basement, intensely deformed by compressive tectonics, are cut by two main fault systems trending about WNW-ESE and between N-S and NNE-SSW (Arkin *et al.*, 1971; Beyth, 1971). The first system consists of normal faults up to 80-90 km long, with throws up to some hundred meters. These faults may be gathered into four main belts (Wukro, Mekelle, Chelekwot and Mariam belts) and were active before the Cretaceous, being levelled and overlain by the *Amba Aradam Formation* (Garland, 1980). The second system includes faults of different lengths and throws, more or less parallel to the fault steps of the main rift escarpment which borders the Highlands to the east with a relief of ca 3,000 m, over a distance of ca. 50 km (Kazmin, 1975; Garland, 1980).

These faults have been active since the upper Cretaceous to the recent times as testified by the dislocation of Tertiary volcanics and Quaternary alluvial deposits (Arkin, 1975; Garland, 1980) as well as by the seismicity which characterizes the eastern escarpment (Mohr, 1962; Gouin, 1979).

Geomorphological framework

The geomorphologic evolution of the eastern Tigray highlands starts with an extensive planation surface (PS1) which truncates the Pre-Palaeozoic basement (Merla & Minucci, 1938; Abul-Haggag, 1961; Coltorti *et al.*, 2007). This surface is very flat and crops out due to re-exhumation processes, north and west of the Mekelle Outlier (e.g. around Adigrat, Akliku *et al.*, 1978).

The older rocks which post-date the planation surface belong to the *Enticho Sandstone Formation*, Late Carboniferous or Ordovician in age (Dow *et al.*, 1971). This unit is composed of a wide variety of coarse grained continental sediments which testify the occurrence of fluvial-aeolian environments under dry conditions.

In their upper part, the Enticho sandstones interfinger with the Edaga Arbi Glacials (Arkin *et al.*, 1971), till deposits testifying very cold climatic conditions during the Ordovician. Immediately north of Mekelle, the exhumed PS1 outcrops on top of a raised horst (Atsbi horst), being only covered by scattered remnants of the latter deposits.

Both formations are unconformably overlain by the Adigrat Sandstones (upper Trias- lower Jurassic; Blandford, 1870): a thick fluvial sequence with cross bedded units and fossil woods, indicating a wide alluvial plain crossed by meandering channels (Bosellini *et al.*, 1997). The presence of reddish shaly units at different levels indicates the incidence of both deep weathering and lacustrine sedimentation in the alluvial plain. The unconformity, which covers at least the whole Permian, should be related to another planation episode, for which, however, no clear supporting geomorphological evidence has been found. The huge differences in thickness, from less than 80 to 700 m between western and eastern Tigray suggest the occurrence of noteworthy syn-sedimentary tectonics (*Jurassic rifting*; Bosellini *et al.*, 1997).

The Jurassic marine ingression from southeast (Bosellini *et al.*, 1997) caused the deposition of some hundred meters of marine sediments (*Antalo Limestones*; Blandford, 1870; Merla & Minucci, 1938). The transition to the marine sequences has been progressive as testified by the increasing amount of shallow marine shales and calcarenites at the base of the sequence. However, the occurrence of hardgrounds and lateritic soils suggests local oscillation during the first stages of the ingression. The marine environment extended for some distance north and west of Mekelle, pinching over the Adigrat Sandstones, even if the exact extension is unknown since there is no clear remnant of the corresponding coast line. The total thickness in the Adigrat area is more than 1000 m (Tefera *et al.*, 1996). Subsequently (till the Late Jurassic), the environment progressively changed to tidal and peritidal with the deposition of the *Agula Shales* (Arkin *et al.*, 1971).

In the Early Cretaceous (Bosellini *et al.*, 1997), again under generalised continental conditions, a new important planation surface (PS2) truncated the previously described sequence all around the area, extending as far as southern Ethiopia, Eritrea and Yemen. The PS2 cuts across ESE-WNW trending normal faults (Wukro fault belt, Melele fault, Chelekwot fault belt) which were active during the Jurassic, and extends to the north where it exhumed the PS1 from the Pre-Cretaceous sedimentary cover (Arkin *et al.*, 1971; Aklilu *et al.*, 1978; Russo *et al.*, 1996). West and south of Mekelle (Hagere Selam, Mt. Amba Aradam) this planation surface is a key horizon, being unconformably buried by the *Amba Aradam Formation*, mainly made of coarse grained quartz sandstones and conglomerates, with intercalated shales and lateritic soils testifying an alluvial plain environment. The thickness of the *Amba Aradam Formation* as well as the mean size of the sediments increase southward (Tefera *et al.*, 1996).

In the surroundings of Mekelle, the *Amba Aradam Formation* is overlain by the Trap volcanics, a sequence of flood basalts emplaced during the Oligocene-Miocene, in the first stages of the main Ethiopian rifting. According to Merla & Minucci (1938) the transition between the two formation corresponded to another planation even if the differences in thickness within the Trap sequences seems to indicate a gently rolling landscape instead of a flat planated surface.

The Trap volcanics (Oligocene–Miocene) constitutes the last major depositional unit affecting a large area. Younger volcanic activity continued only locally creating strato-volcanoes (as e.g. in the Semien Mts). Many dolerite dykes and sills, having the same chemical-petrographic composition of the overlying volcanics, are intruded along fractures, faults (e.g. along the Mekelle fault) and bedding planes (e.g. in the Mt. Amba Aradam area).

A further important erosional episode deeply truncated the Trap volcanics as well as the underlying rocks, causing a widespread re-exhumation of the PS2 and PS1 surfaces west and south of Mekelle, here lowered by the WNW-ESE set of Jurassic normal faults (Merla & Minucci, 1938; Arkin *et al.*, 1971).

After the Trap emplacement, the area was affected by continuous uplifting (Faure, 1975) and prevailing erosional processes, connected with the formation of the Main Ethiopian Rift. In this context, N-S trending normal faults were active, dislocating the Trap volcanics and producing the high tectonic escarpment which divides the Tigray highlands from the Danakil lowlands. Denudation processes generated the stepped morphology typical of the Ethiopian highlands (“Amba” landforms), related to strong contrasts between stiff and soft lithologies. Deep-seated lateral spreading phenomena affected the slopes where the Amba Aradam sandstones and conglomerates overly the *Agula Shales*, as at Mt. Debre Kwala and Mt. Amba Aradam.

The downcutting firstly generated large and relatively shallow valleys, oriented ca. E-W, as the one preserved across the Mekelle Outlier or around Mai Nebri. These could represent a pre-rift

western oriented drainage network similar to the one described in the Main Rift of Kenya by Ollier (1990). Subsequently, the creation of the Rift escarpment captured the drainage and diverted it to the Afar area, locally generating small lake basins.

After this phase, in the Mekelle Outlier and where post PS1 sediments crop out, denudation processes generated the stepped morphology typical of the Ethiopian Highlands. These processes were driven by the presence of strong contrast between lithologies with different stiffness, which created stepped slopes as well as stepped river profiles. Out of these areas, where the erosional processes were more intense, usually in connection with the more elevated areas, the landscape is dominated by the exhumed PS1.

The ongoing uplift induced regressive erosion in the river valleys, creating deep gorges in correspondence of hard levels (such as limestone layers or dolerite sills) where linear incision is the dominant process and no major alluvial deposition and river terraces can be formed. In the inner areas, not yet reached by the backward river erosion, the landscape modelling is mostly dominated by climate induced processes, such as parallel slope retreat and pedimentation as well as alternation of fluvial aggradation and terracing without any major valley deepening. Selective erosion has deeply modified the original geomorphological setting of the described planation surfaces, giving rise to wide valleys in correspondence with the *Agula Shales* (as at Adi Goudum, and around Wukro and Mekelle), where the planes of WNW-ESE Jurassic normal faults, levelled by the PS2, have been strikingly exhumed. The best preserved fluvial sediments are Holocene in age, as documented by a large number of ^{14}C dates from buried organic-rich soils and peaty deposits (Brancaccio *et al.*, 1997; Berakhi *et al.*, 1998; Dramis *et al.*, 2003). Although radiometric dates are lacking, older gravelly alluvial terraces, weathered on top by a reddish soil, may be referred to the Late Pleistocene.

References

- Abul-Haggag Y., 1961. *A contribution to the physiography of northern Ethiopia*. University of London, The Athlone Press, 153 pp.
- Aklilu Assefa, Amenti Abraham, Beyth M., Dow D.B., Garland C.R., Temesgen Haile & Hailu Tsegaye 1978. *Geological map of Adigrat area. Sheet - ND 37-7, (1:250'000)*. Ministry of Mines, Geological Survey of Ethiopia, Addis Ababa.
- Almond D.C., 1986. *Geological evolution of the Afro-Arabian dome*. Tectonophysics 131, 301–332.
- Arkin Y, Beyth M., Dow D.B., Levitte M., Temesgen Haile & Hailu Tsegaye, 1971. *Geological map of Mekelle sheet ND 37-11 Tigre Province*. Ministry of Mines, Energy & Water Resources, Geological Survey of Ethiopia, Addis Ababa.
- Berakhi Ogbaghebriel, Brancaccio L., Calderoni G., Coltorti M., Dramis F. & Mohammed Umer, 1998. *The Mai Maikden sedimentary sequence: a reference point for the environmental evolution of the Highlands of Northern Ethiopia*. Geomorphology 23 (2), 127-138.
- Beyth M., 1971. *The geology of central and western Tigre*. Unpublished report, Min. Mines, Addis Ababa.
- Beyth M., 1972. *Paleozoic-Mesozoic Sedimentary Basin of Mekelle Outlier, Northern Ethiopia*. Amer. Ass. Petrol. Geol. Bull. 56 (12), 2426-2439.
- Blandford W.T., 1869. *On the geology of a portion of Abyssinia*. Q. Jl. Geol. Soc. 25.
- Blandford W.T., 1870. *Report on the geology of a portion of Abyssinia*. Assoc. J. Geol. Soc. London 25, 401-406.
- Bosellini A., 1992. *The Continental margins of Somalia*. Am. Ass. Petrol. Geol. Memoir 53, 185-205.
- Bosellini A., Russo A. & Getaneh Assefa, 1995. *Il Calcare di Antalo nella regione di Macallè (Tigrai, Etiopia settentrionale)*. Rend. Fis. Acc. Lincei, s. 9, 6, 253-267.
- Bosellini A., Russo A., Fantozzi P.L., Getaneh A. & Tadesse S., 1997. *The Mesozoic succession of the Mekelle outlier (Tigre province, Ethiopia)*. Memorie di Scienze Geologiche 49, 95-116

- Brancaccio L., Calderoni G., Coltorti M., Dramis F. & Ogbaghebriel B., 1997. *Phases of soil erosion during the Holocene in the highlands of western Tigray (northern Ethiopia): A preliminary report*. In Bard, K. A. (ed.), *The Environmental History and Human Ecology of Northern Ethiopia in the Late Holocene*, Istituto Universitario Orientale, Naples, 29-44.
- Coltorti M., Dramis F. & Ollier C.D., 2007. *Planation surfaces in Northern Ethiopia*. *Geomorphology* 89, 287-296.
- Dow D.B., Beyth M. & Tsegaye H., 1971. *Paleozoic glacial rocks recently discovered in Northern Ethiopia*. *Geological Magazine* 108, 1, 53-60.
- Dramis F., Umer M., Calderoni G. & Haile M., 2003. *Holocene climate phases from buried soils in Tigray (northern Ethiopia). Comparison with lake level fluctuations in the Main Ethiopian Rift*. *Quaternary Research* 60, 274-283.
- Faure H., 1975. *Neotectonics in the Afar (Ethiopia, T.F.A.I.)*. In: Suggate R.P., Creswell M.M. (eds.), *Quaternary Studies*, R. Soc. New Zealand, Wellington, pp. 121-126.
- Garland C.R., 1980. *Geology of the Adigrat Area*. Ministry of Mines, Energy and Water Resources Geological Survey of Ethiopia, Memoir 1, 51 pp.
- Getaneh Assefa, 1991. *Lithostratigraphy and environment of deposition of the Late Jurassic-Early Cretaceous sequence of the central part of Northwestern Plateau, Ethiopia*. *N. Jb. Geol. Paleont. Abh.* 182 (3), 255-284.
- Geukens F., 1966. *Geology of the Arabian Peninsula-Yemen*. *Geol. Surv. Prof. Paper* 560-B, 23 pp.
- Gouin P., 1979. *Earthquake history of Ethiopia and the Horn of Africa*. Intern. Development Research Centre, 118E, Ottawa, Ontario, 259 pp.
- Hofmann C., Courtillot V., Féraud G., Rochette P., Yirgu G., Ketefo E. & Pik R., 1997. *Timing of the Ethiopian flood basalt event and implications for plume birth and global change*. *Nature* 389, 838-841.
- Hutchinson R.W. & Engels G.G., 1970. *Tectonic significance of regional geology and evaporite lithofacies in northeastern Ethiopia*. *Phil. Trans. Roy. Soc. London., s. A.*, 267, 313-329.
- Justin-Visentin E., 1974. *Petrografia, chimismo e petrogenesi dei corpi subvulcanici di Macallè (Tigray – Etiopia)*. *Mem. Ist. Geol. Miner. Univ. Padova* 31, 1-33.
- Kazmin V., 1971. *Precambrian of Ethiopia*. *Nature* 230, 176-177.
- Kazmin V., 1975. *Explanation of the Geological Map of Ethiopia*. Geological Survey of Ethiopia Bull. 1, 14 pp.
- Levitte D., 1970. *The geology of Mekelle. Report on the geology of the central part of sheet ND 37-11*. *Geol. Survey Ethiopia*, 66 pp., Addis Ababa.
- Mengesha Tefera, Tadiwos Chernet & Workneh Haro, 1996. *Explanation of the geological map of Ethiopia. Scale 1:2.000.000*. 2nd Edition, Ethiopian Institute of Geological Survey, 80 pp. 2nd ed. EIGS, Addis Ababa.
- Merla G & Minucci E., 1938. *Missione geologica nel Tigray. Vol. 1 "La Serie dei Terreni"*, Rendiconti della Reale Accademia d'Italia, Centro Studi per l'Africa Orientale Italiana, 3, 362 pp.
- Mohr P.A., 1962. *The geology of Ethiopia*. Addis Ababa University Press, 268 pp.
- Mohr P.A., 1986. *Sequential aspects of the tectonic evolution of Ethiopia*. *Mem. Soc. Geol. It.* 31, 447-461.
- Morton W.H., 1976. *The geology of Enticho, Tigre*. *Bull. Geophysical Observatory, Ethiopia* 16, 1- 15.
- Ollier C.D., 1990. *Morphotectonics of the Lake Albert Rift Valley and its significance for continental margins*. *Journal of Geodynamics* 11, 343-355.
- Pik R., Deniel C., Coulon C., Yirgu G., Hofmann C. & Ayalew D., 1998. *The northwestern Ethiopian Plateau flood basalts: Classification and spatial distribution of magma types*. *J. Volcanol. Geothermal Res.* 81, 91-111.
- Rochette P., Tamrat E., Féraud G., Pik R., Courtillot V., Ketefo E., Coulon C., Hoffmann C., Vandamme D. & Yirgu G., 1998. *Magnetostratigraphy and timing of the Oligocene Ethiopian traps*. *Earth Planet. Sci. Lett.* 164, 497-510.
- Russo A., Getaneh Assefa & Balenwol Atnafu, 1994. *Sedimentary evolution of the Abay River (Blue Nile) Basin, Ethiopia*. *N. Jb. Geol. Palaont. Mh.* 5, 291-308.
- Russo A., Fantozzi P.L., Solomon Tadesse, Getaneh Assefa, Neri C., Russo F., Asfossen Asrat, Peccerillo A. & Valera P., 1996. *Geological map of the Mekelle outlier (western sheet)*. Italian Cooperation – Addis Ababa University, Addis Ababa.
- Saxena G.N. & Getaneh Assefa G., 1983. *New evidence on the age of glacial rocks of northern Ethiopia*. *Geol. Mag.* 120, 6, 549-554.

- Silvestri A., 1973. *Orbitoline mesocretacee degli Strati di Graua*. In *Missione Geologica dell'AGIP nella Dancalia Meridionale e sugli Altipiani Hararini (1936-1938)*. Acc. Naz. Lincei 4, 101-138.
- Tadesse T., Hoshino M., Suzuki K. & Iizumi S., 2000. Sm-Nd, Rb-Sr and Th-U-Pb zircon ages of syn- and post-tectonic granitoids from the Axum area of northern Ethiopia. *Journ. Afr. Earth Sc.* 30, 2, 313-327.
- Tesfaye Chernet & Gebretsadik Eshete, 1982. *Hydrogeology of the Mekele area (ND37-11)*. Ministry of Mines and Energy, Ethiopian Institute of Geological Surveys, Addis Ababa, 50 pp.
- Zanettin B. & Justin-Visentin E., 1973. *Serie di vulcaniti etiopiche 1 – La serie dell'altipiano etiopico centro-orientale*. *Boll. Soc. Geol. It.* 92, 313-327.

11. Geomorphology of the Mt. Amba Aradam south-eastern slope

Asfawossen Asrat¹, Coltorti M.², Dramis F.³ & Pieruccini P.²

¹ Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

² Department of Earth Sciences, University of Siena, Italy

³ Department of Geological Sciences, “Roma Tre” University, Rome, Italy

Geological framework

The Amba Aradam Mt. (Fig. 1) area is part of the Mekele outlier, characterised by the full outcrop of the Mesozoic sedimentary sequence. This sequence starts with the deposition, in fluvial environment, of the up to 700 m thick *Adigrat Sandstone Formation*, made of well sorted crossbedded quartzarenites, bioturbated silt-shales and laterite beds, more common in the upper part. The upper boundary occurs through transitional beds (up to 30 m thick) made of shales, calcarenites, sandstones and lateritic soils. Those transitional beds are interpreted as the beginning of the general transgressive phase, dated to the early Oxfordian, that led to the deposition of the *Antalo Limestones Formation* (or *Antalo Supersequence*, following Bosellini *et al.*, 1997), a complex transgressive carbonate-marly sequence which characterise the first flooding of the African craton after the Paleozoic-Late Jurassic mainly continental deposition.



Fig. 1. The southern slope of the Amba Aradam Mt.

However those rocks do not crop out in the field trip area where the older rocks belong to the *Agula Shales Formation* (Levitte, 1970, Arkin *et al.*, 1971 and Beyth, 1972), named in order to distinguish the upper part of the *Antalo Limestone Formation* (Blandford, 1870). They are mainly made of medium to thick layers of greyish marls and marly clays (but colours range also from whitish to reddish and purple), which are interbedded with coquinoid limestones, quartzitic sandstones and gypsum layers. Their deposition has been associated to several regressive cycles that interrupted the general transgressive trend (Bosellini *et al.*, 1997).

The upper boundary of this formation is made of an abrupt angular unconformity overlain by the *Amba Aradam Formation*, up to 200 m thick, made of coarse-grained quartz sandstones, quartz conglomerates lenses, purple, violet and yellowish shales and lateritic beds. The age of the *Amba*

Aradam Formation is unknown but an approximate Early Cretaceous age can be extrapolated by the age of the underlying formations as well as. the only possible reference data are provided by a calcareous level within the "*Upper Sandstone*" of Harar, Chercher and Arussi, whose paleontological content gave an Aptian-Albian age (Silvestri, 1973).

The angular nature of the basal unconformity suggests a tectonic origin for the Early Cretaceous uplift evidenced also by the burial of pre-*Amba Aradam* regional faults.

The uplift was followed by the intrusion of dolerite sills and dykes of Oligocene age that mainly affected the well stratified *Agula Shales Formation* inducing large- and small-scale deformations such as folding and detachments.

Structural landforms

The slopes of the Amba Aradam relief are characterised by a stepped morphology (Coltorti et al., 2009) due to selective erosion of the Mesozoic bedrock intruded by doleritic sills (Fig. 2).



Figure 2. *Structural surface on a dolerite sill on the eastern slope of Mt. Amba Aradam.*

Superficial deposits

Reddish, unsorted, boulder-dominated debris covers the Mt. Amba Aradam south-eastern slope; from the base of the Amba Aradam formation scarp to the slope foot, where it is found on top of small isolated reliefs. Its deposition can be associated to the retreat of the Amba Aradam formation scarp and the related aggradation of a depositional glacia, deeply dissected in the following times (Middle Pleistocene?).

Four main phases of soil formation are recorded in the last 5,000 yr BP, each one followed by erosive events and alluvial deposition. However, the main degradation phase is the present-day one, with stream incision, gully erosion and dissection of the sedimentary sequence in some case down to the bedrock (Fig. 3).



Figure 3. *Gully erosion nearby Bet Gebriel.*

The soil erosion phases and burial by alluvial sediments indicate aggradation of the alluvial plain by the way of sheet-floods, gravity flows and in-channel deposition. The correlation of these events with human impact is proved for the younger phases (<3,000 yr BP) due to the presence of archeological remains. The older phases might be correlated to the climatic changes recorded in other areas of Ethiopia, although the similarity of the events and their duration could also be related to human influence.

Gravitational features

Landslides of various typologies affect the slopes of the area (Nyssen *et al.*, 2002; Coltorti *et al.*, 2009). In particular, the debris accumulated at the foot of the main scarp of the Amba Aradam relief shows large landslides mainly dormant whereas active rotational slides and debris- and mud-flows affect the marly-clayey lower slopes (Fig. 4).



Figure 4. *The chaotic debris that constitute a landslide body. Stripes of marly-clayey rocks are involved in the movement.*

Excursion stops

Stop 1. General view of the Amba Aradam Mountain and the Adi Goudum plain from the road to Mekelle near the May Keyih Village.

Stop 2. Hintalo Town: erosional features and deformations in the Agula Shales and lateral spreading of the overlying *Amba Aradam Formation*. Gully erosion and mass movements on the slope.

Stop 3. Short walk to the Amba Aradam Mt. top and panoramic view of the surrounding area.



Figure 5. A historical document: Hintalo Town and Amba Aradam in 1868 (Nyssen et al., 2009). The photograph was realised as part of the military expedition in which Blandford (1870) did also his geological observations.

References

- Arkin Y, Beyth M., Dow D.B., Levitte M., Temesgen Haile & Hailu Tsegaye, 1971. *Geological map of Mekelle sheet ND 37-11 Tigre Province*. Ministry of Mines, Energy & Water Resources, Geological Survey of Ethiopia, Addis Ababa.
- Beyth M., 1972. *Paleozoic-Mesozoic Sedimentary Basin of Mekelle Outlier, Northern Ethiopia*. Amer. Ass. Petrol. Geol. Bull. 56 (12), 2426-2439.
- Blandford W.T., 1870. *Report on the geology of a portion of Abyssinia*. Assoc. J. Geol. Soc. London 25, 401-406.
- Bosellini A., Russo A., Fantozzi P.L., Getaneh A. & Tadesse S., 1997. *The Mesozoic succession of the Mekelle outlier (Tigre province, Ethiopia)*. Memorie di Scienze Geologiche 49, 95-116.
- Coltorti M., Pieruccini P., Dramis F. & Asfawossen Asrat, 2009. *The geomorphological map of Mt. Amba Aradam southern slope (Tigray, Ethiopia)*. Journal of Maps, v. 2009, 56-65.
- Levitte D., 1970. *The geology of Mekelle. Report on the geology of the central part of sheet ND 37-11*. Geol. Survey Ethiopia, 66 pp., Addis Ababa.
- Nyssen J., Moeyersons J., Poesen J., Deckers J. & Mitiku H., 2002. *The environmental significance of the remobilisation of ancient mass movements in the Atbara-Tekeze headwaters, Northern Ethiopia*. Geomorphology 49, 303-322.
- Silvestri A., 1973. *Orbitoline mesocretacee degli Strati di Graua*. In *Missione Geologica dell'AGIP nella Danalia Meridionale e sugli Altipiani Hararini (1936-1938)*. Acc. Naz. Lincei 4, 101-138.

12. Sediment transport in the Geba River system

Amanuel Zenebe^{1,*}, Matthias Vanmaercke^{2,3}, Jean Poesen², Gert Verstraeten², Jan Nyssen⁴, Gebreyohannes Girmay^{1,2}, Mitiku Haile¹, Hans Bauer^{1,2}, Jozef Deckers²

¹*Mekelle University, Department of Land Resources Management and Environmental Protection, POBox 231, Mekelle, Ethiopia*

²*Department of Earth and Environmental Sciences, K.U.Leuven, Celestijnenlaan 200E, B-3001 Heverlee, Belgium*

³*Fund for Scientific Research—Flanders, Belgium*

⁴*Department of Geography, Ghent University, Krijgslaan 281(S8), B-9000 Gent, Belgium*

**Corresponding author: (amanuelzenebe@gmail.com)*

1 Introduction

Soil erosion by water is one of the most important geomorphological processes in the Northern Ethiopian highlands. Studies on river discharge and sediment yield at the intermediate catchment scale (100 – 10 000 km²) are however hardly available in the Ethiopian highlands. Nevertheless, huge investments are made for dam construction works in this region. Due to a lack of reliable river discharge and sediment yield data many dams and reservoirs have been over-dimensioned (Haregeweyn, et al., 2006). Likewise, many reservoirs fill up with sediments at an alarming rate because of the underestimation of sediment yield. This research, therefore, aims at a better understanding the river discharge and sediment yield dynamics in the Geba River system.

2 Study area

This study was conducted in the catchment of Geba River, a tributary of Tekeze (Atbara) and Nile River (Fig. 1). The Geba drains an area (A) of 5133 km² in the highlands of Tigray, northern Ethiopia. The Geba catchment is located between 38°38'E and 39°48'E and between 13°18'N and 14°15'N, and is representative for the northern Ethiopian highlands regarding its bio-physical characteristics, i.e. climate, geology, soils, topography, and land use. Ten tributaries of the Geba were monitored in this study: Suluh (SU), Genfel (GE), Agula (AG), Ilala (IL), Upper Geba (UG), May Gabat (MY), Endasselassie (EN), Middle Geba (MG), Upper Tankwa (UT) and Lower Tankwa (LT). Several of these catchments are nested. SU, GE, AG and IL are tributaries of UG. UG, MY and EN are tributaries of MG. Furthermore, UT is a tributary of LT, which flows in to Geba a few hundred meters downstream of the Middle Geba gauging station (Fig. 1).

The long term average yearly rainfall in the catchment is 646 mm, strongly concentrated in July-September. During the rainy season, convective clouds are generally formed at the end of the morning, leading to rain showers in the afternoon. The Geba catchment lies between altitudes of 936 and 3314 m.a.s.l. The topography is mountainous with plateaus that are deeply incised by river gorges. The geology of the Geba catchment consists of a basement complex plateau having an upper sedimentary rock layer with some doleritic intrusions and capped by basalt trap series. Alluvium occurs along narrow incised river valleys. The catchment is extensively cultivated including steep and stony valley sides. Effective soil and water conservation measures (stone bunds) were constructed throughout the catchment since the 1970s (Munro et al., 2008).

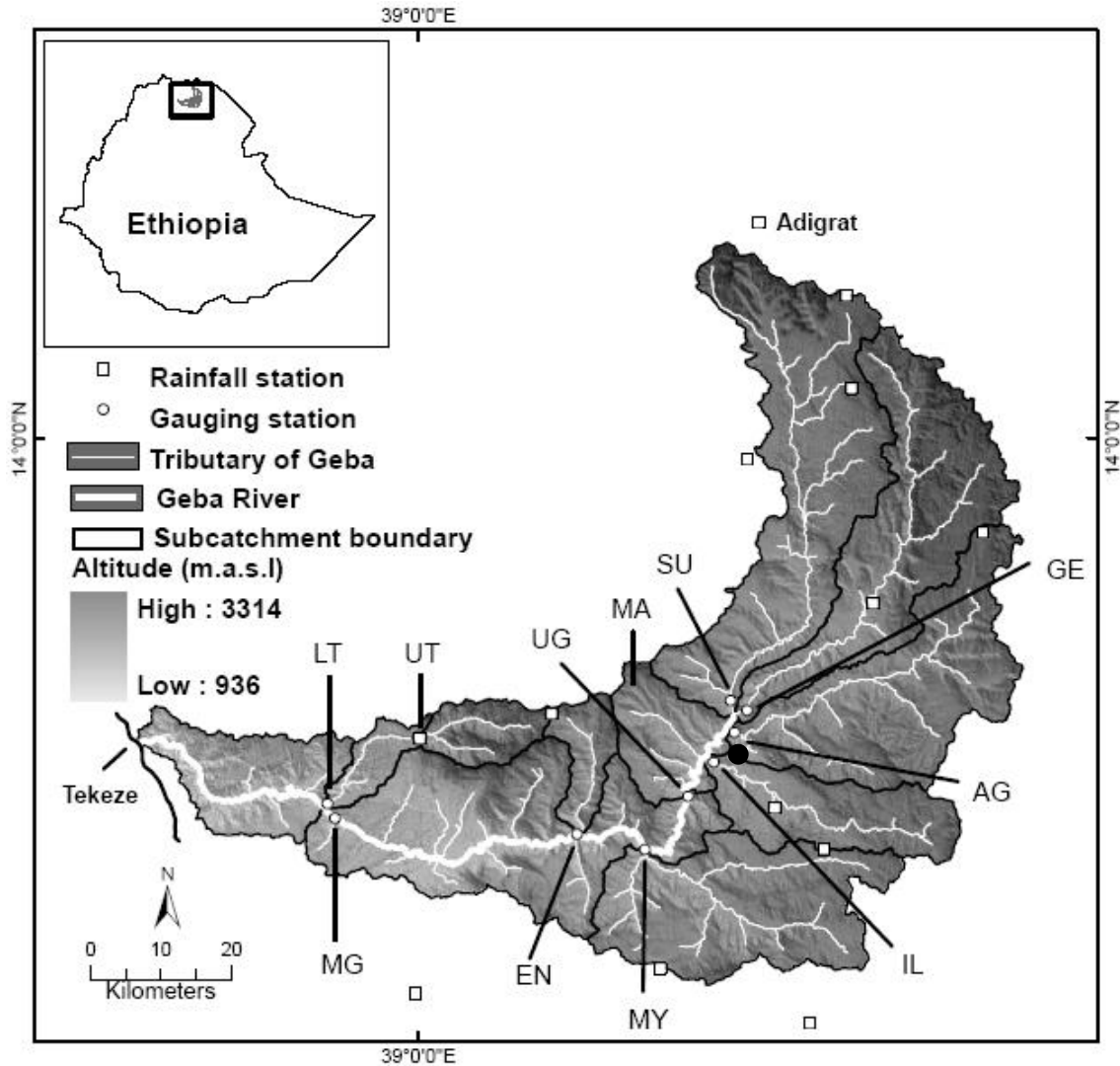


Fig. 1. River and rainfall monitoring stations of Geba catchment (after Zenebe et al., submitted). Red dot indicates excursion viewpoint.

3. Methodology

River discharge and suspended sediment concentration measurements were conducted during the rainy seasons (July – September) of 2004-2007 in ten monitoring stations of Geba catchment (Fig. 1). Discharge was determined using the velocity-area method, and depth-discharge rating curves were developed to estimate the continuous discharge from automatically recorded 10-minute interval depth series using pressure transducers (Zenebe, 2009; Vanmaercke et al., 2010). Suspended sediment samples ($n = 2846$) were taken at the monitoring stations in the Geba catchment from 2004 to 2007 (Vanmaercke et al., 2010). Simple and multiple regression models were applied for identifying the catchment controlling factors of river discharge and area-specific sediment yield (SSY) (Vanmaercke et al., 2010; Zenebe et al., subm.).

4. Results and discussion

4.1 River discharge

The average total estimated river discharge for the Geba catchment is $0.56 \cdot 10^9 \text{ m}^3 \text{ a}^{-1}$ (Zenebe et al., subm.). It ranges between 0.013 and $0.48 \cdot 10^9 \text{ m}^3 \text{ a}^{-1}$ for studied sub-catchments with a minimum area of 130 km^2 (EN) and maximum area 4592 km^2 (MG) respectively. The total runoff volumes of the sub-catchments increase with catchment area. There is a good relationship between rainfall and runoff indicating that rainfall is the major controlling factor of the river discharge.

The runoff coefficients (RCs) vary between 10% and 44% in the Geba catchment. The RCs decrease with catchment area ($R^2 = 0.35$) (Fig. 2); whereas the extent of limestone in the sub-catchments negatively affects runoff depth ($R^2 = 0.45$) and runoff coefficient ($R^2 = 0.41$). This is most probably due to the fractures and karstic features in the rocks.

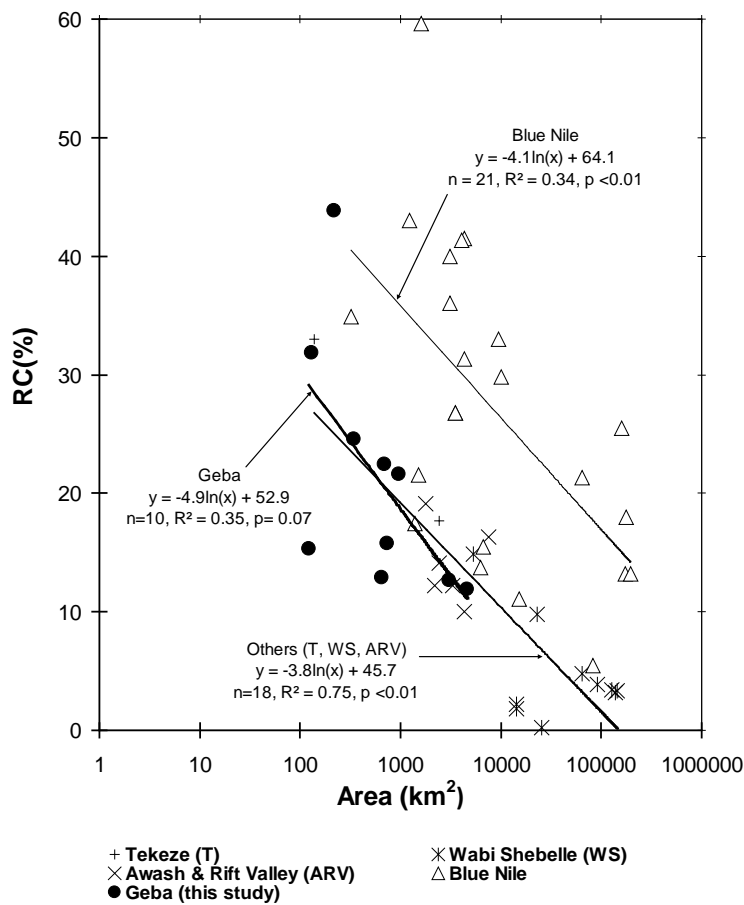


Fig.2. Annual runoff coefficients (RC) vs. drainage area (A) of Geba sub-catchments (Zenebe et al., subm) in comparison with annual RC for other Ethiopian rivers (Nyssen et al., 2004).

4.2 Suspended sediment concentration (SSC) and sediment yield

Suspended sediment concentrations (SSC) increase with runoff discharge and are significantly higher at the beginning of the rainy season than towards the end. The area-specific sediment yield (SSY) ranges between 497 and $6543 \text{ ton km}^{-2} \text{ a}^{-1}$ and varies significantly between different years and sub-catchments. There is a positive relationship between SSY and rainfall ($R^2 = 0.37$) indicating that rainfall is a major controlling factor of SSY (Vanmaercke et al., 2010).

4.3 Flash floods and associated sediment yield

The largest part of the runoff in all monitored catchments took place in the form of flash floods (Fig. 3), i.e. high discharge events that occur in a very short period of time. The hydrologic regime is characterized by flashfloods due to intense convective rainfall, combined with the steep topography and often poor soil cover (Vanmaercke, et al., 2010). These floods mostly occur in the evening or night and often have a steep rising limb with flow depths rising from several centimeters to 3–8 m in less than 1 h (Zenebe, 2009). With regard to sediment transport, both positive and negative hysteresis occurs in the Geba catchment. Mostly there is a positive hysteresis, which is generally attributed to sediment depletion in upper slopes of a basin, sometimes even before the runoff has peaked (Williams, 1989; Vanmaercke et al., 2010).

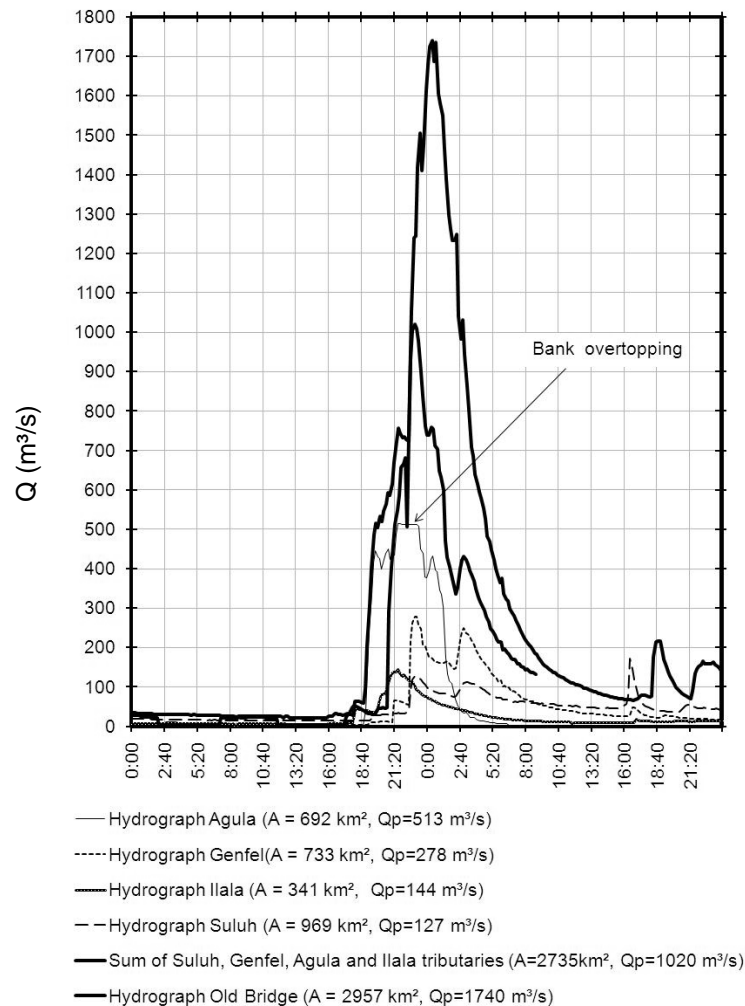


Fig. 3 Hydrograph of Upper Geba and its monitored tributaries during the flash flood of August 26-27 2006 (Zenebe et al., submitted).

4.4 SSY and catchment area

The relationship between catchment area and SSY is complex, as it is scale dependent and, furthermore, depends strongly on active erosion processes (de Vente and Poesen, 2005; Vanmaercke et al., 2010). Nyssen et al. (2004) found a decreasing significant negative

relationship between A and SSY in Ethiopia. However, this relationship included almost no observations for medium-sized catchments ($100\text{--}10,000\text{ km}^2$), and it would underestimate the SSY values of this study. The higher than expected SSY for medium-sized catchments (Fig. 4) can probably be explained by the geomorphologic characteristics of the Ethiopian highlands (Vanmaercke et al., 2010): in catchments up to 4000 km^2 there is little possibility for redeposition as they are generally steep with well confined rivers, whereas larger catchments include extensive floodplains.

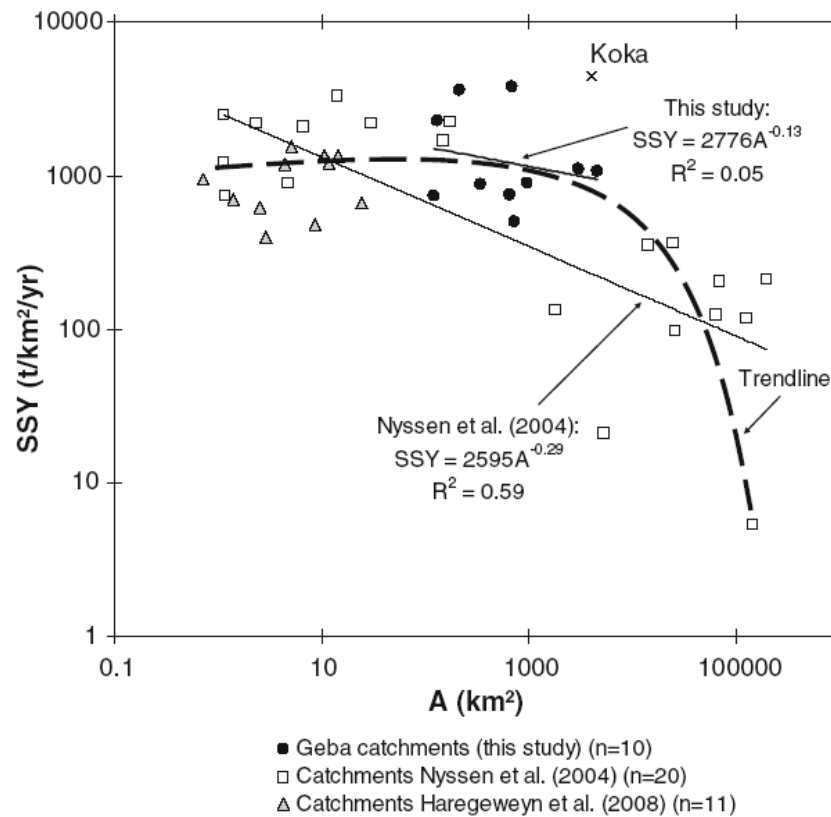


Fig. 4. Yearly sediment yield (SSY) in relation to catchment area (A). Available sediment yield data from other studies were also included (Nyssen et al., 2004; Haregeweyn et al., 2008). Data for Koka are probably overestimated and were not included in the regression analysis of Nyssen et al. (2004). Trend line is obtained by free hand curve fitting (Vanmaercke et al., 2010).

Cumulative distribution analyses of the continuous sediment export data indicate that roughly 50% of the sediment was exported during $<5\%$ of the measuring period (Fig. 5). This clearly illustrates the high temporal variability in sediment export (Vanmaercke et al., 2010). Hence, expensive measurement campaigns should focus on sampling flash floods.

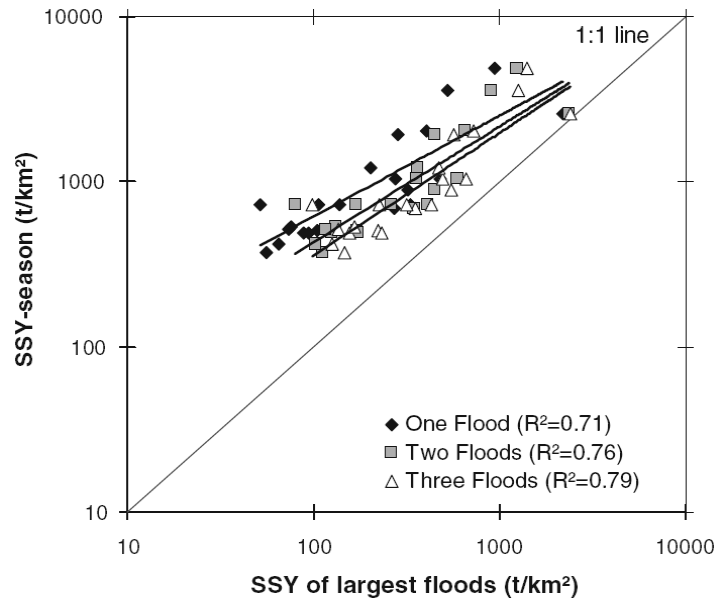


Fig. 5. Relations between the suspended sediment yield (SSY) of the largest one to three floods and the seasonal sediment yield for all data of the ten monitored sub-catchments (n=21) (Vanmaercke et al., 2010)

Soil and water conservation measures have a positive impact on the reduction of runoff and SSY of small catchments in the Ethiopian highlands (Haregeweyn et al., 2008; Nyssen et al., 2009). In contrast, this study showed no significant correlation between RC and estimated stone bund density (SBD) of each sub-catchment (Zenebe, 2009; Zenebe et al., subm.). Similar results were also found between SBD and SSY (Vanmaercke et al., 2010). Both cases (RC and SSY) tend to decrease with SBD although the relationship is insignificant. The lack of complete data on all types of soil and water conservation measures (e.g. soil bund and check dams are not considered) may result in less correlation of SBD with RC or SSY. Moreover, as stone bunds are constructed in all sub-catchments, this may result in less contrast among the catchments to generate a difference in RCs and SSY. Taking into consideration the high spatial variation in runoff and SSY, integrated watershed management would be crucial to reduce the runoff and sediment yield responses in the Geba sub-catchments.

5 Conclusions

The sub-catchments of Geba show large temporal and spatial variation in river discharge due to the variation of rainfall and other bio-physical characteristics in the catchments. Flash floods are intense with large volumes of river discharge and sediment yield causing casualties, and damage to infrastructures. Such events are difficult to predict since these floods depend mainly on local rain storms. The runoff depth is controlled by rainfall and proportion of limestone in the catchment. Runoff coefficient decreases with catchment area, as well as with the proportion of limestone in the catchment and tends to decrease with increasing density of soil conservation structures. Measured sediment yields of medium-sized catchments in the northern Ethiopian highlands are higher than estimations of previous studies. Increasing vegetation cover and strengthening on-going soil and water conservation measures have a positive effect by decreasing runoff and sediment yield. Insight of temporal and spatial variability of river

discharge and sediment yield is important to prevent casualties, damage to infrastructure and allow correct design of water storage facilities.

Acknowledgments

This study was conducted in the framework of VLIR-Mekelle University's IUC-Land Project (Belgium-Ethiopia). Amanuel Zenebe received postdoc financial support from VLIR and was hosted at K.U. Leuven. The help of Hailay Hagos, Kedir Mohammed, Berhane Berhe, Kim Vanhulle, Annelies Beel, Isabelle Neyskens, Elke Soumilion and all other students and guards who helped with the collection and processing of the field data is gratefully acknowledged.

References:

- de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. *Earth Science Reviews*, 71: 95-125.
- Haregeweyn, N., Poesen, J., Nyssen, J., De Wit, J., Haile, M., Govers, G., Deckers, J., 2006. Reservoir sedimentation in Tigray (Northern Ethiopia): Characteristics and sediment deposition problems. *Land Degradation and Development*, 17: 211-230.
- Haregeweyn, N., Poesen, J., Nyssen, J., Govers, G., Verstraeten, G., de Vente, J., Deckers, J., Moeyersons, J., Haile, M., 2008. Sediment yield variability in northern Ethiopia: a quantitative analysis of its controlling factors. *Catena* 75:65–76
- Munro R.N., Deckers, J., Mitiku Haile, Grove, A.T., Poesen, J., Nyssen, J., 2008. Soil landscapes, land cover change and erosion features of the Central Plateau region of Tigray, Ethiopia: Photo-monitoring with an interval of 30 years. *Catena*, 75: 55–64
- Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., Lang, A., 2004. Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. *Earth-Sci. Rev.*, 64: 273–320.
- Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Mitiku Haile, Nigussie Haregeweyn, Moeyersons, J., Martens, K., Amanuel Zenebe, Van Camp, M., Tesfamichael Gebreyohannes, Deckers, J., Walraevens, K., 2009. Impact of soil and water conservation on catchment hydrological response - a case in northern Ethiopia. *Hydrological processes* 24: 1880-1895.
- Vanmaercke, M., Zenebe, A., Poesen, J., Nyssen, J., Verstraeten, G., Deckers, J., 2010. Sediment dynamics and the role of flash floods in sediment export from medium-sized catchments: a case study from the semi-arid tropical highlands in northern Ethiopia. *Journal of Soils and Sediments*, 10: 611-627.
- Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology*, 111: 89–106.
- Zenebe, A., 2009. Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment, northern Ethiopia, PhD dissertation, Department of Geography, K.U. Leuven.
- Zenebe, A., Vanmaercke, M., Poesen, J., Nyssen, J., Verstraeten, G., Haregeweyn, N. Mitku Haile, Kassa Amare, Deckers, S (submitted). Spatial and temporal variability of river discharge in degraded semi-arid tropical catchments of the Northern Ethiopian Highlands. *Land Degradation and Development*.

