CHAPTER 2

Reconstructing environmental changes since the Last Glacial Maximum (LGM) in the Geba Basin, Northern Ethiopia, by geomorphic process interpretation and land management evaluation

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ABSTRACT: The palaeoenvironmental evolution of the Geba Basin in Northern Ethiopia since the Last Glacial Maximum (LGM) certainly is a good indicator for the climatic conditions, but there is evidence that climate has been affected by the interference of humans with the hydrological cycle, especially since the second half of the Holocene. Before ~15 cal ky BP, Ethiopia knew a dry climate in the lower parts and cold and also dry conditions in the Simen and Bale Mountains, in phase with the LGM. But while elsewhere in Ethiopia the cold/dry conditions continued till ~10–11 cal ky BP, the Geba Basin enjoyed moist conditions from ~15 cal ky BP onwards and no clear explanation can be given for this. These conditions continued in Tsigaba till ~3 cal ky BP and in many valley bottoms, till 50 years ago or even nowadays. This article presents evidence suggesting that the 'arid environmental conditions' which started in some places as early as ~5 cal ky BP, in other places only very recently, are more a human-induced than an astronomically steered phenomenon. Our research indicates that man has the necessary tools to bend off the present tendency towards aridification.

2.1 INTRODUCTION

The timing of late glacial events in the tropical mountains of Africa corresponds to the one in higher latitudes (Shanahan *et al.*, 2006). The Last Glacial Maximum (LGM) is linked to relatively cold and dry climatic conditions in West Africa (Petit-Maire, 1989) and in the Main Ethiopian Rift (MER) (Butzer *et al.*, 1972). However, there remain doubts whether climatic evolution in the high plateaus of the African Horn, is in phase with the evolution in the lower lying MER bottom (Moeyersons *et al.*, 2006; Marshall *et al.*, 2009) and further with the one in South and West Africa and the Congo basin.

Doubts are also raised about the climatic indicator value of MER lake levels alone because changes in water supply are also influenced by the tectonically induced rearrangement of the fluvial drainage network in the MER (Sagri *et al.*, 2007). Furthermore, a glance at the recent literature reveals that Mid- to Late-Holocene climatic variations appear to be less well coupled with changes across Africa and elsewhere (Shanahan, 2006). It has been suggested (Nyssen *et al.*, 2004), that humans became a factor increasingly important in environmental management, obliterating the precessional forcing of climate since middle to Late Holocene times.

Palaeoclimatic understanding in Ethiopia is of uttermost importance because this country occupies a geographical key position between the northern and central African 'lowlands', climatically phased with the LGM-Holocene transition, and the so–called Southern African Superswell (Summerfield, 1996).

This article presents evidence of Late Pleistocene and Holocene palaeoclimatic conditions and timing in the Geba Basin in Tigray, Northern Ethiopia (Figure 1). This basin is located in altitude below 3.000 m asl, meaning that no indications of palaeoglaciations are expected to be present. On the other hand, it is located on the shoulder of the Danakil Depression (DD), and it has been questioned recently to what degree palaeoclimatic indications from the lakes in the MER-bottom are representative for this area (Moeyersons *et al.*, 2006).

This paper addresses two major problems: 1) the definition of the LGM environment in Tigray and the timing of the transition between the Pleistocene and the Holocene; 2) the reason and nature of the Late Holocene 'aridification' which has affected the highlands from between ~5 to ~4 ky BP onwards and which culminates in the 'desertification' of today. Data and arguments were collected in the frame work of geomorphological, agricultural and hydrogeological research over the last decade.

2.2 MATERIALS AND METHODS

2.2.1 The study area

The Geba Basin is a banana shaped 5.200 km^2 region in Tigray, Northern Ethiopia. From upstream to downstream, the basin dips southwards in the northern part and turns westward in the south-western part (Figure 1). The Geba River is a tributary of the Tekeze which joins the Nile in Atbara, Sudan. The outlet of the basin is at ca 900 m asl, and the highest point, in the North, reaches ca 3.000 m asl.

The geology of the basin comprises in the central part, between lines A and B (Figure 1), the Mesozoic succession of the Mekelle Outlier (Bosellini *et al.*, 1995), composed of the Antalo Supersequence. This slightly eastward dipping succession of mostly limestones and shales is about 600 m thick in the area. A number of Mekelle dolerite sills appear in this succession (Arkin *et al.*, 1971; Merla *et al.*, 1979).

