Land Degradation in the Ethiopian Highlands

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Jan Nyssen, Jean Poesen, Sil Lanckriet, Miro Jacob, Jan Moeyersons,
Mitiku Haile, Nigussie Haregeweyn, R. Neil Munro,
Katrien Descheemaeker, Enyew Adgo, Amaury Frankl,
and Jozef Deckers

Abstract

The high soil erosion rates in the Ethiopian highlands find their causes in the combination of erosive rains, steep slopes due to the rapid tectonic uplift during the Pliocene and Pleistocene, and human impact by deforestation, overgrazing, agricultural systems where the open field dominates, impoverishment of the farmers, and stagnation of agricultural techniques. Travelling in the Ethiopian highlands, one can see many soil and water conservation structures. Indigenous knowledge and farmers' initiatives are integrated with these introduced technologies at various degrees. This chapter addresses the status and drivers of land degradation in northern Ethiopia, including changes over the last century.

Keywords

Desertification • Soil erosion • Slope processes • Soil and water conservation

21.1 Introduction

The rugged landscapes of the Ethiopian highlands have been imprinted and partly degraded by agriculture since 3 millennia at least (Nyssen et al. 2004b). This chapter particularly addresses rainfall, runoff, and soil erosion processes. The high soil erosion rates by water and tillage as well as by landsliding in the Ethiopian highlands find their causes in the combination of erosive rainfall, steep slopes due to the rapid tectonic uplift during the Pliocene and Pleistocene, and human impact by deforestation, overgrazing, agricultural systems where the open field dominates, impoverishment of the farmers, and stagnation of agricultural techniques (Ståhl 1974; Girma and Jacob 1988; Ståhl 1990). In flat areas and on stone-covered slopes (Nyssen et al. 2002b; Van de Wauw et al. 2008), soil profiles have not yet been fully truncated by soil erosion that is concomitant to tilled agriculture. Agricultural practices are well adapted to the environment: the *mahrasha* tillage tool (the traditional 'ard' plough) was developed during the high-tech Axumite period; the cropping systems fit seamlessly to soil catenas (Nyssen et al. 2008a); and the farming systems are well adapted to interannual variation in rainfall conditions (Pietsch and Machado 2014). Whereas, technically, under the traditional circumstances, agricultural adaptation to soil and climate variability is nearly optimal, land management has for long been hampered by unequal access to land and prevalent free grazing. Most reports from the first half of the twentieth century (e.g. Giglioli 1938a, b; Joyce 1943) recognised the soil erosion problem but did not consider that it was a major problem. Frankl et al. (2011) have shown that the gullies

J. Nyssen (✉) · S. Lanckriet · M. Jacob · A. Frankl
Department of Geography, Ghent University, Ghent, Belgium
e-mail: jan.nyssen@ugent.be

J. Poesen · R.N. Munro · J. Deckers
Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium

J. Moeyersons
Royal Museum for Central Africa, Tervuren, Belgium

M. Haile · N. Haregeweyn
Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia

K. Descheemaeker
Department of Plant Sciences, Wageningen University, Wageningen, The Netherlands

E. Adgo
College of Agriculture and Environmental Science, Bahir Dar University, Bahir Dar, Ethiopia

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currently visible in the landscape started to develop in the 1960s. This chapter addresses the status and causes of land degradation in northern Ethiopia over the last century.

21.2 Rainfall and Runoff as Driving Forces for Soil Erosion Processes

The climates of Ethiopia are complex: 'Within short horizontal distances, climates from tropical to sub-humid and sub-tropical to arctic can occur' (Krauer 1988). Precipitation and air temperature vary mainly with elevation, but slope aspect also plays an important role. Furthermore, precipitation decreases and seasonality increases with latitude.

21.2.1 Precipitation Patterns

From the end of June onwards, the Intertropical Convergence Zone (ITCZ) is situated at its most northerly position (16°N–20°N). The southern air masses, limited to the lower layers of the atmosphere, bypass the highlands and reach them from the south-west, giving way to the main rainy season (Goebel and Odenyo 1984). Generally, clouds are formed at the end of the morning, as a result of evaporation and convective cloud formation due to daytime heating of the soil, and cause rains in the afternoon. In Afdeyu station, on the Eritrean highlands, 80 % of daily precipitation takes place between 12 and 16 h (Krauer 1988). (All mentioned localities are indicated on Fig. 21.1). This convective nature of rainfall also explains why individual showers have a very local distribution. At the end of the summer, the ITCZ returns quickly to the south, preventing the arrival of monsoon rain. This is the end of the rainy season in the highlands.