13. Soil-landscape relationships in the basalt-dominated uplands of Tigray – example in May Leiba

(Summarised from Van de Wauw et al., 2008)

J. Van de Wauw¹, G. Baert², J. Moeyersons³, J. Nyssen⁴, Nurhusein Taha⁵, Amanuel Zenebe^{5,6}, J. Poesen⁶, J. Deckers⁶

¹ *Laboratory of Soil Science, UGent, Krijgslaan 281/S8, 9000 Ghent, Belgium*

² *BIOT Departement, Hogeschool Gent, Voskenslaan 270, 9000 Ghent, Belgium*

³ *Royal Museum for Central Africa, Leuvensesteenweg 13, 3080 Tervuren, Belgium*

⁴ *Geography Department, UGent, Krijgslaan 281/S8, B-9000 Ghent, Belgium*

⁵ *Mekelle University, P.O. Box 231, Mekelle, Ethiopia*

⁶ *Department of Earth and Environment Sciences, K.U.Leuven, Celestijnenlaan 200E, B-3001 Heverlee, Belgium.*

1. Scope

Though knowledge about the distribution and properties of soils is a key issue to support sustainable land management, existing knowledge of the soils in Tigray (Northern Ethiopian Highlands) is limited to either maps with a small scale or with a small scope. The goal of this study is to establish a model that explains the spatial soil variability found in the May-Leiba catchment, and to open the scope for extrapolating this information to the surrounding basalt-dominated uplands.

2. Study methods

A semi-detailed (scale: 1/40 000) soil survey was conducted in the catchment. Profile pits were described and subjected to physico-chemical analysis, augerings were conducted, and profiles were classified according to the World Reference Base for soil resources (WRB) (IUSS Working Group WRB, 2006). This information was combined with information from aerial photographs and geological and geomorphologic observations (**Figure 1,2**).

3. Geology

The May-Leiba catchment is a part of the Mekelle outlier which consists of sub horizontal alternating series of cliff forming and non cliff forming Antalo limestone of Jurassic age, overlain by Agula Shale (Jurassic age) in the SE corner of the study area (figure 2). At the northern side of the catchment, the unconformity of the contact between Antalo limestone and the overlying Amba Aradom sandstone may be observed in the field. The top of the table mountains consists mainly of Amba Aradam sandstone of Cretaceous age and by two series of Tertiary basalt flows (Nyssen et al., 2002). In between these basalt layers silicified lacustrine deposits (Garland, 1980) can be locally found. The Mesozoic succession of the Mekelle outlier is described by Bosellini et al. (1997).

The formation of the rift valley tectonic uplifts of about 2500 m and differential erosion resulted in stepped sub horizontal landforms. The highest point of the catchment is located on a basalt ridge at 2835 m a.s.l. At the south-east of the study area a dolerite sill outcrops, inducing an extra uplift in the higher lying sandstone and basalt.

4. Geomorphology

Important in this area are different landslides. They occur within the limestone area, but can also cause basaltic material to be deposited on down slope located limestone areas, which makes them very important for soil distribution. Research on these landslides has been done in nearby

areas, including the southern fringe of the catchment (Nyssen et al., 2002 and section 14 , p. 77 in this excursion guide).

5. Soils and soil-landscape relationships

To create the soil map, different approaches are possible: the pedologic approach and the physiographic or geomorphologic approach (Wielemaker et al., 2001). The first method tries to create maps with taxonomic pure soil data or soil associations. The geomorphologic approach uses soils as part of the landscape. We have chosen for this geomorphologic approach because extrapolating the results of the soil map needs this geomorphologic information, and we believe that for most uses of the soil map will be combined with such geomorphologic information.

The main driving factors that define the variability in soil types found were: 1) geology, through soil parent material and the occurrence of harder layers, often acting as aquitards or aquicludes; 2) different types of mass movements that occupy large areas of the catchment; and 3) severe human-induced soil erosion and deposition. These factors lead to “red-black” Skeletic Cambisol–Pellic Vertisol catenas on basalt and Calcaric Regosol–Colluvic Calcaric Cambisols–Calcaric Vertisol catenas on limestone (**Figure 3**). Leading to the soil map which is shown in **Figure 4**.

The driving factors can be derived from aerial photographs. This creates the possibility to extrapolate information and predict the soil distribution in nearby regions with a comparable geology. A model was elaborated, which enables the user to predict soil types, using topography, geomorphology, geology and soil colours, all of which can be derived from aerial photographs. This derived model was later applied to other catchments and validated in the field.

References:

- Bosellini, A., Russo, A., Fantozzi, P.L., Getaneh Assefa, Solomon Tadesse, 1997. The Mesozoic succession of the Mekele outlier (Tigre Province, Ethiopia). *Memorie di Scienze Geologiche*, 49: 95-116.
- Garland, C., 1980. Geology of the Adigrat Area. Ministry of Mines, Energy and Water Resources, Geological survey of Ethiopia, Addis Ababa, 51 pp.
- IUSS Working Group WRB, 2006. World Reference base for soil resources 2006. World Soil Resources Report, 103. FAO, Rome, Italy, 126 pp.
- Nyssen, J., Moeyersons, J., Poesen, J., Deckers, J. and Mitiku Haile, 2003. The environmental significance of the remobilisation of ancient mass movements in the Atbara-Tekeze headwaters, Northern Ethiopia. *Geomorphology*, 49(3-4): 303-322.
- Van de Wauw, J., G. Baert, J. Moeyersons, J. Nyssen, K. De Geyndt, Nurhussein Taha, Amanuel Zenebe, J. Poesen, and J. Deckers. 2008. Soil-landscape relationships in the basalt-dominated highlands of Tigray, Ethiopia. *Catena* 75: 117-127.
- Wielemaker, W.G., de Bruin, S., Epema, G.F. and Veldkamp, A, 2001. Significance and application of the multi-hierarchical landsystem in soil mapping. *Catena* 43(1): 15-34

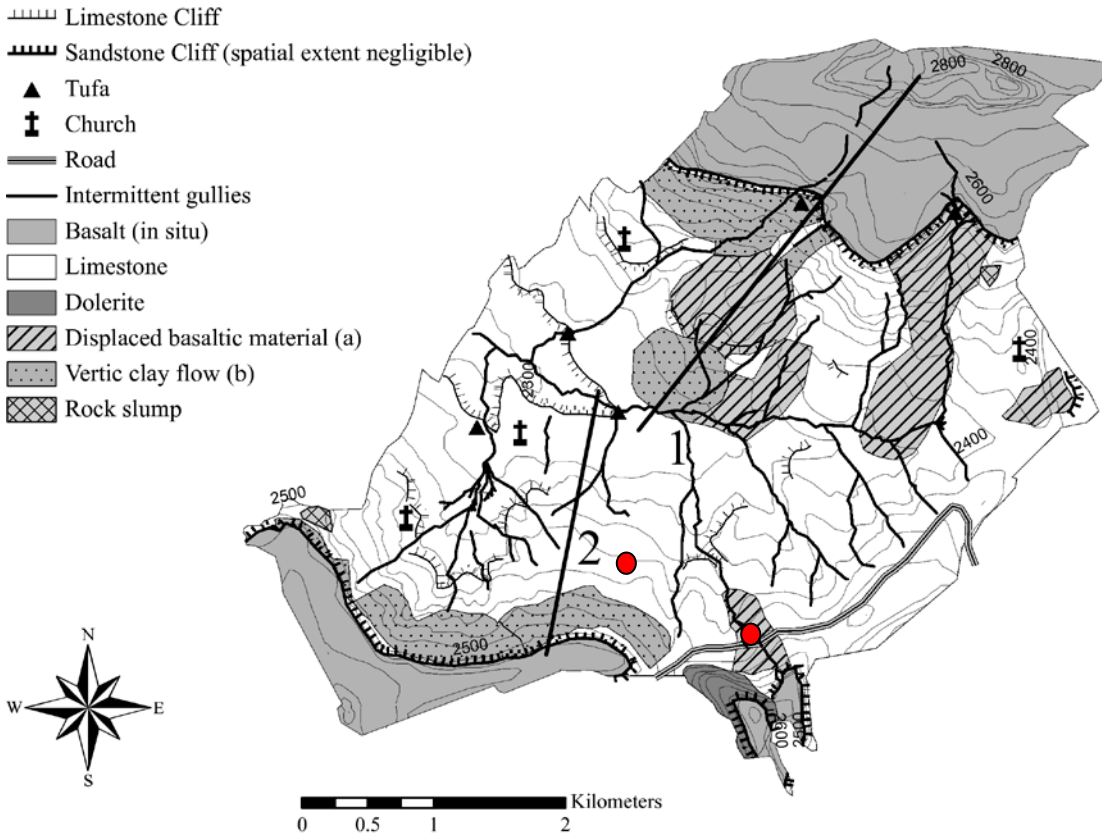


Figure 1: Geologic and geomorphic map of the May Leiba catchment. The two bold lines indicate the position of the transects shown in Fig. 3. Red dots indicate location of excursion stops.

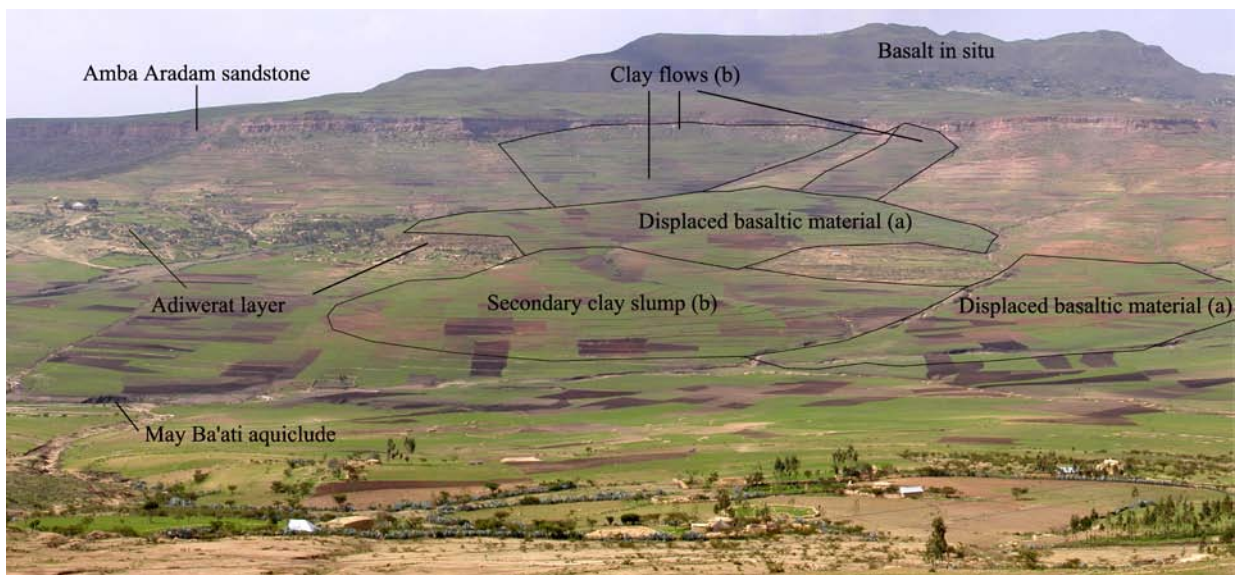
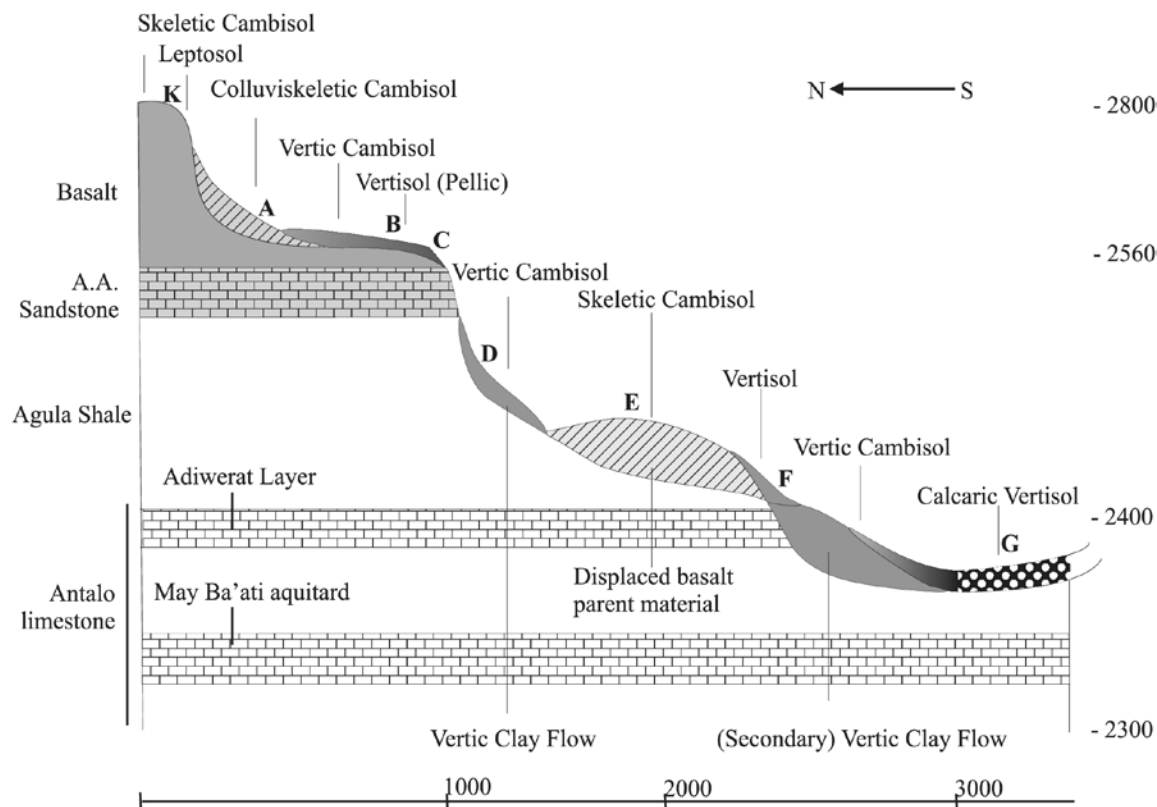


Figure 2: Overview of the northern side of the May-Leiba catchment. Different kinds of mass movements are depicted: (a) large scale landslides which move basaltic parent material downslope; and (b) flows of vertic clays, deposited at the foot of the sandstone cliff, or similar secondary flows at the foot of large scale landslides.

Transect 1



Transect 2

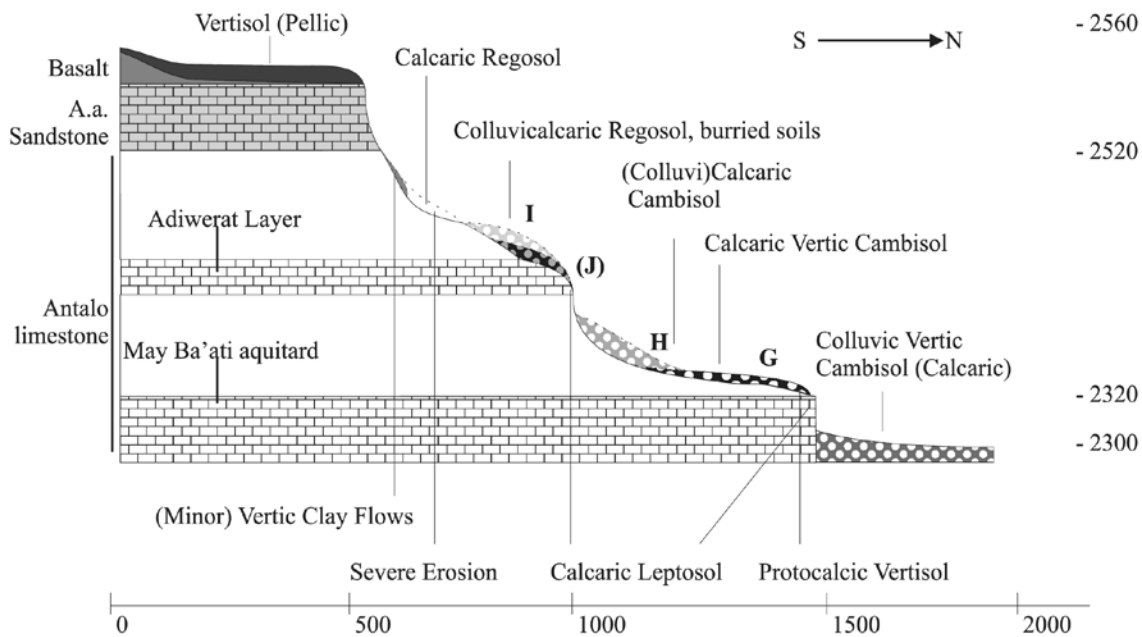


Figure 3: Catena on basalt and basaltic mass movement deposits (transect 1) and on limestone (transect 2). Hatched greys show displaced basaltic parent material. Dark grey denotes vertic clays, white dots calcaric properties.

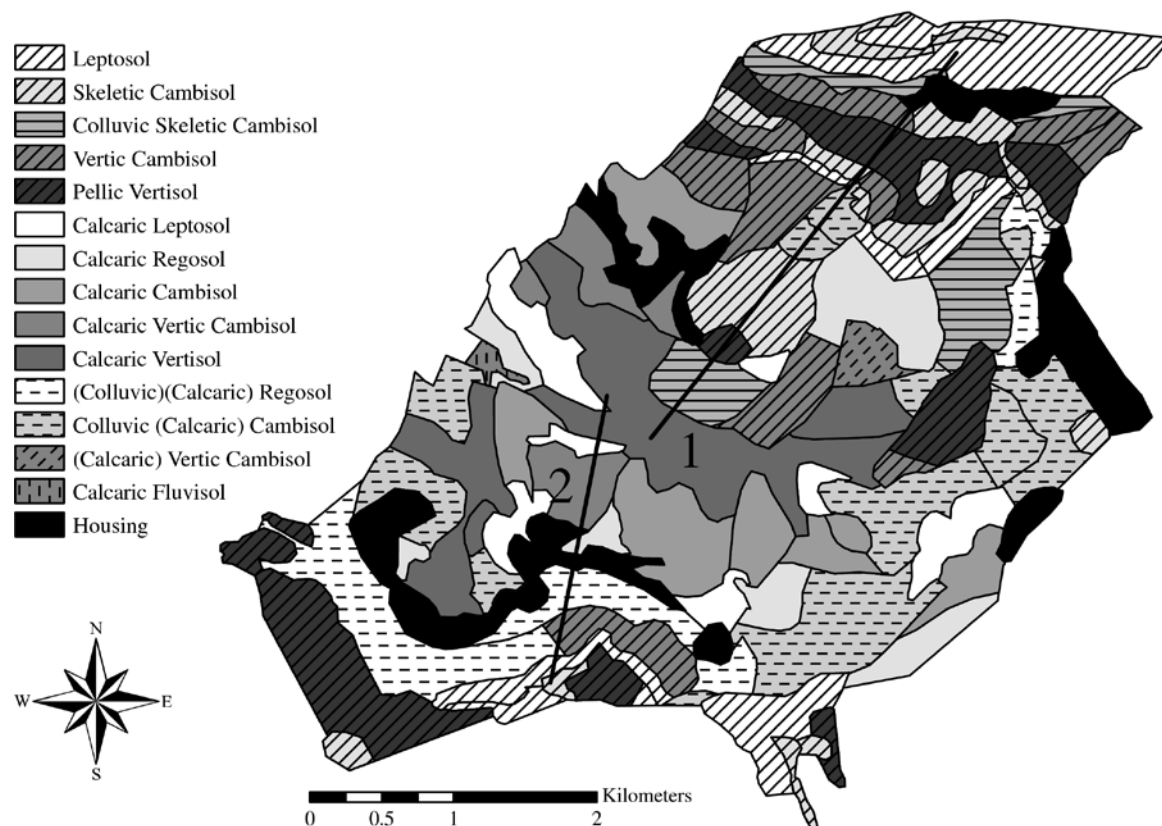


Figure 4: Soil map of the May-Leiba catchment. Within the soilmap full lines indicate basalt parent material. Dashed lines indicate a complex of limestone and basalt parent material. The grey-value determines the degree of profile development. The horizontal pattern indicates colluvial deposits. The two bold lines indicate the position of the transects shown in Figure 3.

14. Rainfall-triggered slope failures on shale hillslopes; the case of Amba Raesat

Kifle Woldearegay^a, Wulf Schubert^b, Kurt Klima^c, Abera Mogessie^d,

^a Department of Applied Geology, Mekelle University, Ethiopia

^b Institute of Rock Mechanics and Tunnelling, Graz University of Technology, Austria

^c Institute of Applied Geosciences, Graz University of Technology, Austria

^d Institute of Earth Sciences, Karl-Franzens University of Graz, Austria

1. Introduction

The hillslopes which are underlain by Agula shale formation in Mekelle area, northern Ethiopia, are frequently affected by rainfall-triggered slope failures. Among the localities with records of slope instability are Hagereselam, Ambaradom, and Adishu areas (Fig. 1). Slope failures in the Hagereselam area have affected a gravel road (Nyssen et al., 2002). Landslides in the Ambaradom area have blocked a gravel road, while slope instability in the Adishu area (about 7 km west of Adishu town in a locality called Keyeh Tekli) have caused major damage on about 6 hectare of agricultural land and on 30 rural houses. A total of 120 people were displaced from the Adishu landslide-affected areas, and many rural people are still living in terrains potentially endangered by slope instability.

This paper presents causes and failure mechanisms of landslides on shale hillslopes in the Mekelle area, with the case of Hagereselam area (more precisely: the slopes of Amba Raesat, in the southern part of May Leiba catchment).

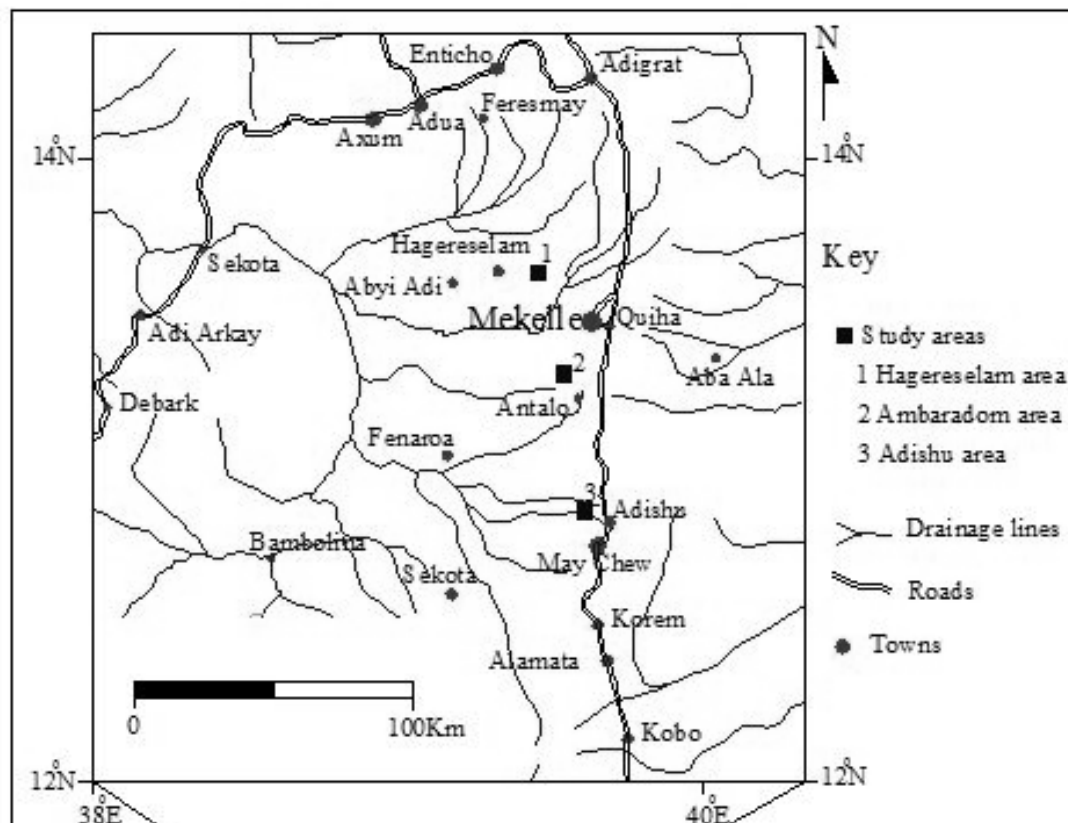


Fig. 1. Location of the landslide affected areas on shale hillslopes in northern Ethiopia.

2. The study area

The investigated site is characterized by high topographical variability, with elevations ranging from about 2000m to 2800m a.s.l. Morphologically, the area is associated with mountains, and steep hillslopes. Most of the area is represented by sparse or no vegetation cover, with moderately dense trees in localized cases/as patches.

The nearest meteorological station at Hagreselam receives annual precipitation that vary from about 800mm to 1200mm; with main rainfall season being in the months June to September.

3. Materials and methods

Failed/unstable slopes were described in the field, following the work of Varnes (1958). Several factors like slope gradients, slope shapes, bedrock lithology, and dimension (length, width and depth) and runout (travel distance) of the failed masses were determined. The slope gradients at source areas of the landslides were estimated from field measurements (using Theodolite) and from 20m or 40m interval topographic contours. The slope shapes of the landslide-affected sites were described based on the nine hillslope forms (Parsons, 1988). The depths of failures were estimated from examinations of scars of recent landslides, and from subsurface data (test pits and trenches).

Schmidt Hammer Rebound tests and tilt tests were performed to estimate the geotechnical properties of the different rocks. The in-situ saturated hydraulic conductivities of soils and highly weathered rocks were estimated using the inverse auger-hole test method (Kessler and Oosterbaan, 1974). In order to properly understand the landslide processes, a representative unstable slope profile was selected for detailed geological, geogydrological and geotechnical evaluations.

Grain-size distribution analysis and Atterberg tests, according to the Unified Soil Classification System (USCS) (US Army of Engineers, 1970), were performed on soil samples. Laboratory direct shear tests were conducted on 2 soil samples.

4. Results of the study

4.1 Characteristics of rocks and soils

The regional geology of northern Ethiopia has been studied by several authors (e.g. Mohr, 1962; Beyth, 1972; Bosellini et al., 1997; Russo et al., 1999). Though this study is mainly based on available geological information, for better understanding of the failure processes, detailed evaluations of the distributions and characteristics of rocks and soils of the landslide affected site was conducted.

4.1.1 Characteristics of rocks

The major rock successions in the landslide-affected sites include Agula shale and Ambaradom sandstone.

Agula shale: it is characterized by gray, green and black, thinly bedded (0.01- 0.2m), moderately to highly weathered shale (marly), which is interlaminated with thin (up to 0.1m thick) limestone beds. In some cases it is intercalated with thin layers (thickness up to 0.05m) gypsum beds.

Ambaradom sandstone: this formation is fine to medium grained, white to pink coloured, thickly bedded (0.5-2.2m), slightly to moderately weathered sandstone, which is interbedded

with thin layers (thickness up to 0.1m) of siltstone/claystone. The geotechnical properties of the Ambaradom sandstone was estimated from field tests (Schmidt Hammer Rebound tests and tilt tests) and laboratory investigations. Results of the study revealed that the Ambaradom sandstone has: (a) an average unit weight of 23KN/m^3 , (b) an average UCS value (MPa) of 100MP, and (c) average friction angle of 30 degrees.

4.1.2 Characteristics of soils

Residual soils and debris materials are the main soil types on the Amba Raesat slopes. For practical reasons, all the different soil types are considered as “unconsolidated deposits”.

Grain-size distribution analysis and Atterberg tests were performed on soils derived from Agula shale, and on fine grain dominated unconsolidated deposits (from the lower sections of the hillslopes). Results indicate that these soils, derived from Agula shale, are characterized by inorganic clays of high plasticity (CH), inorganic clays of low to medium plasticity (CL), inorganic silts, fine sandy or silty soils of high plasticity (MH), and inorganic silts and very fine sands with slight plasticity (ML). The fine grain dominated unconsolidated deposits are represented by clayey sand (SC), inorganic clays of low to medium plasticity (CL), inorganic silts, fine sandy or silty soils of high plasticity (MH), and inorganic silts and very fine sands with slight plasticity (ML). Results of the direct shear tests of the soils derived from Agula shale is indicated in Table 1.

Table 1. Shear strength parameters of the soils derived from Agula shale at Amba Raesat (direct shear test in drained condition).

Sample code	γ (KN/m^3)	c' (KN/m^2)	c_r' (KN/m^2)	$\phi'(^{\circ})$	$\phi_r'(^{\circ})$
HS1	17	22	15	21	16
HS2	20	16	12	22	17

(γ is the moist unit weight; c' is the peak cohesion value; c_r' is the residual cohesion value; ϕ' is the peak friction angle; ϕ_r' is the residual friction angle).

In-situ saturated hydraulic conductivity tests, using the inverse auger-hole test method, were performed on 3 sites. Results indicate that the highly weathered Agula shale has hydraulic conductivity values that range from 4.5×10^{-4} m/s to 1.8×10^{-7} m/s, while that of the fine grain dominated unconsolidated deposits vary from 1.2×10^{-3} m/s to 2.5×10^{-6} m/s.

4.1.3 Down-slope variation in slope mass properties

To understand the processes leading to slope instability in the Hagreselam area, representative unstable slope profile was evaluated. As can be noted from Fig. 2 & Fig. 3: (i) the upper sections are dominated by fractured Ambaradom sandstone, (ii) the middle sections are represented by unconsolidated deposits which display variations in proportions of fine to coarse grain components, with a general trend of fining down the slope, and (iii) the lower section is associated with excavation (road cuts). Underlying the Ambaradom sandstone and the unconsolidated deposits is weathered Agula shale.

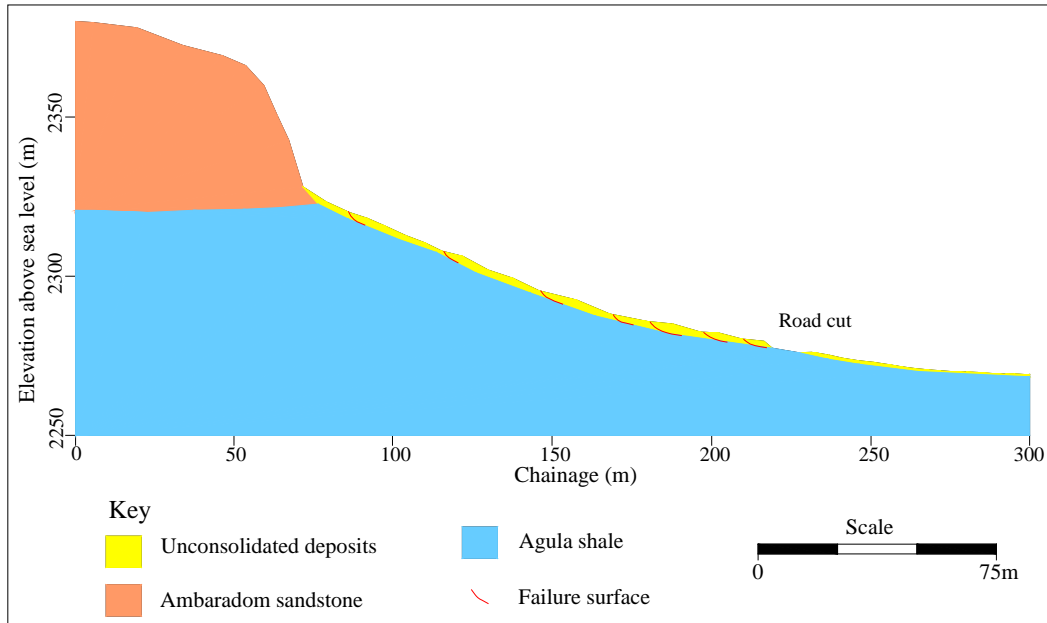


Fig. 2. Slope profile of Amba Raesat (Hagereslam area).



Fig. 3. Landslides on the slopes of Amba Raesat.

5. Types and failure mechanism of landslides

Minor rockfalls and debris/earth slides are the main types of slope failures in the area, though the association of the former type of failure with rainfall events is not yet known. Rockfalls prevailed on steep hillslopes which are represented by the Ambaradom sandstone. The debris/earth slides involved instability of unconsolidated deposits, with failure surfaces at the interface between the soil masses and the underlying weathered Agula shale. The modes of failures are mostly translational slides, with compound types in limited areas where there exist relatively greater thickness of unconsolidated sediments.

Geohydrological evaluation of the landslide-affected area revealed that the upper sections of the hillslopes, dominated by fractured rocks and/or debris materials of higher permeability, are acting as surface/subsurface water recharge zones to the down-slope areas. The underlying Agula shale is

impeding the vertical flow, thus promoting lateral flow of water parallel to the slope surface. The trace of the contact between the unconsolidated deposits and the underlying Agula shale is therefore typically a zone of high potential for the development of seepage forces within the slopes. The fine grain dominated unconsolidated deposits at the lower sections of the hillslopes, due to their low permeability behaviour, are retarding drainage.

High prevalence of debris/earth slides in areas underlain by Agula shale is related to several factors, mainly to its: (a) low shear strength behaviour, (b) low permeability characteristics which enhance the development of seepage forces within the overlying slope masses, and (c) high susceptibility to weathering, erosion and lubrication (softening). Several authors (e.g. Gezahegne, 1998; Ayalew, 1999; Ayalew and Yamaneshi, 2004) studied landslide problems in the Blue Nile gorge in Ethiopia and indicated that the presence of shale materials, overlain by loose soil masses and/or intercalated within more resistant rocks, are important factors affecting slope stability.

6. Conclusion

From the geohydrological evaluation, it can be concluded that the shale hillslopes are favourable for the development of seepage forces within the slopes due to the presence of:

- Fractured rocks and debris materials, of high permeability and high infiltration capacity, at the upper sections of the hillslopes which enhance rainwater percolation and recharge to the down-slope areas,
- Soft and (semi) impermeable bedrock type (Agula shale), underlying the permeable rocks and the unconsolidated deposits, which retard vertical flow of water and promote lateral flow of water parallel to the slope surfaces,
- Fine grain dominated unconsolidated deposits at the lower sections of the hillslopes which retard drainage of water, and hence promote rise in water level within the slopes during heavy rainfall seasons,
- Pervious confined layers at the transition zones between the unconsolidated deposits and the underlying weathered Agula shale, which promote concentrated subsurface water flow and subsurface erosion (piping) of fine materials.

Detailed evaluations of the characteristics of failures, and the relationships between unstable slopes and various factors indicate that rainfall-triggered landslides on shale hillslopes of the northern highlands of Ethiopia are dominantly influenced by the complex interactions of the following factors:

- (1) Slope gradients which generate stresses to promote failures,
- (2) Soft and (semi) impermeable Agula shale bedrock types which are characterized by low shear strength, low permeability, and high susceptibility to weathering, erosion and lubrication (softening),
- (3) Slope shapes that enhance the convergence of surface and subsurface water flow, and hence promote water-pressure build-up within the slope masses,
- (4) Drainage lines (stream/river incision) and/or artificial excavations (road cuts) that cause oversteepening of slopes and removal of materials that could provide support at the toes, and
- (5) Absence of vegetation cover of deeper root penetrations which could have played a positive role on shallow debris/earth slides by increasing the strength of soil masses.

Acknowledgements

Funds for this research were provided by the Austrian Exchange Service (ÖAD), Austrian Development Cooperation in Ethiopia, Mekelle University, Ethiopian Science and Technology Commission, and Ethiopian Transport Construction Design Enterprise and are highly acknowledged.

References

- Ayalew L (1999) The effect of seasonal rainfall on landslides in the highlands of Ethiopia. *Bull. Eng. Geol. Env.*, 58: 9-19.
- Ayalew L, Yamagishi H (2004) Slope failures in the Blue Nile basin, as seen from landscape evolution perspective. *Geomorphology*, 57: 95-116.
- Beyth M (1972) Paleozoic-Mesozoic sedimentary basin of Mekelle outlier northern Ethiopia. *American Association of Petroleum Geologists. Bulletin* 56, 2426-2439.
- Bosellini A, Russo A, Fantozzi PL, Getaneh A, Solomon T (1997) The Mesozoic succession of the Mekelle outlier Tigray province Ethiopia. *Memorie di Scienze Geologiche* 49, 95-116.
- Gezahegn A (1998) Slope instability assessment in the Blue Nile Gorge, Ethiopia. In: Moore, D. & Hungr, O. (Eds.), *Proceedings of the 8th International IAEG Congress*, Vancouver, Balkema, Rotterdam. Pp. 1437-1442.
- Kessler J, Oosterbaan R (1974) Determining hydraulic conductivities of soils. In: *Drainage principles and applications*. International Institute for land reclamation and improvement, Wageningen, The Netherlands, Vol. 16 (III), pp 253-296.
- Mohr PA (1962) In *The Geology of Ethiopia*. II Poligrafico, Asmara, 268pp.
- Nyssen J, Moeyersons J, Poesen J, Deckers J, Haile M (2002) The environmental significance of the remobilization of ancient mass movements in the Atbara-Tekeze headwater, Northern Ethiopia. *Geomorphology*, 49: 303-322.
- Parsons AJ (1988) *Hillslope Form*. Routledge: London. 212pp.
- Russo A, Fantozzi P, Tadesse S (1999) Geological map of Mekelle Outlier (Western Sheet), 1: 100000 scale. *Cooperazione Italiana*, Roma.
- U.S. Army of Engineers (1970) *Laboratory Soils Testing*. Engineer Manual, EM 1110-2-1906.
- Varnes DJ (1958) *Landslide Types and Processes*. *Landslides and Engineering Practice*, Eckel E.B. (Ed.), Highway Research Board, Special Report, Vol. 29, 20-47.

15. Using the sediment of Maileba reservoir for land reclamation

Gebreyohannes Girmay^{1,2}, Jan Nyssen³, Jean Poesen², Roel Merckx², Hans Bauer^{1,2}, Mitiku Haile¹, Jozef Deckers²

(after Gebreyohannes et al., 2011)

¹ Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia

² Department of Earth and Environmental Sciences, K.U.Leuven, Belgium

³ Department of Geography, Ghent University, Belgium

Accelerated soil erosion leads to siltation of reservoirs in Northern Ethiopia and decline of their life span (Nigussie et al., 2006). As in northern Ethiopia the reservoirs are dry at the end of the dry season, we evaluated the potential of recycling these sediments for land reclamation. This land reclamation method, that seems obvious, is however poorly described in literature (Fonseca et al., 1998). The Maileba catchment (Van de Wauw et al., 2008) was chosen for this study.

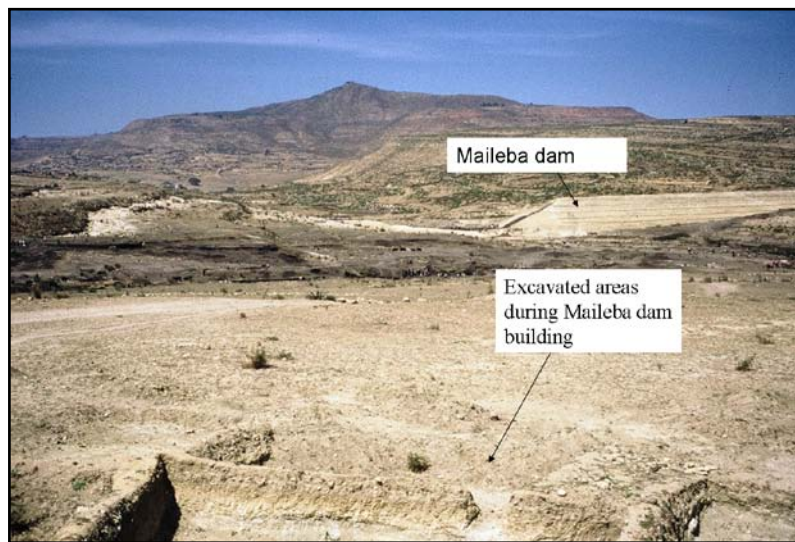


Figure 1. Maileba dam under construction in 1998, looking downstream. The core of the dam consists of compacted black clay soil excavated from the valley bottom, whereas the bulk fill material is composed of weathered marl excavated on the valley sides, including the area where the experiment was conducted in 2009 (at left on the photograph).

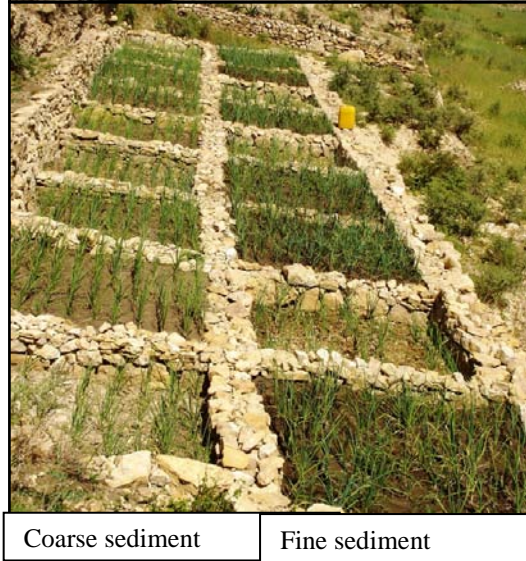


Figure 2. Plot lay out and performance of garlic (*Allium sativum*) (August, 2009). The planting date was July 4, 2009. One plot size is 2 m x 2 m. Coarse sediment (left line of plots) represents application of silty clay loam sediment and fine sediment represents application of silty clay sediment as treatments of the sub-plots, except for the control plots without sediment applied, such as the lower left plot.

Bare lands, from where fill material had been excavated (Fig. 1), were reclaimed with 15 cm and with 30 cm thick layers of sediments, and planted with a local garlic (*Allium sativum*) cultivar

(Fig. 2). Total biomass and bulb yield were 3 times higher on the reclaimed plots than on the control plots (11.7 t/ha versus 3.6 t/ha for the biomass; 7.7 t/ha versus 2.0 t/ha for the yield); however, sediment thicknesses did not make any significant difference in crop productivity (Fig. 3). When transport and labour cost are taken into account, plots with 15 cm of sediments had in the first cropping season already a benefit-cost ratio of 3, while those with 30 cm had a benefit-cost ratio of 0.9. This study shows that using reservoir sediments is an economically viable strategy for land reclamation as it may improve income with as much as 76%. In view of the magnitude of reservoir sedimentation in semi-arid areas throughout Tigray, the outcome of this research shows the way to turn this major problem into an opportunity which will contribute to poverty alleviation.

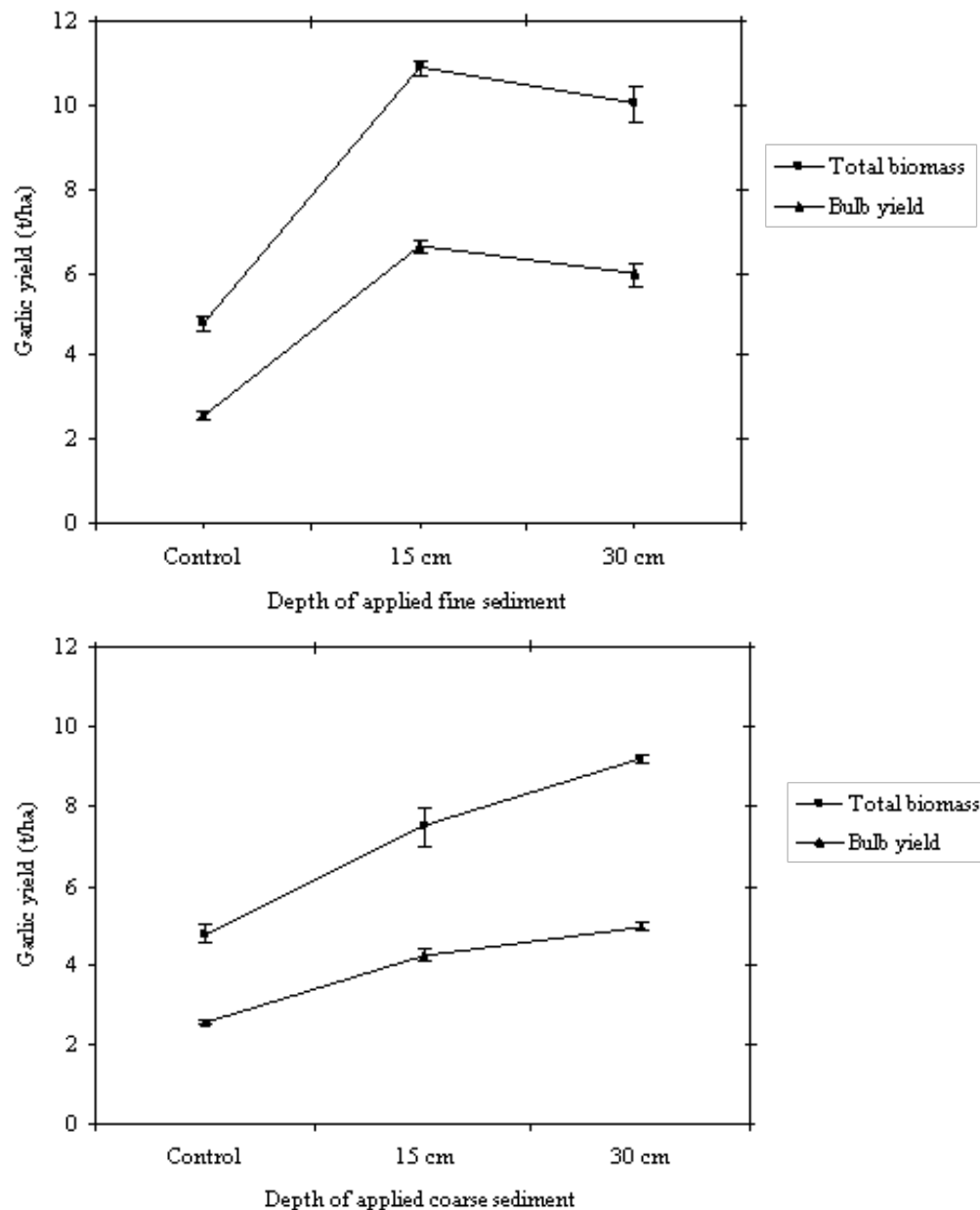


Figure 3. Effects of the application of different depths of sediment on garlic yield (t/ha) ($n = 6$). Top: fine sediment; bottom: coarse sediment.

References

- Gebreyohannes Girmay, Nyssen, J., Poesen, J., Merckx, R., Bauer, H., Mitiku Haile, Deckers, J., 2011. Land reclamation using reservoir sediments in Tigray, northern Ethiopia. *Soil Use and Management*, submitted.
- Fonseca, R., F.J.A.S. Barriga and W.S. Fyfe, 1998. Reversing desertification by using dam reservoir sediments as agriculture soils. *Episodes*. 21, 4; 218-224.
- Nigussie Haregeweyn, Poesen, J., De Wit, J., Mitiku Haile, Govers, G., Deckers, J. 2006. Reservoirs in Tigray: characteristics and sediment deposition problems. *Land Degradation & Development* 17, 211-230.
- Van de Wauw, J., Baert, G., Moeyersons, J., Nyssen, J., Nurhussein Taha, Amanuel Zenebe, Mintesinot Behailu, Poesen, J., Deckers, J., 2008. Soil-landscape relationships in the basalt dominated uplands of Tigray, Ethiopia. *Catena*, 75: 117-127.