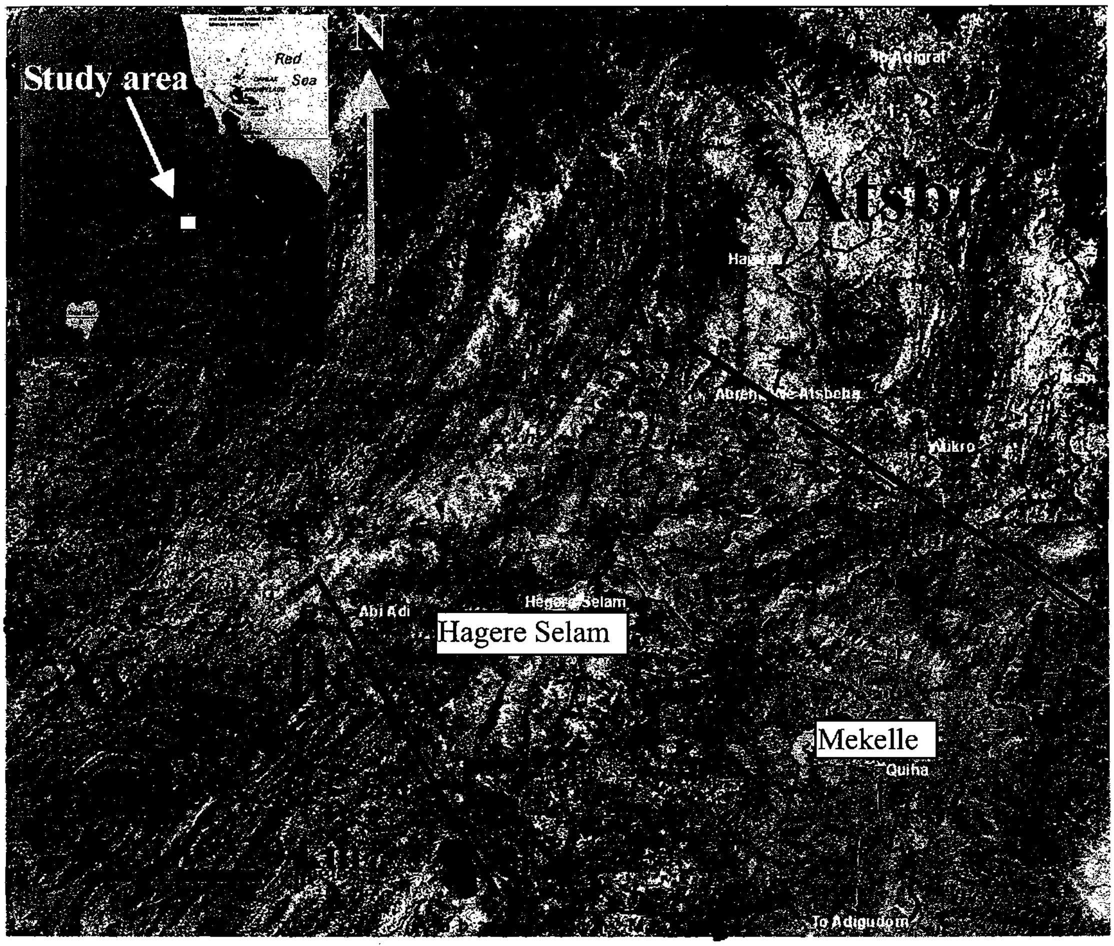

Figure 1. The Geba River Basin, indicated by a thin black line on a false colour ETM image (bands 123). The region of Hagere Selam has been studied for landsliding, tufa dam building and the effectiveness of soil and water conservation. Lines A and B delimit the middle basin, with mainly Mesozoic rocks, from the Atsbi highlands and the Avergelle lowlands, both underlain by Proterozoic rocks.

The Antalo Supersequence rests on Adigrat sandstone and is unconformably overlain by the Amba Aradam sandstone, considered as Cretaceous in age. In the Avergelle lowlands to the South-West of line B and on the Atsbi Highlands to the North of line A (Figure 1), Palaeozoic sedimentary rocks, described by Beyth (1972), Tesfaye and Gebretsadik (1982) and Garland (1980) crop out. Tertiary basalts occur in the extreme North of the basin and on a few massifs along the water divide between the Geba Basin and the Werei Basin, to the North and North-East of Hagere Selam. In the frame work of our studies, the geological map of the Geba Basin has been worked out in detail (Tesfamichael *et al.*, 2009).

The topography of the central part of the catchment is mainly structurally controlled by the subhorizontal geological stratigraphy. This gives rise to the characteristic high cliffs, escarpments and structural subhorizontal surfaces. The Avergelle lowlands and the Atsbi highlands, where Palaeozoic rocks appear, show both a topography characterized by SSW-NNE oriented ridges, reflecting the folded structure of the basement. The granite intrusion of Negash, in the North of the basin, forms a dome-like relief.

Climatic data are summarized by Tesfamichael (2009). Because of the altitude, mean maximum air temperatures are moderate, reaching ca 20°C to 23°C in the northern and central part of the basin, while in the 'lowlands' of Avergelle the mean max air temperature goes up to 32°C. The mean annual rainfall varies from ca 400 mm y^{-1}

in the North to well above 900 mm y^{-1} in the South of the basin. 77% of the annual rainfall is confined to the 'kiremt' rainy season, which extends from June to September. The eight other months of the year give only occasionally light 'belg' rains in some parts of the basin during the months March to May. Nyssen *et al.* (2005) have shown that the short duration high intensity rain storms in Hagere Selam are among the world's most energetic ones because of the big rain drop size. According to the International Convention to Combat Desertification (UNEP, 1994), the region should be considered as being affected by desertification because the proportion of the annual precipitation over the potential evapotranspiration is below 0,65.

The natural vegetation in the Geba Basin is highly degraded by human activities. On the eastern water divide with the DD, the Des'a forest is present. It is a degraded remnant of the Afromontane forest with Juniperus and Olea (Friis, 1992). If the landscape is nowadays largely deforested, small patches of forest around churches as well as in places, which are difficult to access, are secondarized remnants of a former climax vegetation (Descheemaeker *et al.*, 2006).