Abebe and Apparao (1989) calculated from 241 stations in Ethiopia a mean annual precipitation of 938(±83) mm year^{-1}. For the highlands, annual precipitation varies between 450 mm year^{-1} in Tigray and more than 2,000 mm year^{-1} in the south-west of the country (Krauer 1988). The interaction of latitude and altitude controls total annual precipitation (Troll 1970). At the regional scale, one should, however, also take into account that during the rainy season winds come essentially from the south-west, as well as orographic effects. Valleys are preferred flow paths for the penetration of humid air masses into the highlands (Nyssen et al. 2005) and rainfall distribution is highly erratic (Jacob et al. 2013).

21.2.2 Rainfall Erosivity in the Ethiopian Highlands

High rainfall erosivity is an important factor of soil erosion in the highlands. Data from two automatic rain gauges installed in central Tigray during one year (1975 and 2001, respectively) indicate that 30–70 % of all rain events had an intensity >25 mm h^{-1} (Hunting Technical Services 1976; Nyssen et al. 2005). Krauer (1988) obtained from the rainfall data of six Soil Conservation Research Programme (SCRP) stations mean annual universal soil loss equation (USLE) rainfall erosivity indices *R* between 166.6 (Afdeyu, Eritrea) and 543.7 J cm m^{-2} h^{-1} year^{-1} (Anjeni, Gojam). Hurni (1979), in an analysis of rainfall erosivity in the Simien Mountains, insisted on two other particularities of Ethiopian mountains: erosivity due to hail (2.5 times more important than erosivity due to rain) and the influence of hillslope aspect. A soil surface unit exposed to wind receives a greater quantity of water than a surface unit with an opposite exposure.

Given that rainfall characteristics in tropical highlands are different from those of more temperate climates, it is difficult to apply erosivity equations, such as those proposed in (R) USLE (Wischmeier and Smith 1978; Renard et al. 1997), which have been developed for North America, to rainfall on the Ethiopian highlands. Based on drop size measurements, Nyssen et al. (2005) showed that for the same rainfall intensity, rainfall erosivity is significantly higher in the Ethiopian highlands compared to elsewhere in the world because of larger raindrop sizes, also during low intensity rain events. Moreover, in the absence of a network of automatic rain gauges, maximum hourly rainfall intensities could be measured only in a small number of research stations in Ethiopia.

Rainfall erosivity is a function of the depths and intensities of the individual rainstorms, and these are not closely related to annual precipitation. However, the United States data indicate that for a given annual precipitation, the range of likely erosivity values can be somewhat narrowed by knowledge of the general climatic conditions in the particular geographic area (Wischmeier and Smith 1978). In East Africa (i.e. Tanzania, Kenya, and Uganda), the relationship between total precipitation and erosivity index improves if rainfall stations are grouped by geographical area (Moore 1979). For Ethiopia, Hurni (1985) and Krauer (1988) elaborated, from monthly data of 6 SCRP stations, correlations between USLE's *R*-factor and mean annual rainfall and Krauer (1988) presented an isoerodent (rain erosivity) map of Ethiopia. More recently, several studies have reported rain erosivity data for Ethiopian rain stations, as well as for other stations in Africa (e.g. Vrieling et al. 2010; Diodato et al. 2013).

21.2.3 Runoff and Infiltration

In Ethiopia, surface runoff production has been measured at various temporal and spatial scales (from runoff plot to