16. The effect of soil and water conservation treatments on rainfall-runoff response and soil losses in the Northern Ethiopian Highlands: the case of May Leiba catchment

Gebeyehu Taye ^{a,b,*}, Jean Poesen^b, Jozef Deckers^b, Daniel Tekka^{a,c}, Nigussie Haregeweyn^{a,d}, Bas van Wesemael^c, Jan Nyssen^e

^a *Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia*

^b *Department of Earth and Environmental Sciences, K.U.Leuven, Belgium*

^c *Department of Geography and Geology, UCLouvain, Belgium*

^d *Tottori University, Japan*

^e *Department of Geography, Ghent University, Belgium*

1. Introduction

In Tigray region, an attempt has been made at different levels to reduce the effect of moisture stress on agricultural productivity through water harvesting, and 54 earth dams were constructed from 1994 to 2003. Haregeweyn et al., (2006) emphasized that the most important challenges related to water harvesting schemes are siltation, and less water storage in the reservoirs compared to design capacity. Losses due to seepage, evaporation and to physical soil and water conservation (SWC) structures in the catchment are not well documented. In the same study differences of inflow were also observed between years before and after treating catchments with SWC structures attempting to reduce sediment inflow into the reservoirs. In the first three years the inflow was high in some reservoirs but with the construction of SWC structures, the runoff volume delivered decreased. This already indicates that the impact of SWC structures on the hydrological responses of the catchments has been overlooked during the planning and designing phases of most water harvesting structures in Tigray. Understanding the effect of SWC treatment on hydrological responses is crucial for proper design of water harvesting schemes and to resolve conflict of interest arising between treating catchment with different SWC measures and collecting water in the reservoir for irrigation. The overall objective of this study is therefore, to better understand runoff generation processes in areas treated with different SWC measures and thereby, to contribute to better water resources management for local communities in semi-arid highlands of Ethiopia. More specific objectives include: 1. quantify the effect of different SWC treatments on rainfall-runoff response at plot scale 2. Identify the major factors and their relative importance in controlling the transformation of rainfall to runoff within plots. 3. Determine the effect of SWC measures on soil loss reduction for different land use and slope.

2. Description of the Study Area

The May Leiba catchment and its major geological and geomorphic features are described by Van de Wauw et al. (2008) and on p. 72 in this excursion guide. More than 80% of rainfall at May Leiba is concentrated and occurs between June and September (Nyssen et al., 2005), preceded by more dispersed rain during March to May. The region is characterised by recurrent drought and extreme moisture stress which during some years results in crop failure due to very short growing period (Fig.2). The average monthly air temperature ranges between 12 and 19 °C. Cropland is the major land use in the catchment covering around 65% of the area and other land uses include rangeland for grazing, residential areas and exclosures.

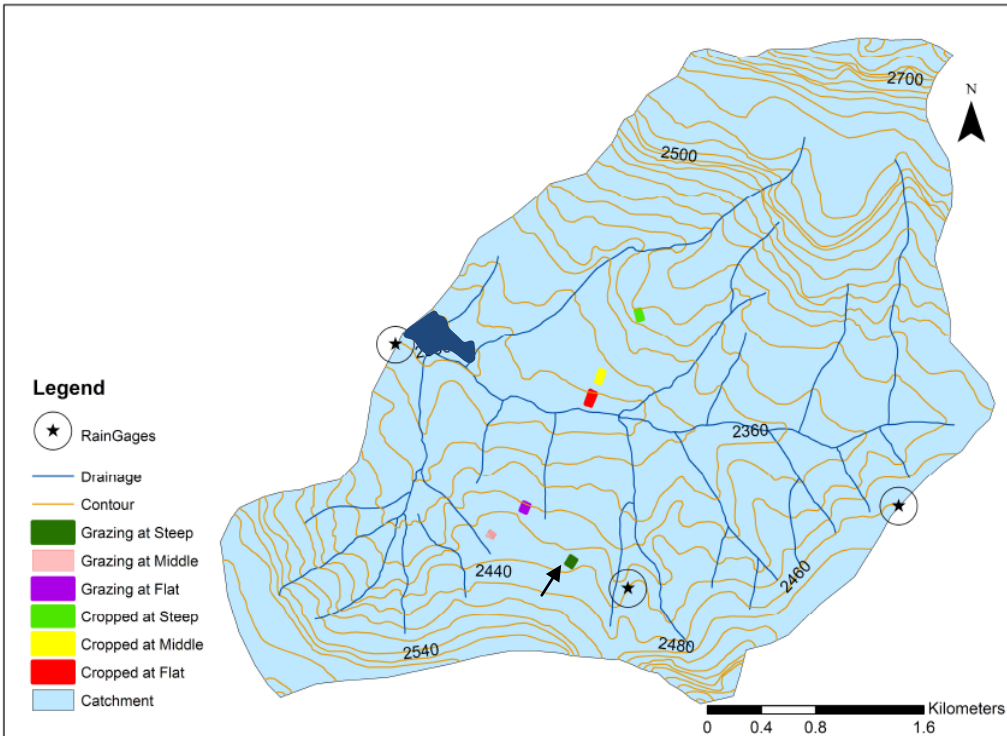


Figure 1. Study catchment with the location of runoff and rainfall measuring sites. Arrow indicates the visited plot

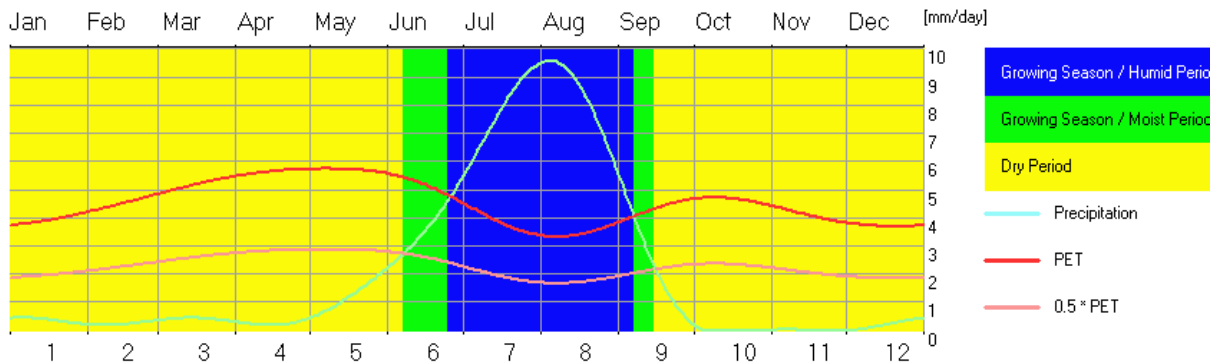


Figure 2. Long-term averages from FAO's «New LocClim» tool.

3. Methodology

Field-sized runoff plots on rangeland (600-630 m²) and on cropland (770-1000 m²) were installed in February to April 2010 before the rainy season. These plots were located on three slope ranges; gentle, middle and steep slopes of the rangelands and croplands. Measuring sites on the rangelands had three SWC treatments (stone bund, trench and stone bund with trench) plus one control plot; while those on croplands had two SWC treatments (stone bund and stone bund with trench) and one control for each site. All plots were bounded with soil bunds (50cm wide 30-45cm high). Run-on interception ditches were installed to protect the plots from inflow. The plots were kept 3 m apart to avoid interflow of water from one plot to the next and lined with geomembrane plastic to store the runoff generated from each plot.

The depth of water in the trench is measured and water is removed manually on a daily basis. The runoff collecting trenches were designed to accommodate runoff resulting from extreme rainfall events using the maximum rainfall recorded from 2004 to 2006, and maximum runoff coefficient. Runoff volume was calculated from runoff depth measurements using depth-area relationship, subtracting the direct rain falling on the trench. To compensate for trench geometry, runoff depth measurements were taken at five fixed points along the trench (Fig. 3).

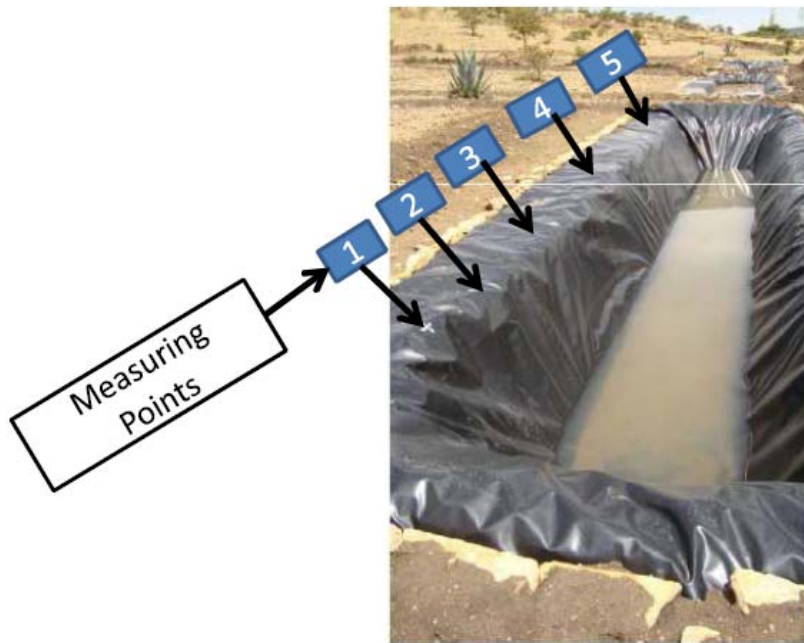


Figure 3. Water collecting trench at the foot of a runoff plot and measuring points for water depth

Ground cover by vegetation was monitored on a weekly basis using point count method at 50 cm interval during the rainy season. Runoff samples were collected to determine sediment concentration after thoroughly mixing the water in the collector trench using floor brush. The samples were filtered using Whatman no. 42 filter paper. The sediment was oven dried at 105°C for 24 hours and weighed and then soil loss was calculated and expressed in tons/ha/yr. The runoff depth for each plot was calculated by dividing runoff volume by the plot area.

One way ANOVA has been used to test effects of SWC treatments on runoff response. Two ways ANOVA were also used to see the effects of SWC treatments against land use and slope. Statistically significant means were separated using Tukey LSD family wise 95% confidence interval.

4. Results and discussion

4.1. Effect of SWC treatments on plot runoff

The runoff plots at every site were similar in all biophysical characteristics (i.e. slope gradient and aspect, land use, soil type and geology) and showed significantly different ($p < 0.000$) runoff responses due to type of SWC structures. Runoff response was the highest for the control plots at all sites (Fig. 4).

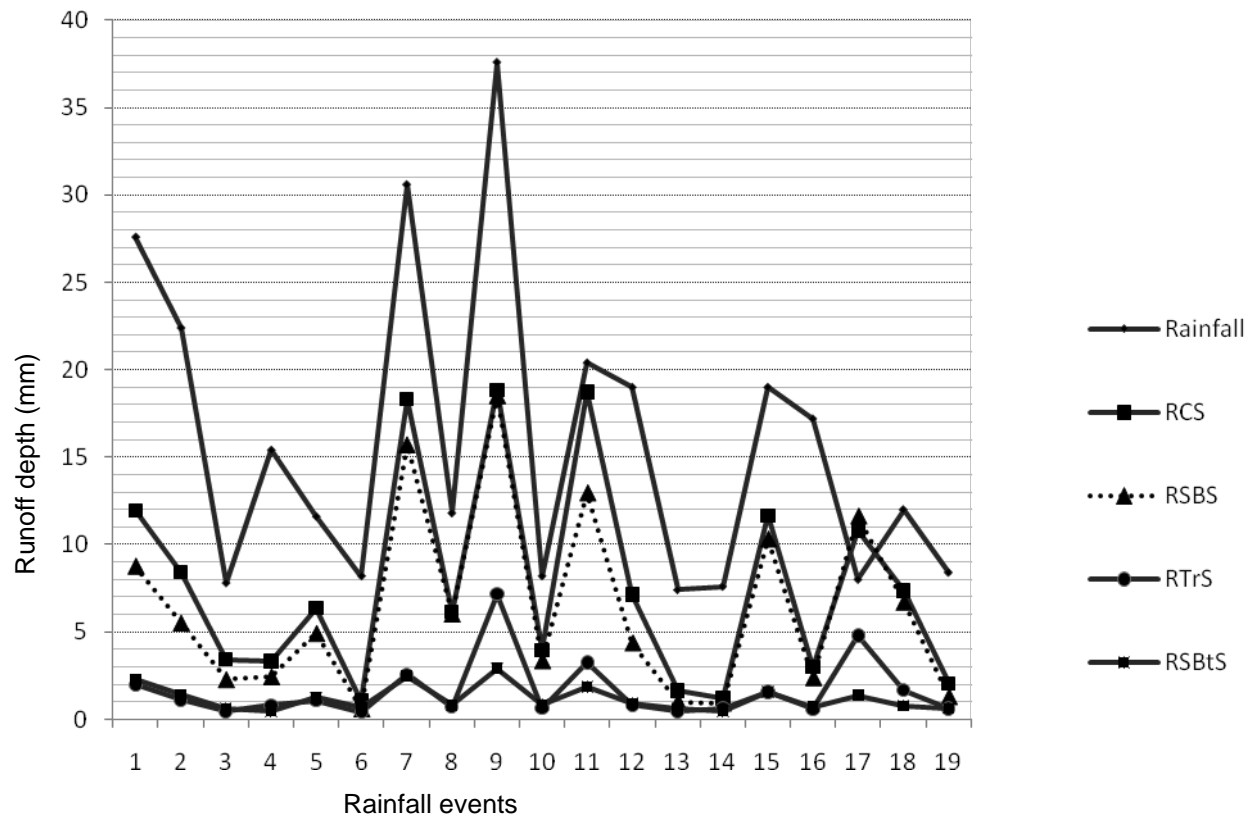


Figure 4. Runoff to rainfall relationship for the different SWC treatments on the experimental plot on rangeland with steep slope (RCS control, RSBS stone bund, RTrS trench, RSBtS stone bund with trench).

The runoff responses for different SWC treatments follow the rainfall trend however; specific runoff response also depends of the rainfall characteristics. Different depths of rains can produce a similar amount of runoff, if intensity or antecedent soil moisture conditions are different. This is clearly indicated by events 7, 9, and 11 (Fig. 4). Runoff depth is correlated with rainfall depth ($R^2 = 0.64$). During all observed rainfall events the runoff reduction effect of trenches and stone bund with trench is very strong (Fig. 5) at the beginning of the rainfall season. However, during the rainy season storage capacity of the trench progressively decreased due to sediment accumulation in the trench and erosion of the soil bund downslope of the trench. It seems that they also have similar runoff response for smaller rainfall event but when storage capacity of trench is exceeded plot runoff response also increases. Compared to the control plot average runoff reductions were 85%, 62% and 17% for stone bund with trench, trench and stone bund respectively on rangelands. On cropland, runoff reduction effects were less, only 11% and 61% reduction was observed for stone bund and stone bund with trench respectively. Less runoff reduction effect of SWC treatments on cropland compared to rangeland may be due to the additional effects of crop cover, soil management and other agronomic practices. Runoff reduction of 40-50% on intensively cultivated cropland treated with bunds was reported earlier (Hurni et al., 2005). Nyssen et al., (2010) also reported that reemerging springs at the foot slopes of treated catchments and rise in groundwater table are related to the introduction of SWC structures.

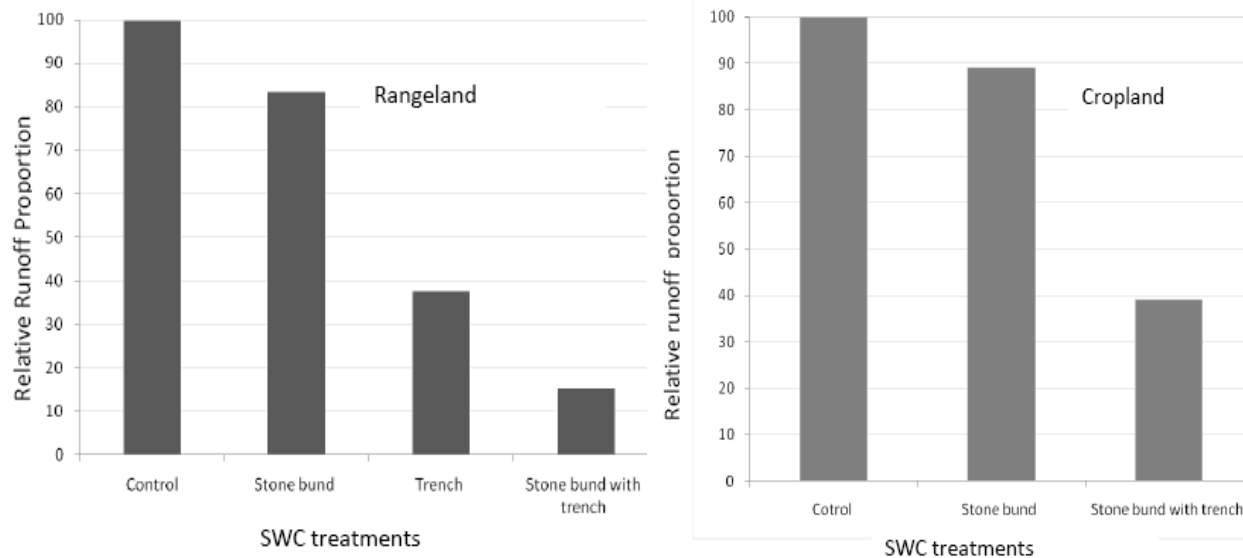


Figure 5. Relative runoff proportion for different SWC treatments compared to control ($n = 3$)

4.2. Effect of slope gradient on runoff responses

Slope is an important topographic variable affecting soil erosion rate and catchment runoff responses. However, the effect of slope in this study remains insignificant ($p = 0.62$) to explain runoff variability among SWC treatments. Besides unaccounted spatial rainfall variability, this is attributed to local differences in soil infiltration rate as influenced by parent material, rock fragment cover and soil type. Runoff depth from the gentle slopes was even higher than from steep and moderate slopes because of the vertic nature of the soil which affects the rate of infiltration once the top layer is saturated. Descheemaeker et al. (2006) have shown that runoff in Tigray, even in areas with restoring vegetation, is mainly Hortonian. Runoff response to rainfall occurs before the soil gets saturated. The influence of rock fragment cover which dramatically increases with slope gradient in the study area is another reason; the negative relationship between runoff depth and rock fragment cover is well documented (de Figueiredo and Poesen, 1998).

4.3. Effect of land use on plot runoff responses

Land use effect on plot runoff response was very significant ($p < 0.000$). Runoff response is higher for rangeland as compared to cropland (Fig. 6). This is probably due to soil cultivation during the beginning of the rainy season and increased vegetation cover later during the rainy season on cropland in contrast with reduced infiltration, increased runoff and soil erosion on rangeland (Stroosnijder, 1996; Mwendera and Mohamed, 1997).

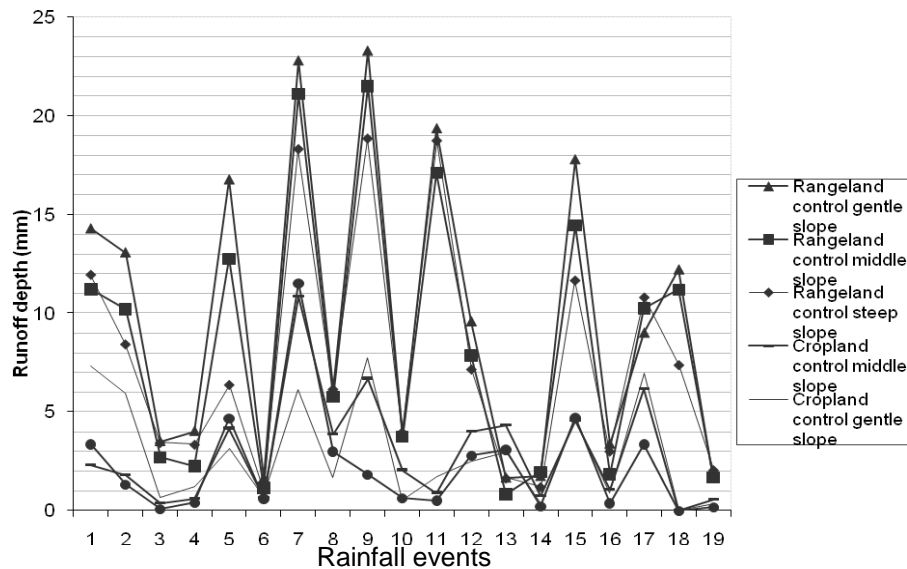


Figure 6. Effect of land use on runoff response

4.4. Effect of SWC treatments on soil loss

Particularly on steep slopes, soil loss is much lower on cropland compared to rangeland (fig. 7) probably due to a larger vegetation cover during the rainy season. The amount of soil loss from plots is different for different due to SWC treatment (Fig. 7). The soil loss from the control plot is always higher for all land uses, slope categories and regardless of the type of crops grown. The soil loss reduction of stone bund in this study was 69% for rangeland. On cropland soil loss reduction due to stone bund was 89% which is attributed to the combined effect of vegetation cover and soil management on cropland. Soil loss reduction due to stone bund with trench and trench were even more.

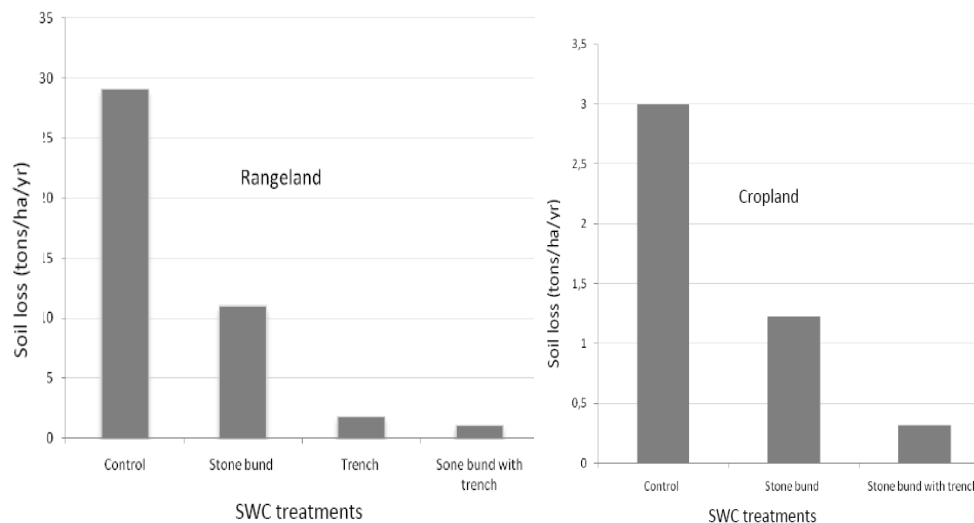


Figure 7. Effects of SWC treatments and land use on soil loss on steep slopes

5. Conclusions

Introduction of SWC structures may highly reduce the runoff delivered to storage structures such as ponds and reservoirs. Introduction of stone bund with trench, trench and stone bund led to runoff reduction by 85%, 62% and 17% respectively for rangelands. The effect of SWC structures on runoff responses is highly influenced by land use while the effect of slope gradient is negligible. On average, the introduction of stone bunds can reduce soil loss by 68%; this effect will significantly reduce sediment load to the reservoirs while runoff reduction is less. Therefore massive construction of stone bund would be recommended because of high runoff response and significant soil loss reduction. There should be optimum level of SWC intensity so as to let some surface flowing to the reservoir while significantly reducing sediment load; in this regard trenches and stone bunds with trenches should be used only in parts of the catchment where complete in situ conservation of water is desired.

References

- Descheemaeker K., Nyssen J., Rossi J., Poesen J., Raes D., Mitiku. H., Muys B., Deckers J. 2006. Runoff on Slopes with Restoring Vegetation: A Case Study from the Tigray Highlands, Ethiopia. *Journal of Hydrology*, 331: 219-241.
- de Figueiredo, T., Poesen, J. 1998. Effect of rock fragment characteristics on interrill runoff and erosion of a silty loam soils. *Soil & Tillage Research*, 46: 81-95.
- Haregeweyn, N. 2006. Reservoir Sedimentation in the North Ethiopian Highlands: Assessment and Modeling of Controlling Factors and Impacts. PhD Dissertation, K.U. Leuven, Belgium.
- Hurni, H., Kebede, T., Zeleke, G., 2005. Implications of change in population, land use and land management for surface runoff in the upper Nile basin areas of Ethiopia. *Mountain Research and Development*, 25,:147-154.
- Mwendera, E., Mohamed, A., 1997. Hydrological response to cattle grazing in Ethiopian highlands. *Agriculture, Ecosystems and Environment*, 64: 33-41.
- Nyssen, J., Vandenreyken, H., Poesen, J., Moeyersons, J., Deckers, J., Mitiku, H., Salles, C., Govers, G., 2005. Rainfall Erosivity and Variability in the Northern Ethiopian Highlands. *Journal of Hydrology*, 311: 172–187.
- Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Zenebe, A., Van Camp, M., Mitiku, H., Haregeweyn, N., Moeyersons, J., Martens, K., Gebreyohannes, T., Deckers, J., Walraevens, K., 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. *Hydrol. Process.*, 24: 1880-1895.
- Stroosnijder, L. 1996. Modeling the effect of grazing on infiltration, runoff and primary production in the Sahel. *Ecological Modelling*, 92: 79-88.
- Van de Wauw, J., Baert, G., Moeyersons, J., Nyssen, J., De Geyndt, K., Nurhussein Taha, Amanuel Zenebe, Poesen J., Deckers J. 2008. Soil–landscape Relationships in the Basalt-dominated Highlands of Tigray, Ethiopia. *Catena*, 75: 117–127.

17. Apple tree introduction and adaptation in the Tigray highlands

Getachew Hruy^{1,8}, Yikunoamlak Teklebirhan², Tom Deckers³, Alemtsehay Tsegay¹, Negash Aregay¹, Dereje Ashebir¹, Kassa Amare⁴, Hans Bauer⁴, Jan Nyssen⁵, Mitiku Haile⁶, Kindeya Gebrehiwot⁶, Dirk Raes⁷, Johan Keulemans⁸, and Jozef Deckers⁷

¹Department of Crop and Horticultural Sciences, Mekelle University, P.O. Box 231, Mekelle, Ethiopia, ²MU-IUC Apple research team, Hagere Selam, Ethiopia, ³PCFruit, Fruittuinweg 1, B - 3800 St.Truiden Belgium, ⁴MU-IUC Research Coordinator, Mekelle University, P.O.Box 231, Mekelle, Ethiopia, ⁵Department of Geography, Ghent University, Krijgslaan 281 S8, B - 9000 Ghent, Belgium, ⁶Department of Land Resources Management and Environmental Protection, Mekelle University, P.O.Box 231, Mekelle, Ethiopia, ⁷Institute for Land and Water Management, K.U.Leuven, Celestijnenlaan 200E, B - 3001 Heverlee, Belgium, ⁸Laboratory for Fruit Breeding and – Biotechnology, K.U.Leuven, W. De Croylaan 42, B - 3001 Heverlee, Belgium.

1. General context of apple introduction in Tigray: livelihood and natural resource conservation

Tigray is a region of contrasts. In one hand, it is one of the origins for agriculture and on the other hand, it is characterized by conditions of widespread poverty and food insecurity. The majority of its population is engaged in agricultural production as a major means of livelihood though its production is very low to the extent of not meeting the consumption requirement of the households. The picture for the mid- to highlands of the region, in which the majority of the population lives and agriculture has been practiced for many centuries is severe. In those areas, rain-fed agriculture has expanded to marginal areas and farmers are forced to cultivate steeper slopes, often without the application of effective conservation measures. This has resulted in land degradation, declining agricultural productivity, malnutrition and health problems. Hence, the major challenge faced today in those highlands is learning how to make high returns or outputs of crops and livestock while still conserving the essential natural resources, which will be needed for the survival of future generations. Both the regional and national policies have been geared towards eradicating poverty by increasing income at household level. In this regard, high income generating enterprises are being sought for adoption by farmers. Particularly for the highlands, apple growing has been selected as one strategy in diversify the farming system and then improve family nutrition and income generation at household level, and mitigate land degradation through better land husbandry. To this effect, various government and non-government organizations, including Mekelle University have been involved in the introduction, adaptation and distribution of apple trees to individual farmers.

2. Project background

In the frame of an institutional collaboration project (MU-IUC) between different Flemish Universities in Belgium and Mekelle University (MU) in Ethiopia. The More Crop per Drop (MCPD) project is one of the six research projects financed. The objective of MCPD project is to promote integrated crop production management to small-scale farmers in the region to increase the productivity of staple food crops (tef – *Eragrostis tef*, barley – *Hordeum vulgare*, maize – *Zea mays*, etc.) and to diversify the cereal based farming system (introduction of adapted temperate fruit trees) in order to sustain food self-sufficiency and food security in the region. Apple introduction and adaptation, as one component of MCPD Project, had started through the introduction of some standard apple cultivars like ‘Gala’, ‘Golden Delicious’, ‘Jonagold’, ‘Granny Smith’ and ‘Fuji’ starting from 2003/2004. These cultivars were planted in Mekelle University campus (2200 m a.s.l.) and in May Zahla near Hagere Selam (2650 m a.s.l.). Since

then, research has been carried out to study the biophysical performance of these cultivars under the conditions of these highlands.

3. History of apple in Ethiopia

Though the exact period is not known, it is believed that apple trees were introduced into the tropical mountains of southwestern Ethiopia some 60 years ago by missionaries, and to Adigrat (Tigray) some 35 years ago (Ashebir *et al.*, 2009). Unfortunately, systematic observations have been carried out only once in the Ethiopian highlands at three climatically diverse sites on apple cultivars introduced in 1976 (Rice and Becker, 1990). In that trial, it was found that the trees performed well even at Bedessa, the lowest (1600 m.a.s.l.) and warmest site (14-18 °C min. and 28.5-32.5 °C max. temperature). However, it is only in the last five years that apple production has started to increase in volume. Reasonable efforts are underway by various government and non-government organizations to integrate apple fruit production into the existing cereal based farming system of the country. GTZ in Amhara, Tigray and Oromia, Kalihiwot in Chench and MU-IUC are among the major actors in this regard.

4. Summary of research results

Generally, it is admitted that the major limiting factor for deciduous fruit production in Ethiopia is the lack of adequate winter-chilling in most of the country. The results reported here were obtained from trials designed to evaluate the effectiveness of spraying with hydrogen cyanamide (Dormex), with winter oil and hand defoliation at different doses and combinations, with the aim of improving and synchronizing the bud break and the blossoming period of standard apple cultivars. The results show that both chemicals are effective for dormancy release of the cultivars. Furthermore the effectiveness of hydrogen cyanamide in apple dormancy release is increased when combined with winter oil (Fig. 1). The defoliation treatment alone was not sufficient to break dormancy for the cultivars, with the notable exception of Jonagold and Fuji, suggesting the possibility of growing these two cultivars under farmers' management without use of chemicals. All in all, the research results indicate that it is possible to develop new apple production in the mountain region of Tigray, Ethiopia.

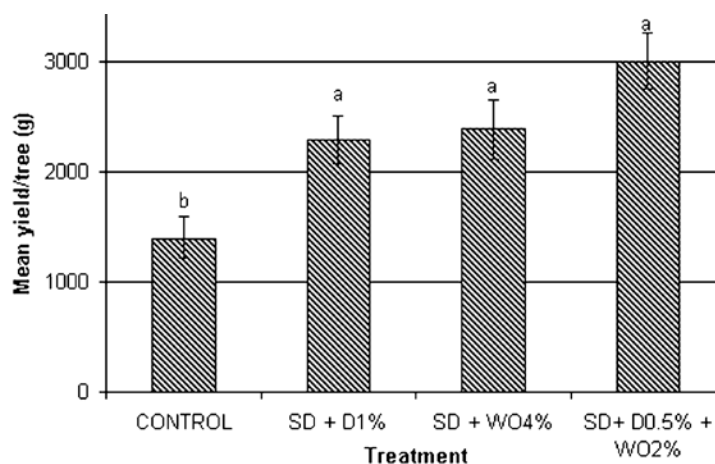


Figure 1. Effects of spraying chemicals on apple production at Hagere Selam and Mekelle University experimental sites. SD = Single defoliation; D0.5%, D1% and D2% = Dormex applications, and WO4% and WO2% winter oil applications (after Ashebir *et al.*, 2009).

5. Apple extension

The research findings were promising and it has been found vital to transfer the technology to farmers. Hence, in the belief that, with proper cultural practices for apple trees under these highland conditions, farmers can increase their income, diversify their farming system and enrich their diet with essential minerals and vitamins, the project has started to multiply virus free planting materials of apple. Moreover, to reach farmers at the grass root level, a memorandum of understanding was signed between Mekelle University and the Tigray Bureau of Agriculture and Rural Development in 2007, including the plan to distribute 10,000 grafted apple trees every year for five years. In the previous years, the project had distributed more than 4000 grafted trees to farmers for free. Currently the project has more than 5,000 two-year-old grafted apple trees which are ready for distribution during January to February 2011.

Moreover, the apple research team at Mekelle University offers training and necessary technical advice regarding apple production and management to beneficiaries for free before the time of tree distribution and after the distribution. Some of the technical advices given were: the need to apply manure, bending of the lateral branches to induce flowering and expose the branches to light as the apple trees are sun loving plants, need of defoliating the leaves during their dormancy period, need of pruning of weak, damaged and excessive branches in a tree, and grafting techniques. So far under the programme 200 farmers and 40 extension staff have been trained in apple production. Small holder farm-households are the target groups supported with the main objective of contributing to improvement in income and overall living conditions of the farmers. Highland fruits are also contributing to the improvement in diet and health of the benefiting households, as well as to better management of land resources through integration of soil and water conservation activities.

Based on the advice and by applying their own agronomic practices some of the farmers were able to produce apple fruit for consumption and others sold some fruit in addition to their home consumption (see the case study and Table 1). A detailed inventory at the homesteads of four apple producing famers at May Shehi (some 10 km south of Hagere Selam) showed that each of them manages 30 to 306 apple trees (Table 1). Besides a lesser amount for home consumption and some that were destroyed by birds, the largest part of fruits harvested per year is sold at the market. However some trees had virtually no yield due to negligence, but also mismanagement of the trees. In addition, the farmers commented that apple trees make the area more attractive for bees, which supports the bee-keeping enterprise recently started by the youth. Moreover, apples also help to stabilize hill slopes and halt environmental degradation, even without resorting to expensive bench terracing, which has been the traditional system in the hill and mountain areas.

Case study - Mr. Gebrekiros Gebru is one of the farmers who has benefited from the apple production in May Shehi near Hagere Selam. He was asked to comment about the contribution of apple trees to his household economy. He said, “many families of my surrounding including myself have now started to benefit from apple production. I used to grow grains around my homestead, but have found that apples are much more lucrative. I have a total of 15 apple trees currently under production and another 291 apple trees that have not yet reached production. I was able to harvest 15 kg of fruits from some trees in one season. In the 2009-2010 cropping season alone, I sold 150 kg of apples at a price of 30 Birr per kg, my family ate 10 kg and few fruits were also eaten by birds. All in all, last year, I was able to satisfy for my home and able to consume more apple fruits than any time before. On top of that, I was able to earn money by

selling the fruits in Mekelle and Hagere Selam markets and have started saving.” This suggest that farmers with 20 trees on their backyard can generate an income of at least 9000 Birr per annum, two times as much as the return from half a hectare of tef. “For all this thanks to MU-IUC and the Bureau of Agriculture at Hagere Selam, as I was given four apple trees in 2005. Now I use the land intensively and grow a total of 306 apple trees”. Asked about his future plans, he answered: “I have the plan to plant more apple trees and increase my earnings as of the coming year. But I am worried about the problems of birds and powdery mildew.”

Table 1. Number of apple trees and their harvest performances under farmers own managemnt at May Shehi in 2009-2010 cropping season. First few trees were planted in 2004-2005 and others have been added through the years.

Name	Total number of trees	Trees under production	Maximum harvest of a tree (kg)	Total fruits harvested (kg)	Apples consumed at home (kg)
Gebreselassie Gebru	30	15	15	100	5-10
Gebrekiros Gebru	306	15	20	150	10
Zebruabruk Kidan	60	15	10	40	5
Hiwot Gebregziabher	94	9	20	150	10

6. Conclusion

Generally, adaptation and growth performance of apple tree is encouraging in the Tigray highlands, with good survival rates. Farmers were able to successfully establish and manage plantations. Yields as high as 20 kg per tree were obtained from some trees. Such promising results suggest that by developing apple fruit trees in the highlands, the farmers’ income can be substantially improved and erosion problems can be reduced. However, many technical problems are yet to be solved in order to provide answers to farmers who are interested to plant apples in the highlands. Appropriate ways of follow-up of apple trees planted in farmers backyards need to be explored. Moreover, all the production techniques, skills and knowledge required for appropriate and maximum production should also be introduced to the farming community together with supplying of the trees. Preparation of production manuals in such a way that it will be easily understandable by development agents is very crucial. Besides the elaboration of a manual in the local Tigrinya language, the provision of intensive trainings to development agents, subject matter specialists and farmers is crucial.

7. References

- Ashebir, D., Deckers, T., Nyssen, J., Bihon, W., Tsegay, A., Tekie, H., Poesen, J., Haile, M., Wondumagegnehu, F., Raes, D., Behailu, M. & Deckers, J. (2010). Growing apple (*Malus domestica*) under tropical mountain climate conditions in northern Ethiopia. *Experimental Agriculture*, 46: 53-65.
- Rice, R.P. and Becker, S. (1990). Observations on apple and plum performance and response to growth control treatments at three climatically diverse sites in Ethiopia. *Acta Horticulturae* 279, 209-212.

18. Rural marketing in Tigray: the case of Hagere Selam market

Abebe E. Alemu^{1,2}, Mathijs, E.¹, Maertens, M.¹, Kidanemariam G.^{1,2}, Nyssen, J.³, Deckers, J.¹, Bauer, H.⁴, Kassa Amare⁴

¹*Department of Earth and Environmental Sciences, Catholic University of Leuven, Leuven, Belgium (abebejigu@yahoo.com)*

²*College of Business and Economics, Mekelle University, Mekelle, Ethiopia*

³*Department of Geography, Ghent University, Ghent, Belgium*

⁴*Research Coordinators, VLIR-MUIUC, Mekelle University, Ethiopia*

Introduction

Based on the 2007 census conducted by the Central Statistical Agency of Ethiopia (CSA, 2008), the Tigray Region has an estimated total population of 4,314,456; among which 19.5% are urban inhabitants. The region is primarily agricultural and the majority of the population is employed in this sector. Agriculture is dependent on unreliable rainfall. Livestock play an important role in the rural economy of Tigray. They are sources of draft power for tillage and transportation, cash income from sale of livestock and livestock products, food such as milk for household consumption and manure to maintain soil fertility. Tigray has 47 districts (woredas) and among them, Degua Temben is one, which has a relatively cool temperature. Hagere Selam is the capital of the Degua Temben District, where all the district offices are located.

Rural marketing

Marketing can be defined as the performance of business activities that direct the flow of goods and services from producers to consumers. In broader terms marketing is defined as a system of business activities designed to plan, price, distribute and promote want satisfying products (goods and services) to present and potential customers (Berman and Barry, 1982; Kotler, 2001; Stanton et al., 1985).

Rural marketing incorporates the marketing of agricultural products, rural industrial products and services of many kinds. The trade channels for different types of commodities available in rural areas are private, cooperatives, processors and state agencies. A village economy can't be developed without effective and efficient rural marketing. Thus production and marketing are the two facets of a coin. Rural marketing constitutes the nerve centre of rural development activities. Rural marketing is a two way marketing process that encompasses marketing of products which flow to rural areas and products which flow to urban areas from rural areas. So rural marketing broadly defined is concerned with the flow of goods and services from urban to rural and vice-versa.

The rural marketing system contains the buyer, the seller and the mechanism that helps to transfer the goods from producers to consumers. Products in the rural marketing system can be agricultural products, industrial products, services, livestock and live stock products, etc. In the rural marketing system, producers can be farmers, manufacturers, query industries and assembly industries. Buyers in the rural market include the consumers, wholesalers, retailers, the farming community and cooperatives. Operators in between are: retailers, wholesalers and cooperatives (Abebe et al., 2010).

Products in rural markets of Tigray

Products available in the rural marketing system of Tigray are mainly agricultural products consisting of staple crops such as barley, wheat, sorghum, beans and teff; vegetables including tomato, potato, cabbage (Fig. 1), lettuce, swisschard and onion; fruits like orange, banana, cactus, apple (emerging fruit); livestock and livestock products such as milk, butter, yoghurt, cheese, egg, chicken, goat and sheep; apiculture products, mainly honey (white, yellow and red honey); firewood, charcoal and poles; and home-made hardware, such as pottery, oven covers or farm implements.



Fig 1. Cabbage and salad in open market at Hagere Selam

Market institutions and linkages

Large parts of these agricultural products are exchanged mainly in open markets, through cooperatives and in a few of the producers sell through contracts. Transaction costs and resource constraints are claimed to be pushing farmers to adopt any of these mechanisms of coordination (Williamson, 1979). Open markets are located mainly in the district towns and some major satellite villages and perform once in a week where buyers and sellers from various areas meet in these open markets. In open markets, different measurement units are used and generally comprise unstandardized cups that are conventionally accepted by the agents in the market (Abebe et al, 2010; Fredu et al, 2006).



Fig.2. Units of measurement for crops at Hagere Selam market

These cups are made from tin that is used to measure grains in the market and they are also used to measure milk and honey in open markets. Standardized balance as unit of measurement is employed by retailers who buy different types of vegetables and fruits from smallholder producers and supply it to other buyers in the market. However, balances as are used only for a few products.



Fig 3. Kilogram as unit of measurement



Fig 4. Honey sellers waiting for buyers in H/Selam

The second types of marketing institutions are production cooperatives and marketing cooperatives. Production cooperatives are composed of individual farmers who own resources and produce together. Marketing cooperatives are composed of producer members who produce agricultural products individually and bring outputs together for marketing. The cooperatives collect, store and sell products of its members. Members will share benefits and losses according to their contributions. In Hagere Selam there are two dairy processing cooperatives comprising more than 80 members. Members supply fresh milk to the cooperatives and the cooperatives sell boiled milk, yoghurt, and butter to various consumers and snacks at Hagere Selam and the nearby city Mekelle. There are also multipurpose cooperatives collecting agricultural products from farmers and supplies fertilizer, other inputs, and convenience goods to its members; and other buyers within the rural community.

There are mead houses (locally called ‘mes’ houses) which prepare honey wine (add value to honey) and supply it to various consumers. Hagere Selam is known for its best ‘mes’ quality and visitors of Hagere Selam use to take ‘mes’ while going back home.



Fig 5. Mead house at Atsibi

Moreover, contractual agreements in Tigray concern mainly the sale of milk and honey. For instance, honey producing households and cooperatives have contracts with Dimma Beekeeping and Honey processing PLC.

Industrial products

Several industrial products such as convenience goods, clothes, shoes, agricultural inputs such as fertilizer are also supplied in the rural marketing system. Cooperatives play a pivotal role in

getting fertilizer and other input distribution, as well as credit from government and other development institutions.

Market operators

The actors in the rural marketing system in Tigray are producers and village traders who produce, transport goods to and from the secondary markets, store and dispatch the produce as the market situation warrants. For instance, the actors in the honey supply chain are presented in Fig 6.

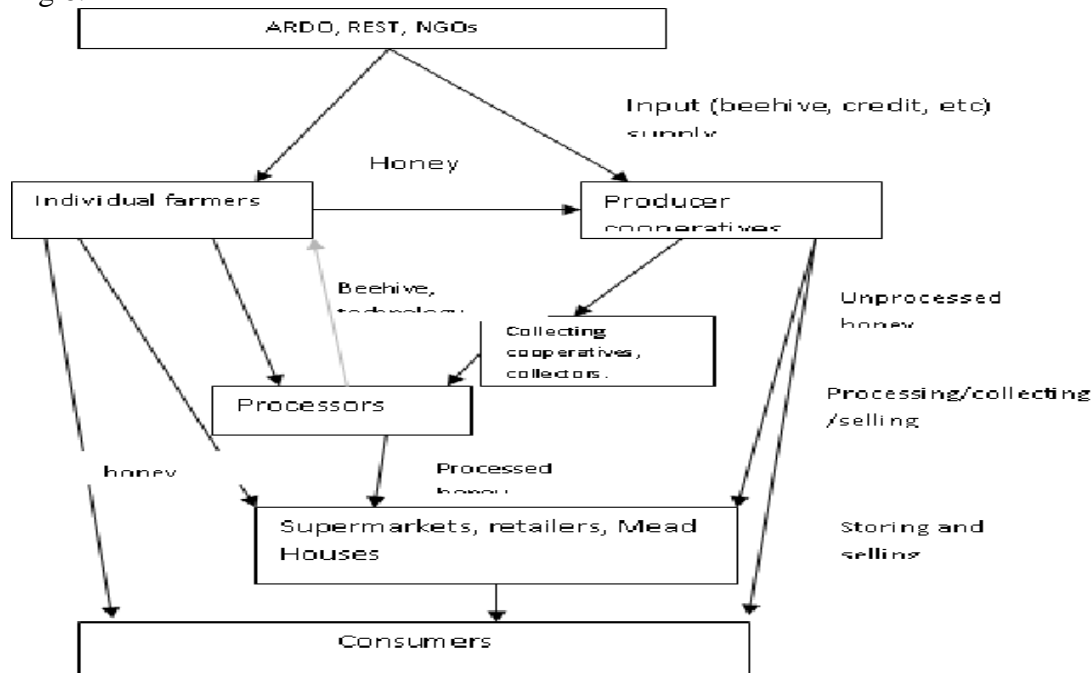


Fig. 6. Honey supply chain and operators in the chain. (Source: Abebe et al., 2010)

The second type of trader forms is the link between the village level and the secondary market level. They sell produce on a commission base, which they collect from the seller as well as from the buyer. The third types are cooperatives (Bijman, 2000) which operate on the principle of commissioning. Their role could include some sort of cleaning up the produce, processing, weighing, packing, and dispatching to centers of transportation and markets.

Obstacles in the rural marketing system

- Archaic transport system (no or bad roads): smallholder farmers' travel from villages located far from the district market. Rural marketers used to walk and use pack animals for transportation. Buyers travelling from Mekelle use bus transportation system which is relatively frequent. In recent years, where roads are present, many farmers can afford travelling and shipping their goods by bus or small lorry.
- Lack of sorting, processing, grading and labeling leads to inability to compete with imported goods: standardized units of measurement are emerging but not well utilized by the trading agents. Quality control mechanisms are still in their infant stage. To detect milk quality, cooperatives use lactometers but its availability is very limited. Therefore, poor quality frequently occur that derive personalized, relation or trust based marketing that affects free flow of goods in the marketing system.