2.2.2 A review of the current Late Quaternary palaeoclimatic knowledge in Ethiopia

Late Pleistocene conditions and the transition to Early Holocene times

Pre-Holocene conditions have been studied in several regions in Ethiopia (Figure 2). Hurni (1989) and Messerli and Rognon (1980) discussed palaeoclimatic conditions of the Ethiopian highlands of Bale and Simen during the Quaternary. They described glacier cirques, moraines and periglacial solifluction deposits. This combination of landforms indicates that part of the high mountains above 3.000 m asl was glaciated during the LGM. Cores from the Bale Mountains, dated by ^{14}C from inside and outside the glaciated area suggest that the northern valley glaciers may date from the LGM. Estimated equilibrium line altitudes for these glaciers and the ice-cap are 3.750–4.230 m asl (Osmaston *et al.*, 2005). The beginning of deglaciation has been estimated at 14 to 13 ^{14}C cal ky BP (Umer and Bonnefille, 1998) and ice melting ended progressively between 12,6 and 11,8 ^{14}C cal ky BP (Tiercelin *et al.*, 2008). The pre-Holocene vegetation in the Bale Mountains was sparse and consisted mainly of grasses, Amaranthaceae, Chenopodiaceae and *Artemisia*, indicating an arid climate. The first start

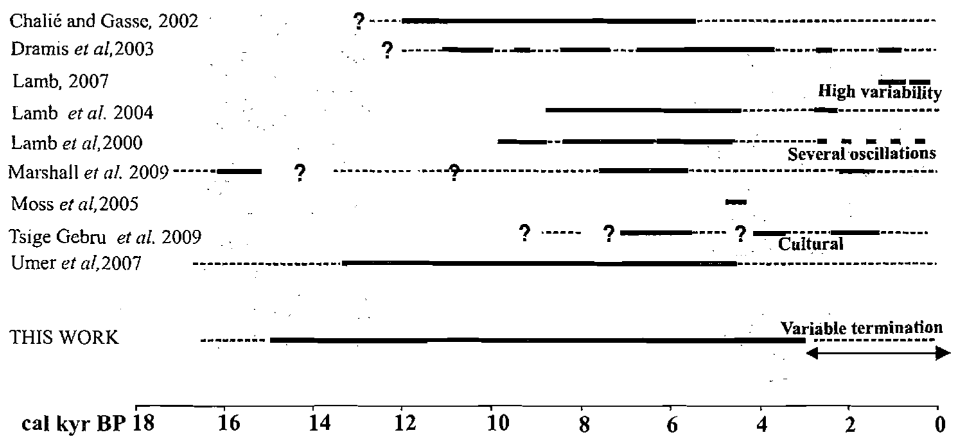

Figure 2. Recent palaeoclimatic interpretations for Ethiopia. Thick lines: relatively moist; thin dashed lines: relatively arid; Question marks: uncertainty about extent in time; grey belt to the left: generally accepted LGM-arid conditions; grey belt to the right: often considered as late-Holocene climatic aridification. The results of Moeyersons *et al.* (2006), discussed further in this work are added as a comparison.

for moister conditions at 13,4 cal ky BP was interrupted by the Younger Dryas interval and moist conditions prevailed since 11,2 cal ky BP (Umer *et al.*, 2007).

Recent work at Lake Ashenge, located on the verge of the DD-shoulder at about 80 km to the South of the Geba Basin shows a high lake level, linked to a more humid climatic pulsation between 16,2 to 15,2 cal ky BP (Marshall *et al.*, 2009). This pulsation interrupted a dry period which ended at 11,8 cal ky BP. This humid pulsation could not be registered in the sediments of Lake Tana. This lake had a low water level without overflow to the Blue Nile before 14,7 cal ky (Lamb *et al.*, 2007).

Since Street, (1980), lake levels in the MER and elsewhere have been considered as a proxy for climatic conditions, low stands being related to dry environmental conditions. According to Butzer *et al.* (1972), lake levels in the MER were often low before early Holocene high stands. Wherever information is available for the period preceding 12 ky BP, it has been consistently shown that lakes were much smaller. This has been confirmed a few years ago for Lake Abiyata (Chalié and Gasse, 2002).

The Holocene

The Holocene record subsequent to the maximum of 10 to 8 ky BP is more complex. During this maximum, it seems that lakes in many parts of tropical Africa were greatly enlarged. Where evidence for the previous span of time is well resolved, it appears that lake level rises leading to this high stand began about 12 ky BP (Butzer *et al.*, 1972).

For a long time it was believed that Early Holocene conditions were relatively moist and that this humid period results from orbital forcing. But an overview of work done since 2000 (Figure 2) suggests that changes from Late Pleistocene dry conditions to a humid Early Holocene climate are not in phase everywhere. Most authors find also that the wet conditions during Early Holocene times were interrupted by dry spells (Lamb *et al.*, 2000; Dramis *et al.*, 2003; Tsige Gebru *et al.*, 2009; Marshall *et al.*, 2009).

The phased climatic evolution is completely lost at the end of the Early Holocene humid interval when relatively drier conditions arrive. This transition took place at lake Tilo at ~4,5 ky BP (Lamb *et al.*, 2004), but it clearly appears (Figure 2) that this climatic change was spread over some 2000 years in the different localities, and hence was far from being simultaneous over the whole country. Furthermore, the subsequent environmental evolution differs much from place to place and is generally characterized by short but severe oscillations in the same place (Lamb *et al.*, 2000, 2007) or by dry environments created by human activities (Tsige Gebru *et al.*, 2009). The Holocene environmental evolution has been related not only to climate change but also to land use changes introduced since 7 cal ky BP (Philipson, 1998). The role of prehistoric man in the environmental history of Tigray has been summarized by Bard *et.al.* (2000) as follows: (1) the plateau experienced a more humid climate with a denser vegetation cover during the Early Holocene; (2) soil erosion due to vegetation clearing began in the Middle Holocene; (3) agricultural activity was intensified in the Late Holocene, as a consequence of the rise of a state; (4) demographic pressure increased from the early first millennium BC to the mid-first millennium AD, causing soil erosion; (5) environmental degradation and demographic decline occurred in the late first millennium AD; (6) the vegetation cover was regenerated in the early second millennium AD; and (7) progressive vegetation clearance started again in the second half of the second millennium AD. In the context of archaeological investigations, it is noteworthy to mention the presence of important concentrations of lithic assemblages of Middle Stone Age artifacts (Aerts *et al.*, 2010) in Northern Ethiopia.