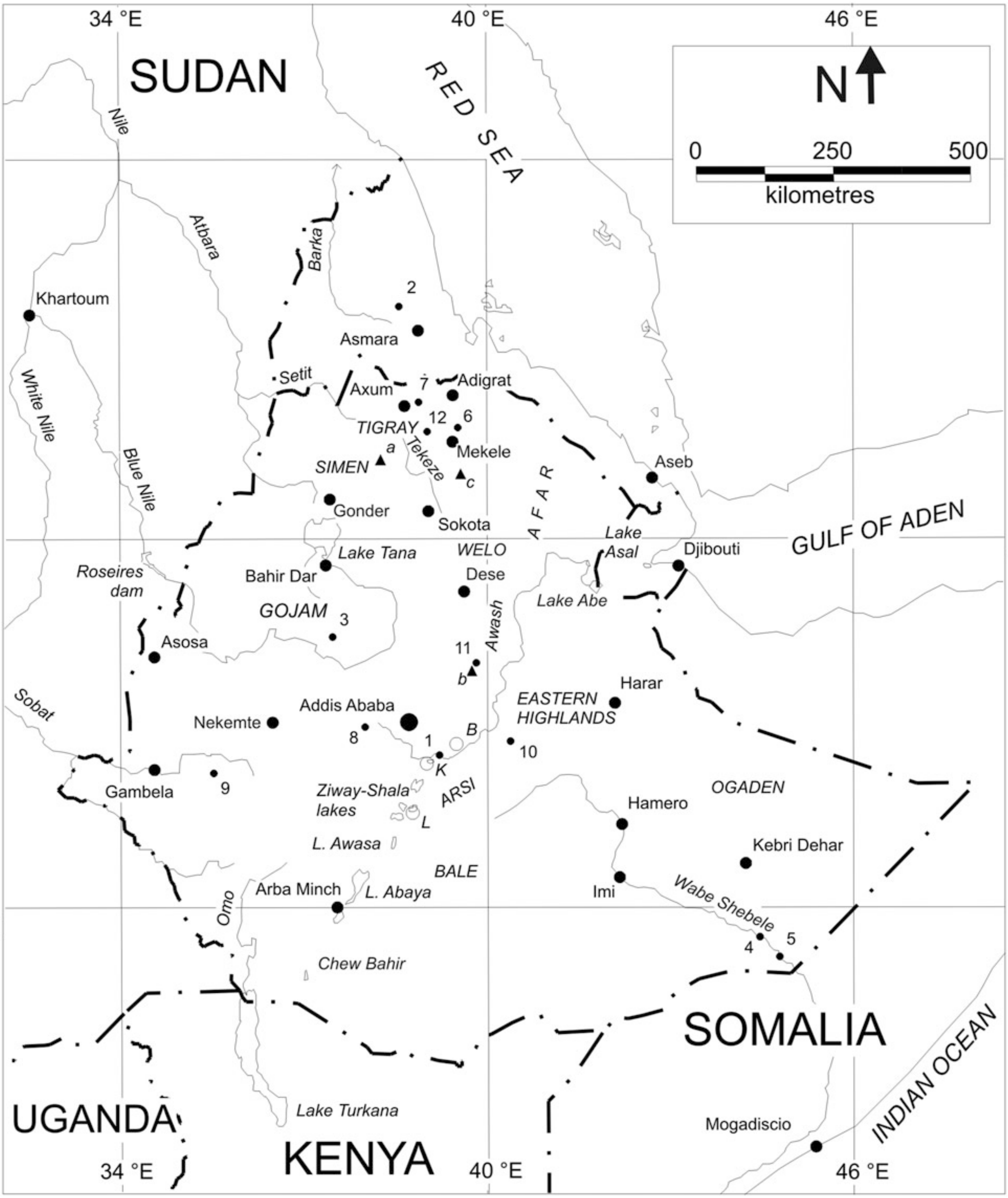

Fig. 21.1 Map of Ethiopia and Eritrea, with indication of localities mentioned in this chapter. Minor localities indicated with numbers: *1* Adama/Nazret + Debre Zeit, *2* Afdeyu, *3* Anjeni, *4* Kelafo, *5* Mustahil, *6* May Makden, *7* Adwa, *8* Ambo, *9* Dizi, *10* Hunde Lafto, *11* Debre Sina, *12* Dogu'a Tembien; summits are represented by *triangles*: *a* Ras Dejen, *b* Ankober, *c* Amba Alage; *open dots* represent lakes: *B* Lake Besaka, *K* Koka reservoir, *L* Lake Langano

catchment). Runoff has been monitored in the SCRP catchments and data series of up to 12 years are available (SCRP 2000). Generally, runoff coefficients (RC) from small (<1,000 m^2) runoff plots are very variable (0–50 %) (Nyssen et al. 2004b), which is attributed to the variable experimental conditions. Besides different slope gradients, local

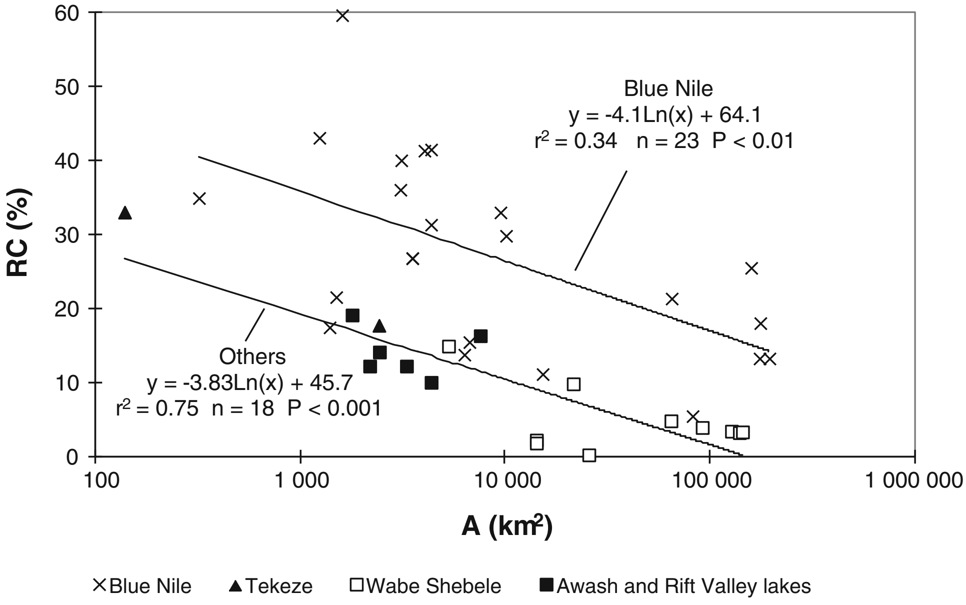

Fig. 21.2 Runoff coefficients (RC) versus drainage area (A) for catchments of the basins of the Blue Nile, Tekeze, Wabe Shebele, Awash, and Rift Valley lakes (after Nyssen et al. 2004b)