- Warehouse shortage: though a few private warehouses exist, there are no institutions that offer warehouse or storage service. In case the producer do not find acceptable price to her/his produce, s/he has to take it back home. Therefore, they prefer to sell the product at the price they get rather than looking for better market situations.
- Absence of strong organization of producers: producer organizations are fragile and instable. Sometimes members want to free ride and want to benefit at the expense of others which weakens the cooperative societies. However, the Selam Dairy cooperative at Hagere Selam is one of the cooperatives in Tigray that is well functioning and well serving its members.
- Primary/village markets are functioning once a week and secondary markets that work day to day are very far from farming communities: the district market is the nearest market and it takes place once in a week (Saturday) – with only resale activity going on the other days of the week. Therefore, producers need to wait. If they want to travel to Mekelle, the transportation costs and other transaction costs may be unaffordable to smallholder producers.
- Lack of product diversification: farmers producing identical products which results in seasonal excess supply as well as lack of exchange among themselves.
- Information asymmetry: farmers lack market information; the dissemination of price information through the regional radio is introduced to change the situation – mobile telephone would be another option. The information asymmetry prevailing among the farmers erodes their competitive strength.
- Smallholder farm production: this limits the amount of produce to the market and affects transaction costs. Many smallholders produce at subsistence level and they lack commercial/market orientation. They also lack market driven products (cash crops are missing), though there is an improvement in this respect.
- High transaction costs such as searching buyers, negotiation and monitoring costs.
- Lack of effective institutions to enforce contract or payment; to some extent this is compensated by the existence of informal control mechanisms.

References

- Abebe E., Mathijs E., Maertens M., Deckers, J., Kidanemariam G., Bauer H. (2010). Supply Source Selection in the Downstream Dairy supply Chain in Tigray; paper presented at the 8th international conference on the Ethiopian Economy; Addis Ababa, Ethiopia, June 24-26,2010.
- Berman, B. Evans, J.R. (1982), *Marketing*, New York, Macmillan Publishing Co., Inc.,
- Bijman, J., (2002). Essays on Agricultural Cooperatives: Governance Structure in Fruit and Vegetable Chains, ERIM Ph.D Series Research in Management, Erasmus University, Rotterdam.
- Fredu N, Zaid N, Kidanemariam G., Abebe E, Mihret B, Tollens E., Deckers S., Nyssen J (2006) Participatory Rural Appraisal Report of Selected Villages in Tigray, Tigray Livelihood Paper No. 2, VLIR-MU IUC Program.
- Kotler, P., (2001) *Marketing Management*, 10th ed. (The Millennium Edition), Prentice – Hill, Inc.
- Stanton, W.J, Miller, K.E., Laton, R.A. (1985) *Fundamentals Marketing*, Sydney, McGraw- Hill Book Company.

19. Beekeeping innovation by farmers in Tigray for generating income and restoring natural vegetation

Ma'ar project

Hagere Selam (Ethiopia)

<http://www.vzwmaar.be/> (Belgium)

Introduction

The Ma'ar project is a collaboration between a Belgian non profit organisation (“vzw Ma'ar”) and the Tigray based “Association for innovation and development on beekeeping and its results”. The wider aim of the project is to contribute to socially, economically and ecologically sustainable development in Northern Ethiopia by supporting small beekeepers.

To achieve this, Ma'ar works around three cornerstones, being:

- Innovation by farmers
- Honey production and nature restoration in exclosures
- Fostering cooperative and social economy



The Farmer Innovation Centre (FIC)

Established in 2008 in an exclosure in a steep valleyside near Hagere Selam, the FIC is an open-air experimental area, where farmers are given the chance to experiment with different techniques, invent improved beehives, and share information.



Training for innovative farmers by experts from Holetta Bee Research Centre

Current experiments compare honey production between different hive types, bee colonies and orientation of hive entrance. The effect of improving the bee flora through a simple small scale irrigation system is assessed. Hybrid beehives, combining the virtues of traditional and modern hives, are developed.

Regular trainings are held in the FIC, both by nationally renowned institutes (Holetta Bee Research Centre) and international experts (Prof. Jacobs, Ghent University). The knowledge

gathered from the experiments and the trainings is spread to wider groups of farmers through regular information booths on the local market, group trainings and open-door days for interested farmers, radio broadcasts, and the farmer networks in the villages. While the experiments in the FIC are managed by a group of 5 farmers, the centre received about 20-30 visits from interested farmers per month in 2010.



Training given by FIC members to female beekeepers of the region



Demonstration in the FIC for interested farmers and staff from Mekelle University



Modified hive construction

20. Livestock fodder development as an essential component of catchment management: case study in Mai Zeg-Zeg

Nigussie Haregeweyn^{1,2,*}, Abraham Girmay^{2,3}, Yayneset Tesfay², Atsushi Tsunekawa¹, Mitsuru Tsubo¹, Jan Nyssen⁴, Jean Poesen⁵

¹ Arid Land Research Center, Tottori University, 1390 Hamasaka, Tottori 680-0001, Japan

² Department of Land Resources Management and Environmental Protection, Mekelle University, P.O. Box 231, Ethiopia

³ ADCS Mekelle May Zeg-zeg project, Mekelle, Ethiopia

⁴ Geography Department, Gent University, Krijgslaan 281 (S8), B 9000, Gent, Belgium

⁵ Department of Earth and Environmental Sciences, Division of Geography, K.U. Leuven, Celestijnenlaan 200 E, B-3001 Heverlee, Belgium

* Corresponding author: nigussie_haregeweyn@yahoo.com

1. Introduction

Integrated watershed management (IWM) practices are key interventions that have been implemented since the last decade with the aim of conserving land resources and hence to improve the agricultural productivity in the Tigray highlands, Northern Ethiopian. Accordingly, an IWM intervention was set up on Mai Zeg-zeg watershed in Dogua Tembein district of Tigray since 2004 with a scientific support obtained from Mekelle University and K.U. Leuven, Belgium and with a financial support obtained from the Trocaire (Ireland) through the Adigrat Diocesan Catholic Secretariat Mekelle branch (ADCSM). The intervention had three major natural resource components to address: soil, water and vegetation. The impact of the interventions on the first two components has been well documented in the successive works of Nyssen et al. (2009) and Nyssen et al. (2010). However the vegetation component, especially the crop-livestock interaction, an important part in the local farming system, has never been studied so far. This study evaluated the performance of the IWM interventions in relation to livestock fodder development (FD) in the Mai Zeg-zeg watershed.

2. Materials and methods

The watershed covers land of, and is located in between four *tabias*, local administration units: Michael-Abiy, Aynmbirkekin, Selam and Hagere Selam, and has an area of about 400 ha. The study was based on a survey of 120 households; focus group discussions and field measurements (biomass of exclosure grasses and survival count of multipurpose fodder trees - MPFTs).

3. Results and discussion

3.1 Fodder development systems in the Mai Zeg-zeg watershed

Table 1. Fodder development systems in the Mai Zeg-zeg watershed, and level of the respondents' participation.

Fodder development systems	Part of the respondents
Exclosures and homestead agroforestry.	42 (35.0%)
Exclosures, cropland agroforestry and homestead agroforestry.	66 (55.0%)
Cropland agroforestry and homestead agroforestry	3 (2.5%)
Exclosures and cropland agroforestry	9 (7.5%)

Fodder development was seen by the community as a component of the IWM. Three types of fodder development interventions (Table 1) are practiced by the local community with the

possibility of one farmer participating in multiple interventions. These are: (1) plantation of multipurpose fodder trees on cropland (also called cropland agroforestry systems), (2) plantation of multipurpose fodder trees on homesteads (homestead agroforestry systems) and (3) introducing of exclosures and plantation of multipurpose fodder trees within it (exclosure systems).

3.2 Type and extent of multipurpose fodder trees planted in the Mai Zeg-zeg watershed between 2004 and 2009

The first two main aims for cropland agro-forestry and exclosure systems were: to reduce land degradation primarily and to get supplementary/livestock fodder secondarily (Table 2).

Table 2. Purpose of implementing cropland agroforestry, homestead agroforestry and exclosure system; respondents' reflection.

Purposes	Cropland Agroforestry	Homestead Agroforestry	Exclosure
	<i>n</i>	<i>n</i>	<i>n</i>
Get livestock fodder	94	95	120
Improve soil fertility	88	90	0
Reduce land degradation	107	47	120
Get fuel wood & wooden materials	22	53	60
Get cash- or food-for-work	22	0	24
Improve spring discharge	0	0	36

Soil and Water conservation (SWC) practices including plantation of three types of multipurpose fodder trees (MPFT's) (i.e., *Sesbania sesban*, *Chaemacytisus palmensis* and *Leucaena leucocephala*) were implemented in the three systems. In total, 264573, 32426 and 82000 MPFTs were planted in the catchment in croplands, homesteads and exclosures respectively by the collaboration of ADCSM and Degua Tembein Woreda Agriculture and Rural Development (WoARD) office with the *tabias'* community.

3.3 Management methods employed under the different forage development systems in the Mai Zeg-zeg watershed

Table 3. Management systems of the three fodder development interventions, respondents' reflection.

Management Method	Cropland agroforestry	Homestead agroforestry	Exclosure systems
Bylaw base	108 (97%)		120 (100%)
Individual base		95 (100%)	
Bylaw and individual base	3 (3%)		

The study found that the management method of exclosures is through enforcement of local bylaws, the homestead agroforestry system is based on and individual-based management, whereas the cropland agroforestry system employs essentially the bylaw system (Table 3). Most of the communities prefer exclosures to be managed by ADCSM and WoARD office (Table 4) as they may seek for employment opportunities. However this approach seems not

sustainable. The bylaw of cropland agroforestry focuses only on protecting the area from free grazing. The focus group discussion described that the *Tabia* leaders and local courts give more focus to the accomplishment of the enclosure bylaws. As a result the cropland agroforestry bylaw system is rarely implemented properly.

Table 4. Ranking of the current responsible bodies for protection of the exclosures, respondents' reflection.

Responsible bodies	n
By community (by contributing guards fee)	72
By village leaders (through payment from other sources)	120
By WoARD/ADCSM-Mai Zeg-zeg project	120

3.4 Survival counts of the multi-purpose fodder trees planted in the Mai Zeg-zeg watershed

The survival count (Fig. 1) of five consecutive years (2005-2009) shows that the performance of the three FD systems is different. The average survival of the MPFTs in the first and second inventory, five and ten months after plantation, of the first year is 68% for enclosure followed by 54% for homestead agroforestry and 46% for cropland agroforestry systems. Survival in all systems continued to decline severely in the second year with a decrease by 97%, 71% and 40% in cropland agroforestry, homestead agroforestry and enclosure systems respectively. High mortality of the seedlings is found in the first two years for all systems in general and particularly very severe in the cropland agroforestry system. The survival in each system after the third year tends to be constant; the average survival count of the three years (2007-2009) is 18% in enclosures, 5% in homestead agroforestry and almost none (1%) in cropland agroforestry.

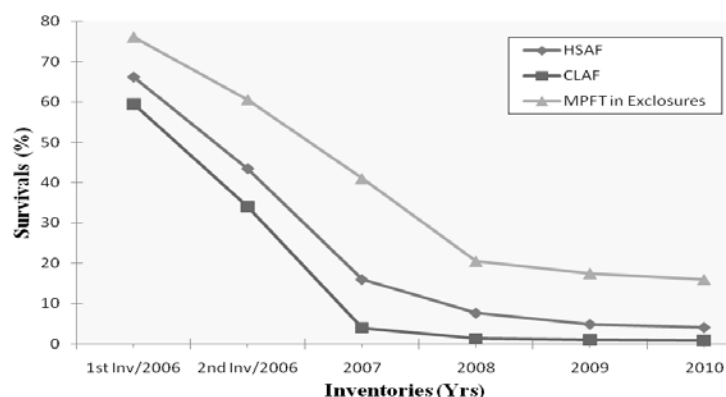


Fig 1. Survival records of MPFT's for five consecutive years in the three systems of fodder development: Homestead agroforestry, Enclosure and Cropland agroforestry. For trees planted in 2005.

3.5 The contribution of the fodder development interventions in improving the feed availability in the Mai Zeg-zeg watershed

None of the community members used MPFT's from cropland agroforestry or enclosures as source of supplementary feed for their livestock. Nevertheless, a few farmers used from homestead agro-forestry. In October 2009, the mean annual above ground dry biomass yield of

grass recorded from two exclosures (Hichi and Harena) was 1550 kg/ha and 1390 kg/ha. It contributed about 20 % of the livestock feed source in the watershed (Table 5). It is the third source next to the major source i.e. crop residues (50%) and grazing (including aftermath grazing; 29%). Homestead agroforestry had limited contribution (1%) to the feed availability while the cropland agroforestry system did not contribute. Similar studies in other similar aged exclosures of the district showed the mean annual yield of the grass is 1110 kg/ha (Cleemput et al.).

Table 5. Ranking of feed availability in Mai Zeg-zeg watershed, respondents' reflection

Feed Sources	Feed availability
	n
Crop residue	120
From grazing areas(including aftermath)	118
Exclosures (hay)	116
Homestead Agroforestry/MPFT's	6
Cropland Agroforestry/MPFT's	0
Multipurpose fodder trees from exclosure	0

3.6 Factors influencing the sustainability of the forage development interventions

The agro forestry interventions did not meet the intended purpose to be used as a supplementary feed for reasons associated with both pre and post implementation of MPFTs (Tables 6 and 7). The occurrence of long dry seasons was the key common factor that influenced the performance of MPFTs in the three systems. Furthermore, poor plantation techniques and poor pit preparation techniques had also significant negative influence on the performance in all three systems. Analysis of the factors per forage development system shows that in cropland agroforestry, the farmers invoke the absence of detailed technical training, absence of watering of the planted MPFTs, free grazing and pulling up of the planted seedlings were found to have significant negative influence. Similarly in homestead agroforestry, absence of detail technical training, poor supervision by experts had negative significant influence on the other hand, on-time watering, protection (fencing) of MPFTs, interest to use MPFT as feed and better transportation of seedlings were found to have a positive influence. In exclosure systems, plantation by the community in a campaign, weak bylaws and damage caused by rodents were found the main factors that influenced the performance negatively. In general, the local watershed management committee had not enough power to implement the livestock fodder development successfully.

Table 8. Factors pre & during plantation that led to failure of the multipurpose fodder trees in the three systems.

Pre & during plantation factors	Cropland Agroforestry	Homestead agroforestry	MPFTs in exclosure
	n	n	n
Premature seedlings	40	40	40
Transportation problems	112	24	106
Lack of practicing hardship tolerance for the seedlings	30	58	20
Poor preparation of pits	41	73	41
Poor plantation techniques	110	35	134

Table 9. Factors that led to failure of the multipurpose fodder trees in the three systems after plantation

Post plantation factors	Cropland agroforestry	Homestead agroforestry	MPFTs in exclosure
	n	n	n
Destruction of seedlings during plowing	111	0	0
Free grazing	110	43	0
Long dry season	111	66	111
Rodents effect	0	0	94
Fencing problem	0	50	0
No pruning on time	0	71	0

4. Conclusions

The study found that the three forage development systems (cropland, homestead and exclosure agroforestry) that have been introduced in the Mai Zeg-zeg watershed, had significant difference with regard to their performance. Grasses from exclosures performed well and play a great role in improving the feed availability of the watershed. However, the agroforestry interventions did not meet the intended purpose (i.e. use as supplementary feed) for reasons associated with both pre and post implementation of MPFTs. The long dry season in the area is the most important external factor influencing the FD performance negatively. The main reasons is related to lack of detail knowledge and appropriate management practices for the MPFTs. Hence implementation of coping mechanisms such as selection of best forage species adaptable to the local climate, adjustment of planting time and improvement of the soil water availability measures accompanied with effective and sustainable fodder development management systems appropriate for each intervention are needed.

References

- ADCSM, 2009. Annual report of Adigrat Diocesan Catholic Secretariat Mekelle branch Mai Zeg-zeg project
- Nyssen, J., Clymans, W., Poesen, J., Vandecasteele, I., De Baets, S., Haregeweyn, N., Naudts, J., Hadera, A., Moeyersons, J., Haile, M., Deckers, J., 2009. How soil conservation affects the catchment sediment budget: a comprehensive study in the north Ethiopian highlands. *Earth Surface Processes and Landforms*, **34**: 1216–1233.
- Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Zenebe, A., Van Camp, M., Haile, M., Haregeweyn, N., Moeyersons, J., Martens, K., Gebreyohannes, T., Deckers, J., Walraevens, K., 2010. Impact of soil and water conservation on catchment hydrological response: a case in north Ethiopia. *Hydrological Processes*, **24**(13): 1880–1895.
- WoARD (2009). Annual Report of DeguaTembein Woreda Office of Agriculture and Rural Development, Department of Natural Resource Management, Hagere Selam.

21. Monitoring of the remobilisation of the May Ntebteb landslide near Hagera Selam

Miet Van Den Eeckhaut¹, Jan Nyssen², Jan Moeyersons³

¹ Institute for Environment and Sustainability Joint Research Centre (JRC) - European Commission 21027 Ispra (VA), Italy

² Department of Geography, Ghent University, Belgium

³ Geomorphology and Remote sensing, Royal Museum for Central Africa, B-3080 Belgium

Introduction

During the last decade, slope failures were reported in a 500 km² study area in the region of Hagera Selam, Mekelle, northern Ethiopia (Nyssen et al., 2002; Tesfahunegn, 2008; Moeyersons et al., 2008; Van Den Eeckhaut et al., 2009; Shimelies, 2009) (Fig. 1).

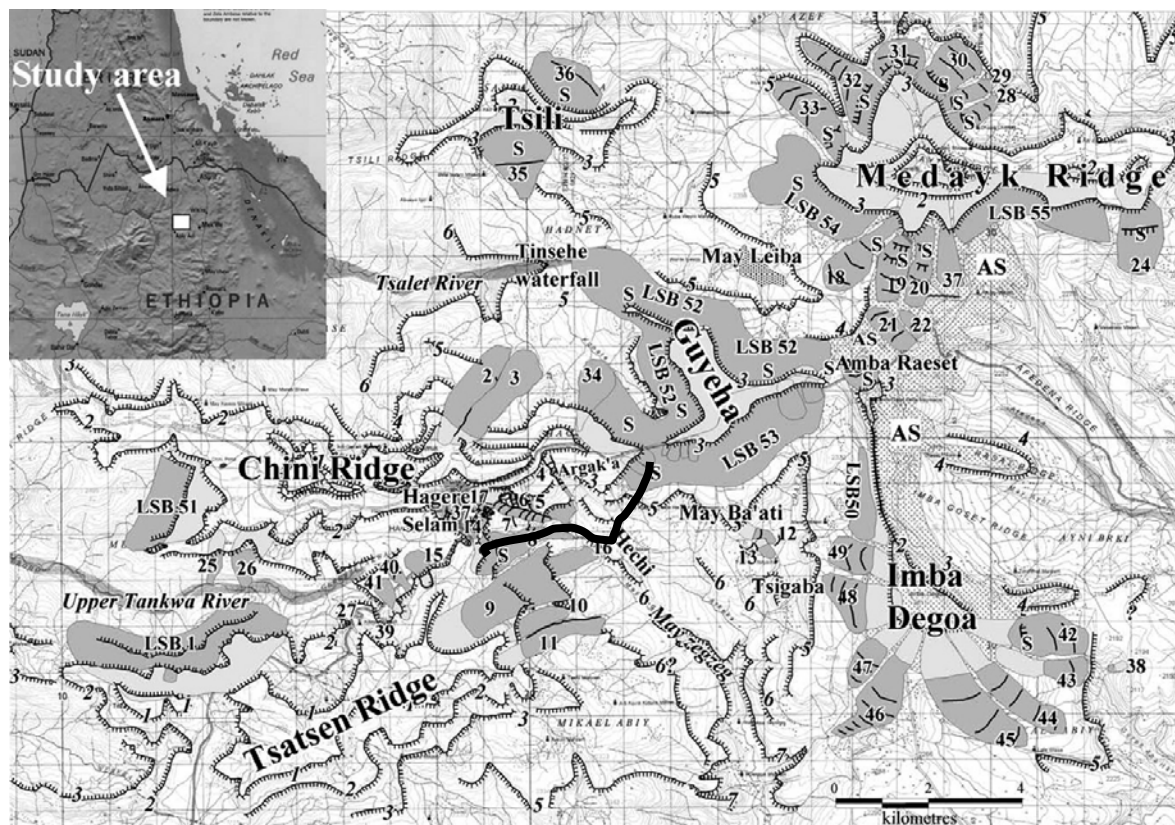
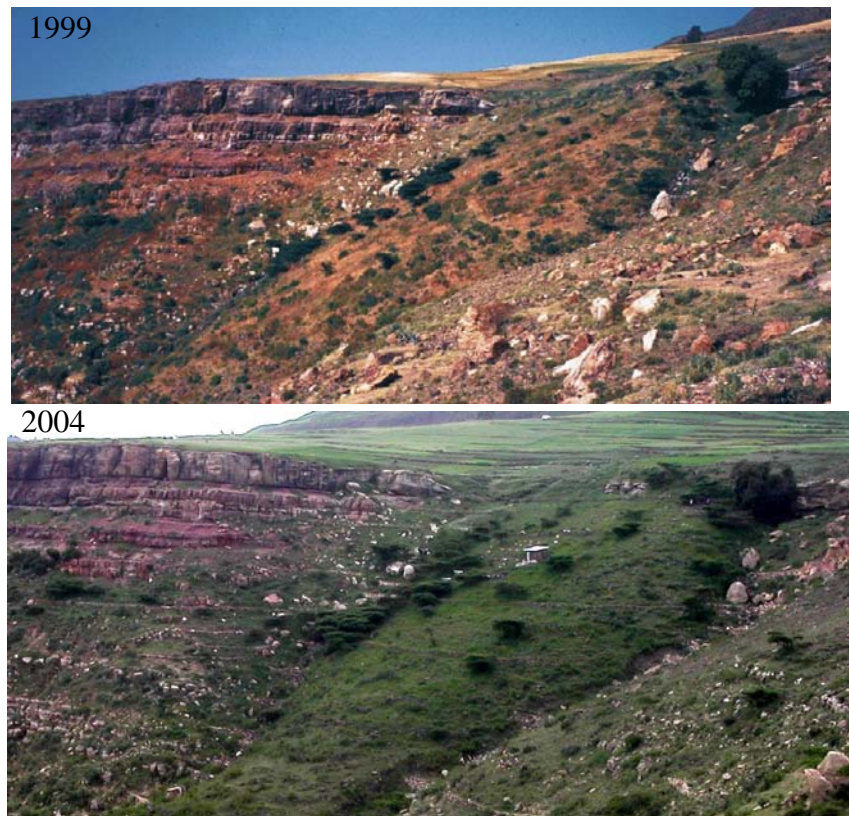


Fig. 1. Location of the study area and distribution of landslides. Landslides and landslide belts (LSB) in grey are numbered. Light grey: erosional or source area; dark grey: depositional area, accumulation lobe. Barbed lines represent cliffs. The light grey zone indicated by AS gives the extension of Agula shales based on Bosellini et al. (1997). Thick line represents the transect walk. Observation point is at the toe (southern edge) of landslide 4 (After Moeyersons et al., 2008).

The majority of the landslides are old debris flows, affecting the plateau basalts and flowing over the plateau edge, producing a sometimes km-long landslide foot, covering the steep plateau escarpment and often reaching the plain 200 to 400 m lower. For a limited number of these landslides reactivations were reported endangering roads and other infrastructure. One of these reactivations concerned the Amba Raeset debris flow in 1999 (see section 14). Nyssen et al.

(2002) attribute the general tendency of reactivation of landslides in the region to changes in land use which contribute to a general increase in the soil water content (i.e. soil and water conservation measures such as conversion of rangeland into exclosures). This decreases the values of the apparent cohesion and of the angle of internal friction and can eventually lead to an



increase of the hydrostatic pressures at the base of the landslide.

Fig. 2: The May Ntebteb flow in 1999 (top) and in 2004 (bottom), provided with several stone bunds.

The land use changes on the May Ntebteb flow (Fig. 1, landslide 4) in 2002-2004 were a unique occasion to test the hypothesis that the installation of stone bunds on the landslide lobe (Fig. 2) and the consequent increase of water infiltration into the soil (Nyssen et al., 2004) resulted in an increasing landslide activity. The displacement of the flow has been monitored between October 1998 and March 2001 (Nyssen et al., 2002). This note discusses the result of a ongoing monitoring campaign which started in 2007.

Materials and methods

The study area

The study area (Fig. 1) is located in Tigray, northern Ethiopia, and covers a 500 km² rectangle in the watershed of the Geba and Werei river basins east and north of Hagere Selam, some 50 km west of Mekelle. The area was chosen because it reveals a complete geological section with Paleozoic and Mesozoic sandstones, carbonates and limestones overlain by Tertiary basalts (Fig. 3). Especially the latter are believed to be prone to slope failure. The present-day, structural landscape of tabular, stepped ridges of Tsatsen (2912 m a.s.l.), Chini (2757 m a.s.l.), Guyeha (2600 m a.s.l.), Tsili (2700 m a.s.l.), Medayk (2835 m a.s.l.), and Imba Degoa–Amba Raeset (2611 m a.s.l.) is resulting from differential erosion of the subhorizontal and monoclinial

lithological layers. Between these ridges there are several hundred meter deep valleys. The occurrence of cliffs and steep escarpments is typical.

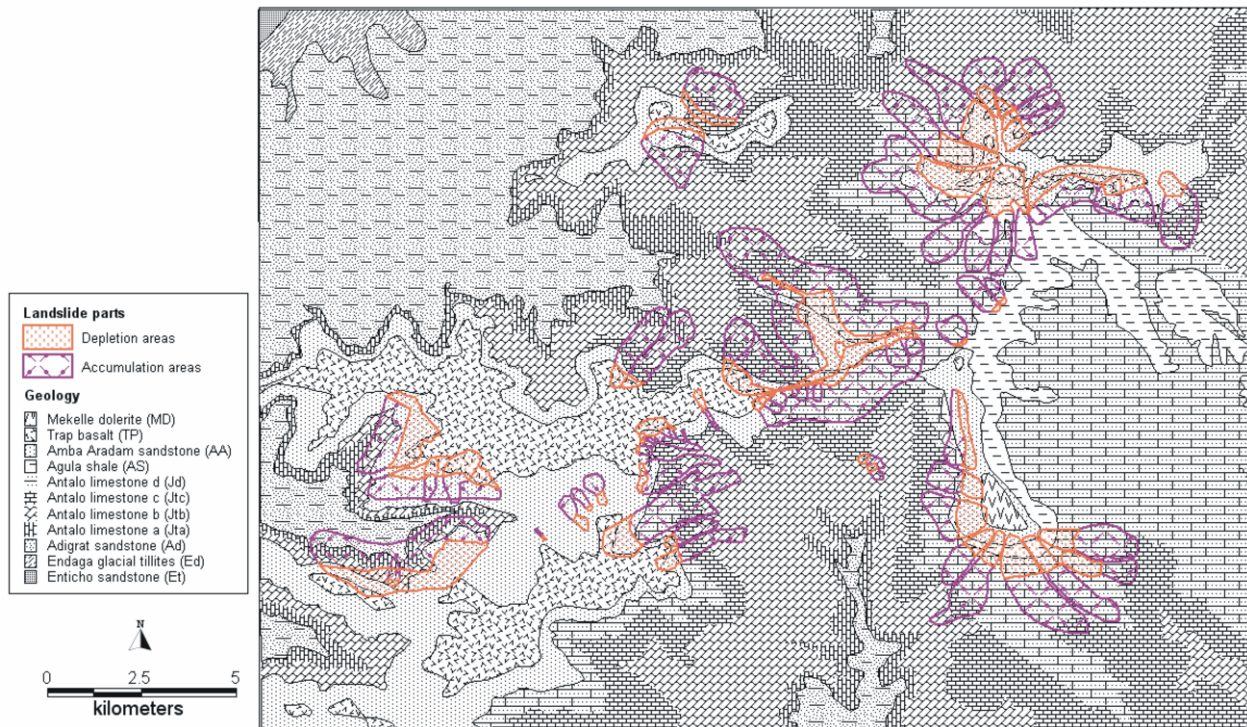


Fig. 3. Geological map of the study area (after Russo et al., 1999) with overlay of landslide depletion and landslide accumulation areas (Van Den Eeckhaut et al., 2009).

The oldest geological formation in the study area, deep in the valleys of the May Zeg-zeg, Tsaliet and upper Tankwa rivers is the Upper-Palaeozoic Adigrat sandstone. It is overlain by marine Antalo limestones of Jurassic age, about 500 m thick. Agula shales, which form the upper part of the Antalo supersequence (Bosellini et al., 1997) are present in a small belt around the Imba Degoa–Amba Raeset and on the elongated pass between the latter and the Medayk Ridge (Fig. 1; 3). Agula shales, where present, or Antalo limestones are truncated by a peneplanation disconformity (see section 28), overlain by Amba Aradam sandstone of Cretaceous age and by two series of Tertiary basalt. The latter are separated by partially silicified lacustrine deposits. The base and lower part of most ridges in the study area typically display outcrops of the Antalo supersequence, mostly only Antalo limestones, often in the form of massive limestone cliffs. The Amba Aradam sandstone and the tertiary basalts form the tabular extensions on top of the ridges, table mountains or plateaux.

The May Ntebteb flow is a recently reactivated ancient debris flow (Fig. 1, landslide 4). It has an affected area of 0.11 km² (with a length of 1100 m and a width of 100 m) and a displaced volume estimated at 1.7 10⁶ m³. The depletion and accumulation area have a slope of 52 and 13% respectively (Nyssen et al., 2002). The drainage channels that developed on both landslide boundaries are typical for old landslides.

The measuring method

To investigate the displacement of the May Ntebteb flow a network of measuring points was installed on and around the flow and measured with a laser theodolite. Amba Aradam sandstone boulders and rock fragments of dimensions of decimeters to meters were used as marker points. Only blocks which are for their major part embedded have been used so that rock creep over the surface can be excluded as possible source of error. Hence, the movement rate of the blocks is suggested to represent the movement rate of the landslide debris, which mainly consists of swelling clays resulting from the weathering of the plateau basalts. In April 2007, 45 measuring points were selected (Fig. 4). Three fixed reference points, A, B, and C upslope of the main scarp were used to put up a local coordinate system. Within the landslide-affected area 36 measuring points were marked and 6 measuring points were selected a few meters outside the landslide affected area in order to verify that the flow indeed moves faster than the surrounding sediment slopes. All measuring points were holes in rocks made by means of a chisel and indicated with paint (Fig. 5).

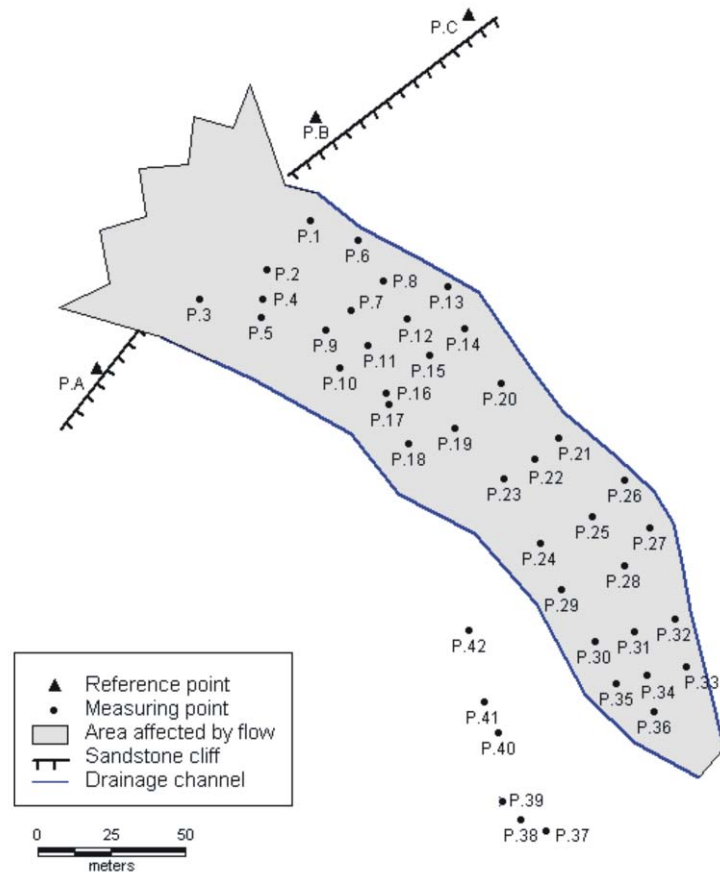


Fig. 4: Distribution of the marked blocks with a schematic representation of the sandstone cliff, area affected by the debris flow and drainage channels. Slope direction is to the South-east.

The same monitoring technique has been used during the period October 1998 - March 2001 (Nyssen et al., 2002), but the blocks were arranged on one line along the central axis of the lobe.

This line extended for 83 m downslope from the cliff. The measurements which started in 2007 used much more block points, enabling a distinction of the spatial variability of the movement.

Provisional results

Till now there has only been done one reading of the displacement of the 45 blocks, in the middle of August 2008. Table 1 shows some results, but they have to be interpreted with care. The points outside the landslide-affected area clearly show less displacement compared to the points inside the landslide. For the six uppermost



Fig. 5: Example of marker point

points, which cover about the 50 upper meters of the lobe, the mean displacement was 6.7 cm in the downslope direction. Compared with the displacement measured between October 1998 and March 2001, estimated at 6.4 cm in the 83 upper meter of the lobe (Nyssen et al., 2002), we measured an increase (doubling) of the creep rate. This might strengthen the hypothesis that the change in soil use (Fig. 2) on the lobe and in the upslope contributing area influences positively the creep rate.

The 2008 measurements also suggest differential movement within the debris flow. For the more downslope points the displacement was generally lower (average 3.7 cm) but not always in the downslope direction only and hence these points are more difficult to interpret. It can be deduced that the acceleration in the movement starts upslope, where slopes are steeper, and decreases in downslope direction causing compression and pressure increase in the middle part of the lobe. However, future measurements are required to confirm whether this is a continuous trend.

Table 1: Displacement measured between August 2008 and April 2007

	Reference points (PA-C)	Point in affected area		Point outsided affected area P37-42
		P1-6	P7-36*	
Mean	0.006	0.067	0.037	0.014
Stdev	0.002	0.039	0.014	0.009

* For P7-36 the measured displacement was not always in the downslope direction.

References

- Bosellini, A., Russo, A., Fantozzi, P.L., Assefa, G., Solomon, T., 1997. The Mesozoic succession of the Mekelle outlier (Tigre province, Ethiopia). *Mem. Sci. Geol.* 49, 95–116.
- Moeyersons, J., Van Den Eeckhaut, M., Nyssen, J., Tesfamichael Gebreyohannes, Van de Wauw, J., Hofmeister, J., Poesen, J., Deckers, J. and Mitiku Haile, 2008, Mass movement mapping for geomorphological understanding and sustainable development: Tigray, Ethiopia. *Catena*, 75, 1: 45-54
- Nyssen, J., Moeyersons, J., Poesen, J., Deckers, J., Mitiku Haile, 2002. The environmental significance of the remobilization of ancient mass movements in the Atbara-Tekeze headwaters, Northern Ethiopia. *Geomorphology* 49(3-4):303-322
- Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Mitiku Haile, Lang, A., 2004. Human impact on the environment in the Ethiopian and Eritrean Highlands – a state of the art. *Earth Science Reviews*, 64/3-4: 273-320
- Russo, A., Fantozzi, P.L., Solomon, T., Getaneh, A., Neri, C., Russo, F., Asfwossen, A., Peccerillo, A., Valera, P., 1996. Geological Map of the Mekelle Outlier (Western Sheet), Italian Cooperation. Addis Ababa University, Addis Ababa.
- Shimelies Ahmed Aboy, 2009. Slope stability analysis using GIS and numerical modeling techniques. Master dissertation, Interuniversity programme of science in physical land resources, Universities of Ghent and Vrije Universiteit Brussel, September 2009, 127 p.
- Tesfahunegn Abera Gebreslassie, 2008. Landslide risk assessment with the help of GIS and remote sensing around Hagere Selam. Master dissertation, Interuniversity programme of science in physical land resources, Universities of Ghent and Vrije Universiteit Brussel, July 2008, 69 p.
- Van Den Eeckhaut, M., Moeyersons, J., Nyssen, J., Amanuel Abraha, Poesen, J., Mitiku Haile, Deckers, J., 2009. Spatial patterns of old, deep-seated landslides: a case-study in the northern Ethiopian highlands. *Geomorphology*, 105:239-252.

22. The sediment budget of May Zeg-zeg catchment and its components

Jan Nyssen¹, Wim Clymans², Jozef Naudts², Jean Poesen², Ine Vandecasteele³, Nigussie Haregeweyn⁴, Jan Moeyersons⁵, Jozef Deckers², Mitiku Haile⁴

¹ Department of Geography, Ghent University, Gent, Belgium

² Department of Earth and Environmental Sciences, K.U.Leuven, Heverlee, Belgium

³ Department of Geology, Ghent University, Gent, Belgium

⁴ Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia

⁵ Royal Museum of Central Africa, Tervuren, Belgium

*Corresponding author. Email: jan.nyssen@ugent.be

An overall approach to assess the effectiveness of soil conservation measures at catchment scale is the comparison of sediment budgets before and after implementation of a catchment management programme. In the May Zeg-zeg catchment (187 ha – Fig. 1) in Tigray, north Ethiopia, integrated catchment management has been implemented since 2004: **stone bunds** were built in the whole catchment (Fig. 2), vegetation was allowed to regrow on steep slopes and other marginal land (**exclosures**), stubble grazing abandoned, and **check dams** built in gullies (Fig. 3; Fig. 4). Land use and management were mapped and analysed for the situation before (2000) and after catchment management (2006) (Fig. 5; Fig 6), whereby attention was also given to the quantification of changes in soil loss due to the abandonment of stubble grazing (Table 1). Sediment yield was also **measured at the catchment's outlet**. A combination of decreased soil loss (from 14.3 t ha⁻¹ y⁻¹ in 2000 to 9.0 t ha⁻¹ y⁻¹ in 2006) and increased sediment deposition (from 5.8 to 7.1 t ha⁻¹ y⁻¹) has led to strongly decreased sediment yield (from 8.5 to 1.9 t ha⁻¹ y⁻¹) and sediment delivery ratio (from 0.6 to 0.21). This diachronic comparison of sediment budgets (Fig. 7; Fig. 8) revealed that integrated catchment management is most effective and efficient and is the advisable and desirable way to combat land degradation in Tigray and other tropical mountains.

References

- Nyssen, J., Clymans, W., Poesen, J., Vandecasteele, I., Nigussie Haregeweyn, Naudts, J., Moeyersons, J., Mitiku Haile, Deckers, J., 2009. How soil conservation affects the catchment sediment budget - a comprehensive study in the north Ethiopian highlands. *Earth Surface Processes and Landforms*, 34: 1216-1233.
- Nyssen, J., Poesen, J., Mitiku Haile, Moeyersons, J., Deckers, J., Hurni, H., 2009. Effects of land use and land cover on sheet and rill erosion rates in the Tigray Highlands, Ethiopia. *Zeitschrift für Geomorphologie*, 53(2): 171-197.
- Nyssen, J., Naudts, J., De Geyndt, K., Mitiku Haile, Poesen, J., Moeyersons, J., Deckers, J., 2008. Soils and land use in the Tigray Highlands (Northern Ethiopia). *Land Degradation and Development*, 19: 257 - 274.
- Nyssen, J., Poesen, J., Desta Gebremichael, Vancampenhout, K., D'aes, M., Gebremedhin Yihdego, Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Nigussie Haregeweyn, Mitiku Haile, Deckers, J., 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. *Soil and Tillage Research*, 94: 151-163.
- Nyssen, J., Poesen, J., Veyret-Picot, M., Moeyersons, J., Mitiku Haile, Deckers, J., Dewit, J., Naudts, J., Kassa Teka, Govers, G., 2006. Assessment of gully erosion rates through interviews

and measurements: a case study from Northern Ethiopia. *Earth Surface Processes and Landforms*, 31(2): 167-185.

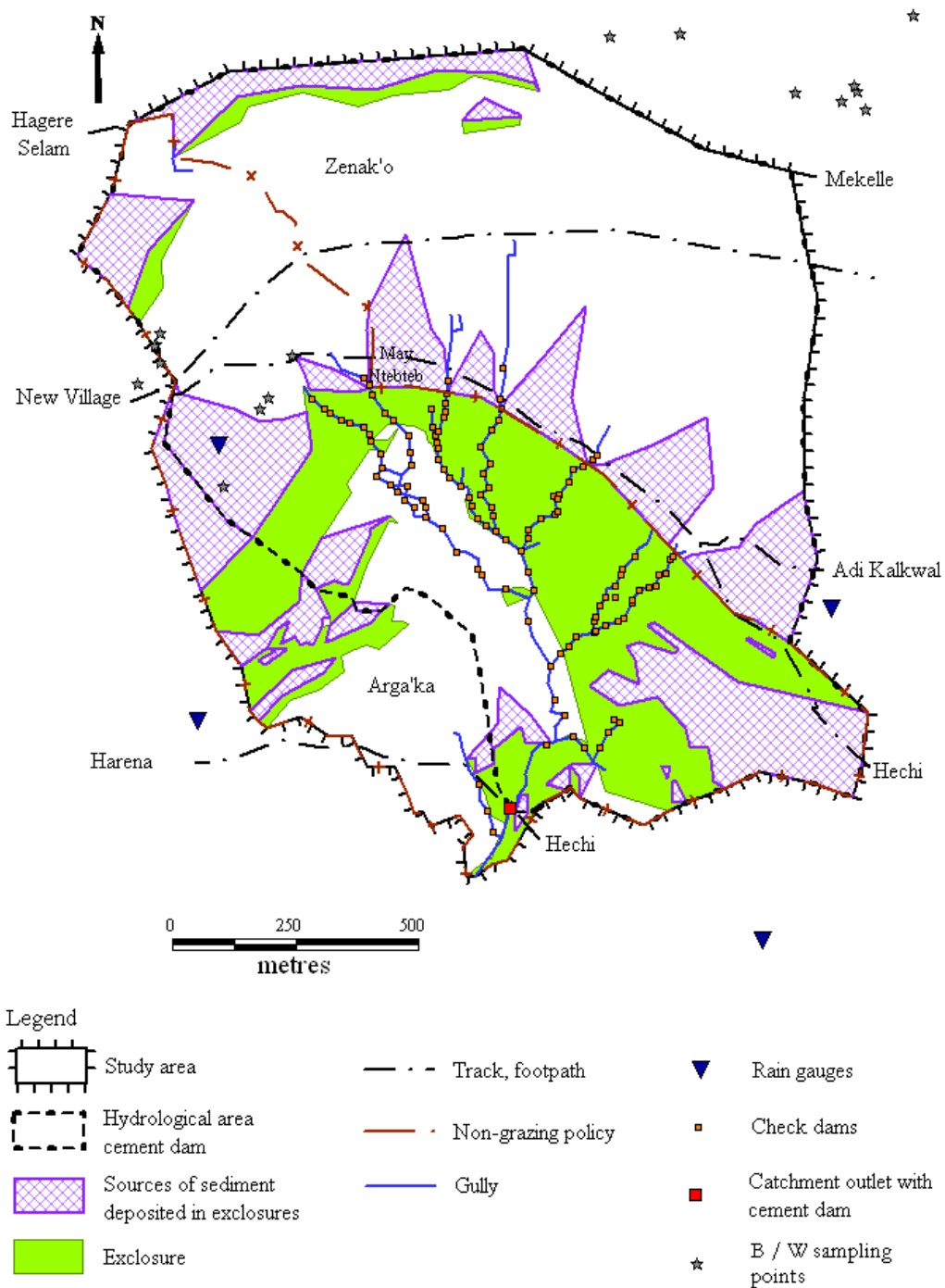


Figure 1. May Zeg-zeg catchment with location of SWC techniques (in 2006) as well as research instrumentation. BW stands for above-ground biomass.

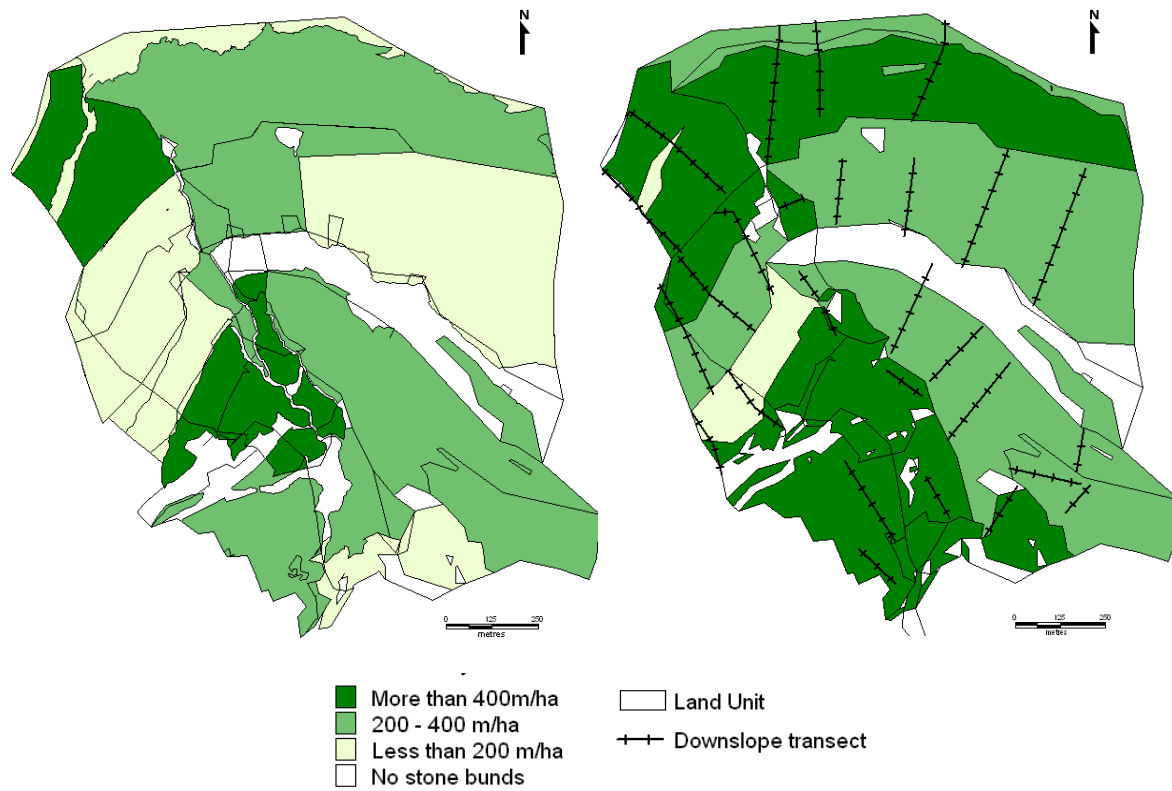


Figure 2. Stone bund densities in 2000 (left) and 2006 (right). Position of the 2006 downslope transects for measurement of stone bund density is indicated.