Also pollen and charcoal analysis confirms that the vegetation in the highlands of Northern Ethiopia has changed in response to human impact during the last 3 ky (Darbyshire *et al.*, 2003). Although the role of man on the environment is generally recognized, archaeological research has worked long time with the idea of climatic determinism to explain the rise and fall of prehistoric societies, as done by Butzer (1981) in the case of Aksum. Recent research, however, admits that growing population and agricultural intensification have played an important role in forest cutting and landscape stability management (French *et al.*, 2009). In all Tigray, the period of forest disappearance and of the end of tufa dam build-up varies from one locality to another. Ancient soils, related to the presence of the primary forest (Brancaccio *et al.*, 1997), were covered by colluvium after 5,16 ± 0,08 cal ky (May Makden, Tigray) to 0,3 ± 0,06 cal ky BP (Adi Kolen, Tigray). Finally, the end of tufa build-up in May Makden is estimated to have occurred after 4,23–3,76 cal ky BC (Ogbaghebriel Berakhi *et al.*, 1998).

Also outside Ethiopia, Mid- to Late-Holocene variations in West-Africa and South-Africa appear to be less coupled with changes across Africa and elsewhere (Shanahan *et al.*, 2006; Scott and Nyakale, 2002).

2.2.3 Strategies to gain palaeoclimatic information

Over the last decade multidisciplinary research programmes have addressed the following research topics:

- Geomorphologic mapping and study of landslides and their distribution in the Hagere Selam region (Moeyersons *et al.*, 2008a; Nyssen *et al.*, 2002a; Van Den Eeckhaut *et al.*, 2008)
- Geomorphologic mapping, study and ^{14}C and U/Th dating on tufa dams (Moeyersons *et al.*, 2006)
- A throughout revision, completion and compilation in GIS of the geological map of the Geba Basin (Tesfamichael *et al.*, 2009)
- Regional groundwater flow modelling (Tesfamichael, 2009)
- Studies on the specific sediment yield and sediment bound nutrient export in 8 reservoir catchments (Nigussie Haregeweyn *et al.*, 2008)
- Studies on the efficiency of several soil and water conservation techniques (Nyssen *et al.*, 2008; Nyssen *et al.*, 2004; Vancampenhout *et al.*, 2006; Desta Gebremichael *et al.*, 2005)
- Assessment of spatial and temporal variability of river discharge, sediment yield and sediment-fixed nutrient export in Geba River catchment (Zenebe Abraha, 2009)
- Studies of the causal factors of gullying (Nyssen *et al.*, 2002b; Nyssen *et al.*, 2006; Veyret-Picot *et al.*, 2004)
- Studies on the restoration of dry Afromontane forest by using several techniques (Aerts *et al.*, 2008)
- Studies on the regrowth of woody vegetation in exclosures and the buffering capacities of exclosures to concentrated runoff (Descheemaeker *et al.*, 2006; 2009).

Although these studies did not directly intend to study the palaeoclimatic history of the highlands, most of them provide a lot of information about the points of discussion addressed below.

2.3 RESULTS

2.3.1 Late Quaternary environments and timing in the Geba Basin

In the Geba Basin, eight freshwater tufa dams, considered to be of Holocene age have been studied in detail (Moeyersons *et al.*, 2006). These phytoherms developed in formerly existing river beds, estimated to be of Late Pleistocene age. The river beds supporting the tufa dams contain thick deposits of river pebbles, rounded stones and even boulders up to some decimetres in size. These beds indicate a river regime, characterized by high energy floods, much alike the flash flood dynamics of braided rivers in arid or degraded savannah conditions.

The freshwater tufa deposits are the sedimentary response to karstic system activity (Magnin *et al.*, 1991; Peña *et al.*, 2000). Their presence is related to relatively wet environmental conditions, with significant plant cover and with nearly perennial river flow and percolation (Goudie *et al.*, 1993). U/Th ages on tufa and on speleothems in tufa dams suggest that this drastic change in river regime from highly seasonal to nearly perennial base flow took place before 15 U/Th ky BP. This is 4 to 5 ky before the first signs of post-LGM humid conditions deduced from former lake extensions in the Ethiopian and Kenyan rift (Moeyersons *et al.*, 2006). The occurrence of long lasting moist conditions long before 10 to 11 ky BP has also been found at Lake Ashenge (Marshall *et al.*, 2009). It can not be excluded that during the LGM forest refugia (Prentice and Jolly, 2000) were present on the heights below the glaciation equilibrium line. Important is also that tufa build up is related to underwater growth of algae and mosses. This means that photosynthesis is needed in the building process, which implies a low turbidity content of the river flow (Ford and Pedley, 1996). This is supplementary strong evidence for a river regime with much less pronounced peaks than today and thus with a consistent base flow.