differences in soil texture, land use, vegetation cover, organic matter content, or rock fragment cover result in a wide range of infiltration rates obtained from runoff plots. Results on RC from runoff plots are therefore not representative for RC of catchments.

For large catchments (A ≥ 100 km^2), RC decreases with increasing catchment area (Fig. 21.2). The already mentioned conditions for high RC (presence of open field and high rainfall) are mainly found in the Blue Nile basin. For this reason, two data series can be considered. The Tekeze, Awash, and Wabe Shebele basins are mainly situated in dry sub-humid to arid regions (Mersha 2000). In the Wabe Shebele basin, Bauduin and Dubreuil (1973) explained a decreasing RC with an increasing catchment size by the fact that small catchments are mostly situated in the headwaters where nearly impervious, basalt-derived soils dominate, and also by a smaller mean annual basin precipitation in the larger catchments which include (semi)arid lowlands. The rainfall and runoff data for catchments in the Blue Nile basin suffer, according to its authors (USBR 1964), from the lack of precision in delimiting drainage areas (A) for smaller basins. Representative catchment precipitation data are also difficult to obtain given poor station density and large spatial variability of rainfall (Conway and Hulme 1993). Conway (1997) pointed to short mean observation periods (i.e. 1.5 years) and possible errors in rainfall data. Despite the wide scatter for the Blue Nile basin, it can be observed that RC are larger than those for the other basins but that they still follow a parallel trend (Fig. 21.2). Decreasing RC values with increasing A values in the Blue Nile basin are thought to be a result of (a) runoff transmission losses, due to evaporation and possibly lithological changes, and (b) less rainfall and larger potential evapotranspiration in the western areas of the Blue Nile catchment along the border with Sudan, which reduces the overall runoff depth for the whole catchment (Conway, personal communication 1999). In situ water harvesting and the construction of small reservoirs have both led to strongly decreasing RC at catchment scale, and to increased levels of the water tables (Nyssen et al. 2010; Berhane et al. 2013). However, significant differences in RC between the sub-catchments within the 5,000 km^2 Geba basin could not be demonstrated, most probably due to the overall implementation of soil and water conservation (SWC) activities (Zenebe et al. 2013). Additional research on this topic is currently being conducted in Lake Tana basin (Poppe et al. 2013; Dessie et al. 2014). Particularly, in cases of large-scale conversions of cropland and rangeland to forest, such as on the escarpment upslope from Alamata, effects are very clear, particularly in terms of decreased downstream flooding and changes of hydrogeomorphology (i.e. river channel incision and narrowing) (Gebreyohannes et al. 2014).

21.3 Weathering and Soil Formation

Few studies have been made on weathering of parent material in the highlands. Hövermann (discussion in Bakker 1967) studied the basal Precambrian granites in northern Ethiopia where weathering mantles are up to 120 m deep. No studies exist for Mesozoic sedimentary rocks or for Tertiary volcanics, but the depth of weathering mantle is expected to be much less.

Hurni (1983), through the study of soils developed on periglacial slope deposits, extrapolated soil formation rates for the different agroclimatological zones of Ethiopia.

Zonation in Ethiopia is based on altitude and more specifically on the corresponding local climate. These soil formation rates are mean rates, taking into account rainfall depth and air temperature conditions, but not lithology. They are intended to be compared with soil loss rates, but, to our understanding, cannot be applied to the vast areas where the soil mantle results from sediment deposition rather than from pedogenesis.

21.4 Sheet and Rill Erosion

Most research on soil erosion in Ethiopia focused on sheet and rill erosion (Fig. 21.3). Hurni (1975, 1978, 1979) studied thoroughly the Jinbar valley (3,200–4,000 m a.s.l.) in the Simien Mountains. Andosols occupy the whole valley, which is partially under rangeland and degraded forest and partially under barley. The depth of the A-horizon was measured at some 300 sites in cropland and compared with A-horizon depth in non-cultivated areas for similar slope gradients. Mean total soil profile truncation depth from cropland, occurring between the beginning of permanent human occupation (500–200 years ago) and 1974, was measured as 14.5 ± 2.1 cm, or 950 ± 200 t ha^{-1}, or 2–5 t ha^{-1} $year^{-1}$. Due to elevation and to the proximity of the climatic limit of barley cultivation, deforestation here has started much later than in most other parts of the highlands (Hurni 1982). The variability in soil loss depth is correlated with slope aspect and probably with the age of deforestation (Hurni 1975, 1978). Measurements of sheet and rill erosion rates were conducted in the Ethiopian highlands (Hurni 1985, 1990; Kejela 1992; Herweg and Ludi 1999; SCRP 2000; Nyssen et al. 2009c).