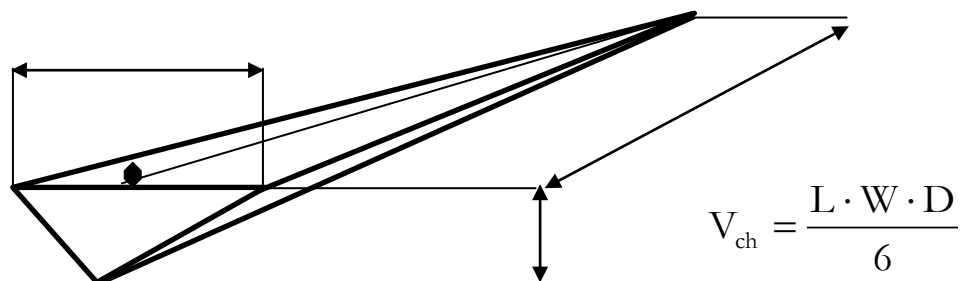


Figure 3. Schematic representation (perspective) of the most common shape of sediment deposition behind check dams in a gully: black dot represents the deepest point, depth (D, m), length (L, m) and width (W, m)

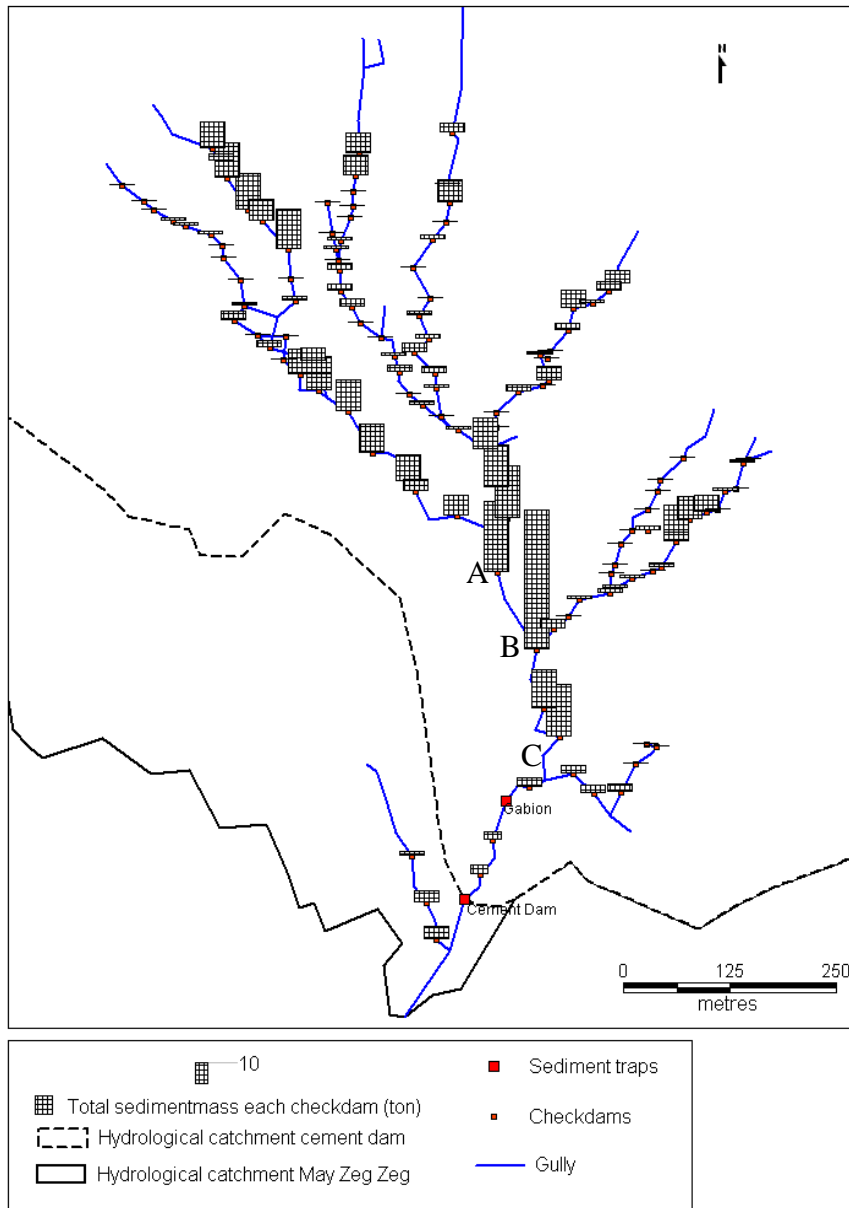


Figure 4. Measured sediment deposition (t) behind check dams in May Zeg-zeg; A, B and C are junctions in the gully system. See Figure 1 for location in the catchment of the gully system with check dams.

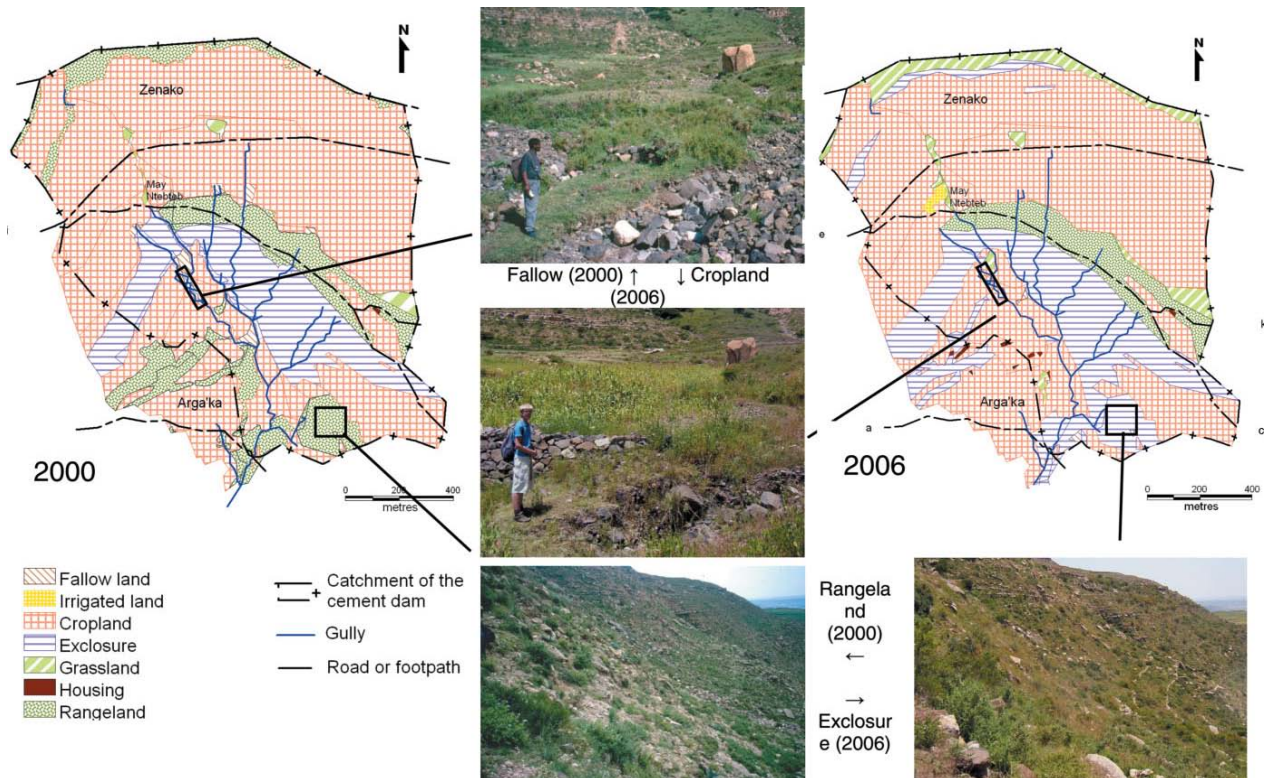


Figure 5. Land use maps of MZZ catchment in 2000 and 2006 with photographs of typical land uses in both years.

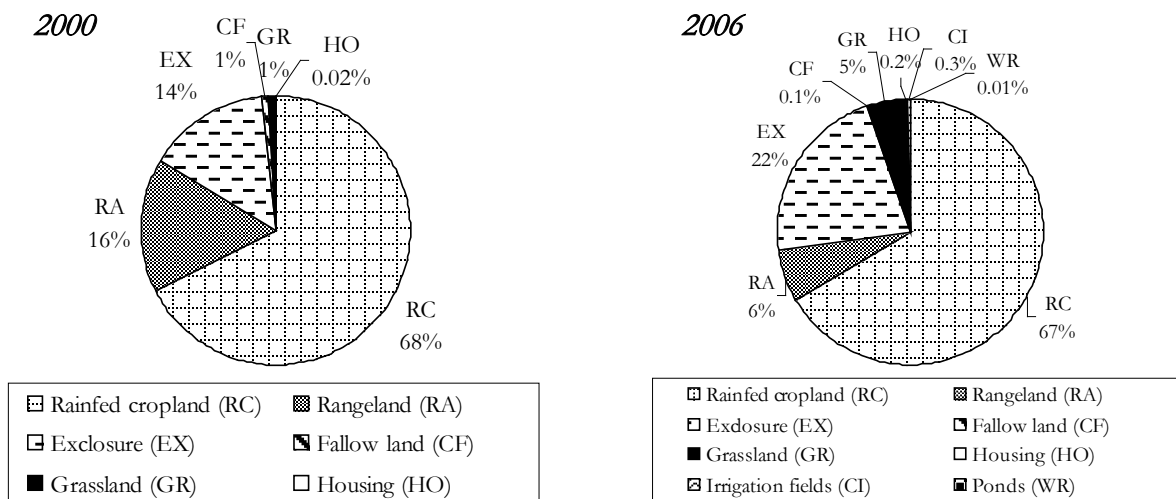


Figure 6. Relative areas of land use types in 2000 and 2006.

Table 1. Measured mean soil loss rates by sheet and rill erosion ($\text{t ha}^{-1} \text{ y}^{-1}$) for each land use category in the MZZ catchment.

Land-use category	Average yearly soil loss rate ($\text{t ha}^{-1} \text{ y}^{-1}$)
Cropland ^a /free grazing ^b	9.9
Cropland ^a /non-grazing ^c	7.9
Exclosures	3.5
Grassland ^d	0.7
Housing ^e	0
Rangeland	17.4

^a As temporary fallow land concerned only 1% of the catchment in 2000 and 0.1% in 2006, it has been incorporated in cropland for sediment budget calculations.

^b On all cropland in 2000, and on part of the cropland in 2006.

^c Assessed in this study.

^d Value established in exclosures with continuous grass cover and 30% shrub cover.

^e Farms and housing compound areas were measured around the outer stone fence: sediment produced within the compounds is assumed to be deposited also within that stone wall.

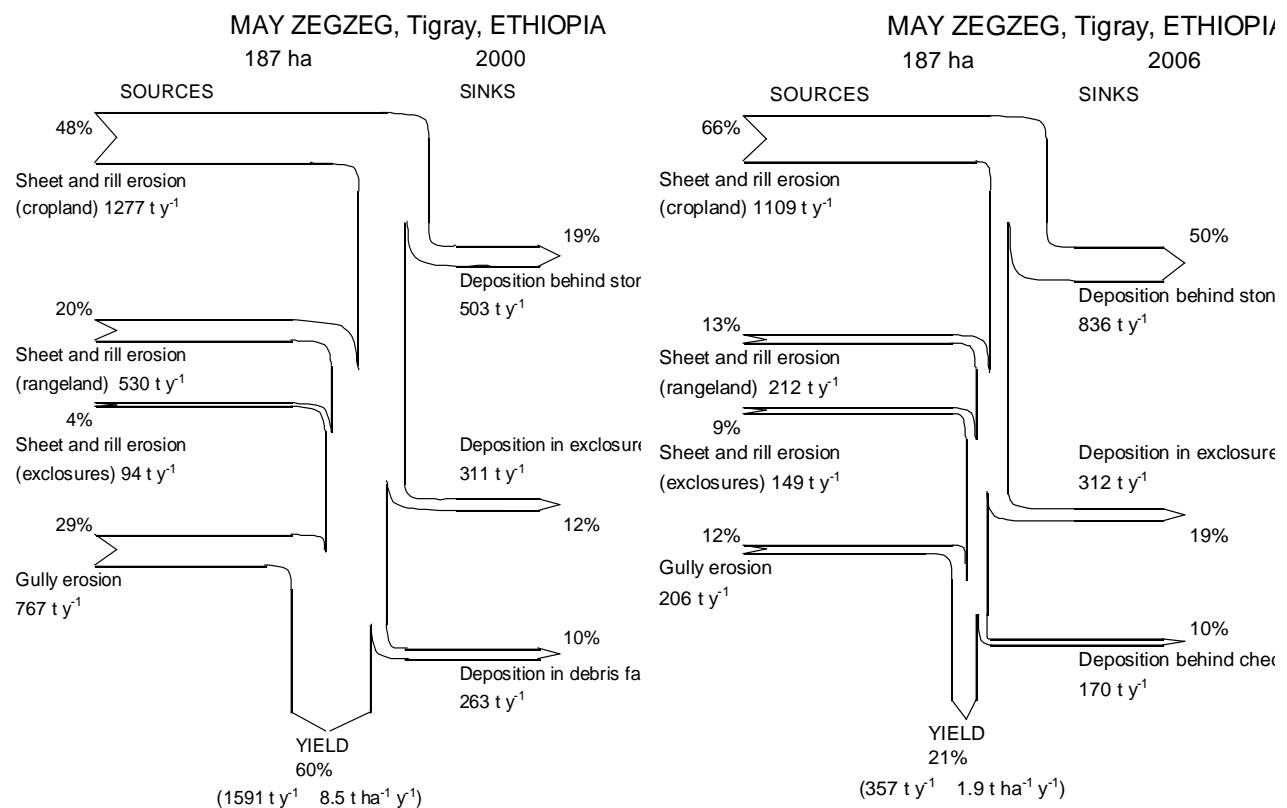


Figure 7. Sediment budgets for MZZ catchment in 2000 (left) and 2006 (right) with computation of sediment sources and sinks. Width of arrows is proportional to sediment masses involved.

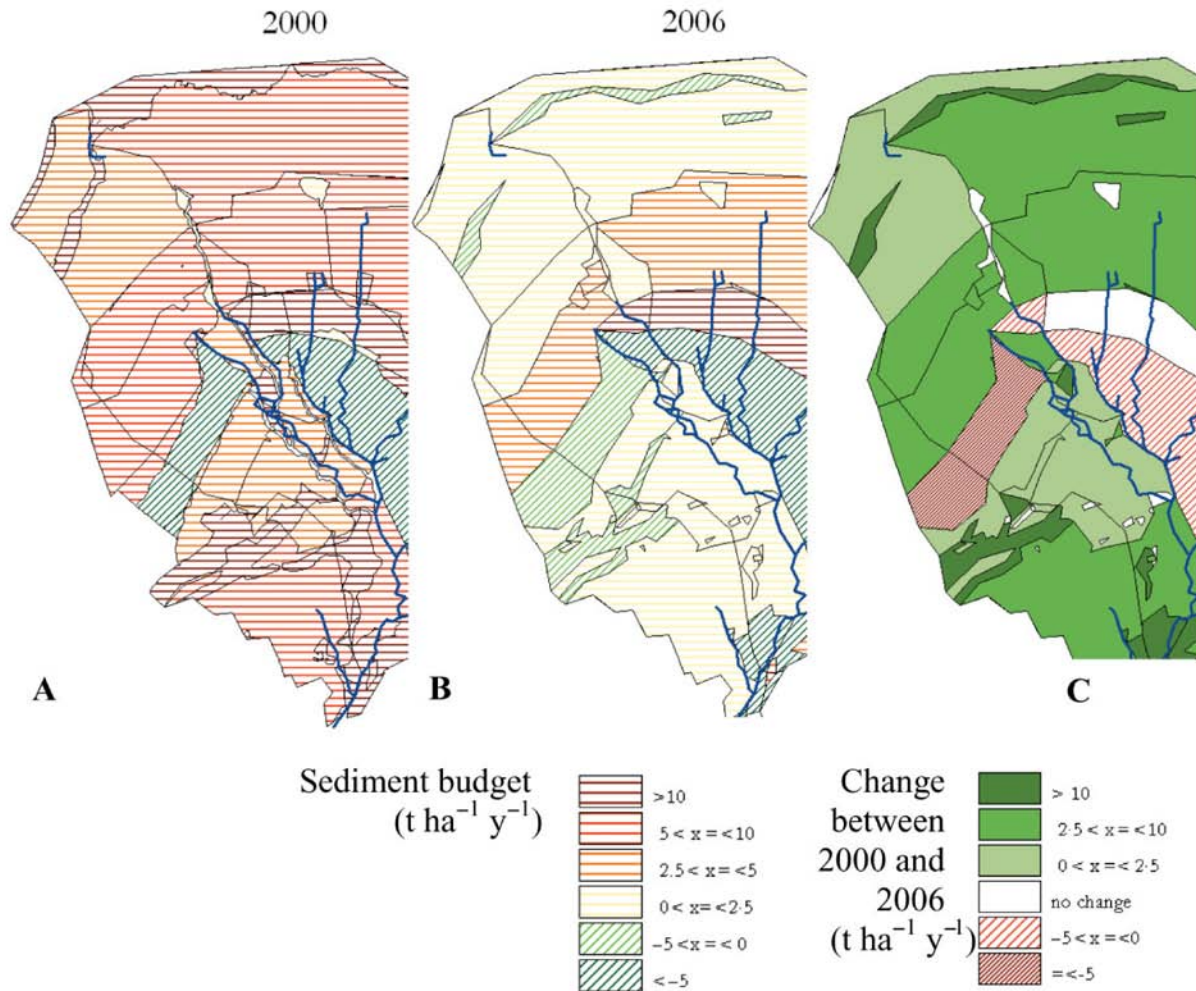


Figure 8. Sediment budget (sediment production minus sediment deposition = sediment yield) ($\text{t ha}^{-1} \text{y}^{-1}$) for each land unit in 2000 (A) and 2006 (B). Sediment delivery areas (sources) are positive (red) and sediment deposition areas (sinks) are negative (green). (C): changes between 2000 and 2006 with improvements (green) and declines (red), related to decreased sediment input. Gully erosion and deposition behind check dams are not represented.

23. Hydro(geo)logy and impact of soil and water conservation measures on the hydrological response in May Zeg-zeg catchment

(After Walraevens *et al.* (2009), Nyssen *et al.* (2010), Vandecasteele *et al.* (2011))

Tesfamichael Gebreyohannes¹, Kristine Walraevens², Ine Vandecasteele^{2,3}, Wim Clymans⁴, Jan Moeyersons³, Katrien Descheemaeker⁵, Amanuel Zenebe⁶, Nigussie Haregeweyn⁶, Kristine Martens², Marc Van Camp², Jean Poesen⁴, Florimond Desmedt⁷, Jozef Deckers⁴, Mitiku Haile⁶, Jan Nyssen⁸

¹ Department of Geology, Mekelle University, Ethiopia

² Department of Geology and Soil Science, Ghent University, Belgium

³ Africamuseum, Tervuren, Belgium

⁴ Department of Earth and Environmental Sciences, K.U.Leuven, Belgium

⁵ CSIRO, Australia

⁶ Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia

⁷ Department of Geology, V.U.Brussel, Belgium

⁸ Department of Geography, Ghent University, Belgium

As part of outreach accompanying research in the region around Hagere Selam, an integrated catchment programme was set up in 2004 in the 200-ha May Zeg-zeg catchment by researchers in cooperation with ADCS, a local NGO. Located at elevations between 2260 m a.s.l. and 2650 m a.s.l., the catchment stretches over the upper Antalo Limestone (Agula'e shale is absent), the Amba Aradom sandstone and basalt. It has a sub-humid tropical mountain climate with high seasonality (Fig. 1). The main objectives were improvement of the livelihood of the communities in three adjacent villages as well as demonstrating and promoting global catchment management towards rural communities in the highlands of northern Ethiopia. This was done by the installation of a sustainable catchment management and a programme for capacity building and awareness raising regarding integrated catchment management. More specifically the project included the implementation of site-specific conservation techniques aimed at increasing water infiltration and conserving soil, i.e. the construction of dry masonry stone bunds on all land and check dams in gullies, the abandonment of post-harvest grazing, and the set aside of degraded rangelands, which results in exclosures.

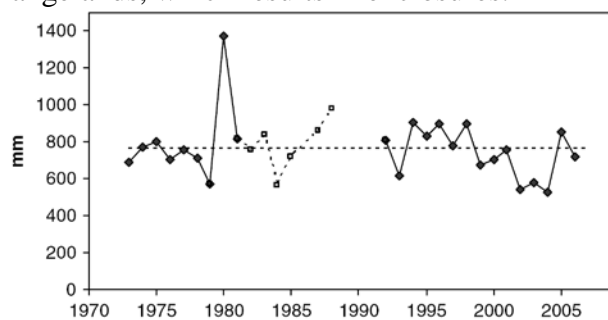


Figure 4. Annual precipitation in Hagere Selam. Annual average is 762 (± 171) mm. Source: National Meteorological Agency (www.ethiomet.gov.et), except 1992–1994: Dogu'a Tembien Agricultural Office. Missing data correspond to the period of civil war and the years thereafter. A tentative reconstruction of yearly rainfall for 1982–1988 was done through correlation with rainfall recorded at Mekelle station, 50 km away; for 1989–1991, rainfall data are also missing for Mekelle

Fig. 1.

Table II. Total and average precipitation (mm) in the study area in the period 2001–2006 sub-divided according to rainy season (June–September) and dry season (October–May)

Period	2001	2002	2003	2004	2005	2006	Average
October–May	116	75	111	32	170	200	117
June–September	606	491	428	526	596	425	512
Total	722	566	540	558	766	626	629

Table 1

In prevision of the upcoming management programme, and in order to be able to investigate its impact, rainfall (Table 1), water table and spring monitoring were undertaken starting from 2001

and lasted till 2007. Intense investigations took place in the rainy season of 2006. The studies concerned the surface hydrology of the catchment, the hydrogeology, and the impact of catchment management on the hydro(geo)logy.

1. Hydrogeological studies

A geological map was produced through geophysical measurements and field observations, and a fracture zone identified in the north west of the catchment (Fig. 2). A perched water table was found within the Trap Basalt series above the laterized upper Amba Aradam Sandstones (Fig. 3). A map of this water table was compiled. Water-level variation during the measurement period was at least 4.5 m (Fig. 4). Variation in basal flow for the whole catchment was measured at the dam near the outlet in the rainy season of 2006 (Fig. 5 and 6) and varied between 12 and 276 m³/day. A groundwater flow model was produced using Visual MODFLOW using parameters for hydraulic conductivity (Table 2, Fig. 7), indicating the general direction of flow to be towards the south, and illustrating that the waterways have only a limited influence on groundwater flow (Fig. 9). The soil water budget was calculated for the period 1995– 2006, which showed the important influence of the distribution of rainfall in time (Fig. 8). Although Hagere Selam received some 724 mm of rainfall per year over this period, the strong seasonal variation in rainfall meant there was a water deficit for on average 10 months per year.

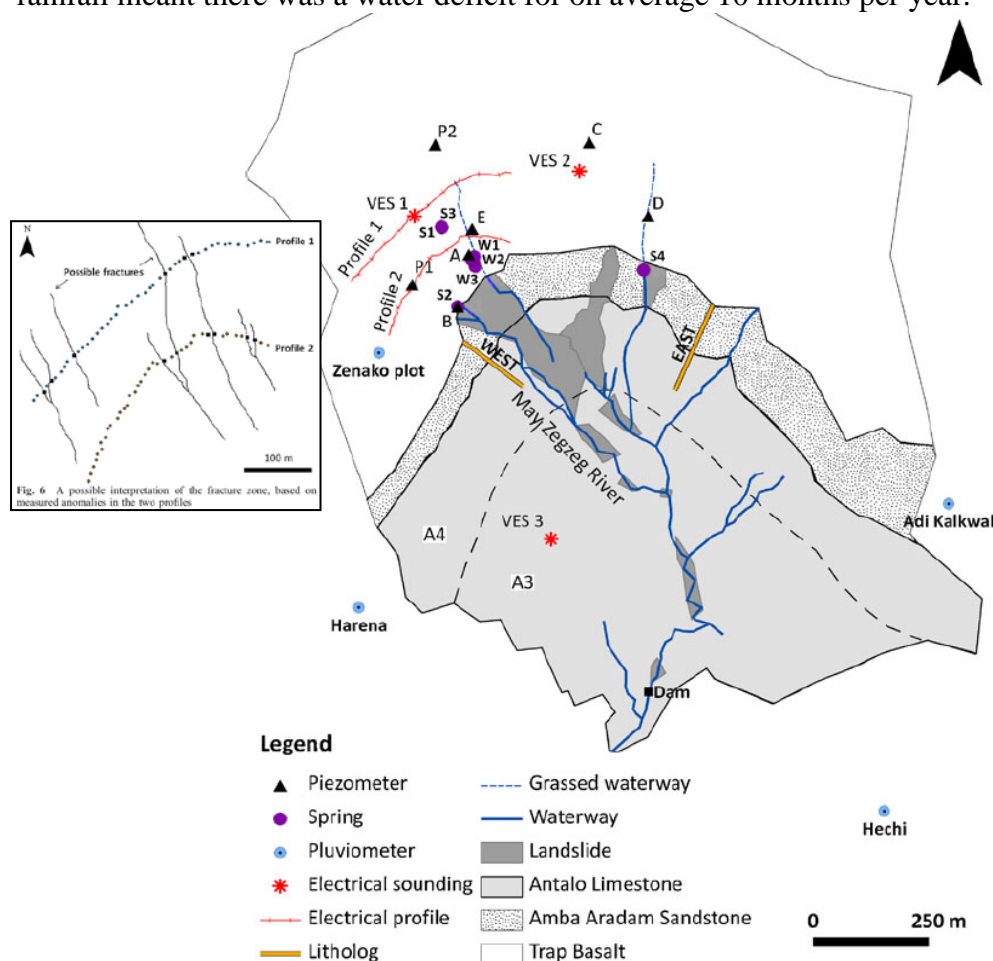


Fig. 3 Geological map of the May Zegzeg catchment. The sub-division of the Antalo Formation into units A3 and A4 is represented black dashed line. The profiles along which lithologs were taken on both sides of the catchment are indicated Fig. 2.

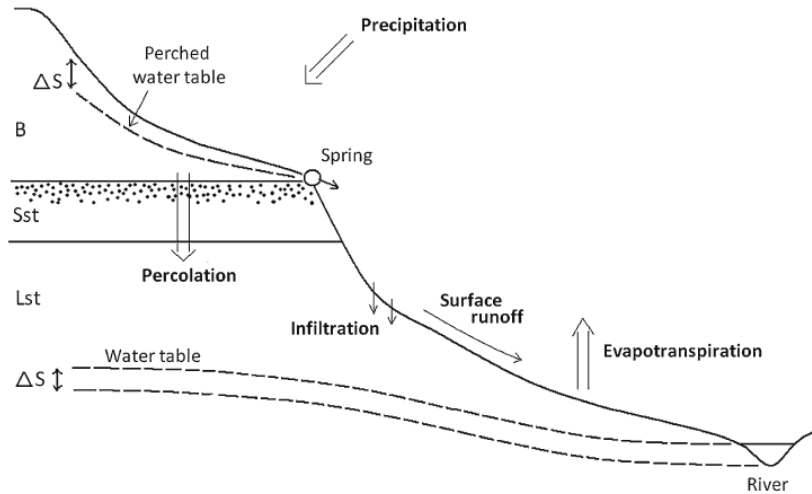


Fig. 4 The hydrological cycle represented in a schematic cross-section of the May Zegzeg catchment. Abbreviations used are basalt (*B*), sandstone (*Sst*) and limestone (*Lst*) for the lithologies, and ΔS for the change in soil water storage. Not to scale

Fig. 3.

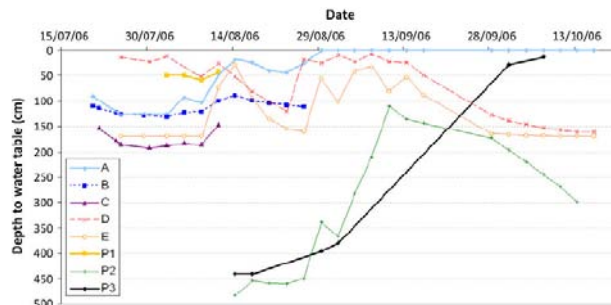


Fig. 4. Water levels (depth to the water table in cm) measured for the period of fieldwork, 2006

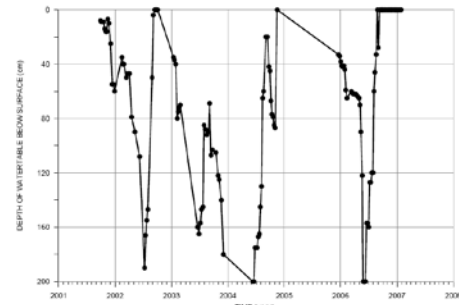
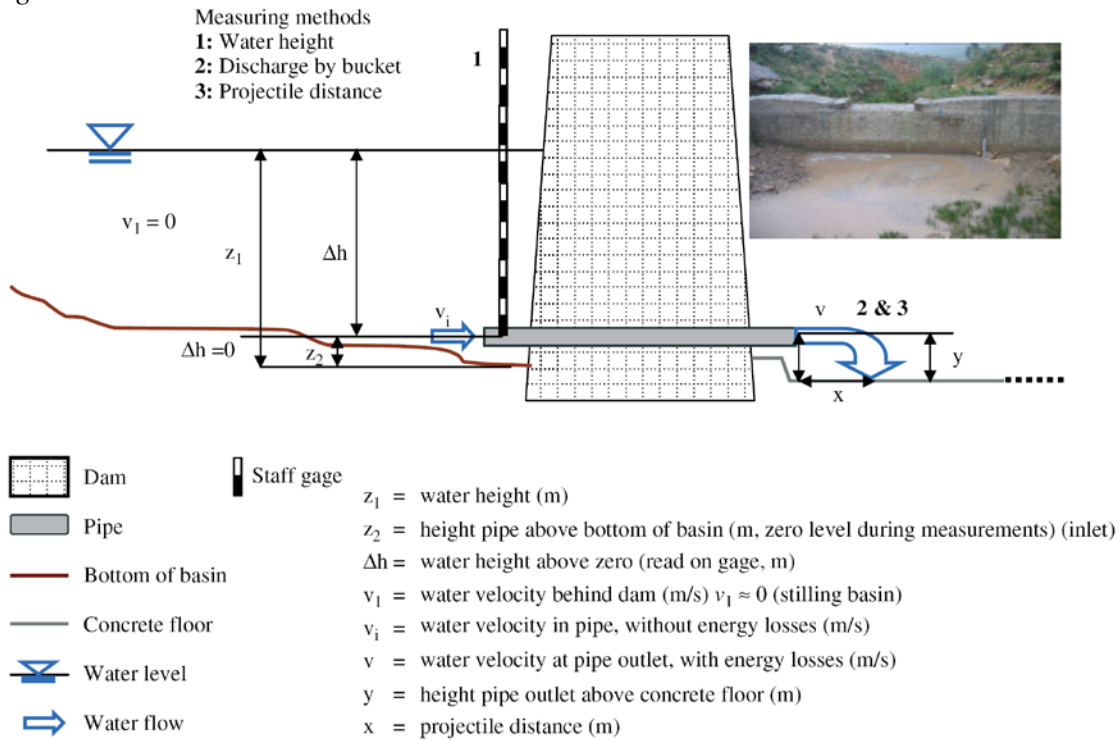


Fig. 4 Measured water table depth in observation Well A (2001–2007).



Schematic representation of the cement dam where runoff measurements were made at the catchment outlet (for location see Fig. 5).

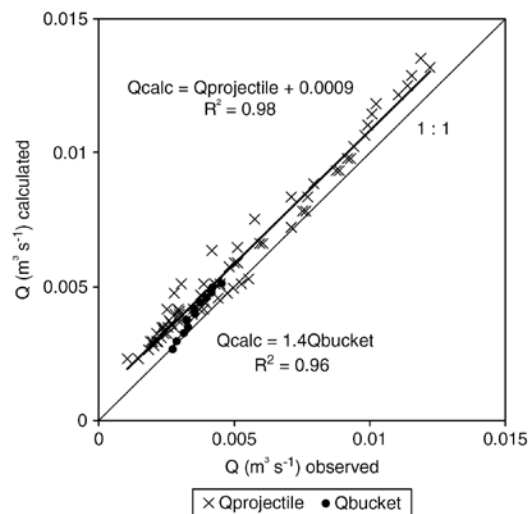


Figure 8. Calculated runoff discharge (Q_{calc} , $m^3 s^{-1}$, based on Bernoulli's equation) as a function of observed runoff discharges [Q_{obs} , $m^3 s^{-1}$, based on (1) projectile trajectory method (crosses) and (2) direct runoff discharge measurements with bucket (dots) at the pipe outlet]

Fig. 6.

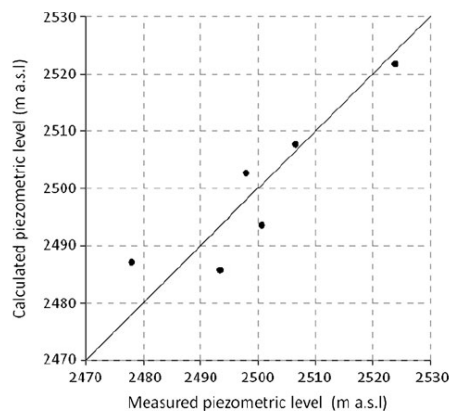


Fig. 12 A comparison of measured and calculated piezometric water levels in the Trap Basalts

Fig. 7.

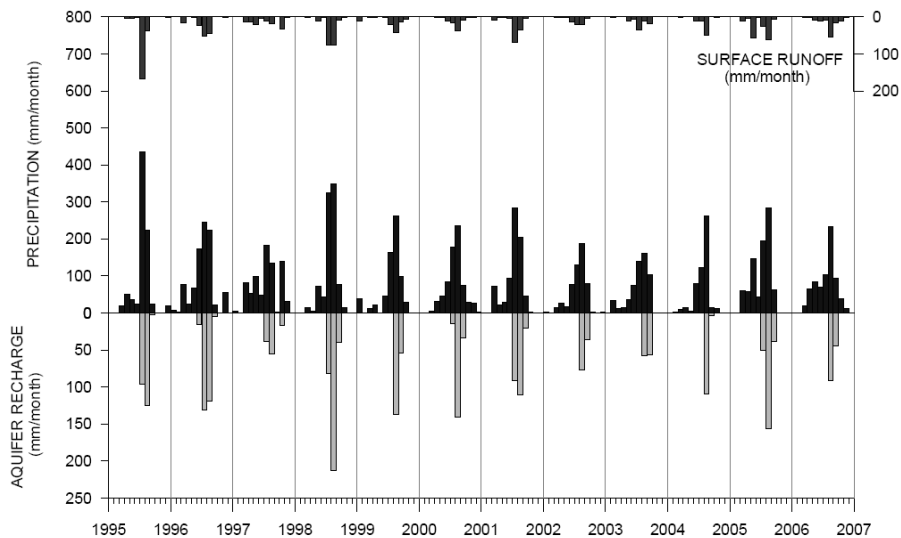


Fig. 8. Precipitation, calculated runoff and aquifer recharge (1995-2006)

Table 3 Hydraulic parameters used in the groundwater flow model

	Lithology	$K_h D$ (m^2/day)	K_h (m/day)	K_v (m/day)
Aquifer 1	Trap Basalts	-	0.025	-
Aquitard	Amba Aradam Sandstone	-	-	2.5×10^{-5}
Aquifer 2	Antalo Limestone	10	-	-

K_h horizontal hydraulic conductivity; K_v vertical hydraulic conductivity; D aquifer thickness (m)

Table 2.

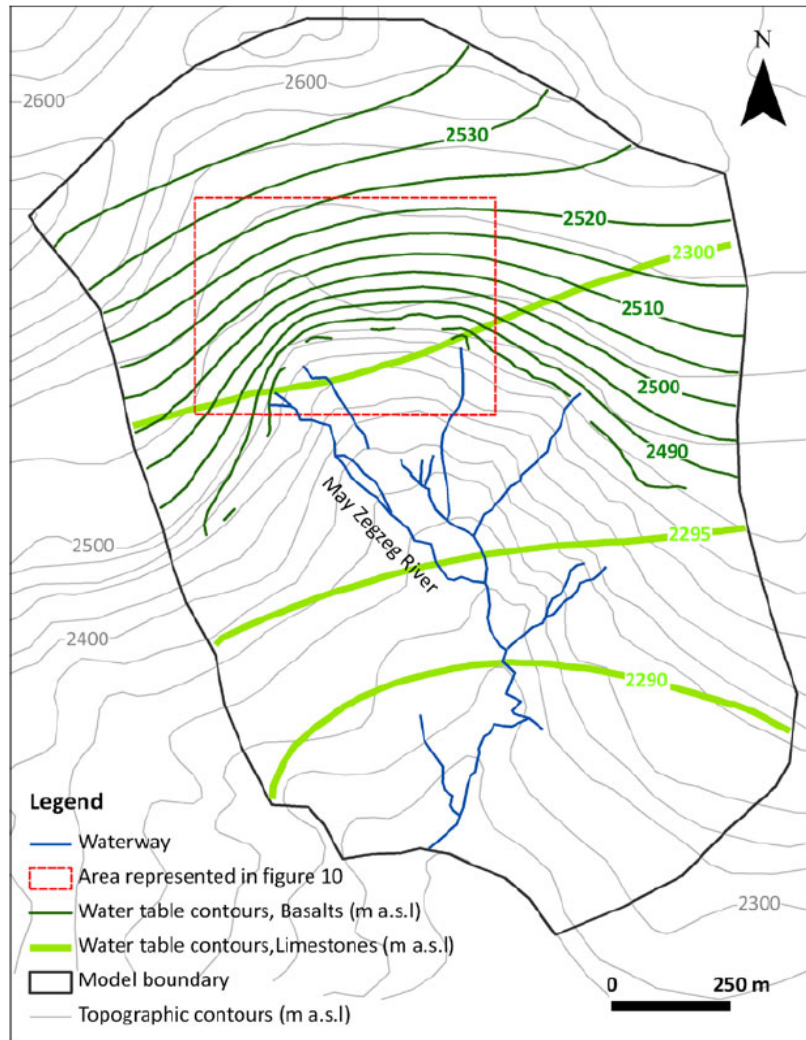


Fig. 9. Calculated piezometric levels in the vertisols/Trap Basalts and Antalo Limestone. The area for which the

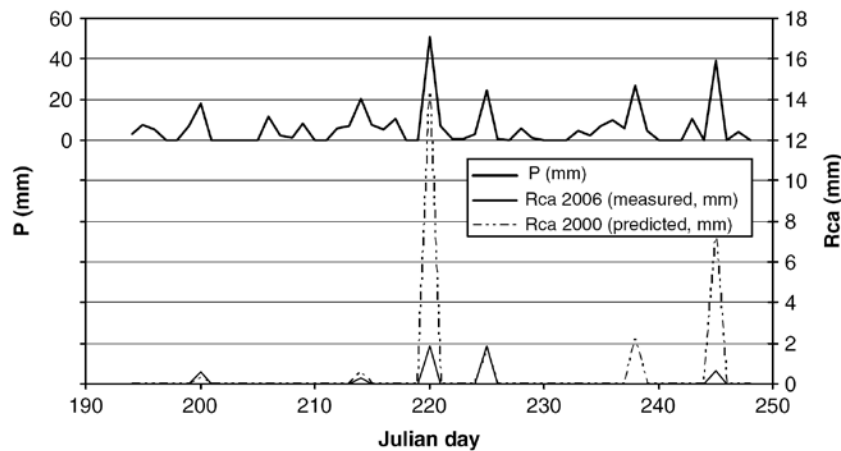
2. Impact of catchment management

Against this general background of catchment hydro(geo)logy, changes in the hydrological response of the catchment after catchment management in 2004 were investigated. Impact studies of catchment management in the developing world rarely include such detailed hydrological components. The management included various soil and water conservation measures such as the construction of dry masonry stone bunds and check dams, the abandonment of post-harvest grazing, and the establishment of woody vegetation. Measurements at the catchment outlet (Fig. 5) indicated a runoff depth of 5 mm or a runoff coefficient (RC) of 1.6% in the rainy season of 2006. Combined with runoff measurements at plot scale, this allowed calculating the runoff curve number (CN) for various land uses and land management techniques (Table 3). The pre-implementation runoff depth was then predicted using the CN values and a ponding adjustment factor, representing the abstraction of runoff induced by the 242 check dams in gullies. Using the 2006 rainfall depths, the runoff depth for the 2000 land management situation was predicted to be 26.5 mm (RC = 8%), in line with current RCs of nearby catchments (Fig. 10).

Table IV. CN for various land use and management types in May Zeg-Zeg catchment, allowing calculation of weighted average CN for 2000 and 2006

Land use and management type	2000			2006		
	CN ^b	Area (ha)	%	CN ^b	Area (ha)	%
Fallow land	89.5	1.6	1.1	89.5	0.1	0.1
Cropland (free grazing, no stone bunds ^a)	79.9	25.7	17.8	79.9	3.0	2.4
Cropland (free grazing, stone bunds of medium quality ^a)	79.4	63.3	43.9	79.4	35.0	27.4
Cropland (free grazing, good stone bunds ^a)	78.5	11.1	7.7	78.5	18.1	14.2
Cropland ('zero' grazing, no stone bunds ^a)	78.7	0.0	0.0	78.7	1.5	1.1
Cropland ('zero' grazing, stone bunds of medium quality ^a)	78.2	0.0	0.0	78.2	4.9	3.9
Cropland ('zero' grazing, good stone bunds ^a)	77.3	0.0	0.0	77.3	22.7	17.8
Exclosure (no stone bunds ^a)	67.3 ^c	24.4	16.9	45.7 ^d	0.0	0.0
Exclosure (stone bunds of medium quality ^a)	66.6	0.0	0.0	45.5	5.0	3.9
Exclosure (good stone bunds ^a)	65.6	0.0	0.0	45.2	29.5	23.1
Grassland	45.7	0.9	0.6	45.7	0.8	0.6
Grassland with dense runoff collector trenches	45.2	0.0	0.0	45.2	3.0	2.3
Rangeland	89.5	17.1	11.9	89.5	4.0	3.2
Land involved in CN calculation		144.1	100.0		127.5	100.0
Land draining to sinks	NA	19.8		NA	37.1	
TOTAL		163.9	100.0		164.7	100.0
Catchment weighted average CN			78.5			68.9

Table 3.



Runoff depth at catchment scale (R_{CA}), as measured in 2006 (after catchment management) and predicted for 2000 (before catchment management), based on 2006 rainfall data (P)

Fig. 10.

Monitoring of the ground water level indicated a rise after catchment management. The yearly rise in water table after the onset of the rains (ΔT) relative to the water surplus (WS) over the same period increased between 2002–2003 ($\Delta T/WS = 3.4$) and 2006 ($\Delta T/WS > 11.1$) (Table 4). Emerging wells and irrigation are other indicators for improved water supply in the managed catchment. Cropped fields in the gullies indicate that farmers are less frightened for the destructive effects of flash floods (Fig. 11). Due to increased soil water content, the crop growing period is prolonged. It can be concluded that this catchment management has resulted in a higher infiltration rate and a reduction of direct runoff volume by 81% which has had a positive influence on the catchment water balance.

Table VII. Maximal yearly rise of the water table in the piezometer (ΔT) compared to precipitation (P) and WS, as derived from detailed water balance calculations in the catchment (Vandecasteele, 2007; Walraevens *et al.*, 2009), over the same periods

	Period	ΔT (cm)	P (mm)	WS (mm)	$\Delta T/P$	$\Delta T/WS$
2002	10 July–13 September	190	406.2	56	0.47	3.39
2003	27 June–4 September	96	345.5	29	0.28	3.31
2004	19 June–4 September	>200	460.8	95	>0.43	>2.11
2006	10 June–26 August	>200	359.6	18	>0.56	>11.11
Average		171.5	393.03	49.5	0.44	4.98

Table 4.



Figure 10. Part of the lower gully system of MZZ before (1998) and after catchment management (2006). Both photographs were taken in August, during the main cropping season. Due to direct runoff abstraction in the upper catchment, gully bed morphology had stabilized and was managed by farmers who could confidently grow crops in the former gully bed. Note also shrub regrowth and slope stabilization on the steeper slopes in the background

Fig. 11.

References

- Nyssen, J., Clymans, W., Descheemaeker, K., Poesen, J., Vandecasteele, I., Vanmaercke, M., Amanuel Zenebe, Van Camp, M., Mitiku Haile, Nigussie Haregeweyn, Moeyersons, J., Martens, K., Tesfamichael Gebreyohannes, Deckers, J., Walraevens, K., 2010. Impact of soil and water conservation on catchment hydrological response – a case in north Ethiopia. *Hydrological Processes*, 24(13): 1880-1895.
- Vandecasteele, I., Nyssen, J., Clymans, W., Moeyersons, J., Martens, K., Van Camp, M., Tesfamichael Gebreyohannes, Desmet, H., Deckers, J., Walraevens, K., Hydrogeology and groundwater flow in a basalt-capped Mesozoic sedimentary series of the Ethiopian highlands. *Hydrogeology Journal*, in press, online early view.
- Walraevens, K., Vandecasteele, I., Martens, K., Nyssen, J., Moeyersons, J., Tesfamichael Gebreyohannes, De Smedt, F., Poesen, J., Deckers, J., Van Camp, M., 2009. Groundwater recharge and flow in a small mountain catchment in Northern Ethiopia. *Hydrological Sciences Journal*, 54: 739-753.

24. Soil and water conservation through introduction of conservation agriculture in Dogua Tembien

Tesfay Araya^{1,2}, Wim M. Cornelis², Jan Nyssen³, Bram Govaerts⁴, Fekadu Getnet^{5,6}, Hans Bauer⁷, Dirk Raes⁷, Mitiku Haile⁶, Jozef Deckers⁷

¹ Mekelle University, Department of Crop and Horticultural Science, POBox 231, Mekelle, Ethiopia.

² Ghent University, Department of Soil Management, Coupure Links 653, B-9000 Gent, Belgium

³ Ghent University, Department of Geography, Krijgslaan 281 (S8), B-9000 Gent, Belgium

⁴ International Maize and Wheat Improvement Centre (CIMMYT), A.P. 6-641, Mexico D.F. 06600, México.