2.3.2 Late Holocene environmental evolution in the Geba Basin

In the Geba Basin, the gradual disappearance of forest since a short time before the end of tufa dam build-up is evidenced by the following combination of arguments: (1) the change in dominance by dicotyledon to monocotyledon phytoliths at the period of tufa growth ending; (2) the accelerated sediment redistribution since that time and several gravel layers of the infillings of the barrier lakes behind the tufa dams, confirming a low vegetation density and soil truncation by runoff; (3) bush fires of grasses in Tukhul, stratigraphically equivalent to or younger than the top of the tufa dam. These arguments suggest that the area became gradually deforested by firing. In Moeyersons *et al.* (2006) the hypothesis is put forward that deforestation and bush fires were the main reasons for important sediment production, leading to increasing river turbidity inhibiting photosynthesis by algae and thus also precipitation of tufa, as shown by Ford and Pedley (1996) in NW Europe.

Another important source of sediments in the rivers probably were—and still are—the many landslides which have occurred at Hagere Selam and towards the North-East (Nyssen *et al.*, 2002a; Moeyersons *et al.*, 2008a). It is known that landslides, especially debris flows (Dikau *et al.*, 1996) can result in very high turbidities. Furthermore, research, complementary to Nigussie Haregeweyn *et al.* (2008) has shown a clear statistical relationship between the presence of landslide lobes and specific sediment yield (SSY) in reservoir catchments in the Geba Basin. The landslides in the Hagere Selam region have never been well dated, but they were tentatively placed within the moist period of tufa dam building, because their triggering needs high hydrostatic pressures, which can be expected during a period of high water tables. But recent studies in natural hazards in Uvira (DR Congo) confirm that landslides rather occur in conditions of lower water tables, showing sudden and short living surges of rise (Moeyersons *et al.*, 2009). Because they create high sediment loads and because their occurrence depends mostly on important oscillations in the water tables, landslides are hydrologically incompatible with tufa dam growth. This is the reason why the landslide activity in the Hagere Selam region is historically placed from the start of tufa dam breakdown up to now. Risk assessment studies (Van Den Eeckhaut *et al.*, 2008) show the imminent risk of landsliding today, which suggests that water table surges at present might be still of the same magnitude as at the time of the start of tufa dam destruction.

At Tsigaba tufa dam, the degradation phase is situated at 3,09 cal ky BP. Both the presence of layered slope deposits and of a burnt soil tend to indicate that deforestation in that area locally started before 1,43–1,26 cal ky BC (Moeyersons *et al.*, 2006).

2.3.3 Nature of the current aridity in the Geba Basin

Forests and present-day climate in the Geba Basin and in Ethiopia

The Geba Basin does only count a restricted number of forest relicts, and this is sometimes ascribed to the arid conditions. The yearly energy received by earth has slightly diminished since the start of the Holocene as a result of astronomical forcing (Crucifix *et al.*, 2002). But ample evidence exists that forests can still survive and even develop in the environmental conditions of today. Cases of natural reforestation after emigration in northern Ethiopia (Darbyshire *et al.*, 2003) show that the evolution of the forest cover was not always towards increasing degradation. Moreover, the strongest arguments for a non-climatically driven deforestation in the Ethiopian Highlands since 5 cal ky BP are that the actual climate still easily supports forest, that forest recovery can be quick in exclosure areas where free grazing for cattle is forbidden (Moeyersons *et al.*, 2006), that reforestation operations are envisaged by foresters (Aerts *et al.*, 2008; Descheemaeker *et al.*, 2009) and can be successful (Eshetu Zewdu and Hogberg, 2000). Moreover, it is just a biased idea that arborescent vegetation should be on retreat. A recent study (Nyssen *et al.*, 2009) shows that overall there has been a remarkable recovery of tree and shrub vegetation and also improved soil protection over the last 140 years.

The reversible nature of current aridity in the Geba Basin

As shown in Figure 2, the aridification in the last half of the Holocene started between ~5 cal ky BP and recently, depending on local situations of deforestation and other land use. This change went hand in hand with a change in river regime which throws some light on the changes in hydrological landscape response. It is known that in many parts of Africa, including most parts of Ethiopia, relicts of the ancient valley network exist (Figure 3), characterized by small channelless valleys, commonly called 'dambos' (Acres *et al.*, 1985), 'tropical valley bottoms' or 'inland valley swamps' (Raunet, 1985). These valleys, mostly with grass or gallery forest vegetation were—and their relicts today still are—characterized by seasonal or even perennial water logging due to the rise of the water table to the surface of the valley bottom. The dense grassy or woody vegetation slows down valley surface water flow. Stratigraphically the channelless