Soil loss occurs mainly at the beginning of the main summer rainy season (*kiremt*). In those regions where spring rains (*belg*) are sufficient for cultivation, these crops have been harvested and the land ploughed again before *kiremt* (Tesfaye 1988). In the northern highlands, spring rain is unreliable and the land is only sown at the beginning of the *kiremt* season, when rains are intensive and their onset more regular. The farmlands have then undergone at least two tillage operations are bare and offer less resistance to splash and runoff erosion (Virgo and Munro 1978). Studies in southern Ethiopia, where deforestation is ongoing, show a tremendous increase in soil loss over the last few decades (Kassa et al. 2013). In the northern highlands, with the advance of the rainy season, soil loss decreases as crop cover increases (Tesfaye 1988). This pattern was also observed and similarly accounted for by Billi (2004) for the suspended sediment concentration in the Meki River, a main tributary to Ziway Lake in the Rift Valley. However, substantial runoff is produced more than one month after the beginning of the *kiremt* rains. In the beginning of the rainy season, most rainfall infiltrates quickly in the dry, tilled farmlands (Gebreegziabher et al. 2009; Zenebe et al. 2013). Furthermore, on Vertisols, which are well represented in Ethiopia (Kanwar and Virmani 1986; Moeyersons et al. 2006), the first rains are well absorbed, because of the deep shrinkage cracks. After some time, with the closing of the cracks, these soils become completely impervious and favour significant runoff production (Bauduin and Dubreuil 1973; Gebreegziabher et al. 2009; Oicha et al. 2010; Araya et al. 2011). Moreda and Bauwens (1998) found the most significant correlation between monthly precipitation and summer flow in the Awash headwaters to occur in August, at the beginning of the second half of the rainy season, when 'there is greater opportunity for flow generation (even for smaller storms) since the catchment is already moist'. Sutcliffe and Parks (1999) estimated that 'early rainfall is required to replenish the soil moisture storage after the dry season'.

Fig. 21.3 Rill erosion at a farmer's field at Wonzima (Blue Nile basin). Rills occur particularly on long and steep slopes without soil conservation structures; here, the depth of the rill is controlled by the tillage pan, on which plough marks of the ard are visible (*Photograph* E. Monsieurs, August 2013)

Table 21.1 The Revised Universal Soil Loss Equation (RUSLE)—adapted for field assessments in Ethiopia (Nyssen et al. 2009c)

Equation: **annual soil loss rate** $A = R * K * S * L * C * P$ (Mg ha^{-1} year^{-1})					
1. ***R*: annual rainfall erosivity** (MJ mm ha^{-1} h^{-1} year^{-1})					
$R = 5.5\ \mathrm{Pr} - 47$					
Pr = annual precipitation (mm)					
2. ***K*: soil erodibility** (Mg h MJ^{-1} mm^{-1}), including effects of rock fragment cover					
$K = [2.1\ M^{1.14}\ (10^{-4})(12 - a) + 3.25\ (b - 2) + 2.5\ (c - 3)] * \mathrm{e}^{-0.04\ (d-10)} * 0.001317$					
M = particle size parameter = (% silt and very fine sand) * (100 − % clay)					
a = percentage of organic matter					
b = soil structure code, ranging between 1 (very fine granular) and 4 (blocky, platy, or massive), with default value 2					
c = permeability class, ranging between 1 (rapid) and 6 (very slow), with default value 3					
d = stone (rock fragment) cover (in %)					
3. ***S*: slope steepness factor** (dimensionless)					
$S = -1.5 + 17/(1 + \mathrm{e}^{(2.3-6.1\ \sin\theta)})$					
θ = slope angle (°)					
4. ***L*: slope length factor** (dimensionless)					
$L = 0.232\ \lambda^{0.48}$ ($5\ \mathrm{m} \le \lambda \le 320\ \mathrm{m}$)					
λ = slope length (horizontal projection, in m)					
5. ***C*: cover-management factor** (dimensionless)					
Dense forest	0.001	Degraded rangeland (<50 % vegetation cover)	0.42	Badlands hard	0.05
Dryland forest; exclosure	0.004			Badlands soft	0.40
Dense grass	0.01	Degraded grass	0.05		
Sorghum, maize	0.10	Tef (in high rainfall areas)	0.25	Fallow hard	0.05
Cereals, pulses	0.15	Tef (in semi-arid areas)	0.07	Fallow ploughed	0.60
6. ***P*: supporting practices** (dimensionless)					
$P = P_C \cdot P_N \cdot P_M$ (on cropland); $P = P_N$ (on other land)					
Ploughing and cropping practices	P_C	Conservation structures	P_N	In situ conservation practices	P_M
Ploughing up and down	1	No conservation structures	1	Stubble grazing; no mulching	1
Ploughing along the contour	0.9	Stone bund (average condition; smaller value for new s.b. and larger for older s.b.)	0.3	Applying mulch	0.6
Strip cropping	0.8	Grass strip (1 m wide; slope ≤ 0.1 mm^{-1})	0.4	Zero grazing	0.8
Intercropping	0.8	Grass strip (1 m wide; slope > 0.2 mm^{-1})	0.8		
Dense intercropping	0.7				