⁵ Ethiopian Institute of Agricultural Research, Pawe Research Center, Ethiopia

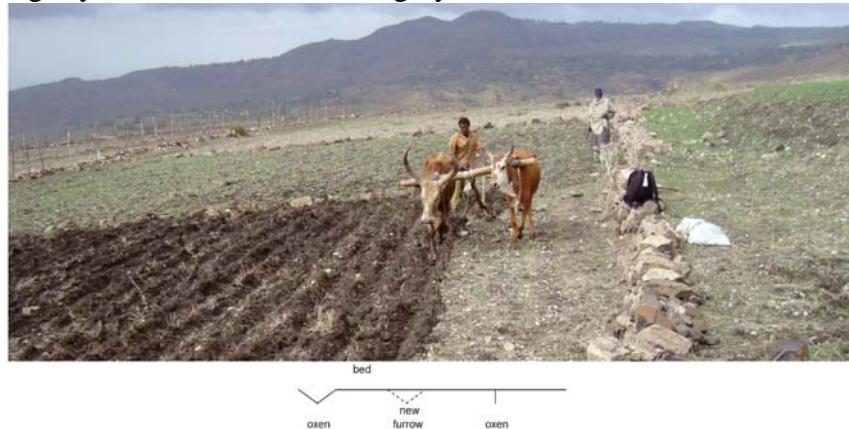
⁶ Mekelle University, Department of Land Resources Management and Environmental Protection, POBox 231, Mekelle, Ethiopia

⁷ K.U.Leuven, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, B-3001 Heverlee, Belgium

Introduction

Land degradation in northern Ethiopia is caused by the complete removal of crop residues at harvest, open grazing of livestock after harvest, and intensive tillage. This has led to reduced soil organic matter which further increases soil erosion and reduces land productivity. The livelihood of 85% of the population of Tigray in northern Ethiopia depends on agriculture, mainly on crop production, and small units of land have been extensively cultivated by subsistence farmers for centuries. Rainfed farming is dominant and has low productivity due to erratic and insufficient rainfall during the growing season. Problems arise from periodic drought, water logging, high tillage frequency, and high runoff rates. Frequent tillage increases loss of soil organic matter because of mixing of soil and crop residues, disruption of aggregates, and increased aeration. Under wet conditions, Vertisols are very susceptible to erosion which is considered to be the major limitation to long-term production. In order to increase crop productivity, soil moisture regimes need improvement. The keeping of large numbers of cattle associated with intensive conventional tillage has caused land degradation by overgrazing. In addition, farmers use the straw as fodder and leave no residues as soil cover. Nyssen *et al.* (2007) report that soil and water conservation structures such as stone and soil bunds are effective. Recent policy in Tigray favours further *in situ* water conservation, stubble management and the abandonment of free grazing (Nyssen *et al.*, 2011). However, until recently there was no practice of implementing conservation agriculture (CA) in Tigray. According to FAO (2010), “CA is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. Interventions such as mechanical soil tillage are reduced to an absolute minimum, and the use of external inputs such as agrochemicals and nutrients of mineral or organic origin are applied at an optimum level and in a way and quantity that does not interfere with, or disrupt, the biological processes. CA is characterized by three principles which are linked to each other, namely continuous minimum mechanical soil disturbance, permanent organic soil cover, and diversification of crop species grown in sequence or associations.” Various studies on CA outline many benefits, including early planting, growing long maturing crops/varieties, runoff and evaporation reduction, soil loss reduction, soil moisture conservation, increased labour efficiency, reduced oxen and straw demand, and enhanced soil fertility (Govaerts *et al.*, 2007). In contrast to conventional agriculture, CA involves the leaving of residues from the previous crop on the soil surface to improve water storage and increase surface roughness. However, results from comparison of CA and conventional agricultural practices over different time periods have

not been consistent between crops, ploughs, soils, climate, and experiments in different parts of the world (Ahuja *et al.*, 2006). Permanent raised bed (PB) (Fig. 1) and reduced tillage (RT) systems using the traditional marasha ard plough, were introduced in Tigray in 2005 on Vertisols to improve water conservation, reduce runoff and soil erosion, and to increase crop yield. In May Zeg-zeg, where free grazing has been abolished, the developed PB or *derdero+* technology (Fig. 1) has also been implemented on ten farmers' fields with a total area of around 2 ha, with good results in terms of crop stand and crop yield, and strongly reduced draught requirement both in number of tillage operations and in required energy (Fig. 2). The objective of this study was to evaluate the effect on runoff, soil loss and crop yield of the different CA tillage systems in Vertisols in Tigray.



*Fig. 1. The PB or derdero+ system involves shaping of beds and furrows by a pair of draught animals with attached marasha (on a farmer's field in May Zeg-zeg, July 2009). Only a single, broad-spaced tillage operation is needed. The farmer replaced one of the oxen in the span by a (weak) cow, as only the sediment accumulated in the previous year's furrows needed to be reworked and less power was needed. Note how the left ox walks in the furrow, which provides guidance for the position of the plough tine in the immediately upslope furrow (After Nyssen *et al.*, 2011).*



Fig. 2. Wheat stand on farmers plots tilled according the Derdero+ system. Location: the excursion point in Hechi, in October 2010.

Materials and methods

The study area. The experiment was conducted under rainfed conditions from 2005-2010 in May Zeg-zeg (13°39'N, 39°10'E) at an altitude of 2550 m a.s.l. in Tigray, northern Ethiopia. Mean

annual rainfall of May Zeg-zeg is 767 mm with more than 80% from mid June to mid September.

The field experiment. The experimental layout was a randomized complete block design with three replications. The plot size was 5 x 14 m and the slope 6.5%. The soil under the experimental trial was a Vertisol. The tillage treatments were (1) conventional tillage (CT), where the soil is ploughed three times per year to create a fine seedbed and with the crop straw being completely harvested without leaving crop residues on the surface, (2) terwah (RT), a traditional in situ water conservation method especially used in tef where broad seedbeds are created using the marasha ard plough by making furrows on the contour at regular intervals of ca. 1.5 m (Nyssen et al., 2011), but which is in the context of this study also tested for crops other than tef and leaving standing stubble, and (3) a newly developed tillage system we called *derdero+* (or PB, permanent beds), which is based on another traditional in situ water conservation technique *derdero*, where at the last tillage operation, the farmers broadcast the seeds over the surface and then prepare beds and furrows along the contour using the marasha, moving the soil and seeds to an upper position on the beds (Nyssen et al., 2011). It protects the crops from waterlogging, while excess water drains towards the furrows where it can slowly infiltrate. The ‘plus’ in *derdero+* stands for the improvements made, including the introduction of permanent beds with standing stubble (>30%), where furrows are prepared on the contour at intervals of ca. 0.6 m. At sowing, seeds are broadcasted over the land and the furrows reshaped, moving the soil to the beds and covering the seeds. Crops grown, from the first to the sixth year were wheat, grass pea, wheat, *hanfets* (wheat and barley sown together), grass pea and wheat. The seed and fertilizer rates were similar for all treatments. Urea fertilizer was not applied to grass pea. The same plots were kept fixed during the six years of study. Weed control was by hand weeding. Non-selective herbicide glyphosate (N-(phosphonomethyl) glycine) was sprayed starting in 2007 at 2 L ha⁻¹ three to four days before planting to control pre-emergent weeds.



Fig. 3. Partial view of the experimental plot at Adi Gudom. On a daily base in the rainy season, and after measurements and samples are taken, the collector trenches are emptied. The runoff plots are located at left.

Data collected. Runoff and soil loss were measured in 4.5 m long, 1.5 m wide (at the top) and 1 m deep collector trenches (Fig. 3), which were located at the down slope end of each plot and lined with thick plastic sheets. The plots were separated by 0.50 m wide ditches to avoid surface or subsurface flow between plots. Runoff data were collected at 8:00 AM after each rainfall event by measuring the height of the water at three sample locations in the trenches. The volumes of the trenches were annually calibrated at the middle of the growing season by relating known amounts of water to depth at three sample locations in the trench following the method of

Gebreegziabher *et al.* (2009) and Oicha *et al.* (2010). Rainfall was recorded daily at 8:00 AM by rain gauge. The collected runoff water was stirred thoroughly and 4 L taken from each trench to determine accumulated sediment in the trenches of each plot. These were filtered using a funnel and Whatman 42 filter paper having a pore size of 2.5 μm . The sediment in the filter paper was oven dried for 24 hours at 105 $^{\circ}\text{C}$ and weighed to quantify soil loss. Grain and straw crop yield were determined at harvest from areas of 2 x 8 m and 2 x 6 m in two replicates per plot.

Statistical analysis. ANOVA was used to test for statistical differences in runoff, soil loss and crop parameters between the management treatments. Data were analyzed using the SAS statistical software (JMP version 5.0), and the standard error of treatment means was used for separation of means. Comparison of means was carried out by Student *t*-tests at $\alpha = 0.05$.

Results and discussion

Runoff and soil loss. Runoff was lowest in PB during the complete study period and it was significantly different ($P < 0.05$) in 2007 and 2010 when wheat was grown, with the largest record from CT, followed by RT (Fig. 4b). Mean runoff during the rainy seasons (three months) of the five study periods was 900, 1011 and 1091 $\text{m}^3 \text{ha}^{-1}$ from PB, RT and CT, respectively. The highest amount of runoff was observed in 2005 followed by 2006. Five years mean runoff coefficients were 23, 26 and 28% in PB, RT and CT, respectively (Fig. 4c).

Soil loss was significantly different ($P < 0.05$) between treatments and in all years except in 2005. Variations across years may be related to crop type and rainfall amount, intensity and distribution. A 4-year mean soil loss of 14, 17 and 24 t ha^{-1} was recorded from PB, RT and CT, respectively (Fig. 4d). The highest soil loss was produced during the grass pea cropping season in 2009, which is related to late sowing date and low vegetation cover of this plant.

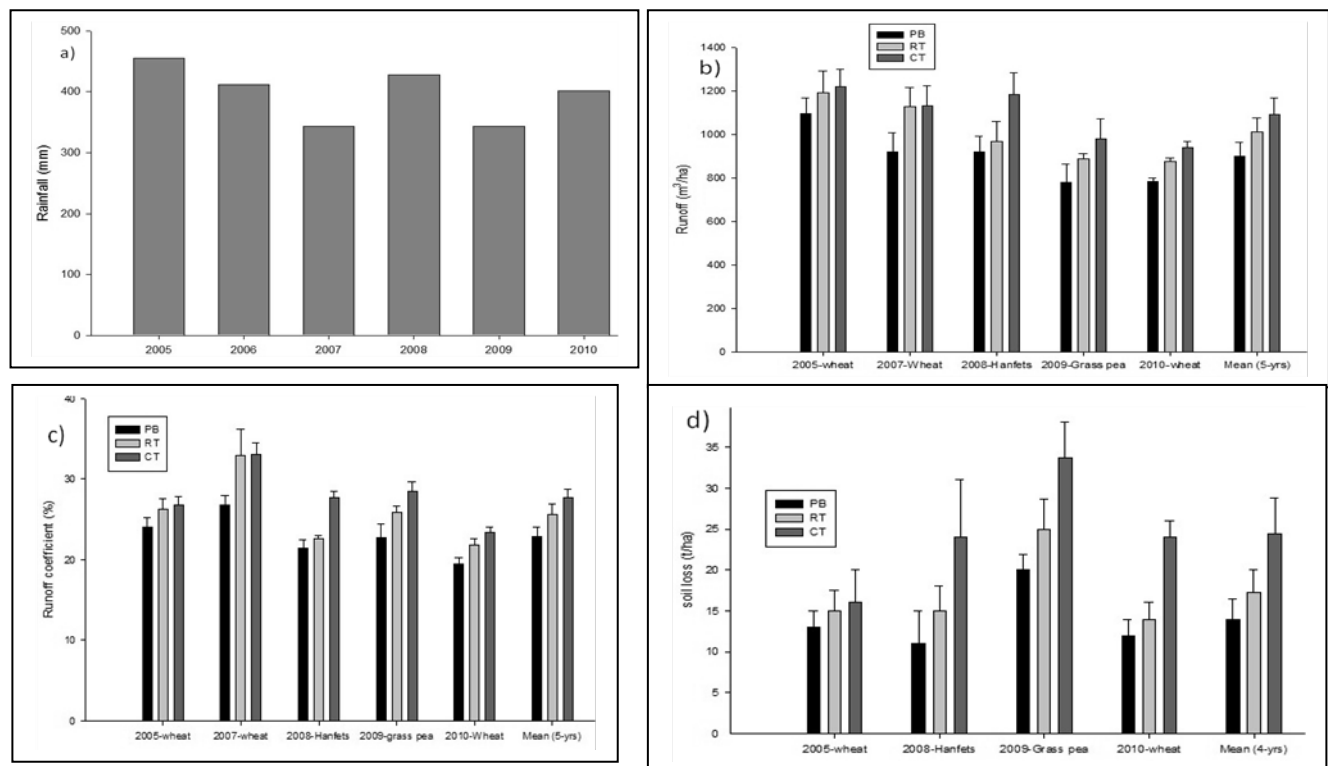


Fig. 4. Rainfall during growing season (a), mean runoff (b), runoff coefficient (c) and soil loss (d) from each treatment throughout the growing period. PB is permanent raised bed, RT is

reduced tillage, CT is conventional tillage. The bars shown represent standard error of mean ($P<0.05$).

Crop performance. Grain yield improvements have become consistent after a period of four years of cropping in CA type treatments, i.e. from 2009 on (Table 1). Grain and straw yield of grass pea in CT was found to be significantly higher in 2006. In 2009, highest grass pea grain and straw yield were observed in RT, whereas in 2010 PB resulted in highest wheat grain and straw yield. Plant height is larger in PB throughout the growing season but especially in the beginning of the rainy season, when, unlike in CT, growth in PB remains unaffected by short dry spells (Fig 5.)

Table 1. Grain and straw yield from each treatment. PB is permanent raised bed (or Derdero+), RT is reduced tillage, CT is conventional tillage, SEM is standard error of mean ($P<0.05$).

year	Crop	Grain yield (t/ha) (mean \pm SEM)			Straw yield (t/ha) (mean \pm SEM)		
		PB	RT	CT	PB	RT	CT
2005	Wheat	3.1 \pm 0.2A	2.7 \pm 0.2A	2.8 \pm 0.1A	-	-	-
2006	Grass pea	2.1 \pm 0.1B	2.1 \pm 0.1B	2.9 \pm 0.2A	2.8 \pm 0.1B	2.9 \pm 0.1B	4.1 \pm 0.2A
2007	Wheat	2.9 \pm 0.1A	2.9 \pm 0.2A	3.0 \pm 0.3A	6.8 \pm 0.3A	6.7 \pm 0.6A	6.9 \pm 0.8A
2008	<i>Hanfets</i>	2.0 \pm 0.1A	1.9 \pm 0.1A	1.9 \pm 0.1A	3.1 \pm 0.1A	3 \pm 0.2A	3 \pm 0.2A
2009	Grass pea	2.2 \pm 0.2AB	2.8 \pm 0.1A	2.0 \pm 0.2B	3.9 \pm 0.4AB	4.4 \pm 0.2A	3.5 \pm 0.3B
2010	Wheat	5.2 \pm 0.1A	4.5 \pm 0.15B	4.0 \pm 0.2C	6.7 \pm 0.7A	5.3 \pm 0.6B	4.7 \pm 0.1C
Mean (2yrs)	Grass pea	2.2 \pm 0.2A	2.4 \pm 0.1A	2.5 \pm 0.2A	3.4 \pm 0.3A	3.6 \pm 0.2A	3.8 \pm 0.2A
Mean (3yrs)	Wheat	3.7 \pm 0.1A	3.4 \pm 0.2AB	3.2 \pm 0.2B	6.7 \pm 0.5A	6 \pm 0.6AB	5.8 \pm 0.5B
Mean (6yrs)	All crops	2.9 \pm 0.1A	2.8 \pm 0.1A	2.8 \pm 0.2A	4.2 \pm 0.2A	4 \pm 0.2A	4 \pm 0.2A

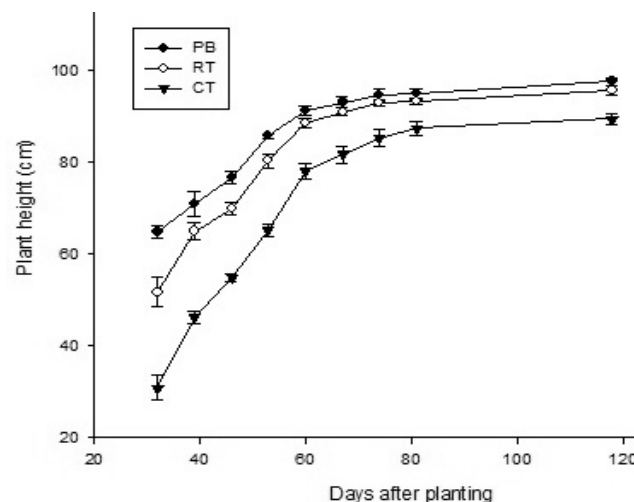


Fig. 5. Plant height of wheat in growing season of 2010

Farmers in the area planted grass pea late in the cropping season to avoid excessive soil moisture conditions which may explain the presence of lower yield in PB. To increase grain yield further in PB may require adjustments in planting time. The mean of two years grass pea did not show

significant yield differences, whereas the mean of three years wheat did show a significant yield difference ($P < 0.05$). The total mean grain and straw yield of all crops in the six years (wheat, *hanfets* and grass pea) were found to be higher in PB, but not with significant difference. The grain and straw yield of improved wheat variety in 2010 was significantly higher in PB followed by RT.

Conclusion

A permanent raised bed planting system with retention of crop residues and to a lesser extent a reduced tillage system was found to be beneficial for raising wheat grain and straw yields, and reducing runoff and soil loss in 2010 in northern Ethiopia. Reduced tillage increased grain yield of grass pea in 2009. Overall, the permanent raised bed planting system with crop residue retention can be an efficient soil and water conservation strategy through reducing the runoff coefficient and draining excess water from the beds through furrow storage. This approach also reduces soil loss and improves soil fertility, thus increasing crop productivity and avoiding further land degradation. However, the improvement in soil physical, chemical and biological properties is slow and the full benefit of permanent raised beds plus retention of crop residues can only be expected after several years. Our results demonstrate the importance of PB in increasing wheat yield and reducing soil loss and runoff. Planting time adjustments in PB treatments can be possible suggestion to further increase grass pea yield. However, the reduced tillage system can also be recommended as a first step for reducing runoff and soil loss and whilst increasing crop yield. The long-term goal should be to achieve a permanent raised bed planting system along with use of crop residues.

Taking into account the reduced input in terms of human and oxen labour, farmers in the study area are now planning to expand the system to the scale of sectors of their village territory.

References

- Ahuja, L. R., Ma, L. & Timlin, D. J. 2006. Trans-Disciplinary Soil Physics Research Critical to Synthesis and Modeling of Agricultural Systems. *Soil Science Society of America Journal*, 70, 311–326.
- FAO. 2010. What is Conservation Agriculture? Available at: <http://www.fao.org/ag/ca/1a.html>; accessed on 28 October 2010.
- Gebregeziabher, T., Nyssen, J., Govaerts, B., Getnet, F., Behailu, M., Haile, M. & Deckers, J. 2009. Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. *Soil Tillage Research*, 103, 257–264.
- Govaerts, B., Sayre, K.D., Lichter, K., Dendooven, L. & Deckers, J. 2007. Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. *Plant and Soil*, 291, 39–54.
- Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., D'aes, M., Yihdego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M. & Deckers, J. 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. *Soil and Tillage Research*, 94, 151–163.
- Nyssen, J., Govaerts, B., Araya, T., Cornelis, W.M., Bauer, H., Haile, M., Sayre, K. & Deckers, J. 2011. The use of the *marasha* ard plough for conservation agriculture in Northern Ethiopia. *Agronomy for Sustainable Development*, in press.
- Oicha, T. Cornelis, W.M., Verplancke, H., Nyssen, J., Deckers, J., Behailu, M. & Haile, M. 2010. Short-term effects of conservation agriculture on Vertisols under tef (*Eragrostis tef* (Zucc.) Trotter) in the northern Ethiopian highlands. *Soil & Tillage Research*, 106, 294–302.
- Tesfay Araya, Cornelis, W.M., Nyssen, J., Govaerts, B., Tewodros Gebregziabher, Tigist Oicha, Fekadu Getnet, Raes, D., Mitiku Haile, Deckers, J., Sayre, K.D., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rain fed conditions in Tigray, Northern Ethiopia. *Soil & Tillage Research*, submitted.

25. Monitoring gully headcut retreat rates in May Bati

(Based on Frankl et al., in prep.)

Amaury Frankl^{1,*}, Jean Poesen², Morgan de Dapper¹, Jozef Deckers², Mitiku Haile³, Jan Nyssen¹

¹ Department of Geography, Ghent University, B-9000 Ghent, Belgium.

² Department of Earth and Environmental Sciences, K.U.Leuven, B-3000 Leuven, Belgium.

³ Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia.

* Corresponding author: amaury.frankl@ugent.be

Data on gully headcut retreat rates and changes therein is non-existent for North Ethiopia. Therefore, gully headcut retreat rates over a period of 1 to 45 years were studied (Frankl et al., in preparation). In the 3 km² large catchment of May Bati (13°39'N, 39°12'E), 24 gully headcuts were monitored during the rainy season (July – September) of 2010. In order to understand the retreat rates, data were collected on topography (catchment area, slope gradient), climate (daily rainfall) and the environment (lithology, soil) and land use. In addition, gully headcut retreat rates over a period up to 45 years were assessed by identifying the location of headcuts on aerial photographs and on historical terrestrial photographs, and by localizing the previous and current (2010) position of the headcuts in the field. The results serve as input for testing several empirical models that predict headcut retreat rates based on findings from elsewhere in the world. The 2010 field observations show that many headcuts do not retreat further because of improved land management and that especially Vertisol areas are still prone to rapid gully headcut retreat as the occurrence of piping at the gully headcuts makes them difficult to manage.

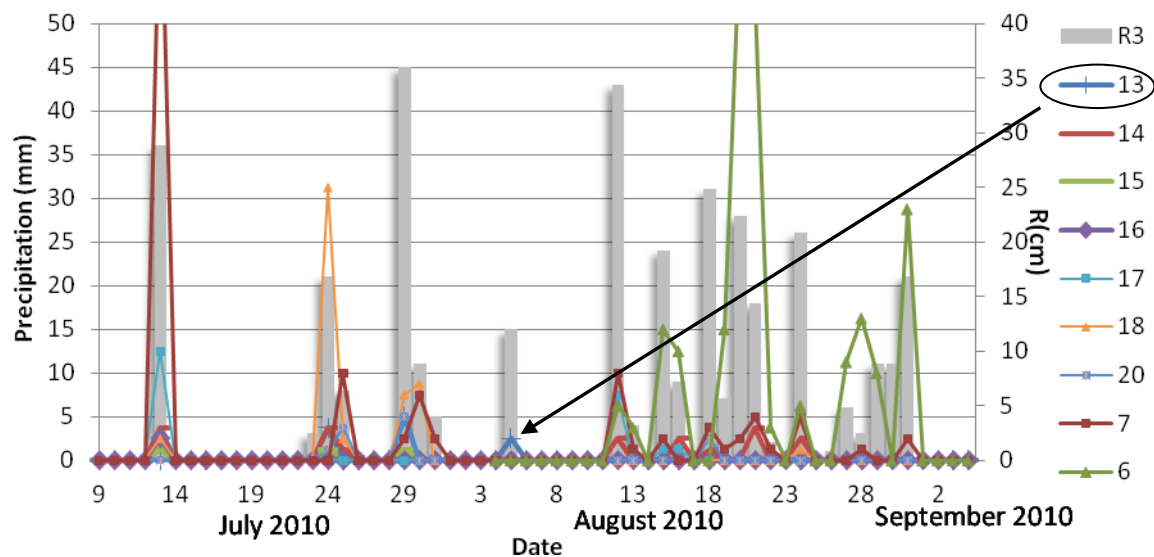


Fig. 1. Linear headcut retreat rates related to daily precipitation in the May Bati catchment in summer 2010 Headcut 13 is visited in the excursion. Headcuts 6 and 7 are developed in Vertisols.

First recorded as a discontinuous gully system on aerial photographs of 1963, the 2010 gully network of May Bati densified (**Fig. 2**), linking hillside gullies to valley bottom gullies and with headcuts situated close to the interfluvia. The present-day activity of 24 gully heads located in the catchment was studied by monitoring their retreat in the rainy season of 2010. The mean linear headcut retreat rate is 0.28 m and varied between 0.02 m and 1.93 m. Highest rates were observed for gullies situated in Vertisols, while low values correspond to gullies situated in exclosures (**Fig. 1**).



Fig. 2. Over the past 50 years, gullying in the catchment of May Bati resulted in a dense gully network. Headcut 13 remained stable during the rainy season of 2010.

Reference

Frankl, A., Poesen, J., De Dapper, M., Deckers, J., Mitiku Haile, Nyssen, J. Assessing gully headcut retreat rates in the semi-arid Highlands of North Ethiopia. In preparation.

26. The travertine dammed sedimentary sequence of Mai Makden

Dramis F.¹, Fubelli G.¹ & Mohammed Umer²

¹ Department of Geological Sciences, “Roma Tre” University, Rome, Italy

² Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

The Mai Makden sequence

Some hundred meters downstream from the Mai Makden village, an exposed sequence of swampy organic sediments dammed by a phytothermal travertine deposit grown at the edge of a waterfall may be observed (Fig. 1). The outcropping bedrock consists of the upper part of the *Antalo Limestone Formation* (Upper Jurassic; Merla & Minucci, 1938; Bosellini *et al.*, 1997), horizontally layered and made up by alternances of limestones and shales. A few km upstream, two springs feed the watercourse with about 5 l/sec total discharge (Chernet Tesfaye & Eshete Gebretsadik, 1982).



Figure 1. The investigated site of Mai Makden.

Due to the presence of limestone rocks (*Antalo Limestone Formation*) and the frequent occurrence of waterfalls due to the stepped long-profile of watercourses, travertine dams are common features in the Mekelle Outlier (Moeyersons *et al.*, 2006). A showy case of travertine dam may be observed at Mai Makden, a village located on the Mekelle –Wukro road. This dam is made up of ca. 15 m thick deposit of phytothermal tufa (Buccino *et al.*, 1978; Pedley, 1990) and is divided into three different lithological units of travertine, separated by layers of coarse gravels and weathered material (Fig. 2). By comparing the last deposition age of the lowermost unit (7800±980 yr BP from U/Th dating at the Roma Tre University U/Th Laboratory) and the first deposition age of the mid unit (ca. 7630±80 ¹⁴C yr BP / 8350-8540 kyr cal BP – from the swampy-lacustrine sequence basal level), a major episode of low deposition rates and dam incision can be located around 8 kyr BP. No date is available for the upper unit even if it seems reasonable to refer the gravelly level at its base to the dry phase which marked the end of the swampy-lacustrine environment.

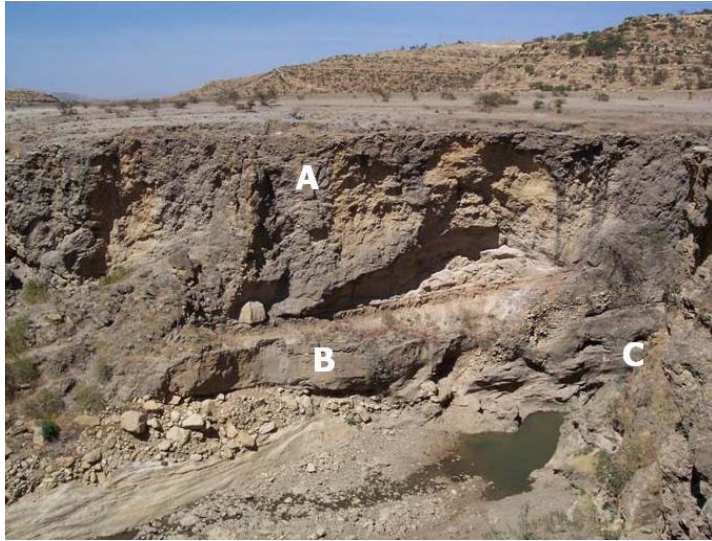


Figure 2. The front side of the Mai Makden dam showing the presence of three different travertine units separated by gravelly layers.

The dammed sedimentary sequence (Fig. 3) is made, from the bottom to the top, of: (a) phytoclastic tufa (Buccino *et al.*, 1978; Pedley, 1990) with local intercalations of thin (up to some dm) phytohermal structures; (b) up to 8 m thick black clayey sediments with lenses of peat and remnants of wood and leaves, dated between 7630 ± 80 ^{14}C yr BP (8350-8540 kyr cal BP) at the base and 4710 ± 70 ^{14}C yr BP (5320-5580 kyr cal BP) at the top (Brancaccio *et al.*, 1997; Dramis *et al.*, 2003), and visibly affected by a network of desiccation fractures, likely due to sub-aerial exposure after the end of the aquatic environment (Berakhi *et al.*, 1998); (c) alternating layers of alluvial gravels, travertine sands and buried soils; d) paleo-channels filled with alluvial sediments and travertine sands and blocks. The uppermost soil, buried under a 1 m thick travertine sand layer, was dated at 3450 ± 50 ^{14}C yr BP (3630-3830 kyr cal BP) (Dramis *et al.*, 2003). The whole sequence is covered by a mantle of colluvial materials, mostly made of soil sediments transported down from the surrounding slopes. Buried dwelling structures, ceramic fragments and charcoal fragments were found at the base of the colluvial deposits (Brancaccio *et al.*, 1997; Berakhi *et al.*, 1998).

The geomorphologic-stratigraphic analysis of the Mai Makden sequence allows us to reconstruct the main evolutionary steps of the area since the beginning of the Holocene. Radiocarbon datings demonstrate that the deposition of travertine at the base of the sequences started before 7310 ± 90 yr B.P., probably in relation with the wetter and milder climatic conditions which set in at the end of the Last Glacial, giving rise to high strandlines in the Rift Valley lakes of Ethiopia (Grove *et al.*, 1975). In fact, the same climatic conditions are favourable for the development of both soil and travertine deposits. The latter, where not derived from hydrothermal water (as in the present case), may be associated with superficial and subsuperficial water circulation systems, enriched in CO_2 by decay of organic matter under a vegetation cover (Goudie, 1972; Viles *et al.*, 1993; Cilla *et al.*, 1994).



Figure 3. *The travertine dammed sedimentary sequence.*

The progressive growth of the travertine dams and the related deposition of lacustrine-swampy sediments (dated from 7130 ± 90 to 5160 ± 80 yr B.P.) show that similar conditions prevailed during almost all the Early Holocene. The remains of wood and the richness in organic matter suggest that a tree vegetation cover has been present in the area during some thousands of years.

The deposition of travertine declined after 5160 ± 80 yr B.P. The whole sequence was then covered by alluvial and colluvial sediments which, together with the end of travertine deposition, indicate a widespread reworking of sediments eroded from the surrounding slopes which underwent a progressive denudation. The occurrence of paleochannels filled with clastics in the upper part of the sequence, indicates the initial breaching of the dam together with a reduction of the vegetational cover, which previously ensured morphological stability to the area. The general context in which the above phenomena occurred may be related to a progressive shifting of climate toward drier conditions, as recognized in other parts of East Africa and in the Maghreb, from around 4000-3500 yr BP to the present (Street, 1979; Gasse *et al.*, 1980; Butzer, 1981; Lézine & Bonnefille, 1982; Ritchie & Haynes, 1987; Williams, 1988; Gasse & Fontes, 1989; Roberts, 1989; Roche & Bikwemu, 1989; Wengler *et al.*, 1994; Lamb *et al.*, 1995; Machado *et al.*, 1998; Lamb *et al.*, 2000; Lamb *et al.*, in 2002; Dramis *et al.*, 2003). In Southern Ethiopia, this general trend seems to have been interrupted by short humid phases (Bonnefille *et al.*, 1986; Mohammed & Bonnefille, 1991).

However, the finding of dwelling structures at Mai Makden and ceramic fragments of undefined age at the base of the alluvial-colluvial deposits in the upper part of the sequence, also supports the hypothesis that the above processes may have been connected, at least in part, with man made deforestation. In fact, widespread anthropic degradation of slopes seems to have occurred during the last three thousand years in all East Africa as well as in the Mediterranean area (Butzer, 1974; Delano-Smith, 1979; Flenley, 1979; Goudie, 1981; Hamilton *et al.*, 1989; Hurni, 1989; Brancaccio *et al.*, 1997). According to the results of archaeological researches (Anfray, 1967; Tringali, 1981; Fattovich, 1990; Bard *et al.*, 2000), the impact of man on the environment of Western Tigray would have increased gradually since the second half of the II millennium B.C. to the kingdom of Aksum (from the second century BC to 800 AD), when grazing and agricultural activities, including the use of ploughing techniques and the emplacement of small reservoirs, reached their maximum development.

Taking into account the difficulty of separating the effects on slope erosion of natural and human factors (Goudie, 1981), and considering that both climatic change and anthropic deforestation may have induced slope erosion processes, it seems reasonable to relate these latter phenomena to both factors. The effectiveness of human impact would have been more and more important in a climatic context progressively less favourable to the growth of trees and the natural restoration of a forest cover on the slopes.

Excursion stops

Stop 1. General view of the Mai Makden travertine dam from the road to Wukro.

Stop 2. Walk to travertine dam and backfill deposits.

References

- Anfray F., 1967. *Matara*, Annales d'Ethiopie 7, 33-53.
- Bard K.A., Coltorti M., Di Blasi M., Dramis F. & Fattovich R., 2000. *Environmental history of Tigray (Ethiopia) during the Holocene: an outline*. African Archaeological Review 17 (2), 65-86.
- Berakhi Ogbaghebriel., Brancaccio L., Calderoni G., Coltorti M., Dramis F. & Umer Mohammed, 1998. *The Mai Makden sedimentary sequence: a reference point for the environmental evolution of the Highlands of Northern Ethiopia*. Geomorphology 23 (2-4), 127-138.
- Beyth M., 1971. *The geology of Central-Western Tigray*. Ministry of Mines, Addis Ababa.
- Bonnefille R., Robert C., Delibrias G., Elenga T., Herbin J.P., Lézine A.M., Perinet G. & Tiercelin J.J., 1986. *Paleoenvironment of Lake Abijata, Ethiopia, during the past 2.000 year*. Geological Society of London, spec. publ., 25, 253-265.
- Bonnefille R. & Umer Mohammed, 1994. *Pollen inferred climatic fluctuations in Ethiopia during the last 3.000 years*. Palaeogeography, Palaeoclimatology, Palaeoecology 109, 331-343.
- Brancaccio L., Calderoni G., Coltorti M., Dramis F. & Ogbaghebriel Berakhi, 1997. *Phases of soil erosion during Holocene in the Highlands of Western Tigray (Northern Ethiopia): a preliminary report*. In *The environmental history and human ecology of Northern Ethiopia in the Late Holocene* (K.A. Bard, Ed.). Studi Africanistici, ser. Etiopica, 5, Istituto Universitario Orientale, Napoli, pp. 29-44.
- Butzer K.W., 1974. *Accelerated soil erosion: a problem of man-land relationships*. In I. Manners and M.W. Mikesell (Editors), *Perspective on environment*, Association of American Geographers, pp. 57-78.
- Butzer K.W., 1981. *Rise and fall of Axum, Ethiopia: a geoarchaeological interpretation*. American Antiquity 46, 471-495.
- Chernet Tesfaye & Eshete Gebretsadik, 1982. *Hydrogeology of the Mekele area (ND37-11)*. Ministry of Mines and Energy, Ethiopian Institute of Geological Surveys, Addis Ababa, 50 pp.
- Cilla G., Coltorti M. & Dramis F., 1994. *Holocene fluvial dynamics in mountain area: the case of the Esino River (Appennino umbro-marchigiano)*. Geografia Fisica e Dinamica Quaternaria 17, 163-174.
- Delano-Smith C., 1979. *Western Mediterranean Europe*. Academic Press, London, 453 pp.
- Dramis F., Umer M., Calderoni G. & Haile M., 2003. *Holocene climate phases from buried soils in Tigray (northern Ethiopia). Comparison with lake level fluctuations in the Main Ethiopian Rift*. Quaternary Research 60, 274-283.
- Fattovich R., 1990. *Remarks on the Pre-Axumite period in Northern Ethiopia*. Journal of Ethiopian Studies 23, 1-33.
- Flenley J.R., 1979. *The Late Quaternary vegetational history of the equatorial mountains*. Progress in Physical Geography 3(4), 487-509.
- Gasse F. & Fontes J.C., 1989. *Paleoenvironments and paleohydrology of a tropical closed lake (L. Asal, Djibouti) since 10,000 yr B.P.* Palaeogeography, Palaeoclimatology, Palaeoecology 15, 109-148.
- Gasse F., Rognon P. & Street F.A., 1980. *Quaternary history of the Afar and Ethiopian rift lakes*. In: Williams M.A.J. & Faure H. (eds.), *The Sahara and the Nile*, Balkema, pp. 361-400.
- Goudie, A.S., 1972. *Duricrusts in tropical and subtropical landscapes*. Oxford University Press, 192 pp.
- Goudie A.S., 1981. *The human impact: man's role in environmental change*. Basil Blackwell, Oxford, 640 pp.

- Griffiths J.F., 1962. *The climate of Africa*. In: E.W. Russell (ed.), *The natural resources of East Africa*, Hawkins, Nairobi, pp. 77-87.
- Grove A.T., Street, F.A. & Goudie, A.S., 1975. *Former lake levels and climatic changes in the Rift Valley of Southern Ethiopia*. The Geographical Journal 141, 177-194.
- Hamilton A., Taylor D. & Vogel J.C., 1989. *Neolithic forest clearance at Ahakagyezi, western Uganda*. In: W.C. Mahaney (ed.), *Quaternary and environmental research on East African mountains*. Balkema, Rotterdam, pp. 435-463.
- Hurni H., 1989. *Late Quaternary of Simen and other mountains in Ethiopia*. In: Mahaney W.C. (ed.), *Quaternary and Environmental Research on East Africa Mountains*. Balkema, Rotterdam, pp. 105-120.
- Lamb H.F., Gasse F., Benkaddour A., El Hamouti N., van der Kaars S., Perkins W.T. Pearce, N.J. & Roberts C.N. (1995). *Relation between century-scale Holocene arid intervals in tropical and temperate zones*. Nature 373, 134-137.
- Lamb A.L., Leng M.J., Ricketts D., Telford R.J. & Umer M.U., 2000. *A 9000 yr oxygen and carbon isotope record of hydrological change in a small crater lake*. The Holocene 10, 167-177.
- Lamb A.L., Leng M.J., Lamb H.F., Telford R.J. & Mohammed M.U., 2002. *Climatic and non-climatic effects on the $\delta^{18}O$ and $\delta^{13}C$ composition of Lake Awassa, Ethiopia, during the last 6.5Ka*. Quaternary Science Reviews 21, 2199-2211.
- Lézine A.M. & Bonnefille R., 1982. *Diagramme pollinique Holocene d'un sondage du lac Abiyata (Ethiopie, 7° 42' Nord)*. Pollen et Spores 3-4, 463-480.
- Machado M.J., Pérez-González A. & Benito G., 1998. *Paleoenvironmental changes during the last 4000 yr in the Tigray, Northern Ethiopia*. Quaternary Research 49, 312-321.
- Merla, G & Minucci E., 1938. *Missione geologica nel Tigray. Vol. 1 "La Serie dei Terreni"*, Rendiconti della Reale Accademia d'Italia, Centro Studi per l'Africa Orientale Italiana, 3, 362 pp.
- Moeyersons, J., Nyssen, J., Poesen, J., Deckers, J., Mitiku Haile, 2006. *Age and backfill/overfill stratigraphy of two tufa dams, Tigray Highlands, Ethiopia: Evidence for Late Pleistocene and Holocene wet conditions*. Palaeogeography, Palaeoclimatology, Palaeoecology, 230/1-2:162-178.
- Mohammed M.U. & Bonnefille R., 1991. *The recent history of vegetation and climate around lake Langano (Ethiopia)*. Palaeoecology of Africa and the Surrounding Islands 22, 275-286.
- Ritchie J.C. & Haynes C.V., 1987. *Holocene vegetation zonation in the eastern Sahara*. Nature 330, 352-355.
- Roberts N., 1989. *The Holocene. An environmental history*. Basil Blackwell, Oxford, 227 pp.
- Roche E. & Bikwemu G., 1989. *Paleoenvironment change on the Zaire-Nile ridge in Burundi; the last 20.000 years: An interpretation of palynological data from the Kashiru Core, Ijenda, Burundi*. In: W.C. Mahaney (ed.), *Quaternary and environmental research on East African mountains*. Balkema, Rotterdam, pp. 231-242.
- Street F.A., 1979. *Late Quaternary lakes in the Ziway-Shalla Basin, South Ethiopia*. Ph.D. Thesis, University of Cambridge, UK, 457 pp.
- Tringali G., 1981. *Note sui ritrovamenti archeologici in Eritrea*. Rassegna di Studi Etiopici 28, 99-113.
- Viles H.A., Burger D. & Goudie A., 1993. *A reason for declining tufa deposition in Germany and Britain*. Abstracts of the 3rd International Conference on Geomorphology, Hamilton, August 23-28, 1993, p.49.
- Wengler L., Vernet J-L. & Michel P., 1994. *Evenements et chronologie de l'Holocène en milieu continental au Maghreb. Les données du Maroc oriental*. Quaternaire 5 (3-4), 119-134.
- Williams M.A.J., 1988. *After the Deluge: The neolithic landscape in Northern Africa*. In: J. Bower & D. Lubbel (eds.), *Prehistoric Cultures and Environment in the Late Quaternary of Africa*. B.A.R. International Series, Oxford, pp. 43-60.

27. The limestone caves of Tigray: their potential for speleothem palaeoclimate studies

Asfawossen Asrat

Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

Extensive limestone beds with great potential for caving are exposed in three regions in Ethiopia: the Mekelle Outlier in the North (Tigray), the Blue Nile Basin in central Ethiopia, and the Ogaden Basin in southeastern Ethiopia (e.g., Mechara karst system). We have been studying the Mechara karst system since 2003 resulting in the discovery of many cave entrances and chambers (Baker et al., 2005; Asrat et al., 2008). Speleothems recovered from these caves gave high-resolution, multi-proxy palaeohydrological and palaeoclimatic signals of the Holocene (e.g., Asrat et al., 2007, 2008; Baker et al., 2007). The results of our investigations in the Mechara karst have been encouraging to extend our studies spatially and temporally. To this effect, we have conducted preliminary field investigations in Tigray, northern Ethiopia, in September 2008. Here we present preliminary results of our investigation.

Numerous entrances into short caves have been identified on thinly bedded limestone cliffs.



Fig. 1. MM-1 stalagmite from Enda Aba Gerima cave in the Mai Mekden travertine dam.

Most of them are dry and relict with little interest. However, four caves contain numerous speleothems (both relict and modern). Abune Aregawi Zaye cave is a 330 m long, 50-60 m wide (at its mid section) and 10 m high chamber formed into a relatively massive crystalline limestone located at the foot of 60 m high cliff. The cave is wet and humid (within cave temperature: 25°C; R.H. 88%). It is decorated with numerous speleothems. Enda Tsadkan is a maze of short entrances into fracture caves located behind a waterfall. Numerous modern stalagmites are growing under fast drips close to the entrance of the caves. Enda Aba Gerima (near the Mai Mekden travertine dam) is a small cave entrance (5 m x 1 m x 5 m) with some relict speleothems. Sheket cave is located at the mid section of a 150 m high vertical cliff facing the Afar rift. The cave (10 m x 50 m x 30 m) is formed into a massive, black limestone bed. Some stalagmites have been growing under slow dripping water.

We have collected 13 stalagmites and all the stalagmites in hand section show continuous visible laminae with alternating growth phases dominated by light and dark coloured calcite, typical of stalagmites in the region (e.g. from Mechara). Preliminary lamina counting indicates that the stalagmites are generally fast growing with an average thickness of ~0.35 mm, and most stalagmites show continuous and regular laminae sequences with no periods of indistinct or discontinuous laminae. All these are indicative of

annual growth of the laminae suggesting that these stalagmites are potentially suitable for high-resolution palaeoclimate studies. Particularly one stalagmite (Fig. 1) from the Enda Aba Gerima cave in the Mai Mekden travertine dam is dated to middle to late Holocene (*unpubl. data*); the palaeoclimate signals recovered from the speleothem are expected to expand our understanding of climate variation in northern Ethiopia, which might have influenced the rise and fall of the Pre-Axumite, and Axumite and later civilizations in the region. Furthermore, the climate records will help to understand the climate dynamics of the region, which is one of the most drought prone in the country.

References

- Asrat A., Baker A., Umer M.M., Leng M.J., Van Calsteren P. & Smith C., 2006 - *A high-resolution multi-proxy stalagmite record from Mechara, Southeastern Ethiopia: palaeohydrological implications for speleothem palaeoclimate reconstruction*. J. Quaternary Sci., 22: 53–63.
- Asrat A., Baker A., Leng M., Gunn J., Umer M. (2008) *Environmental monitoring in the Mechara caves, Southeastern Ethiopia: implications for speleothem palaeoclimate studies*. International Journal of Speleology, 37: 207-220.
- Baker A., Asrat A. & Mohammed M., 2005 - *Expedition Report to the Mechara caves, Southeastern Ethiopia*. Speleology, 5: 8–20.
- Baker A., Asrat A., Fairchild I.J., Leng M.J., Wynn P.M., Bryant C., Genty D. & Umer M., 2007 - *Analysis of the climate signal contained within $\delta^{18}O$ and growth rate parameters in two Ethiopian stalagmites*. Geochimica et Cosmochimica Acta, 71: 2975-2988.

28. Planation surfaces on the road from Mekelle to Adigrat

Dramis F.

Department of Geological Sciences, "Roma Tre" University, Rome, Italy

On the road from Mekelle to Adigrat one can observe most of the basic aspects of the northern highlands geology. Up to Wukro, the road crosses the *Antalo Supersequence* (Bosellini *et al.*, 1997), made of stratified limestone (*Antalo Limestone*) and marls (*Agula Shales*). At Wukro the *Adigrat Sandstone*, the *Edaga Arbi Glacials* and the *Enticho Sandstone* outcrop. More to the north, the road crosses the pre-Palaeozoic metamorphic basement. Other noteworthy geomorphological elements, such as the Mekelle and Wukro fault line escarpments, the PS1 and PS2 exhumed planation surfaces, and the travertine dam of May Maikden can be seen.

The PS2 planation surface was generated in the Early Cretaceous under renewed continental conditions (Bosellini *et al.*, 1997; Coltorti *et al.*, 2007). It truncates the Jurassic marine sequence, extending as far as southern Ethiopia, Eritrea and Yemen. Moreover, the PS2 cuts across ESE-WNW trending normal faults (Wukro fault belt, Melele fault, Chelekwot fault belt) which were active during the Jurassic. To the north, it exhumed the early Palaeozoic PS1 planation surface from the pre-Cretaceous sedimentary cover. West and south of Mekelle (Hagere Selam, Mt. Amba Aradam) this planation surface is buried by the *Amba Aradam Formation*.

The Mekelle fault-line scarp and the pre-Cretaceous PS2 planation surface

The first part of the road, immediately north of Mekelle, crosses the *Agula Shales*, clearly visible at the Elalo River bridge. This formation outcrops also, more to the north on the route, between Agula and Wukro. In this area silty argillites and marl prevail, with insertions of thin layers of coquinoïd limestone and black limestone rich in rests of gastropods and bivalves. The most common lithologies at Wukro are finely laminated dark argillites, dolomitic limestone, and calcareous marls with intercalations of thin layers of gypsum.

Subsequently the road approaches the Mekelle fault-line scarp which puts in contact the *Agula Shales* (hanging wall) and the *Antalo Limestone* (footwall). The fault was active before the Cretaceous, being levelled by the PS2 planation surface (Coltorti *et al.*, 2007) and by the *Amba Aradam Formation*. A thick doleritic dyke crosses the *Antalo Limestone* in correspondence of the fault. On the divide between the Mekelle and Agula catchments, a vast exhumed limb of the PS2 planation surface (Coltorti *et al.*, 2007) which truncates the *Antalo Limestone*, here affected by minor karst features, can be observed.

The Early Palaeozoic PS1 planation surface and the Edaga Garbi Glacials

North of Wukro, the road enters a wide area where the pre-Palaeozoic basement (Tambien Group), intensely shortened by tectonics and more or less metamorphosed, outcrops. It is also intruded by granitic-dioritic bodies (Negash Intrusive Complex). All these formations are sharply truncated by the PS1 planation surface (Coltorti *et al.*, 2007). On the left (western) site of the road it is possible to observe, over a short distance, the *Adigrat Sandstone* (here forming a steep escarpment), the *Enticho Sandstone* and the *Edaga Arbi Glacials* (tillite deposits in this place) (Fig. 1). These latter formations are unconformably overlay the basement, here in contact by fault with the *Adigrat Sandstone*. Likely, this fault was active during the Jurassic and the present

scarp is due to selective erosion following Pliocene-Quaternary uplift of the area. The exhumed PS1 planation surface, locally overlain by limbs of Palaeozoic deposits, largely outcrops on top of the Atsbi Horst, on the right side of the road. More to the north, the road crosses the exhumed PS1 which is also visible as a sharp unconformity between the basement and the overlying sedimentary deposits (Fig. 2).