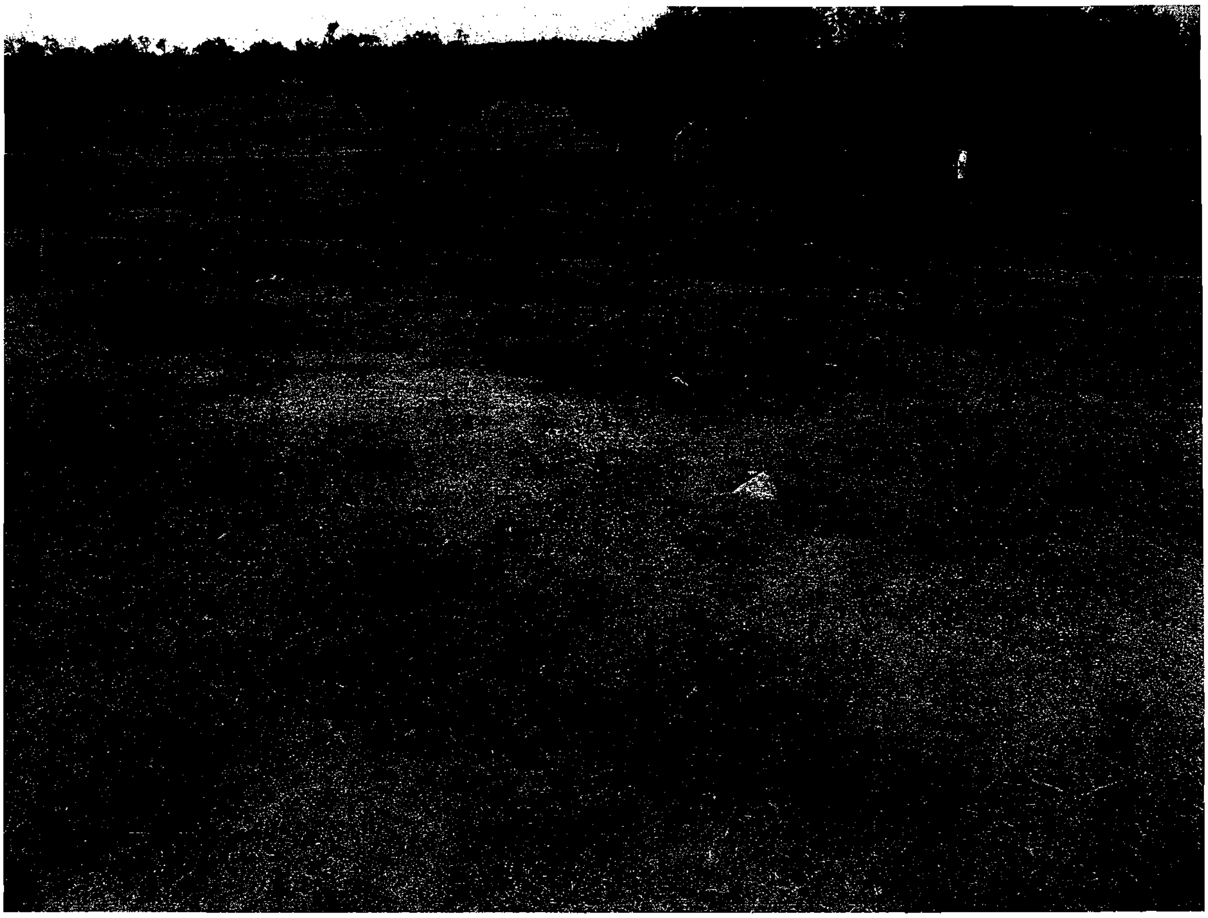

Figure 3. Dambo at the fringe of Des'a forest. An initial stone fragment mulch and the polygonal structures, Gilgai undulations micro-relief, suggest the presence of a thick vertisol in this channelless valley. (Photo: Jean Poesen).

valley bottoms are marked by wedges of alluvial/colluvial valley fills, mostly clayey, sometimes in the form of vertic horizons, sometimes also peat layers, occupying the valley bottom in superposed position. Carnicelli *et al.* (2009) give splendid descriptions of the successions of flat valley bottom deposits along Lake Ziway and dated the present palaeosoils between ~8,3 and 4,7 cal ky BP. According to descriptions by Acres *et al.* (1985) and Raunet (1985), and based on our own experience in Rwanda, the hydrograph of a dambo shows a relatively constant perennial base discharge with retarded and restricted flood response to rains, either individual storms or a rainy season (Figure 4). This delay is due to the fact that channelless valleys are mainly spring fed. We consider this type of river as hydrologically compatible with the humid conditions in the Geba Basin until the Late Holocene. Today, rivers in the Geba Basin show very important flash floods and only restricted base flow (Zenebe Abraha, 2009). This change in river regime reflects a change in the general hydrological behaviour of the landscape with river discharge fed by direct runoff from the hillslopes to a much higher proportion than before. The flat morphology of valley bottoms is no longer in equilibrium with the unprecedented current peak flow discharges, especially when the valley bottoms are devoid of the ancient flow retarding vegetation. Habitants reported how some 60 years ago, a small swampy channelless stream at Dingilet, close to Hagere Selam (Figure 1) cut a 6 m deep channel after runoff coefficients increased as a result of deforestation and agriculture intensification on the surrounding slopes and desiccation induced by Eucalyptus plantation in the valley (Veyret-Picot *et al.*, 2004;

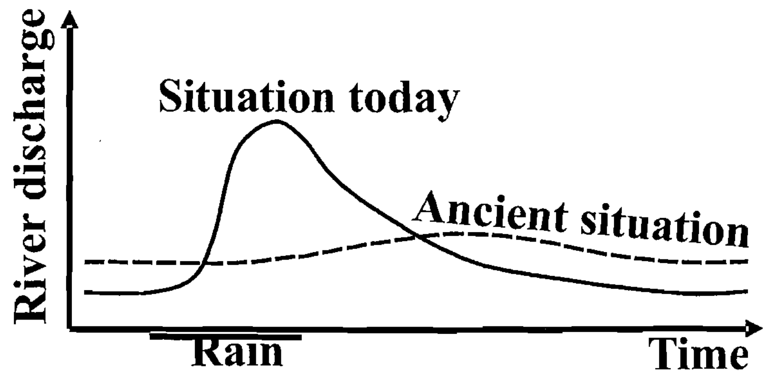

Figure 4. Change in river regime in the Geba Basin in Ethiopia and elsewhere in Africa.