Source Renard et al. (1997). Adaptations: *R* correlation by Hurni (1985); *K* adjustment for rock fragment cover by Poesen et al. (1994); *L* correlation by Hurni (1985); *C* values by Hurni (1985) and Nyssen et al. (2009c); *P* model by Nyssen et al. (2009c); *P* values by Hurni (1985), Nyssen (2001), Gebremichael et al. (2005), Nyssen et al. (2007a, b, 2008b). Limitations as mentioned in Sect. 21.4

From their research, Hurni (1985) and later Nyssen et al. (2009c) adapted the Revised USLE (Renard et al. 1997) to Ethiopian conditions for use by development agents in the field of SWC (Table 21.1). The soil erodibility factor *K* can be assessed from soil textural data, organic matter content, and rock fragment cover (Table 21.1, Sect. 21.2). We recommend including the rock fragment cover, which is a widespread feature in the Ethiopian highlands, as a correction factor for the *K*-value, rather than in the management factor *P* (Nyssen et al. 2002b).

For the *R*-factor (rainfall erosivity), the Ethiopia-specific equation (Table 21.1, Sect. 21.1) may be used, bearing in mind that additional studies, taking into account the above average drop sizes in the Ethiopian highlands, should be carried out (Nyssen et al. 2005). Calculations of the slope steepness factor (*S*) and the slope length (*L*) factor are shown in Table 21.1 (Sects. 21.3 and 21.4). The use of equations for *L* requires caution, since ‘slope length is the factor that involves the most judgement, and length determinations made by users vary greatly’ (Renard et al. 1997). In Ethiopian highland conditions, this runoff length is generally longer than one single farm plot and shorter than the whole slope, from ridge to foot. Cover-management *C* values (Table 21.1, Sect. 21.5) have been reported by Nyssen et al. (2009c). The *P* factor (dimensionless) relates to supporting practices and indicates reduced soil erosion potential due to farming practices and conservation measures. Sub-factors yield one composite P-value (Foster and Highfill 1983) for a conservation system (Table 21.1, Sect. 21.6):

$$P = P_C * P_N * P_M \tag{21.1}$$

where

P_C = Sub-factor for ploughing and cropping practices;
P_N = Sub-factor for conservation structures;
P_M = Sub-factor for in situ conservation practices.

21.5 Gullying

Gullying (Fig. 21.4) is not restricted to the highlands of Ethiopia but is widespread at sub-continental scale in Africa (Moeyersons 2000). In Tigray, the increase of runoff response on many hillslopes has been attributed to an overall lowering of the infiltration capacity of the soils due to removal of natural vegetation (Virgo and Munro 1978; Machado et al. 1998). Buried soils indicate advanced deforestation, which in the Ethiopian highlands might have started around 5,000 ^{14}C years BP (Machado et al. 1998; Nyssen et al. 2004b; Pietsch and Machado 2014). Since the twentieth century, however, vegetation removal has also affected shrub and small tree cover, as well as grass strips in between the farmlands and on steep slopes. This removal of vegetation has further lowered the infiltration capacity of the soils, favoured the occurrence of flash floods, and is considered to be the major cause of rapid gullying in many areas (Frankl et al. 2011). One should also stress the importance of cropland abandonment for gully initiation, especially if it is converted into grazing land. The overgrazed soil surface has a higher runoff coefficient than regularly ploughed farmlands; SWC structures are no longer maintained, and bank gullying often starts at places where these structures collapse.

Brancaccio et al. (1997) explained the present-day processes of channel incision in northern Ethiopia by an increasing erosional power of concentrated runoff due to a decreasing sediment load (clear water effect), associated with the advanced phase of soil erosion on the hillslopes where bedrock is now outcropping. Since the late nineteenth century, gullies were present and though they had become stabilised by 1935, a strong incision phase started in the 1960s due to the above-mentioned factors (Frankl et al. 2011).