Figure 1. *Contacts between the Enticho Sandstone, the Edaga Arbi Glacials and the Adigrat Sandstone.*



Figure 2. *The Enticho Sandstone Formation overlying the PS1 planation surface.*

References

- Bosellini A., Russo A., Fantozzi P.L., Getaneh A. & Tadesse S., 1997. *The Mesozoic succession of the Mekelle outlier (Tigre province, Ethiopia)*. *Memorie di Scienze Geologiche* 49, 95-116
- Coltorti M., Dramis F. & Ollier C.D., 2007. *Planation surfaces in Northern Ethiopia*. *Geomorphology* 89, 287-296.

29. Geology of the rock-hewn churches of Tigray

Asfawossen Asrat

Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

More than hundred twenty rock-hewn churches have been identified in Central and Eastern Tigray; some others have also been identified in other parts of Tigray, including one in Adwa and six in the vicinity of Axum. In Central and Eastern Tigray, especially in the vicinity of Ger'alta area, almost all of the mountains contain one or more rock-hewn churches. In Central and Eastern Tigray, the rock-hewn churches are clustered into four zones (Fig. 1): the Atsbi group, Hawzen-Ger'alta group, Sinkata-Adigrat (Agame) group, and Tembien Group. A detailed account of the geology of the rock-hewn churches in central and eastern Tigray is given in Asrat (2002) and Asrat et al. (2009). Here a brief description of two such churches (one of which in on the excursion line) is given.

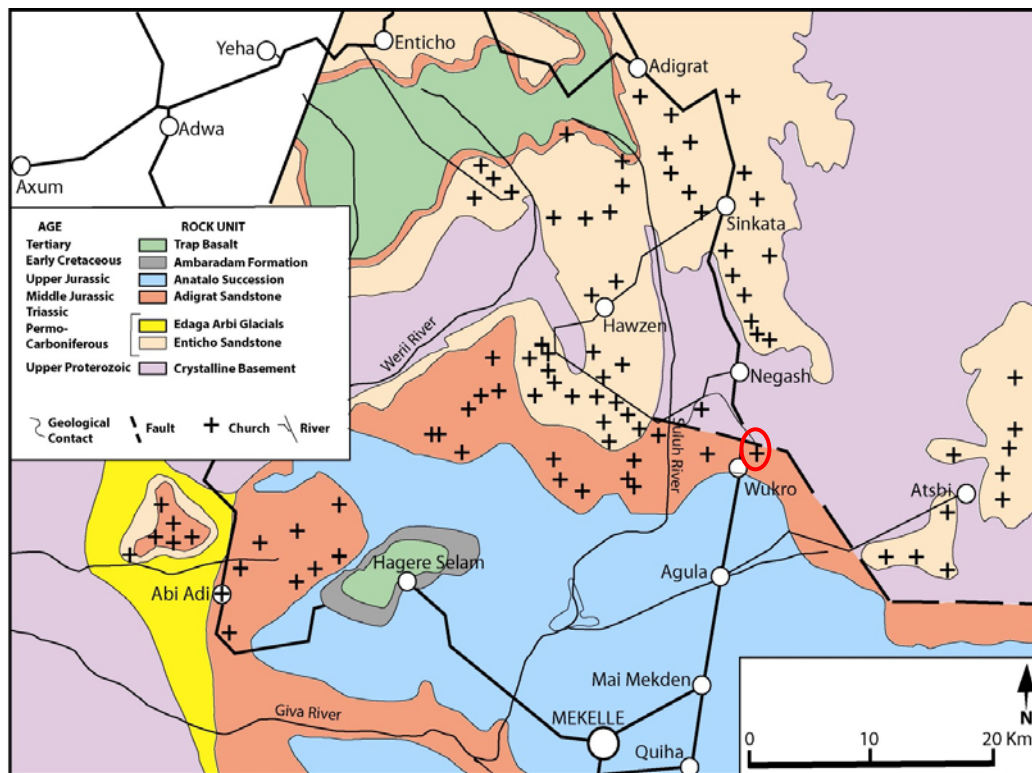


Fig. 1. Simplified geological map of Central and Eastern Tigray, with the location of the rock-hewn churches. The visited church near Wukro is circled in red.

Wukro Ckerkos rock-hewn church:

The church is located in the northeastern part of Wukro town near the Mekelle-Adigrat highway. In the excursion, we shall access this church by crossing the Genfel river, as local pilgrims do. The starting place of our short foot walk is near a monoclinical rock (evidence of faulting) that drew already the attention of visitors in the 1930s (Fig. 2).

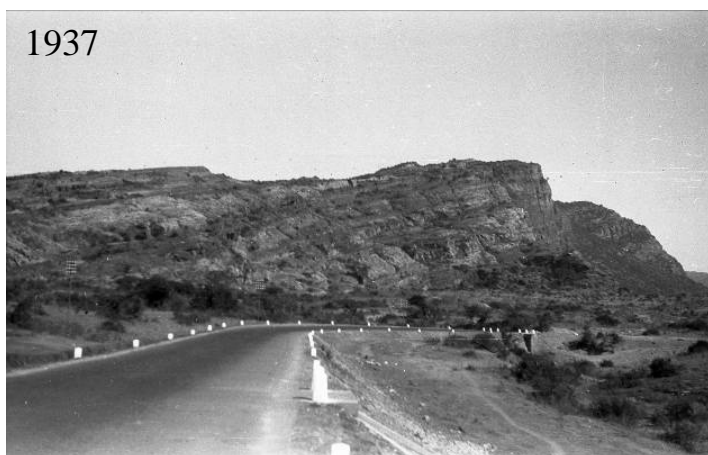


Fig. 2. Wukro, near rock church (1937); photo A. Maugini © Istituto Agronomico per l'Oltremare, Firenze

The church is carved into a massive bed of Enticho sandstone. It is a semi-monolithic church whose sidewalls, front wall, and roof are completely separated and projecting from the main rock. It is attached to the rock only at its floor and at its back wall. A recent modern structure was built over the hewn front porch probably to protect it from damage by rain. However, this inappropriate restoration work obscured the original architecture of the church. The church was believed to have been carved during the same period as that of the church of Abreha-Atsebaha, a claim that is supported by the proximity of the two churches and the similarity in their internal architecture and art-works. Rectangular carved columns of quartz-rich sandstone supporting arches and curved ceilings decorated by similar designs characterize this church. The presence of a sandstone slab with inscriptions of Axumite type in the vicinity of the church may also support the claim that the church dates back to the Axumite period. This church was partly burnt either during the tenth or sixteenth century.

Abraha-Atsebaha rock-hewn Church:

This church is most famous of all the rock-hewn churches in the region because it is located in a most readily accessible site at about 17 km west of Wukro along the Wukro–Hawzen road. It is carved into west facing façade of thick succession of Adigrat Sandstone. To the west of this cliff lies the wide plain of Ger'alta underlain by peneplained Precambrian metamorphic rocks or Palaeozoic Enticho sandstones on top of which are the remnants of the Adigrat sandstone successions forming beautiful mountain peaks whose silhouettes can be observed from tens of kilometres away. Most of these cliffs contain numerous rock-hewn churches. The church is hewn inwards into a thick, vertical cliff face of massive bed of sandstone. Its back wall, floor and roof are attached to the rock. Its two sidewalls are partly carved from the exterior giving it a semi-monolithic appearance. The front wall, now hidden by a built up porch, appears to have been carved like the sidewalls. This rock-hewn church is probably the oldest of its kind as it is considered to have been carved some time during the fourth century AD by the Axumite kings traditionally known as Abraha and Atsebaha. It was partly destroyed and burnt by the Agaw ruler Yodit Gudit sometime during the ninth or tenth century AD. However, the marks of burning left on the stone seem to be so fresh to be as old as thousand years, and may indicate that the burning was of latter date, probably during the war of Gran Ahmed during the sixteenth century AD. The

Italians constructed the front white-painted porch in 1937 during the Italian occupation period. The interior of the church presents a fascinating architecture where the front passage, heavily damaged by the burning, was recently partly reconstructed and covered by recent paintings on cloth. Twelve carved columns rising directly from the floor to support the ceilings dominate the interior of the church. Six of the columns have rectangular cross-section and branch at their tops into four arches supporting curved ceilings. The other six columns have near circular cross-section with wide bases thinning towards the top. These columns support flat ceilings carved higher into the roof rock than the curved ones. The main passage that leads to the holy of holies (inaccessible to visitors) branches into four aisles with curved ceilings. Both the curved and flat ceilings and the upper parts of the walls are decorated by finely carved geometrical figures including labyrinths, crosses, and interconnected squares. As the holy of holies, which is believed to be equally impressive, cannot be accessed, it is not possible to tell the total number and size of columns and aisles in this church.

References

- Asrat, A. (2002) The Rock-Hewn churches of Central and Eastern Tigray: A geological perspective. *Geoarchaeology: An International Journal*, 17: 649-663.
- Asrat, A., Demissie, M., Mogessie, A. (2009) Geo-tourism in Ethiopia: Yeha, Axum, Wukro, Lalibela. *SHAMA Books*, Addis Ababa, 186pp.

30. Glacial geomorphology: the paleozoic sedimentary successions of Northern Ethiopia

Nageshwar Dubey¹, Konka Bheemalingeswara¹ and Jan Nyssen^{2,*}

*1*Department of Earth Science, Mekelle University, P. O. Box 3066, Mekelle, Ethiopia *ndubeych@yahoo.com

2 Department of Geography, Ghent University, Ghent, Belgium

Introduction

Geology of northern Ethiopia commences with the Neoproterozoic basement rocks at the bottom, unconformably overlain by Phanerozoic sedimentary successions in the middle and thick Tertiary basaltic flows (traps) on the top. Among the Phanerozoic sedimentary successions, Paleozoic is scanty, patchy and thin as compared to Mesozoic, which is regular, much thick and dominant. Traditionally, Paleozoic successions of northern Ethiopia are divided into two lithostratigraphic units; (a) the lower Enticho Sandstone Formation (of fluvial origin) and (b) upper Adaga Arbi Glacial deposits (tillites). Bussert and Schrank (2007) differentiated Lower and Upper Enticho on the basis of their lithic characters and suggested latest Carboniferous to Early Permian age on the basis of palynological evidences. This is further supported by the Sacchi et al. (2007) who have suggested Permian age on the basis of petrographic study of pebbles (of volcanics) in tillite.

The present study is a re-examination of the Paleozoic sedimentary succession of Northern Ethiopia in the light of modern concepts of sedimentary environment, facies and lithostratigraphy. Special emphasis is given on interfingering relationships of the above mentioned two Paleozoic units, to know their paleodepositional environments. Their lithostratigraphic rank (Formation) is also examined. Each lithostratigraphic unit is a product of a unique depositional environment; they are diachronous as they vary in age laterally but always retain their lithological characters (with minimum variations). They may comprise of one, or more than one lithology.

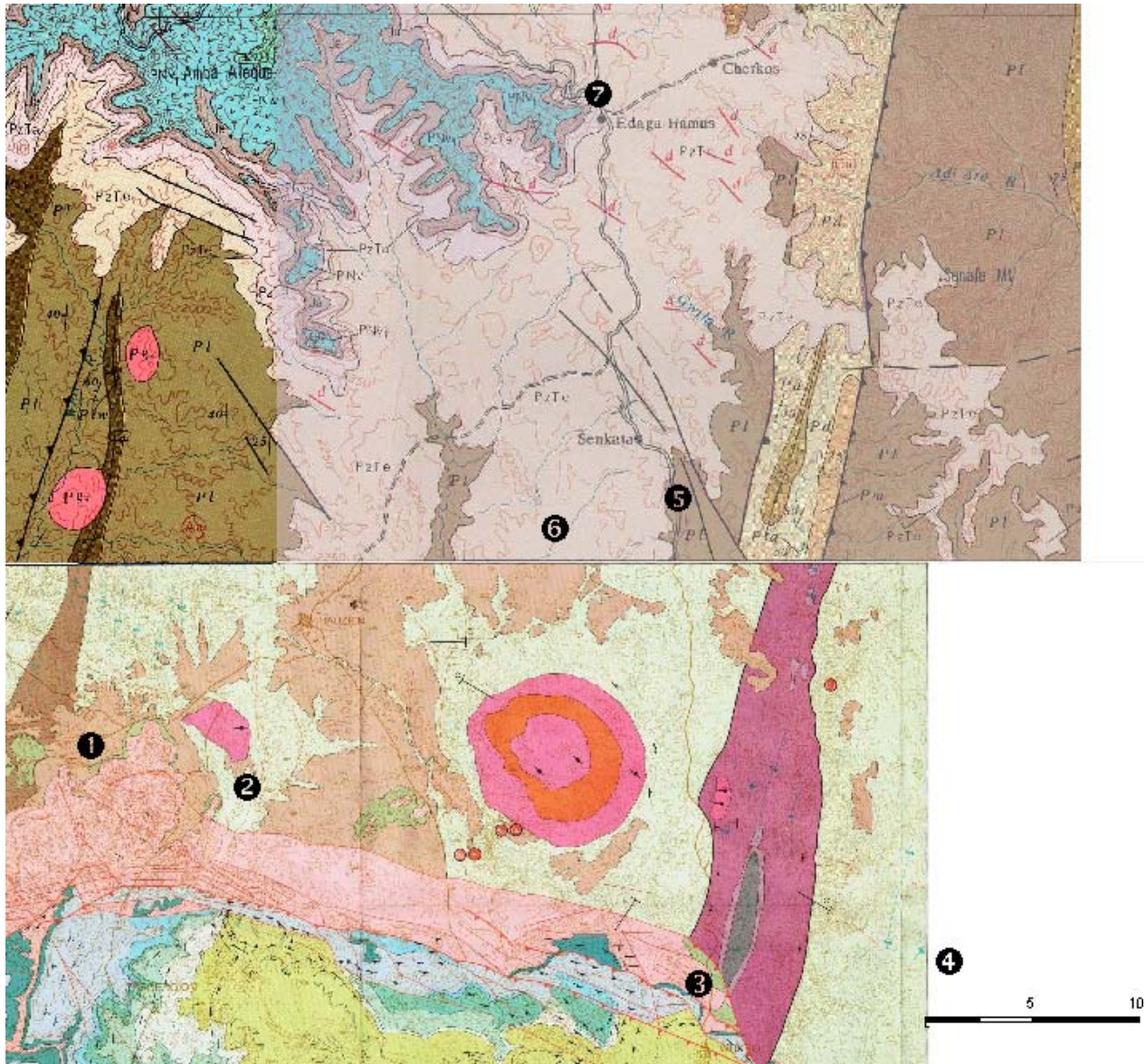
Excursion stops in the study area

Out of the 7 typical locations studied (Fig. 1), 4 will be visited during the excursion:

- (3) North of Wukro: outcropping of: LFD, LFE and LFF;
- (5) Gumisa, South of Senkata: outcropping of LFC, LFD;
- (6) Tsinkaniet: LFA and LFD in the hand-dug well;
- (7) Along the road from Senkata to Edaga Hamus: thick cross-bedded LFC.

Results and discussion

Six major lithofacies were identified in seven sections of the entire Paleozoic succession in the study area, on the basis of dominant lithology, bedding characteristics and structures, grain-size, embedded dropstones and trace/body fossil content. Special attention was also given to the nature of clast size, shape, composition, quality and quantity of matrix. Major lithofacies are:



Compilation of existing geological maps (Garland et al., 1978; Russo et al., 1996). PzT stands for Enticho sand-stone, P1 and Pd are Precambrian. Subhorizontal terrains at the NW and S are Mesozoic and Tertiary. Location of the presented sections is indicated

(a) LFA Breccia-conglomeratic facies: unstratified, very thick unit but heterogeneous in terms of shape, size and composition of clasts. Clasts are dominated by i) angular and sub-angular boulders; and ii) rounded and sub-rounded pebbles and supported by sandy/muddy matrix. Generally it shows white color if supported by siliceous or calcareous cement and dark grey color when supported by mud. Due to presence of iron-oxide cement the unit at places, shows variegated colors particularly maroon, red and yellow. Similarly, presence of silica cement makes it very hard. Presence of big boulders, immature sediment, poor sorting and absence of bedding characteristics supports glacial origin and this litho-facies, and is the main mass of 'tillite' referred in literature. The boulders show significant variation in size and composition and indicate variation in geology at source. It includes- metavolcanicclasts, metavolcanics (both felsic

and mafic), metasediments (slate, phyllite and limestone), granite gneisses, granites, gabbros, rhyolites, aplites etc.



Section - IV
Michael Baraka Church Hill
18km east of Wukro Town

Red color thick glacial deposit (LFA)
with flame/load structure overlying the
basement and underlying LFC



Metavolcanic boulder in red color LFA

(b) LFB Conglomeratic facies: moderately thick unit, characterized by the presence of elliptical, rounded to sub-rounded clasts of boulder and pebble size and sandwiched between sandstone lithologies. Variation in cement provides different colors and hardness to the unit. Elliptical and pointed pebbles are common and some of them show flat broken surfaces possibly due to the load of ice. The matrix of this 'morainic conglomerate' is generally sandy and layering is often found. Boulders showing homogeneity in size and shape, and heterogeneity in composition suggest glacial origin.

(c) LFC Cross-bedded sandstone facies: white, cross-bedded, calcareous, medium to coarse grained arkosic sandstone. Presence of grit and polymictic conglomerate lenses is common. The unit is also iron-rich muddy at places. It represents braided river deposits. But at the same time, presence of large cross-bedding indicates aeolian influence as well. Presence of textural inversion in petrographic study confirms the view. This is the main litho-facies of typical Enticho Sandstone.

(d) LFD Laminated mudstone facies: thinly bedded lacustrine deposits, characterized by thinly laminated ferruginous mudstones, claystones and siltstones. Presence of iron oxide, though poor, provides variegated colors particularly maroon, red and yellow. It suggests low energy depositional environment and at places with well developed 'varves'. Dropstones are not common in this facies indicating little or no glacial influence in the lake environment. At places this litho-facies is green in colour and very hard if silicified during diagenesis.

(e) LFE Non-laminated mudstone facies: similar to the above but characterized by the presence of dropstones and without laminations. It represents a glacial deposit. This is the main mass called 'glacials' in literature.

(f) LFF Sandy/silty limestone facies: generally thin, rare and occasionally present in thick successions of mudstone. It shows presence of smaller dropstones. It is a good example of fresh water limestone deposition during Paleozoic.

Conclusions

The observations suggest that the Paleozoic successions are the result of repetitions (in space and time) of many episodes of glacial, fluvial and lacustrine sedimentation. Thickness of these litho-facies is primarily controlled by the available accommodation space in the basin. Extent of a particular litho-facies depends upon the prevailing environment at that time. Cross-bedded sandstone facies (LFC) indicate wide-spread fluvial activity and well-developed braided fluvial system in the area. Similarly, LFD suggest well developed small to medium size lakes where the clastic material was supplied by both fluvial and glacial activity. On the other hand, LFA/LFB facies indicate exclusive glacial activity.

Further reading:

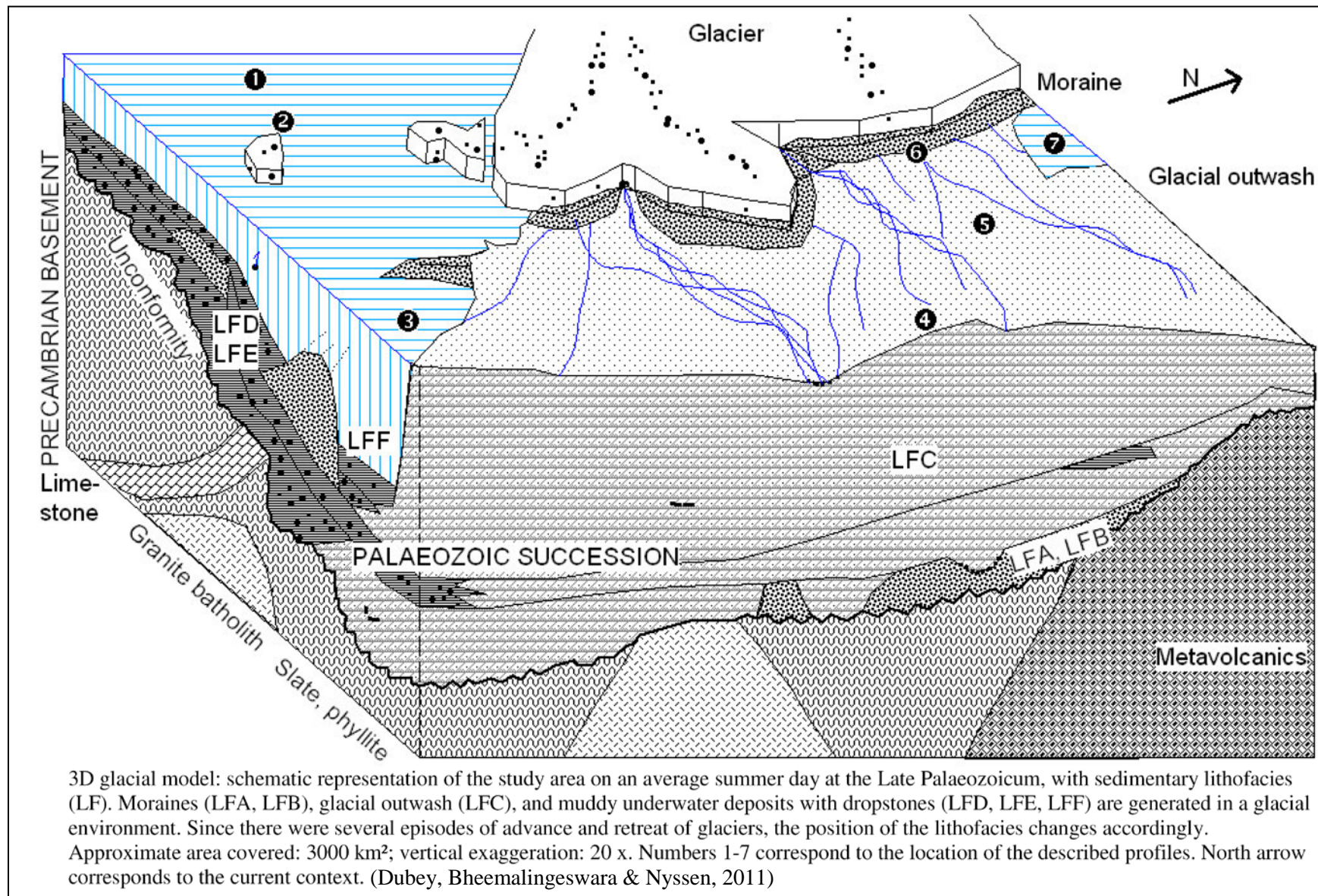
Bussert, R. and Schrank, E. (2007). Palynological evidences for a latest Carboniferous-Early Permian glaciation in Northern Ethiopia. *Journal of African Earth Science*, 49, 201-210.

Bussert, R. (2010). Exhumed erosional landforms of the Late Palaeozoic glaciation in northern Ethiopia: Indicators of ice-flow direction, palaeolandscape and regional ice dynamics. *Gondwana Research*, 18, 356-369.

Dubey, N., Bheemalingeswara, K., Nyssen, J. (2010). Sedimentology and lithostratigraphy of Paleozoic sedimentary successions of Northern Ethiopia. Poster presented at the European Geosciences Union General Assembly, Vienna, 2-7 May 2010. *Geophysical Research Abstracts*, Vol. 12, 2010.

Kumpulainen, R.A., Uchman, A., Woldehaimanot, B., Kreuser, T. And Ghirmay, S (2006). Trace fossil evidence from the Adigrat Sandstone for an Ordovician glaciation in Eritrea, NE Africa. *Journal of African Earth Science*, 45, 408-420.

Sacchi, R., Alene, M., Barbieri, M., and Conti, A. (2007). On the Paleozoic Tillite of the Adigrat Group (Tigrai, Ethiopia). *Periodico di Mineralogia*, 76, 2-3, 241-251.



31. Rockfall shapes the *amba* landscape

(largely based on Nyssen et al., 2006)

Nyssen, J.^{1,*}, Poesen, J.², Moeyersons, J.³, Deckers, J.², Mitiku Haile⁴

¹ Ghent University, Department of Geography, Gent, Belgium

² K.U. Leuven, Division of Geography, Department of Earth and Environmental Sciences, Heverlee, Belgium

³ Royal Museum for Central Africa, Tervuren, Belgium

⁴ Mekelle University, Department of Land Resource Management and Environmental Protection, Mekelle, Ethiopia

* Corresponding author. jan.nyssen@ugent.be

Distinct rock fragment displacements occur on the ambas, or structurally determined stepped mountains of the Northern Ethiopian Highlands. Here we discuss the rock fragment detachment from cliffs by rockfall, quantify its annual rates, and identify factors controlling rock fragment displacement distances on the scree slopes.

The rockfall that can be seen on the escarpment near Wukro occurred in 2006. Characteristics and triggering factors of this particular landslide have never been studied. The general setting is one where the upper part of the escarpment is relatively resistant sandstone, and the lower part consists of soft tillites, that are easily eroded (Fig. 1).

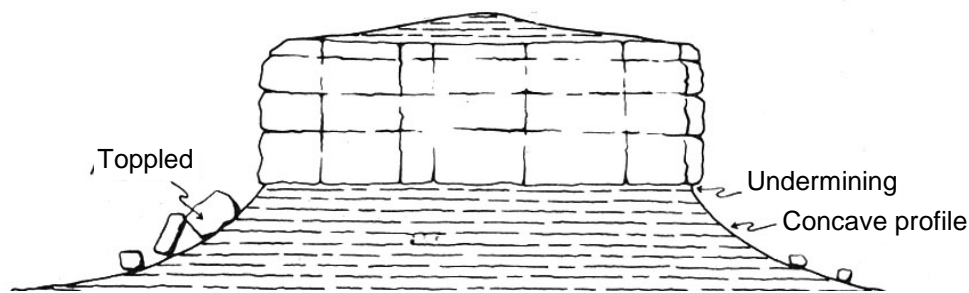


Fig. 1. The resistant rock is undermined and topples. This results in a vertical retreating cliff (After Pannekoek & Van Straalen, 1992).

In case of cliffs without particularly soft underlying material (which is the most common case in Ethiopia), the cliffs become less high when retreating (Fig. 2).

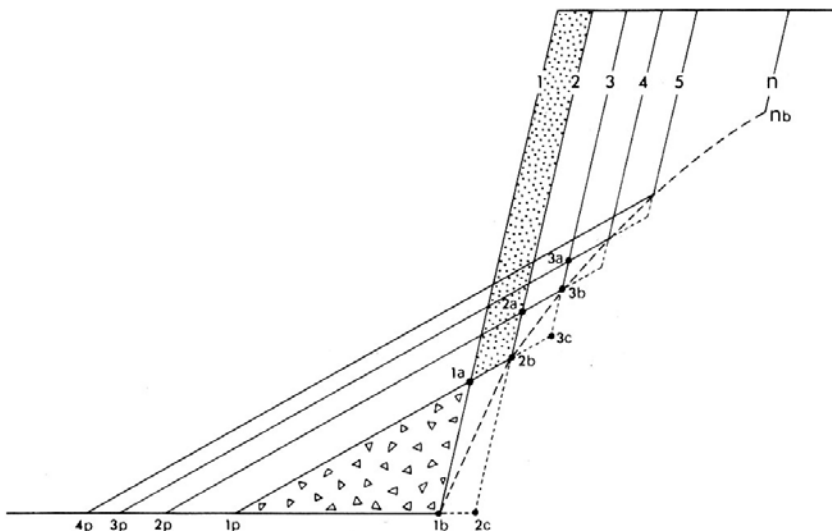


Fig. 2. Cliff retreat in a homogeneous rock formation, without removal of debris by fluvial processes. The debris deposit 1a-1b-1p is formed with cliff retreat from 1 to 2 (After Lehmann, 1933).

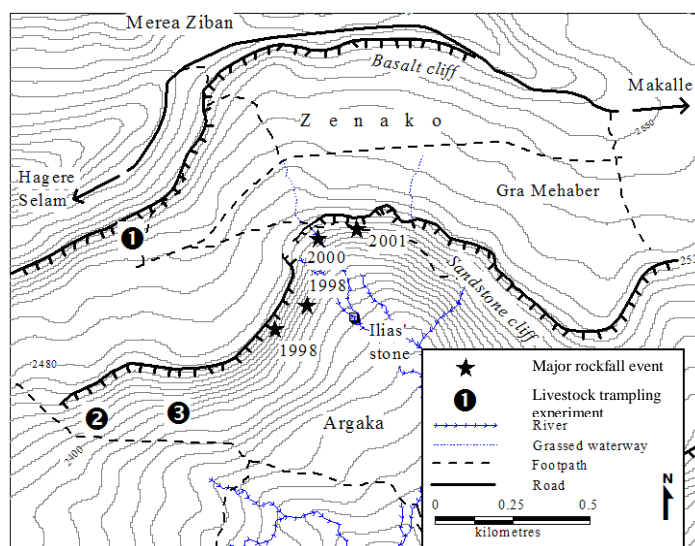


Fig. 3. Location map of major rockfall events (1998 – 2001) and of livestock trampling monitoring sites within the May Zeg-zeg catchment.

In the May Zeg-zeg catchment (Fig. 3), rockfall from cliffs and rock fragment movement on debris slopes by runoff and livestock trampling were monitored over a 4-year period (1998–2001). Rockfall and rock fragment transport mainly induced by livestock trampling appear to be important geomorphic processes. Along a 1500-m long section of the Amba Aradam sandstone cliff, at least 80 t of rocks are detached yearly and fall (Fig. 4, Table 1) over a mean vertical distance of 24 m resulting in a mean annual horizontal cliff retreat rate of 0.37 mm y^{-1} . One of the few studies on sandstone cliff retreat in (sub)tropical regions (Young and Wray, 2000) reported geological scarp retreat rates ranging between 0.15 and 0.25 mm y^{-1} . On the Colorado Plateau, scarp retreat rate averages 0.16 mm y^{-1} (Young, 1985). These mean long-term values are of a similar order of magnitude as our observed short-term cliff retreat rates.



Fig. 4. Photo taken three months after the occurrence of a rockfall event (August 1998) on the sandstone cliff in May Zeg-zeg catchment. Fresh rock fragments (black arrows at the bottom) are easily recognisable by their bright colour. The upper white arrow indicates the origin of these rock fragments at the cliff. Despite vegetation growth, the rockfall path can still be recognised on the backslope.

Table 1. Rockfall events at the 1500 m long sandstone and limestone cliff (1998-2001).

Approx. date	Lithology	Total volume (m ³)	Rock density (kg m ⁻³)	Total mass (10 ³ kg)	Horizontal displacement (m)			Vertical displacement (m)		
					min	max	weighted average	min	max	weighted average
August 1998	Sandstone	10.49	2400	25	4.0	150.9	80.8	1.1	77.9	46.9
August 1998	Limestone	13.36	2535	34	9.2	35.3	14.0	8.5	24.0	11.6
August 2000	Sandstone	70.76	2400	170	5.0	36.2	20.8	1.5	24.0	17.6
August 2001	Sandstone	37.77	2400	91	14.0	66.5	32.5	11.2	33.1	20.2
Mean (1998-2001)		33.10		80			37.0			24.1

Yearly unit rock fragment transport rates on scree slopes ranged between 23.1 and 37.9 kg m⁻¹ y⁻¹ (Fig. 5, Table 2). This process is virtually stopped when exclosures are established (Table 3).



Fig. 5. Tracers (white limestone) displaced over a distance of 6 m in 20 months (Harena rangeland, March 2001). The horizontal rope at the back witnesses original tracer position.

Table 2. Tracer displacement in 20 months, perpendicular to the contour

Site	% of tracers moved	Displacement distance (m) of moved tracers		Mean displacement distance (m) of all tracers
		Mean ^a	Standard deviation	
1 Zenako range	72	1.74 *	± 2.37	1.25
2 Harena range	95	2.31 *	± 1.97	1.80
3 Harena exclosure	66	0.90 #	± 1.00	0.59

^a Different symbols indicate significantly different values ($\alpha = 0.1$) based on unpaired t-student test.

Table 3. Explanatory factors of mean rock fragment movement distance (over 20 months) for the three experimental sites

	<i>Displacement distance (m) of moved tracers</i>	<i>RI</i>	<i>R_C (%)</i>	<i>d₂ (m)</i>	<i>Shrub cover (%)</i>	<i>Long grass cover (%)</i>	<i>Vegetation cover (%)</i>	<i>Smooth surface (%)</i>
1 Zenako range	1.74	46.3	62.4	0.062	21.0	0.0	41.1	20.2
2 Harena range	2.31	29.7	29.7	0.05	21.1	1.3	31.6	53.4
3 Harena closed	0.90	33.8	13.5	0.06	21.7	42.6	65.1	17.9

RI: Roughness index (Eq. 2); *R_C*: Rock fragment cover; *d₂*: Intermediate rock fragment diameter

Corresponding mean rock fragment transport coefficients (*K*) are 32 – 69 kg m⁻¹ y⁻¹ on rangeland but only 3.9 kg m⁻¹ y⁻¹ in densely vegetated exclosures. A conceptual model (Fig. 6) indicates that besides rockfall from cliffs and argillipedoturbation, all factors and processes of rock fragment redistribution in the study area are of anthropogenic origin.

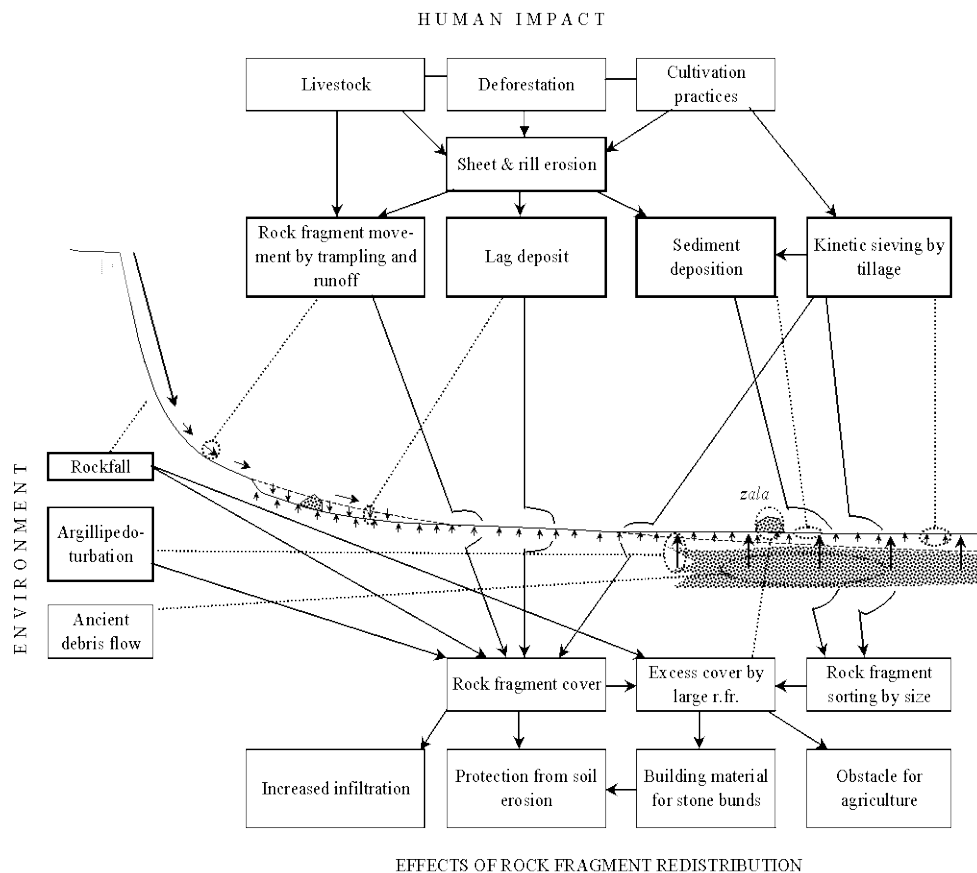


Fig. 6. Major factors in rock fragment redistributions, characterising the present day landscape and agricultural system. Dotted lines refer to rock fragment movements, schematically represented by short arrows in the figure and solid lines indicate relations between factors and processes (bold frames).

References

- Lehmann, O., 1933. Morphologische Theorie der Verwitterung von Steinschlag Wänden. Vierteljahrschrift der Naturforschende Gesellschaft in Zürich, 87, 83-126.
- Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Mitiku Haile, 2006. Processes and rates of rock fragment displacement on cliffs and scree slopes in an *amba* landscape, Ethiopia. Geomorphology, 81: 265–275.
- Pannekoek, A., Van Straalen, L., 1992. Algemene Geologie, Tjeenk Willink, Zwolle/Groningen.
- Young, R.A., 1985. Geomorphic evolution of the Colorado Plateau margin in west-central Arizona: a tectonic model to distinguish between the causes of rapid symmetrical scarp retreat and scarp dissection. In: Hack, J.T., Morisawa, M. (Eds.), Tectonic Geomorphology. London, Allen & Unwin, pp. 261–278.
- Young, R.W., Wray, R., 2000. Contribution to the theory of scarpland development from observations in Central Queensland, Australia. Journal of Geology 108, 705–719.

32. Geology of the Negash area

Asfawossen Asrat

Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

The Northern metamorphic terrain of Ethiopia, including the Negash syncline is represented by a series of thick, inhomogeneous volcano-sedimentary assemblages, which belong to the Arabian–Nubian Shield (ANS) sector of the East Pan-African orogen (Stern and Dawoud, 1991; Asrat et al., 2001, 2003, 2004). This terrain is dominantly characterized by steeply dipping and extensively folded, low-grade metamorphic rocks intruded by various granitic and mafic intrusions (Tadesse, 1997; Alemu, 1998; Tadesse et al., 1999, 2000; Asrat, 2002). This terrain is considered to be formed by lateral crustal growth through processes of arc and terrane accretion during the Pan-African (950–500 Ma) orogenic event where granitic magmatism played an important role. The metamorphic sequence in the Mekele–Adigrat area is composed dominantly of heterogeneous metavolcanics (breccias, agglomerates, bedded tuffs and lavas) all inter-bedded with subordinate marine clastics, rare limestones, tuffaceous slates, redeposited ash, and greywackes composed partly of volcanic fragments, exhibiting considerable lateral variations. The sequence, with a thickness reaching up to 2500 m in some sections, is metamorphosed to greenschist facies except in contact aureoles of plutons. The regional foliation oriented N–S to NNE–SSW appears to have been produced by pervasive shortening during D1 deformation (Alene, 1996). D2 deformation is represented by the development of semi-ductile dextral shear zones. Felsic plutonism of variable age and lithology is a characteristic feature of this metamorphic terrain where syntectonic, late- and post-tectonic granitoids have been identified (e.g. Beyth, 1972; Garland, 1980; Tadesse, 1997; Alemu, 1998; Asrat, 2002). The syntectonic bodies are medium grained epidotized, foliated granites (rarely granodiorites) elongated along the regional strike.

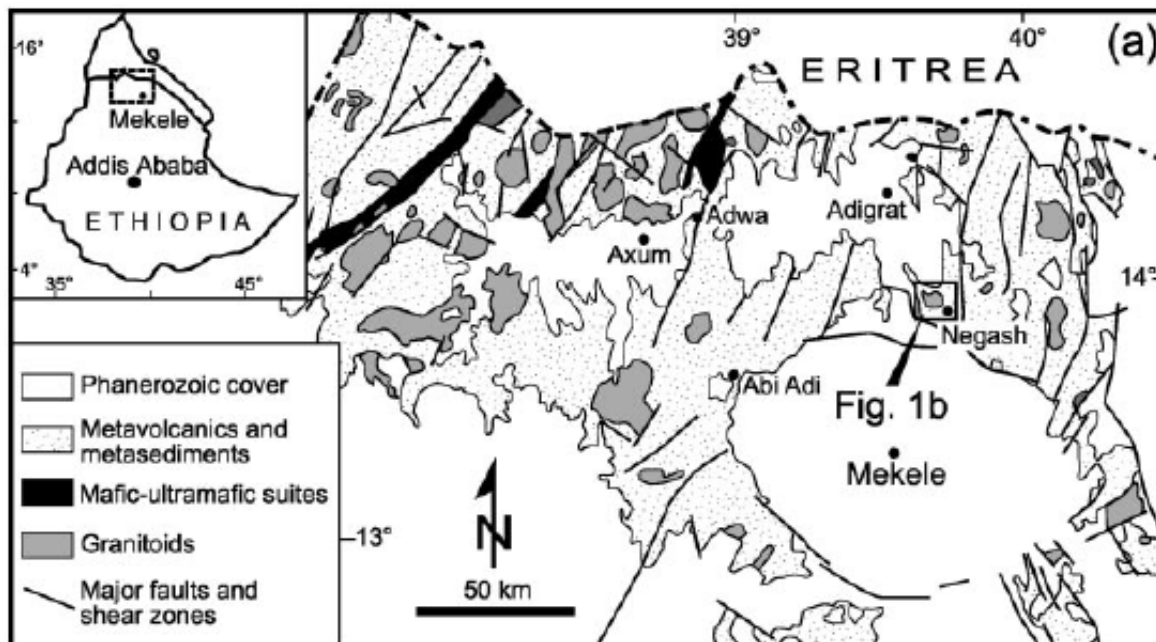


Fig. 1. The Northern metamorphic terrain.

The late- to post-tectonic plutons consist of granites, monzo monzogranites, granodiorites, tonalites, monzonites often accompanied by diorites and gabbrodiorites, and cut by many late stage aplite and quartz porphyry dikes. The late- to post-tectonic granitoids in this area are considered to be Upper Proterozoic to Lower Palaeozoic (660–540 Ma; e.g., Asrat et al., 2004). The Negash pluton, dated to 610 Ma is one of the late tectonic bodies (Asrat, 2002). It crops out in the middle of a low-grade metamorphic inlier in the Mekele-Adigrat area, the Negash syncline (Fig. 1), and is one of several calc-alkaline plutons, which occur to the north especially in the Axum area. They are syn- to post-tectonic granites, monzogranites, granodiorites, diorites and subordinate gabbros, which have mantle-like Sr and Nd isotopic ratios.

References

- Alemu, T. (1998). Geochemistry of Neoproterozoic granitoids from the Axum Area, northern Ethiopia. *Journal of African Earth Sciences* 27, 437-460.
- Alene, M., 1996. Some aspects of the geology and structure of the basement rocks in the Maikenetal–Negash area, Northern Ethiopia. Abstract in IGCP Project 348 (the Mozambique and related orogenies). International Field Conference, Northern Ethiopia and Eritrea, March 15–25, 1996.
- Asrat, A. (1997). Geology and geochemistry of the Negash Pluton and their metallogenic significance, central Tigray. M.Sc. thesis, Addis Ababa University, 159 pp.
- Asrat, A. (2002) Geology, petrology, geochemistry, structure, age and metallogeny of granitoids in the Precambrian terrains of Northern and South-western Ethiopia. Unpublished Ph. D. Thesis. University of Henri Poincare, Nancy I, France, 276p.
- Asrat, A., Barbey, P. & Gleizes, G. (2001). The Precambrian geology of Ethiopia: a review. *Africa Geoscience Review* 8, 271-288.
- Asrat, A. Gleizes, G., Barbey, P. & Ayalew, D. (2003). Magma emplacement and mafic-felsic magma hybridisation: structural evidence from the Pan-African Negash pluton, Northern Ethiopia. *Journal of Structural Geology* 25, 1451-1469.
- Asrat, A., Gleizes, G., Barbey, P., Ayalew, D., Ludden, J. (2003) Magma emplacement and mafic-felsic magma hybridization: structural evidence from the Pan-African Negash pluton, Northern Ethiopia. *Journal of Structural Geology*, 25: 1451-1469.
- Asrat, A., Barbey, P., Ludden, J., Reisberg, L., Gleizes, G., Ayalew, D. (2004) Petrology and isotope geochemistry of the Pan-African Negash pluton, Northern Ethiopia: Mafic-felsic magma interactions during construction of shallow-level calc-alkaline plutons. *Journal of Petrology*, 45: 1147-1179.
- Beyth, M., 1972. The geology of Central and Western Tigray. Ph.D. thesis, Rheinische Friedrich-Wilhelms Universität, Bonn, W. Germany, 200 pp.
- Garland, C.R., 1980. Geology of the Adigrat Area. Memoir No. 1. Ministry of Mines and Energy, Addis Ababa, Ethiopia. 51 pp.
- Stern, A.J., Dawoud, A.S., 1991. Late Precambrian (740 Ma) charnockite, enderbite, and granite from Jebel Moya, Sudan: a link between the Mozambique Belt and the Arabian–Nubian Shield? *Geology* 99, 648–659.
- Tadesse, T., 1997. The Geology of Axum Area (ND 37-6), Memoir No. 9. Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia, 184pp.
- Tadesse, T., Hoshino, M., Sawada, Y., 1999. Geochemistry of low-grade metavolcanic rocks from the Pan-African of the Axum Area, northern Ethiopia. *Precambrian Research* 99, 101–124.
- Tadesse, T., Hoshino, M., Suzuki, K., Iizumi, S., 2000. Sm–Nd, Rb–Sr and Th–U–Pb zircon ages of syn- and post-tectonic granitoids from the Axum area of northern Ethiopia. *Journal of African Earth Sciences* 30, 313–327.

33. Land use and land cover changes in Sinkata village

Kassa Teka^{1,2,*}, Anton Van Rompaey², Jean Poesen², Simon Van Bruyssel², Amanuel Zenebe¹, Deckers, J.²

¹Department of Land Resource Management and Environmental Protection, Mekelle University, Ethiopia

²Department of Earth and Environmental Sciences, K.U.Leuven, Belgium

*Corresponding author: kassateka@yahoo.com

Introduction

Land use and land cover change is one of the most important forms of environmental change occurring in northern Ethiopia. Sinkata *tabia* (village) is one of the drought prone areas of Northern Ethiopia. Like in other parts of Ethiopia, agriculture is the prime occupation of a majority of the people in the *tabia*. Population growth in the Northern Ethiopia has forced the local habitants to bring more land under cultivation (Rawat *et al.* 1996), settlement land, commercial sites, etc. This change in mountain land use dynamics in the area is a matter of concern because of its probable effects on the environment, such as the lowering of groundwater tables, reduced land productivity due to soil degradation and reduced biodiversity (Santram *et al.*, 2005). A better understanding of the land use system and land cover change will help in interpreting current environmental problems in the area and developing a sustainable land use planning and decision-making. It is therefore important to undertake a land use and cover evaluation and change rate measurement in order to generate fundamental land use data of the study area.

The present study is an attempt to understand the land use and land cover changes occurred during the last four decades in the Sinkata *tabia* by using remote sensing approaches and land use data. The outcome of the current study will be helpful for planners engaged in making decisions regarding land use planning and land resource management of the study area and other areas with a similar bio-physical setup.



*Figure 1 and excursion viewpoint. This partial view over the Senkata tabia in 1975 allows the participants to assess land use and cover changes that have occurred in the study period. Photo R.N.Munro (Munro *et al.*, 2008).*

Study area

The *tabia* is one of the 25 *tabias* of Sea'sie'-tsae'dae'mba *woreda* (district), Eastern zone of Tigray National Regional state (Fig 2). It is located at 14°02'N and 39°34' E. The *tabia* consists of 4 *kushets* (hamlets): Sinkata, Chemet, Angol and Dae'ro-Mue'gole. The topography of the area is between 1500 - 2300m a.s.l., in the *weina-dega* (mid-elevation) agroecological zone.