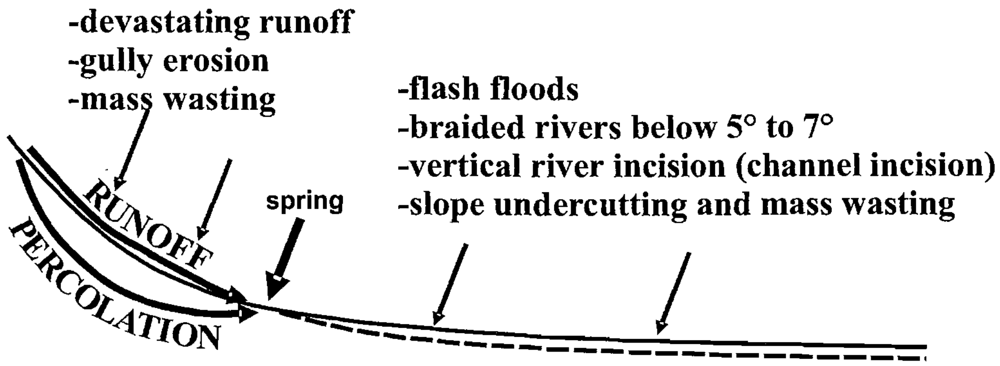

Figure 5. Increase in hydrological risks as a result of runoff increase at the partial expense of the infiltration-exfiltration water circulation.

Nyssen *et al.*, 2006). It seems, therefore, that the aridification since Mid-Holocene times can be characterized by an increasing hillslope runoff production.

Moeyersons and Trefois (2008b) assess the natural risks involved with increasing runoff in Central Africa (Figure 5) and this assessment seems to be valid for the Geba Basin as well. Land use change has certainly played an important role in the increase of hillslope runoff production as a result of an increasing runoff coefficient.

Descheemaeker *et al.* (2006, 2009) show that church forests and exclosure forests are able to trap important sediment and water volumes from upslope and so implicitly demonstrate that deforestation in the Geba Basin should have strongly contributed to the increase of the runoff coefficient. It is known that the construction of roads and houses and urbanisation in general contribute to a very considerable increase in runoff coefficient and, above all, can concentrate runoff to higher than natural discharges. The latter is an important factor in valley side and valley bottom gullying in the Geba Basin along newly constructed roads (Nyssen *et al.*, 2002b) or in flooding in urbanized areas. Nyssen *et al.* (2008) show that all measures delaying runoff, taken region-wide in Tigray counteract the present desertification, even if some of the runoff increase was due to astronomically forced climatic effects of extreme rainfalls.

2.4 CONSIDERATIONS ABOUT DEFORESTATION-CLIMATE COUPLING

Forest plays an important role in the inland alimentation of the hydrological cycle with vapour and vegetation-climate coupling is generally applied in atmospheric general circulation models (Crucifix *et al.*, 2002). Whitmore (1998) and Zhang *et al.* (2001) confirm that in ideal conditions evapotranspiration of forest can be about 1.5 times the evapotranspiration of grassland or grassy crops. But empirical evidence suggests that evapotranspiration by lowland tropical forest in Africa should be higher and reach about the same amount of evapotranspiration per unit of surface as the Atlantic Ocean by evaporation. This stems from the empirical observation that the Aw and Bsh climatic belts of Köppen-Geiger (Peel *et al.,* 2007) cross the African continent straight from West to East, while the Atlantic coast turns to the South at Mount Cameroon. To the West of Cameroon the climatic belts are parallel to the Atlantic coast. This is generally ascribed to the flux of humid air masses to the West African continent, due to the SW trade winds during the Boreal summer. These winds also steer the West African hydrological cycle further inland. But the Aw and Bsh climatic belts East of Cameroon receive trade winds, which have only a restricted trajectory over the Atlantic Ocean. According to Leroux (1983), the trajectory of the July trade winds to the western part of Ethiopia is even mainly continental (Figure 6). It is known that water vapour flux transport from the oceans to the continental land masses only accounts for 1/3 of the precipitation actually recorded (Oki, 1999). But in Eastern Sudan and Western Ethiopia the rainfall coming from the West (Rudloff, 1981) should be mainly 'continental' around the end of June, when the ITCZ is situated at its most northerly position (16–20°N). The uptake of vapour above the forest in the Congo basin and above the Atlantic Ocean and the coastal forest in West-Africa should be of the same order of magnitude because of the general parallelism between the northern tropical forest fringe, as given by Ady and Hazlewood (1965) and the AW and Bsh climatic belts (Figure 5). Less vapour production above the Congolese forest would result in climatic belts, narrowing and/or coming closer to the northern forest limit north of DR Congo.