Gullies in Ethiopia can often be considered as discontinuous ephemeral streams (Bull 1997) comprising a hillslope gully, an alluvial–colluvial cone at the foot of the hill, and renewed incision with gully head formation further downslope in the valley Vertisol. Pediments dissected by gullies are a common feature in many areas (Riché and Ségalen 1973; Berakhi and Brancaccio 1993; Berakhi et al. 1997). In the valley bottoms, initial gully heads often coincide with sinking polygonal structures in Vertisols (Nyssen et al. 2000b), where piping erosion is very active (Frankl et al. 2012).

Fig. 21.4 Gullies, like this one in Harena (Dogu'a Tembien), do not only result in soil loss, but also drain out the landscape (lowering of the water table) and are major obstacles to communication

Active gullying induced by road building on pediments was described by Berakhi and Brancaccio (1993). In a case study along the Mekele—Adwa road, built in 1994, Nyssen et al. (2002a), demonstrated how road building, through the enlargement of drainage areas and the concentration of runoff, induced an artificial exceedance of the critical catchment area at which gully heads are formed for a given slope gradient.

21.6 Tillage Erosion

Soil translocation due to tillage by the ox-drawn ard plough (Fig. 21.5) appears to be an important soil erosion process in the Ethiopian highlands. Assessments of tillage erosion rates indicate that this process contributes on average to half of the sediment deposited behind stone bunds (Nyssen et al. 2000c; Gebremichael et al. 2005). Colluviation occurs in the lower part of the farmland and soil profiles are truncated in the upper part (Herweg and Ludi 1999; Nyssen et al. 2000c). Soil sequences on progressive terraces overlying strongly weathered rock were analysed in the central highlands of Ethiopia, in the Ankober area (Bono and Seiler 1986). At the upper part of the terrace, soils are shallow and water and nutrient storage capacity low. However, in Dogu'a Tembien (Tigray), intra-parcel variability of soil fertility parameters is small. A larger content of soil moisture and of soil organic matter was even observed at the foot of the stone bunds, at the very place where the soil profile has been truncated after stone bund building. Possible effects of soil profile truncation on the values of these two parameters are outbalanced by increased infiltration rates, induced by stone bund building (Vancampenhout et al. 2006). The most common soils in the Ethiopian highlands (i.e. Regosols, Vertic Cambisols and Vertisols) have a quite homogenous composition with depth, which explains low soil fertility gradients in terraced lands.

21.7 Wind Erosion

In the Ethiopian highlands, wind erosion has not been measured and was rarely mentioned. Wind erosion mainly occurs as 'dust devils' in areas with important trampling by humans or cattle, such as market places, footpaths, unmetalled roads, around cattle drinking places or on cropland where post-harvest grazing has taken place. On the numerous isolated mountains or '*inselbergs*', important wind erosion, including the formation of dunes, occurs due to local aerodynamic situation (Uhlig and Uhlig 1989). More research on wind erosion in the Ethiopian highlands seems necessary, as it may have been insufficiently studied.

Wind erosion is especially important in low-lying, dry and hot regions, adjacent to the highlands, such as many places in the Rift Valley. Desert pavements, created by wind erosion, exist around Lake Turkana (Hemming and Trapnell 1957). Wind erosion and deposition contribute to the formation of dunes in the alluvial plains of the Wabe Shebele

Fig. 21.5 Soil tillage by *mahrasha* ard plough, here in Dogu'a Tembien, causes a downslope movement of the topsoil (tillage erosion) (*Photograph* A Roelofs, April 2005)

and to overall deposition of aeolian sediments in that region (Riché and Ségalen 1973). The Eritrean coastal plain is in many places covered by stone mantles produced by deflation as well as by loose sand occurring either as a mantle of variable depth or in the form of mobile dunes (Hemming 1961). Aeolian sediments in the coastal plains can be composed of eroded materials from nearby rocks or brought in by dust storms, which are quite common (Horowitz 1967).

21.8 Mass Movements

Due to steep topography, the presence of lithologies with a low shear strength, torrential rainfall, and in some cases the occurrence of earthquakes, the Ethiopian highlands are also affected by various types of mass movements (e.g. rock falls, debris flows, and slumps). Several studies have mapped landslides in Ethiopia and have analysed their controlling factors (e.g. Moeyersons et al. 2008; Van Den Eeckhaut et al. 2009; Broothaerts et al. 2012). Although many mass movements have been initiated by natural factors, human activities (i.e. land use change, undercutting and overloading during road construction, and improper slope drainage systems) have often contributed to the reactivation of landslides. In south Ethiopia, (Broothaerts et al. 2012) observed many recent landslides along river channels which were triggered by river channel incision due to increased peak flow discharges following deforestation in their catchments. Large landslides redistribute large volumes of sediments in the highlands, hence affecting the spatial patterns of soil types (Van de Wauw et al. 2008).