The total human population of the *tabia* was 5312 (CSA, 2007). According to the census, the population density of the area has increased from 142 in 1994 to 191 persons/km² in 2007.

The larger part of the *tabia* is located on the exhumed Early Palaeozoic planation surface (Coltorti et al., 2007; see p. 143 in this excursion guide). In the plain, the pre-Palaeozoic basement outcrops, composed of metamorphic rocks, locally overlain by limbs of Palaeozoic rocks (Fig. 1). On the hills and cliffs surrounding the plain, these rocks, Edaga Arbi glacials and Enticho sandstone, also outcrop (see p. 148 in this excursion guide). Common soils in this area are soils with an agric horizon such as Lamelli-arenic Luvisols in the plains and on plateaux, in association with Cumulic Arenosols and Arenic Cambisols (Mulugeta, 2007).

Methodology

Data Sources

The basic land use and land cover map sources aerial photographs (1965; 1:50 000) and IKONOS images (2007). The total mapped area was 27.85 km². An interdependent interpretation procedure (FAO, 1996), which consisted of interpretation of the first land use/cover map and then using this first delineation as a reference when interpreting the second map, was followed for delineating land use/cover parcels. For the high resolution of the panchromatic Ikonos image, composite image was developed by combining the RGB colours ('Image fusion'). Multispectral images were developed using the Macro – modeler in Idrisi Andes so that by increasing the pixel size of the multispectral images it is easy to visualize and delineate the different land uses precisely. In developing land uses for 1965, scanned analogous air photograph were used. To avoid geometric distortion, which may be especially important in mountainous terrain, ortho-rectification and geo referencing were carried out on the scanned photographs. This was done by selecting hundreds of points, that remained unchanged on the aerial photographs of 1965 and Ikonos images.

Land use classification.

After ortho-rectification and geo-referencing, land use was mapped using screen digitising in ILWIS 3.3 software. In order to map land use, description adapted from Anderson's (1976) land use and land cover classification system and the land use and land cover of Tigray region prepared by BoANR (2001) were employed and result 8 common land uses (Table 1) were identified.

Table 1. Description of land use and land cover class used for analysis of changes

Land use type	Description based on BoANR (2001)
Cultivated/ arable land	Annual and perennial crops (>70% of the land), frequently observed on level lands (plains, plateaus, foot slopes and valley floors)
Bare land	Land devoid of vascular plants; composed of exposed rock, sand and soil surface.
Grassland	Open grassland/herb found in flat areas, grasses around the river banks in which water table is at or near the surface.

Built-up area	Residences, Administrative buildings, service institutions, small industrial and trade enterprises.
Shrubland	Sparsely cultivated land, bush shrub grassland, shrubland, shrub grassland, degraded shrub grassland
Bushland	Constituted by strata of very few trees, bushes, shrubs and scattered herbs, or grasses. The canopy cover of bush/shrubs is 40 – 60% and that of herbs or grasses is 15 – 20%.
Forest land	Remnant of high natural forest, found in small patches around churches, steep slopes and less populated areas, canopy cover of 50 – 80%.
Water	Any type of surface water

Results and discussion

Out of the total land area, agriculture land covers the majority (66.35%) followed by grassland (14.66%). Forest *land*, which indirectly enhance village economy by providing fuel wood and fodder, and water body area were low (0.83% and 0.07% respectively in 2007) compared to other land use forms (Figs. 2 and 3).

The reduction in agricultural land was partly the result of increased population which led to an increased demand for settlement, and partly to the unavailability of favorable terrain for cultivation in the catchment. This corresponds to the change in number of housings during the study period, i.e. from 348 in 1965 to 561 in 2007. This is in line with the estimate of Döös (2002) that 1 to 2 million ha of cropland are taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (Döös, 2002). This is likely to take place mostly on prime agricultural land located along the road and in river valleys. It is also noted that rural households may consume more land per capita for residential purposes than their urban counterparts (Döös, 2002).

The land areas under bare land during 1965 and 2007 were 338 ha (12%) and 136 ha (5%), respectively. The decrease was mainly due to transformation of bare land to farmland and built-up area (Table 2).

Table 2. Land use changes in the study area

Land use	1965 (ha)	1965 (%)	2007 (ha)	2007 (%)	change (ha)	% change
Farmland	1561	56%	1848	66%	+286	+10
Bare land	338	12%	136	5%	-202	-7
Grassland	435	16%	408	15%	-27	-1
Built-up area	43	2%	154	6%	+111	+4
Shrub land	258	9%	160	6%	-98	-4
Bushland	138	5%	54	2%	-85	-3
Forestland	11	0%	23	1%	+12	+0
Water body	0	0%	2	0%	+2	+0
Total	2785	100%	2785	100%	0	0

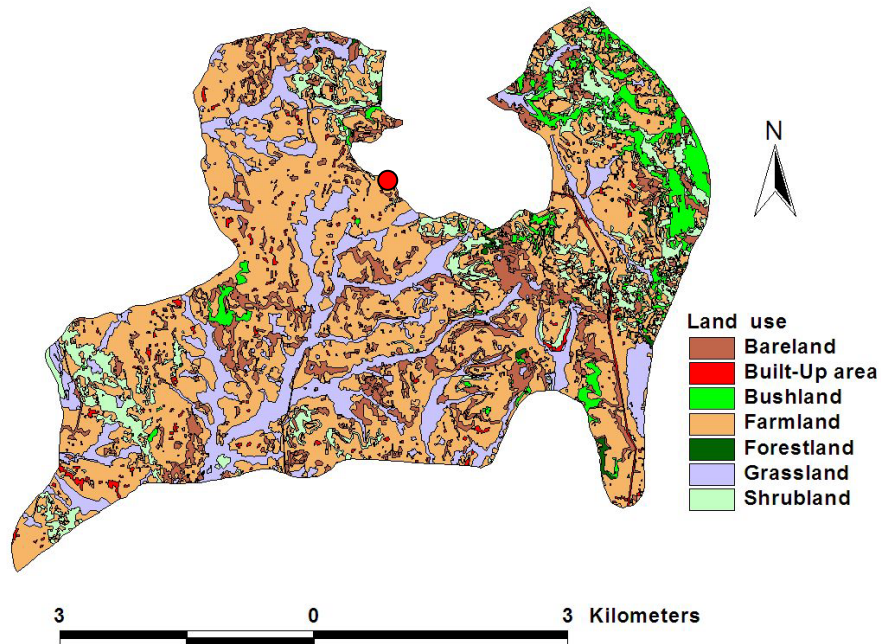


Figure 2. Land use in 1965 in Sinkata tabia – it is the rural area surrounding Freweyni/ Sinkata town which appears as an exclave on the northern side of Sinkata village The excursion viewpoint is indicated by a red dot.

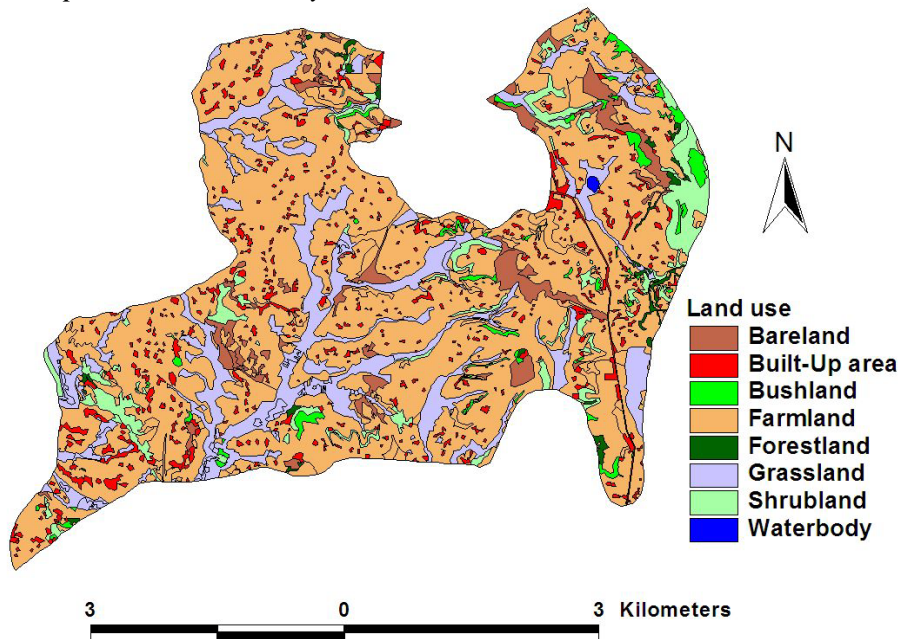


Figure 3. Land use in 2007

Conclusion

The study revealed that the land use and land cover patterns in the study area changed during the last decades. Land areas for agriculture, forest, water body and built-up area showed an increased trend, whereas a decreasing trend was found in grassland, bare land, shrub land and bush land. The decline in grass land and bare land was mainly due to the expansion of the built-up area. Moreover, the increase in arable land area was the result of increased population. In addition, the

huge environmental rehabilitation activities in the village led to the increased extent of natural vegetation cover (forest land). With rapid increase in population within the village, it is likely that development and construction activities will be intensified considerably in the future. Such change in the land use and land cover may cause undesirable impact on the natural environment of the region. An assessment of existing land use and land cover classes will play an important role in developing a proper sustainable land use planning and management systems for the region.

References

- Anderson, J. R., Hardy, E. E., Roach, J. T. and Witmer, R. E. 1976. *A land use and land cover classification system for use with remote sensor data*. Reston, United States Geological Survey, Professional Paper 964, U. S. Government Printing Office, Washington, DC. pp 28
- BoANR, 2001. Bureau of Agriculture and Natural Resources, Land use land cover of Tigray. Land Use Planning and Regulatory Division, Mekelle, Tigray, Ethiopia (2001) pp.213.
- Coltorti, M., Dramis, F. and Ollier C.D., 2007. Planation surfaces in Northern Ethiopia. *Geomorphology* 89, 287-296.
- Döös, B.R., 2002. Population growth and loss of arable land. *Global Environmental Change* 12 : 303-311.
- MoWR, 2008. Nature and features of the Ethiopian River basins, Ministry of Water Resources, Addis Ababa, Ethiopia.
- Mulugeta Degie, 2007. Pedogenetic significance of Enticho sandstone as parent material for soil formation in the landscapes of Rubafeleg and Tsenkaniet catchments, Eastern Tigray. Unpub. M.Sc. thesis, Mekelle University, Ethiopia.
- Munro R N, Deckers J, Grove A T, Mitiku Haile, Poesen J, Nyssen J. 2008. Soil and erosion features of the Central Plateau region of Tigray - Learning from photo monitoring with 30 years interval. *Catena* 75(1), 55-64.
- Rawat, D. S., Farooquee, N .A. and Joshi, R. 1996. Towards sustainable land use in the hills of Central Himalaya, India. *Int. J. Sustain. Dev. World Ecol.* **3**: 57-65.
- Santaram S. Oinam, Yashwant S. Rawat, R.S.Khoiyangbam, Khwairakpam Gajananda, Jagdish C.Kuniyal, and S.C.R. Vishvakarma, 2005. Land use and land cover changes in Jahlma watershed of the Lahaul valley, cold desert region of the northwestern Himalya, India. *Journal of Mountain Science*, vol.2. No.2. pp 129 – 136.

34. Impact of surface water reservoirs on ground water reserves in the highlands of Northern Ethiopia, Tigray region

Tesfamichael G.Yohannes¹, F. De Smedt², K. Walraevens³, J. Nyssen⁴, J. Moeyersons⁵, Mitiku Haile⁶, Kindeya Gebrehiwot⁶, J. Deckers⁷

¹ Department of Geology, Mekelle University, Ethiopia

² Department of Geology, V.U.Brussels, Belgium

³ Department of Geology and Soil Science, Ghent University, Belgium

⁴ Department of Geography, Ghent University, Belgium

⁵ Africamuseum, Tervuren, Belgium

⁶ Department of Land Resources Management and Environmental Protection, Mekelle University, Ethiopia

⁷ Department of Earth and Environmental Sciences, K.U.Leuven, Belgium

An intensive small scale reservoir construction campaign has been carried out by the regional state of Tigray in order to supplement the rain-fed subsistence agriculture in the region, through a regional commission (Commission for Sustainable Agricultural and Environmental Rehabilitation of Tigray (Co-SAERT)), established in 1994. This commission planned to construct 500 reservoirs, each of them with a capacity in the order of 1 million m³, in ten years. Today only about 70 reservoirs have been built throughout Tigray (Fig. 1).



Figure 1. Concentration of small-scale reservoirs south of Mekelle, to the S and SE of Amba Aradom mountain. Area covered is approx. 100 km² and reservoirs are indicated by red circles; the zoom shows Gumselasa reservoir (Source: Google Earth, visited March 15, 2009).

However, most of these micro-dams did not meet the intended goal of supporting rain-fed agriculture through small scale irrigation schemes. Only a few reservoirs can hold sufficient water for irrigation in the planned areas. In 2002, the initiative was evaluated to be ‘failed’ by the responsible authorities and thus the program was interrupted. Though many problems could be

cited for the ‘failure’ of the program, the main problem is known to be reservoir leakage. But information collected from the field show that new springs originated downstream of some micro-dams some time after the construction. Other springs did start to flow more powerful and/or during a longer period of the year. Also in few cases, inhabitants witnessed that the groundwater table in the valleys downstream of dams did rise after reservoir construction. Hence, overall the construction of these small reservoirs is thought to have supplemented the groundwater recharge in the basin, although the exact magnitude is not known.

Although the water level in the reservoirs varies between the wet and dry seasons, it can be safely assumed that the local groundwater level is close to the same level as the reservoirs. Hence, the levels of 37 reservoirs have been inventoried. The inventory was carried out during the dry period and the GPS position and approximate elevation of the surface of the standing water was recorded. Two of these reservoirs have been studied more in detail using diver (automatic data loggers) installations and nearby groundwater wells were sampled for hydrochemical interpretation. The intention is to understand the interaction of the reservoirs and groundwater using water level and hydrochemical measurements both on the reservoirs and the well. Tsinkanet reservoir and two nearby hand-dug wells were investigated from June 1 to November 30, 2006 (Fig. 2). The graphs show that the reservoir level rises to full capacity after a single high rainfall event during the year and that such events are closely linked to the rainy season. During the dry season, sporadic rainfalls do not produce the same effect. This is probably due to dry soils which enhance infiltration in the ground and inhibit large surface run-off. The same is true for the first rainfall events in the wet season, and only when soils become sufficiently moist, rainfalls produced sufficient runoff to fill the reservoir. Afterwards from October to March, the water level in the reservoir decreases again, due to lack of rainfall, irrigation, and evaporation.

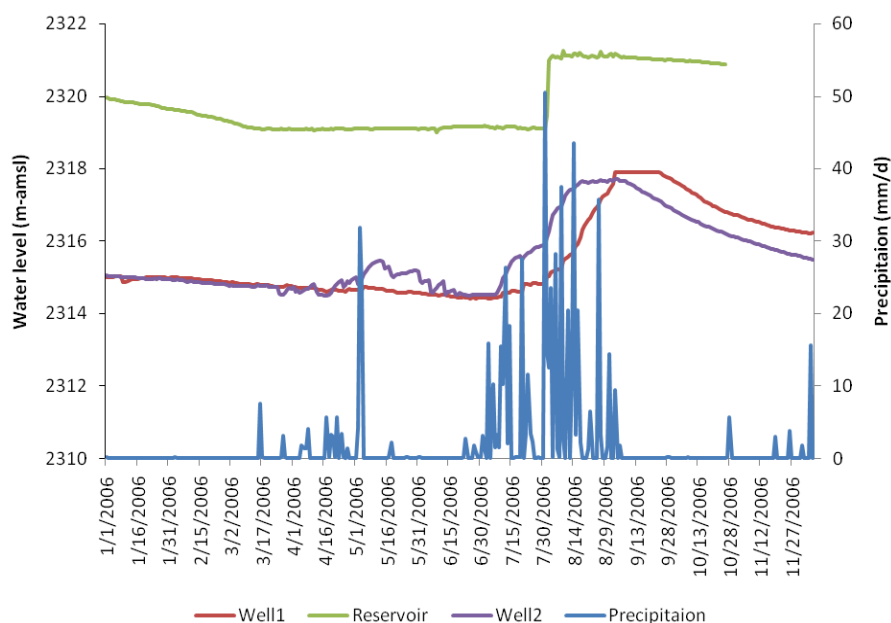


Figure 2. Groundwater and surface water level measurement in the Tsinkanet reservoir and two nearby hand dug wells and precipitation (June 1 to November 30, 2006).

The evolution of the water levels in the wells is somewhat different than the water level of the reservoir. The water level in the wells, especially in well 2, fluctuates while the level of the reservoir is more constant (Fig. 2). This points out that at least part of the groundwater reaching the wells is coming from another source than the reservoir. Hence, this can only be recharge from precipitation in the vicinity of the wells. In addition, it is observed that at the end of the rainy season the water level in the wells decreases long before that of the reservoir, which indicates that groundwater is flowing out to other areas, most likely along the river valley downstream of the reservoir, which is observed to flow most of the year.

The data also show that the groundwater fluctuations are larger and the response to rainfall is faster in well 2 than in well 1. This can possibly be related to soil texture in the vicinity of the wells. Well 2 (twice as far from the reservoir than well 1) is located beneath sandy soils which have a high rate of percolation, while well 1 is located beneath clay or silty clay soils which are less pervious. The possible seepage from the reservoir to the wells through fractures observed around the reservoir is not supported by the measurements. It has been observed that groundwater levels in the area reach the surface towards the end of the rainy season, while the reservoir becomes full much earlier. Moreover, the groundwater levels in the wells continue to decline after the end of the rainy season while the reservoir level remains constant for months. This observation, together with the fact that the wells are shallow (3 to 4 m), leads to the conclusion that the wells are tapping a perched groundwater layer recharged locally by precipitation. Hence, there is no interaction between the wells and the reservoir in the Tsinkanet area.

Water samples collected from the reservoir and the nearby wells to investigate the hydrochemical relationship show the major ion composition (Table 1), both for the Tsinkanet and the Rubafeleg reservoirs (located some 20 km to the ESE, on the Atsbi Horst).

Table 1. Major chemical composition of reservoir and groundwater samples from the Rubafeleg and Tsinkanet sites.

Parameter	Tsinkanet		Rubafeleg	
	Well	Lake	Well	Lake
pH	7.2	7.4	7.4	7.5
EC ($\mu\text{S}/\text{cm}$)	202	250	454	181
Na (mg/l)	13.65	9.9	17.38	5.92
K (mg/l)	1.51	3.75	0.46	1.66
Ca (mg/l)	23.28	26.8	63.83	26.5
Mg (mg/l)	6.08	9.45	10.45	5.38
Fe (mg/l)	0.29	0.21	0.18	0.11
Mn (mg/l)	0	0.01	0	0.01
NH ₄ (mg/l)	0.36	0.21	0	0.17
Zn (mg/l)	0.02	0.02	0	0.01
Cl (mg/l)	8.39	13.92	17.89	7.95
SO ₄ (mg/l)	14.82	33.11	21.63	9.28
NO ₃ (mg/l)	0.94	0.38	12	0.2
NO ₂ (mg/l)	0.02	0.14	0.02	0.02
HCO ₃ (mg/l)	95.16	128	230.58	99.43
PO ₄ (mg/l)	0.03	2.89	2.89	2.89
Si (mg/l)	8.03	<7	11.74	<7

The first apparent difference between water samples from the two sites is that the concentration of most major ions (electrical conductivity (EC), HCO_3^- , Ca^{2+} , Mg^{2+} , Cl^- , and SO_4^{2-}) is higher for samples from Rubafeleg than those from Tsinkanet. Possible reasons for these differences could be related to geological characteristics of the catchments and the wells, and the groundwater residence time. The geology of the Rubafeleg catchment is mainly weathered and fractured metavolcanic and metavolcanoclastics which favors increased concentration of dissolved ions in the groundwater and to some extent in the surface runoff. Moreover, the Rubafeleg reservoir is continuously fed by base flow from the perennial main stream. Hence, surface runoff and base flow from the catchment to the reservoir brings relatively higher concentration of dissolved ions. On the other hand, the groundwater sample was taken from a borehole of about 50 m deep. Considering the low hydraulic conductivity of the metamorphic rock, groundwater at this depth is likely to have relatively higher residence time in the aquifer which results in higher concentration of dissolved ions. On the contrary, the geology of Tsinkanet catchment is dominantly sandstone which has high hydraulic conductivity and less potential to supply dissolved ions. Hence, low concentration of dissolved ions is observed in both the groundwater and the lake, compared to that of Rubafeleg.

Groundwater at Tsinkanet was sampled from about a ca. 4 m deep hand dug well in a sandstone aquifer. The concentration of dissolved ions for the groundwater is found to be less than that of the lake water. This is mainly because of the silica dominated sandstone aquifer (Enticho Sandstone) has low potential to supply dissolved ions, and its high hydraulic conductivity which decreases the residence time of groundwater. The higher concentration of dissolved ions in the lake water compared to the groundwater at Tsinkanet could either be because of the small exposures of metavolcanic rocks upstream, higher evaporation rate of the lake water, domestic effluents from the Senkata town which is located at the upstream part of the catchment, or due to combination of the three. It is also possible that aquatic organisms have contributed to the concentration of dissolved ions in the lake.

Although climatic differences could play a role in the chemical composition of groundwater, because of the diluting effect of groundwater recharge, such effect is not observed in this case. Tsinkanet lake is at an elevation of about 2300 m a.s.l. with an average annual precipitation of 714 mm, while Rubafeleg is located at about 2700 m a.s.l. with an average annual precipitation of 672 mm.

The very low concentration of phosphate in groundwater compared to the lake water at Tsinkanet indicates that groundwater recharge is very local with less accumulation of ions from fertilizers and animal feedlots, while the lake receives these ions from all over the catchment through surface runoff. It is also possible that phosphate is supplied through domestic wastes from Senkata town, which joins the lake water.

Overall, surface and groundwater in the Tsinkanet area are more similar to each other than those of the Rubafeleg area. It is also worth noting that the concentration of most of the chemical parameters in the Tsinkanet area are higher for the lake water than for the groundwater (Figure 4), which usually is the reverse for most natural conditions. Moreover, one can conclude that all waters are rather recent, because they are dominated by HCO_3^- and Ca.

Besides the absence, for Tsinkanet, of a relation between reservoir and wells, we conclude that the reservoir is not losing much water to the subsurface, but some water is leaking through the dam and its basement, and flows to the main river channel.

References

- Dessie Nedaw, Walraevens, K, 2009. Positive effect of micro-dams for groundwater enhancement: a case study around Tsenkanet and Ruba-Feleg area, Tigray, Northern Ethiopia. *Momona Ethiopian Journal of Science*, 59 – 73.
- Gonzalez-Quijano, M., 2009. Groundwater modelling of the Tsinkanet catchment: a Modflow approach to evaluate the impact of small Reservoirs on groundwater recharge. Msc Thesis, 76 p.
- Tesfamichael G.Yohannes, 2009. Regional groundwater flow modeling of the Geba basin, Northern Ethiopia. Phd dissertation, V.U.Brussels, 256 p.

Adwa phonolite plugs and the temple of Yeha

Asfawossen Asrat

Department of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

The Adwa phonolite plugs and domes (Fig. 1) are considered to be Pliocene in age, and are found above the Trap sequence, northeast of Adwa, in an area of about 20 km by 30 km, generally following a northeast-southwest orientation, probably indicating their eruption along a weakness line oriented in the same direction. The plugs are phonolitic to trachytic in composition, forming inverted cone-shaped isolated peaks and circular domes, whose shapes were later modified by differential weathering (Asrat, 2009).



Fig. 1. Adwa volcanic plugs in 1974. At Gendebta, on the Adigrat-Adwa road, 84 km after Adigrat, looking South (photo: Wilson – thanks to R.N.Munro for provision of this photograph).

The significance of these plugs in terms of the ancient (Pre-Axumite) civilization of the region, marked by the Yeha Temple, has been discussed by Asrat (2009). The selection of the Yeha site has been generally attributed to the broad valleys filled with fertile soils. Phillipson (1998) particularly describes the setting of the site in the following terms: “Yeha lies in a well-watered valley with deep fertile soils, surrounded and sheltered by mountains”, and attributes the selection of this site to the exceptional fertility of the soils. However, terrain analysis indicates that the Yeha site lies in a very narrow valley which is surrounded by the phonolite plugs (Fig. 2). The particular valley where the Temple of Yeha, and probably the centre of the civilization, was located lies in a particularly narrow valley of not more than 1 km across. The terrain East of Yeha is mostly rugged as it is covered by the phonolite plugs, while the terrain west of Yeha is covered by highly foliated metamorphic rocks which form elongated ridges and valleys covered by thin soil. The Yeha site is not, therefore, uniquely a broad valley covered by exceptionally fertile soils. The most striking feature of the Yeha site is that it lies at the foot of a phonolite plug which is the western most plug in the rugged terrain. The rugged terrain of the phonolite plugs extends for more than 20 km to the east, northeast and southeast starting from the Yeha site. The Yeha Temple, therefore, seems to be in an exceptionally strategic location as the phonolite plugs may have served as natural garrisons or edifices along a north-south line (broken line in Fig. 2) against any possible attack. This calls for a conclusion that the selection of the site should be

attributed to the exceptional strategic location of the site being surrounded by mountain edifices than to the “exceptional” fertility or “broadness” of the valley.

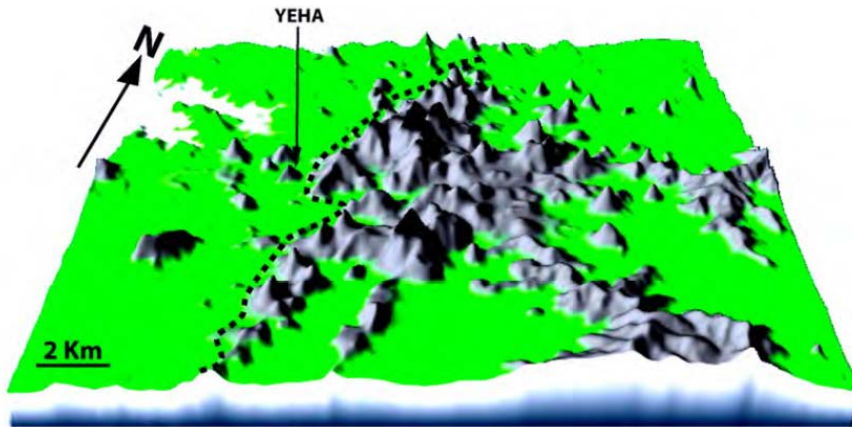


Fig. 2. A Digital Elevation Model (DEM) of the Yeha area constructed from SRTM images. The rugged terrain (grey hills, altitude greater than 2200 m a.s.l.) is the phonolite plugs while the plain field (less than 2200 m a.s.l.) is covered by basalt flows. The dark broken line is considered to be the north-south “barrier”.

References

- Asrat, A. (2009) The Temple of Yeha: Geo-Environmental Implications on its Site Selection and Preservation, In: Ege, S., Aspen, H., Birhanu Teferra and Shiferaw Bekele (Eds): *Proceedings of the 16th International Conference of Ethiopian Studies, Trondheim, Norway, 1-10.*
- Phillipson, D. W. (1998) *Ancient Ethiopia*. London: the British Museum Press, 176 p.

35. Geomorphology and geoarchaeology of the Axum archaeological area

Paolo Billi¹, Rossano Ciampalini², Tekie Fisseha³, Giovanni Ferrari⁴

¹ University of Ferrara, Italy

² UMR LISAH, INRA-IRD-SupAgro, Montpellier, France

³ University of Axum, Ethiopia

⁴ University of Florence, Italy

1. Geomorphology

Axum is one of most important archaeological and historical cities of Ethiopia. The archaeological area stretches on a plateau ranging from 2000 to 2500 m a.s.l. (Fig.1) and it is punctuated by several, dome-shaped hills, with steep slopes, rising 200-300 m above the main plain. On the northern and western side of the town, these hills are formed by nepheline syenite, shallow intrusions (Byeta Giyorgis, Gobo Dura, Gobo Cuho), differentiated acidic plugs, sills and dykes (trachyte, latite, e.g., Mai Qoho, St. Pantaleon hill). The plug hills were considered by Merla et al. (1979) Plio-Quaternary in age, but recent petrographic analysis (Zanettin et al., 2006) and field evidence (Ciampalini et al., 2011; Beccaluva, personal communication) indicate they are older than 20 mln. years. The intrusions, in fact, dislocate the Carboniferous to Permian Edaga Arbi glaciolacustrine (thinly planar bedded siltstone) and fluviolacustrine (crossbedded sandstone and fine grained conglomerate) deposits (Bussert, 2010) and/or quartz sandstones of Adigrat Formation (Permian-Jurassic). Shreds of these formations are found also on the top of the intrusions (Byeta Giyorgis, Gobo Dura).

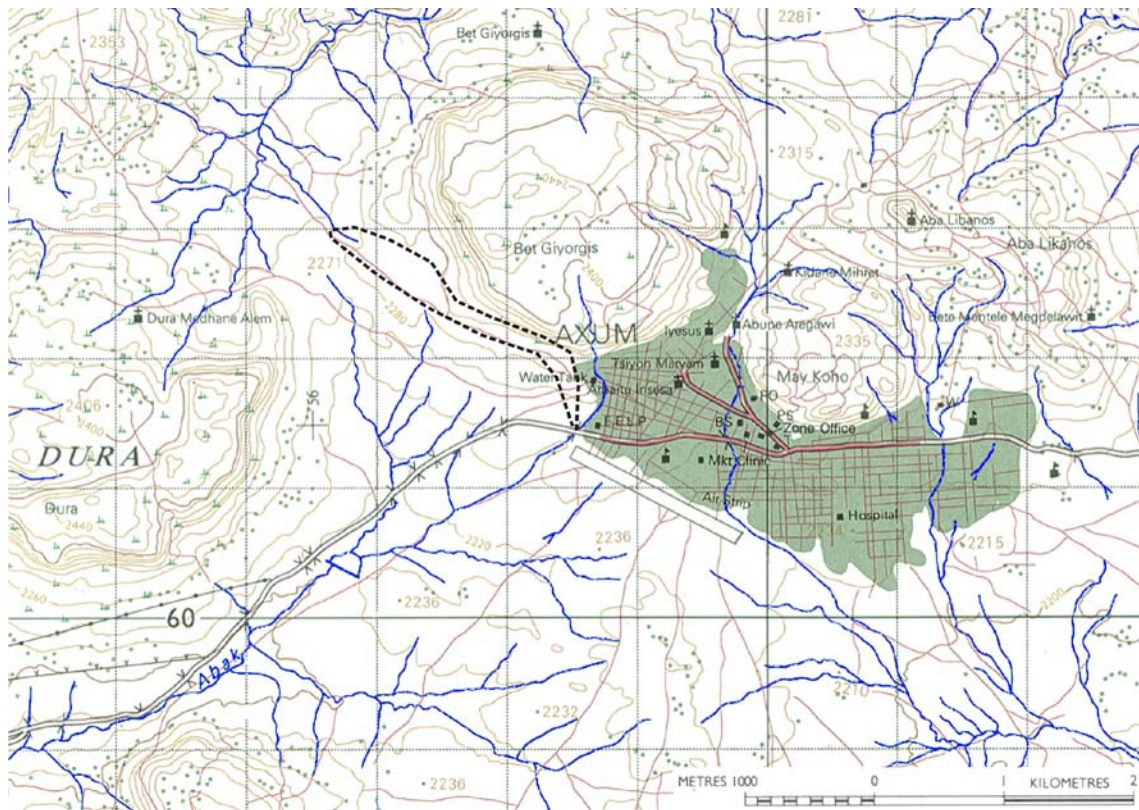


Fig. 1 Topographic map of Axum archaeological area. Dashed line = field visit trail.

The foothill of the intrusions are mantled by Oligo-Miocene basalts that fill all the lowlands and valley bottoms. A few, more recent small trachytic-ryholitic scoria volcanoes are present as well. North-West of Gobo Dura, small outcrops of the Neoproterozoic basement, consisting mainly of schists, are exposed. Quaternary, terraced alluvial deposits fill the valley bottom of the main rivers. Weathering processes have shaped the plug hills forming castle cliffs on the high slopes and kopie and a stepped morphology in the lower parts.

Scree deposits cover the foothill and boulders fields are a common feature all around the plug hills (Ciampalini et al., 2008). Large rind weathered boulders rest on the soil surface or protrude (core-stones) from a several meters thick, saprolite mantle, that includes also laterite duricrusts and witnesses processes of etchplain formation).

Annual rainfall ranges from 600 to 800 mm, but it is characterised by high inter-annual variability. Precipitations are concentrated in the main, monsoon type rains, from mid-June to mid-September and in the unpredictable small rainy season from mid-March to mid-May, originated by cyclonic cells development. Mean annual temperature is around 18°C with low seasonal variability, but large diurnal range.

On top of Byeta Giyorgis, truncated Alfisols (“*makaao*” in the local language) are present. The most weathered parts at the foot of the plug hills has strongly weathered, relict soils, probably Nitisols (“*keyah*”), with argillic horizon and shiny faces preserved under boulders cover. Soils with vertic features (“*bakahel*”) occupy the central part of the plug steps, while real Vertisols (“*walka*”) are typically found on basalts and siltstones. On the plain and on top of the plug hills, land use consists mainly of terraced arable lands, level bench terraces whose stone bunds height decreases with slope gradient. Large grazing areas without conservation practices are found on gently sloping areas with vertic soils, while large arable fields on deep vertisols are in the topographically lower parts of the study area. All crops are rain-fed and include teff, barley, wheat and millet. Some forest exclosures are present near residential areas and churches or in marginal rocky grounds. Stony bunds terraces for agricultural purposes are located mainly across small valley bottom and on stream valley sides. Sharp structural steps, such as those on northern side of Byeta Giyorgis, are used as natural agricultural terraces bounded by kopies or man made stone mounds.

In the terraced fields, ploughing is predominantly along the contour lines.

2. Palaeoagriculture and erosion dynamics

The oldest evidence for cultivation (basically plough marks), has been assumed on the base of the chronology of the terraces associated with archaeological records, thus date back to the Proto (2400 – 2040 BP) or Early Axumite (2040 – 1850 BP times - Fattovich, 1997). Agriculture on the footslopes around the syenite plugs of Axum has been performed through a very old technique of terracing, in order to reduce slope gradient, soil erosion, and to improve water infiltration and retention. This technique seems to be very effective provided the fragile balance between the terrace step and the escarpment is constantly maintained. The terrace system is managed as a whole, like in the Middle East: the upslope terraces are mainly used for grazing and water harvesting, the downslope are mostly exploited for cropping. The terrace sequence is consequently built as an univocal system at a time and the upper terraces is not to be considered as an expansion of the lower agricultural areas under human dynamics.

The traditional plough still used in the region is the *maresha*, an “ard plough” that seems to have been introduced in Ethiopia between 1000 and 400 BC by Semitic tribes (Yemen) or even before by Cushitic speaking peoples from north-eastern Sudan. The soil includes large boulders and the impact of the plough against shallow buried or protruding stones is not uncommon. The occurrence of plough marks is therefore an evidence in itself for cultivation. Plough marks on stone weathered surfaces, varnishes, patinas, etc., indicate old cultivations. Such pedo-geological features were used to reconstruct past ground surfaces on lands presently cultivated, degraded or strongly dissected (Fig. 2). Ancient plough marks may be found at different height above the ground, with the highest being the oldest, thus providing valuable information on the thickness of soil loss, provided some dating on the basis of archaeological evidence is available, such as is the case of Axum. A systematic study of these ancient plough marks suggests that the total soil loss starting from Axumite times ranges between 1.9 and 4.8 t ha⁻¹ y⁻¹ over a time interval of 1850 years (Ciampalini et al. 2008). These mean values are lower than the threshold erosion rate commonly accepted by international soil conservation agencies and highlight that the traditional land conservation practices were very effective on the long time span and confirm that increasing human pressure is not a cause for degradation, provided sustainable land use and management adopted. Moreover, the presence of illuvial clay cutans in the Bt horizon of terrace soils demonstrates the stability of the deposits, whereas the lack of skeleton in the soil is an evidence of farmers driven aggradation.

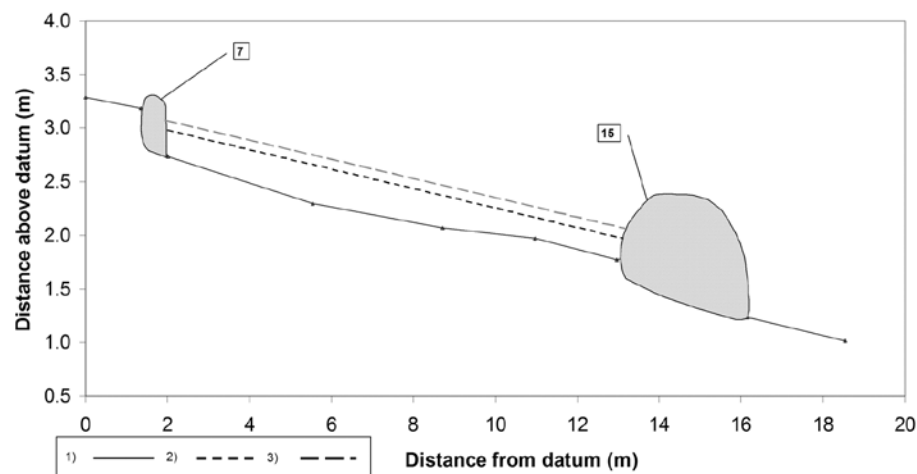


Fig. 2. Example of a transect. 1) present ground surface; 2) surface linking the upper plough mark belts; 3) ground surface before the cultivation started. The numbers in the squares refer to individual boulders with plough marks.

The slope of the modern terraces is lower than the original one, due to aggradation of soil material against the rock bund. The strike of plough marks on the boulders surface gives information also about the ploughing orientation that was found to correspond with the contour lines.

By contrast, recent changes in the land use from agriculture to grazing, brought about during the Derg administration (1974-1987), and a progressive decrease of stone bunds maintenance or the abandonment of the agricultural activities produced an incredibly high soil loss which strongly accelerated land degradation. By using the plough marks method, soil erosion, referred to the last 35 years, resulted to have a median value of 63.1 t ha y⁻¹ (first and third quartiles of 33.4 and 81.7 t ha y⁻¹, respectively) (Ciampalini et al. 2011) (Table 1). These results were checked by

means of two independent methods developed by other authors for the same region (Haregeweyn et al., 2005; Gebremichael et al., 2005). Haregeweyn et al. (2005) used the recalibrated PSIAC model for Ethiopian Highlands, whereas Gebremichael et al. (2005) provided an extended field survey and soil erosion survey in similar terraces in Tigray, including basic parameterisation such as the computation of USLEs P factor using many measured control sites. These methods were used to get an estimation of soil loss for both the maintained system with traditional agricultural practices and the abandoned condition whereby the terraces were turned from crop into graze land without maintenance and consequent erosion and destruction of the terraces structures. For the traditional practices, Gebremichael et al. (2005) methodology gives an average soil erosion rate of $3.04 \text{ t ha}^{-1} \text{ y}^{-1}$, whereas Haregeweyn et al. (2005) methodology returns a rate of $3.15 \text{ t ha}^{-1} \text{ y}^{-1}$, i.e. values very close to that ($2.5 \text{ t ha}^{-1} \text{ y}^{-1}$) obtained by the plough marks method. Using a parameterisation based on the present degraded situation, for almost bare and uncultivated soil, higher values of soil erosion rate, namely 30.9 and $7.2 \text{ t ha}^{-1} \text{ y}^{-1}$, were obtained by the modified USLE and PSIAC procedures, respectively. For a few small watersheds in Tigray, Haregeweyn et al (2005) measured specific sediment yields ranging from 4.9 to $18.2 \text{ t ha}^{-1} \text{ y}^{-1}$, whereas Gebremichael et al. (2005) found an average net soil loss rate of $18 \text{ t ha}^{-1} \text{ y}^{-1}$ for stone bunds terraces in Tigray highlands. The differences with our findings can be mainly accounted for by the higher slope gradient and shorter field length (eight time higher the topographic factor LS) of Gebremichael et al. study terraces and by the occurrence of gullies and extensive catchment portions without conservation practices in the study reservoirs of Haregeweyn et al. (2005). However, it is worth noticing that for our study terraces the soil erosion rates calculated by such well established procedures are very close to the values obtained by the plough marks method. This confirms the reliability and accuracy of the plough marks method, provided a good dating of the terraced surfaces is available (Fattovich, 1997; Sernicola, 2008).

Table 1. Erosion rates ($\text{t ha}^{-1} \text{ y}^{-1}$) calculated with different methods for different land management in the study area and in the Tigray highlands.

Method	Ancient (traditional terraces)	Recent (no terraces*)	Tigray highlands
Plough marks	2.46	63.14	
PSIAC	3.15	7.20	
USLE	3.04	30.91	
Haregeweyn et al. (2005)			11.55**
Gebremichael et al. (2005)			18.00***

* abandoned terraces; ** small reservoirs; *** stone bunds terraces

3. Lithic artifacts and prehistoric sites

In October 2007, a preliminary survey recorded potential prehistoric sites of Middle Stone Age (MSA) and Late Stone Age (LSA): Gobo-Dura, Gonda-Nebri, and Merchen (Tekie, 2008). These sites have variable-density and variable-sized surface lithic artifacts, predominantly on a very disturbed agricultural lands except the Gonda-Nebri site which is found on a river bank of

alluvial sediments. The Merchen site located North-East of Axum, has an extensive and fairly dense scatter of mode 3 very roughly grained quartzite and flint lithics extending over a large area at the base of Gobo-Kubo. Among those lithic artifacts found in this site are radially prepared cores (Fig. 3). The lithic artifacts collected consisted of a multifunctional long quartzite flakes, rarely denticulated, and their dorsal surfaces bearing linear and radial flake removal scars. The dorsal surface of the cores usually has linear scars, with rough retouch along one edge.

Four collected flakes bore opposed striking platforms. Two side scrapers were also noted, bearing slight retouch along a single edge and, occasionally, very heavy hinge fracturing.

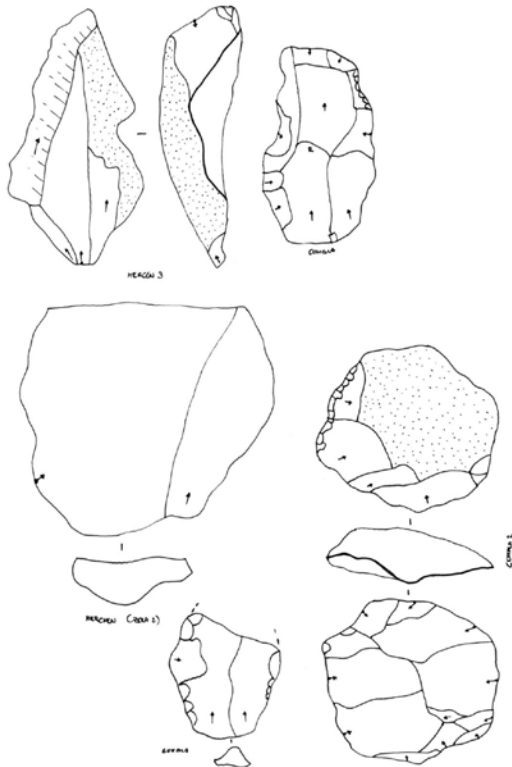


Fig. 3. Sketches of prehistoric artifacts found in the study area showing radially prepared core typical of the MSA type and a side scraper of LSA. (Drawing by M. Arzarello).

Middle Stone Age Sites

Three sites containing MSA material were noted during the 2007 survey. MSA material is readily recognized by use of prepared-core technology and a rather limited raw material repertoire. Variably-utilized blades are the most abundant tool types, mainly single striking platform, although a few bipolar forms were noted, most with radial flake removal scars on their dorsal surfaces. Retouched tool forms largely are limited to scrapers of variable size with evidence of a prepared core technology. Radial types dominate the cores. The raw material for the MSA are micro-crystalline quartz, with occasional chert, sandstone, quartzite, mudstone and rarely basalts.

Later Stone Age Sites

Very few diagnostic lithic artifacts of long blades have been found in the Merchen site. The industry is based on long, non-retouched and mainly light-medium utilized flakes, fabricated from sedimentary and metamorphic rocks such as quartzites. The majority of these blade forms are manufactured from single and opposed platform cores. Some end-scrapers which are fabricated from a range of micro-crystalline and macro-crystalline quartzes have also been noted. Generally, the most abundant tool type remains the basic flake, either with single or opposed striking platforms. Like MSA elements of these assemblages, the range of raw material selected is broad: micro-crystalline quartz, cherts, and occasional low grade metamorphic rocks. Core forms show a radial preparation patterns. Very few or no microliths are noticed.

Raw Materials

Based on the lithic materials, two kinds of cores for making blades in the Merchen site are supposed: cores with a flat surface producing thin and wide blades, with limited preparation of one or two opposing platform and cores for producing thicker blades from the narrow face of a blank. Judging by the lithic industry, it might be stated that the area of Axum, could have been occupied by prehistoric people who used these lithic artifacts in their day to day activities. It seems also that the presence of a few nonlocal materials, mainly obsidian, found in the area, would imply movements and exchanges of raw materials could have been persistent activities during the MSA and LSA time.

References

- Bussert, R., 2010, Exhumed erosional landforms of the Late Palaeozoic glaciation in northern Ethiopia: indicators of ice-flow direction, palaeolandscape and regional ice dynamics, *Gondwana Research*, 18, 356-369.
- Ciampalini, R., Billi, P., Ferrari, G., Borselli, L., 2008. Plough marks as a tool to assess soil erosion rates: A case study in Axum (Ethiopia), *Catena* 75, 18-27.
- Ciampalini, R., Billi, P., Ferrari, G., Borselli, L., Follain, S., 2011, Historical land management changes and soil erosion as determined by plough marks and field evidences in the Aksum area (Ethiopia), submitted to *Agriculture, Ecosystems and Environment*.
- Fattovich, R., 1997. Archaeology and Historical Dynamics: the Case of Bieta Giyorgis (Aksum), Ethiopia, *Annali dell'Istituto Universitario Orientale* 57, 46-79.
- Gebremichael, D., Nyssen, J., Poesen, J., Deckers, J., Haile, Mitiku Govers, G., Moeyersons, J., 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia, *Soil Use and Management* 21, 287-297.
- Haregeweyn, N., Poesen, J., Nyssen, J., Verstraeten, G., de Vente, J., Govers, G., Deckers, S., Moeyersons, J., 2005. Specific sediment yield in Tigray-Northern Ethiopia: Assessment and semi-quantitative modelling, *Geomorphology* 69, 315-331.
- Merla, G., Abbate E., Azzaroli A., Bruni, P., Canuti, P., Mazzuoli, M., Sagri, M., Sacconi, P., 1979. A geological map of Ethiopia and Somalia 1:2.000.000 and comment, University of Florence, Italy.
- Sernicola, L., 2008. L'urbanizzazione dell'altopiano del Tigray in epoca aksumita, Ph D Thesis, Università degli Studi di Napoli L'Orientale, Napoli.
- Tekie Fisseha, 2008, Geomorphological and Geo-archaeological map of Axum site (Northern Part of Ethiopia), MSc Thesis, University of Ferrara, 76pp.
- Zanettin, B., Bellieni, G., Justin Visentin, E., 2006, Stratigraphy and evolution of the trachy-rhyolitic volcanism of the Senafe area (Eastern Eritrean Plateau), *Jour. African Earth Sci*, 45, 478-488.