The climatic impact of massive tropical deforestation is regularly addressed (Whitmore, 1998). In Amazonia Gash *et al.* (1996) observed reduced rainfall and higher rainfall irregularities downwind of deforested zones. In West-Africa, it has been suggested by Roose (1994) that the exploitation of mangroves and savannah along the coast will hamper rainfall in the Sahel. Claussen *et al.* (1999) explain the abrupt desertification in

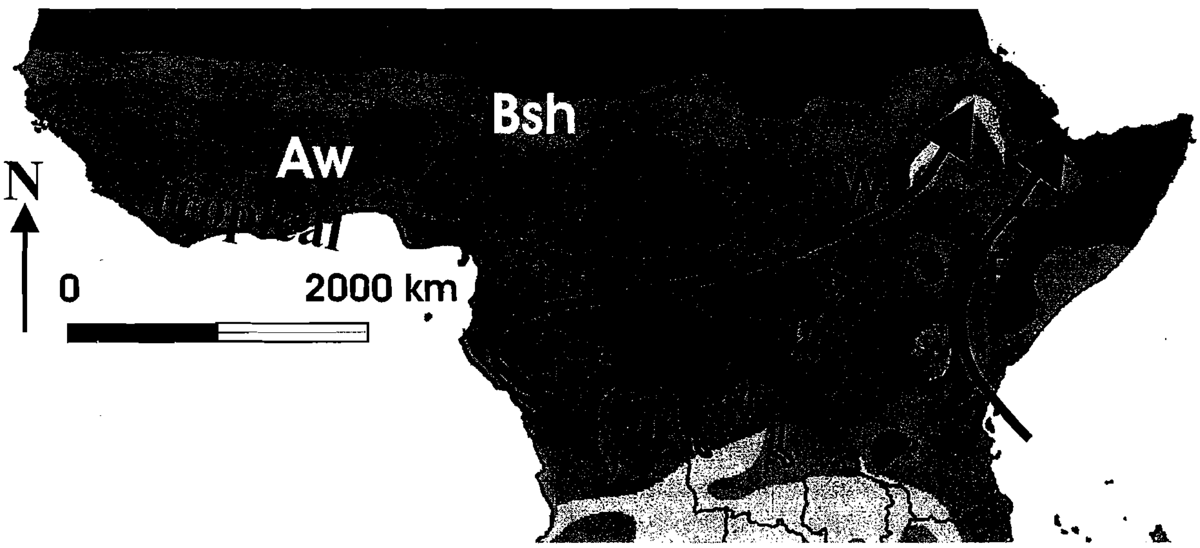

Figure 6. Extension of the tropical rain forest and climatic Köppen belts Aw and Bsh to the North. The W arrow indicates the mean trajectory of the western trade winds in the month of July. The E arrow gives the approximate path of the trade winds from the Indian Ocean.

North-Africa during the Mid-Holocene in terms of vegetation-atmosphere feedbacks in the climate system. Zeng *et al.* (1999) confirm that variations in vegetation enhance climate variability in the Sahel and Taylor *et al.* (2002) show that changes in vegetation in the Sahel can cause substantial reductions in rainfall. In the case of Ethiopia, there is no doubt that deforestation either along the path of the western or eastern trade winds will have contributed to less rainfall in the study area. Human-induced land changes since 7 cal ky BP (Philipson, 1998) started about thousand years before the first local manifestations of the more dry to arid conditions (Figure 2).

2.5 CONCLUSIONS

This study reveals the following information about the environmental evolution in the Geba Basin in Northern Ethiopia since the LGM:

1. Before 15 U/Th ky BP most tributaries of the Geba were of the braided or winding river type. These rivers are indicators for an irregular river regime with flash flooding, probably as a result of an important contribution from hillslope runoff.
2. From 15 U/Th ky BP to ~3 cal ky BP the river regime was markedly opposite. The building up of numerous tufa herms in the old river channels shows that the river regime was characterized by consistent base flow. Mechanical erosion, resulting in high sediment loads, was replaced by chemical karstic erosion types, depending on the presence of a rather luxurious vegetation. Tentatively we see rivers whose knick points on cliffs were stabilised by tufa dams. Upslope of Tsigaba dam a lake existed and we attribute the development of channelless valleys upstream of tufa dam lakes to this period. Because the transition from seasonal to more perennial hydrologic landscape behaviour at 15 U/Th ky BP has only been locally observed, astronomical forcing for the environmental transition at that particular moment remains questionable. The recent finding by Marshall *et al.* (2009) of moist conditions around Lake Ashenge between 16,2 and 15,2 cal ky BP shows that environmental conditions in Tigray locally oscillated during the LGM. The post LGM overflow of Lake Tana is situated between 15,2 and 14,75 cal ky BP (Lamb *et al.*, 2007).
3. The gradual change, first to less humid environmental conditions and later to aridity, was dated at Tsigaba around ~3 cal ky BP. This period is up to the present characterized by important geomorphic activity. Landslides, often of the debris flow type occur. The tufa dams degrade by river incision and weathering and the flat bottom river sections behind the dams or elsewhere are actively incised as a result of flash flooding. Increased hillslope runoff creates gullies and sheet and rill wash. The original forest cover has nearly completely disappeared. Although the astronomical energy balance is somewhat lower today than during the Holocene optimum, there does not exist any ground of evidence that forest cover reduction is the result of decreasing rainfall. On the other hand increasing evidence points to the negative impact of regional or generalized anthropogenic deforestation on annual precipitation. We agree that climatic conditions became gradually drier during the second part of the Holocene, but they should be due to forest cutting locally as well as in regions to the South of the study area where the trade winds are passing. Forest cutting and regrowth history can be responsible for the variation over time of the start of increasing aridity since ~5 cal ky BP in the Geba Basin.

This is probably one of the earliest interventions of humans in the hydrological cycle and hence in climate.

ACKNOWLEDGEMENTS

This article is a spin-off of the following projects: 1) research programme G006598 N funded by the Fund for Scientific Research—Flanders, Belgium (1998–2001); 2) The Flemish Inter-University Council Own Initiatives Zala Daget project EIN2001PR237 (2002–2008); 3) The Flemish Inter-University Council Institutional University Cooperation Mekelle University—Land Management and Hydrogeology Projects (2003–2013).

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