21.9 Sediment Deposition

On the back- and footslopes of cliffs, a 'classic' sorting of deposited sediment generally occurs, the coarse sediments (rock fragments) being deposited on the debris slope, and the finer material on the footslope, as shown by Riché and Ségalen (1973) in the Wabe Shebele basin. Belay Tegene (1998) emphasised the importance of continuous deposition of colluvium on convergent footslopes which prevents the development of mature soil profiles. Hurni (1985) shows, for a 116 ha catchment in Welo, that the rate of sediment accumulation (17 t ha^{-1} $year^{-1}$) is more important than the rate of sediment export through the drainage system (7 t ha^{-1} $year^{-1}$). In a well-vegetated catchment in south-western Ethiopia, sediment accumulation rates are 30 t ha^{-1} $year^{-1}$ and sediment export rates through the river only 1.1 t ha^{-1} $year^{-1}$. Here, most of sediment deposition occurs in densely vegetated areas along riverbanks. A sediment budget for a 200 ha catchment in Tigray highlands indicates that 59 % of sediment produced by water erosion is deposited within the catchment (Nyssen et al. 2007b). Reuter (1991) and Descheemaeker et al. (2006b) stressed the magnitude of sediment and organic carbon stored in colluvium on footslopes and reforested areas (exclosures sensu Aerts et al. 2009). Sediment deposition in floodplains and natural lakes is important, but the rates have not been studied systematically in Ethiopia.

21.10 Land Degradation and Desertification

Although climatic conditions (0.05 < annual precipitation/potential evapotranspiration < 0.65) in parts of the northern highlands and in the low-lying parts of the country would justify the use of the term 'desertification' (UNEP 1994), the term 'land degradation' will be used to indicate environmental degradation throughout the country. Two major factors inducing land degradation in the Ethiopian highlands are generally considered: drought and land use changes.

21.10.1 Rainfall Variations and Drought

Attention to famines in Ethiopia has created a popular view of a drought-stricken country, with a tendency towards decreasing annual rainfall. The decline of rainfall in the Sahel observed since about 1965 was also seen to a lesser extent in the north-central Ethiopian highlands (Camberlin 1994; Seleshi and Demarée 1995). However, unlike the Sahel, a comparison between two reference periods (1931–1960 and 1961–1990) yields no significant changes in mean precipitation over Ethiopia, but an increased inter-annual variability (Hulme 1992). Analyses of long-term time series of annual precipitation, both for Addis Ababa and the northern highlands, show that although the succession of dry years between the late 1970s and late 1980s produced the driest decade of the last century in the Ethiopian highlands, there is no evidence for a long-term trend or change in the region's annual rainfall regime (Conway 2000a; Conway et al. 2004).

With respect to the inter-annual rainfall variability, Conway (2000b) found a coefficient of variation below 20 % for the wetter areas, but far above that for drier areas to the north and at lower altitudes (see also Chap. 4, this volume). (Hoffmann 1987) also found annual rainfall variability strongly dependent on climatic region: <10 % in the area around Jimma with a tropical rain climate and >45 % in semi-desert areas. Dry years were observed in 1913–1914, 1937, 1941, 1953, 1957, 1965–1966, 1969, 1973–1974, 1976, 1979, 1983–1984, and 1987 (Camberlin 1994). It is evident that, in an already degraded environment, a dry year has a very negative impact, not only on agricultural production, but also on the environment (i.e. overgrazing, cracking of Vertisols, and groundwater depletion). RC in such a year are higher (Casenave and Valentin 1992; Valentin et al. 2005) and result in increased soil erosion.

Besides yearly precipitation, its seasonal distribution must be considered as well. Unlike West Africa, according to Hulme (1992), the seasonality of rainfall over Ethiopia slightly decreased between 1931–1960 and 1961–1990. However, evenly distributed rains mean also that a larger percentage of precipitation falls outside the crop growth season, or that there is a shift from one rainy season to another, particularly decreased summer (*kiremt*) and increased spring (*belg*) rains in the northern Ethiopian highlands (Camberlin 1994; Seleshi and Demarée 1995; Seleshi and Demarée 1998). Differences between the temporal pattern of spring and summer rains are expected to reflect different levels of influence from the Indian and Atlantic oceans (Conway 2000b).

21.10.2 Human Settlement and Changes in Land Use and Land Cover

Human settlement with concomitant agricultural exploitation induces significant changes in land use and land cover, which in turn alter infiltration and runoff conditions, as well as soil erosion processes (Olson 1981; Bunney 1990). Detailed studies show that settlement decisions were made on a clear ecological basis, especially from the beginning of the pre-Axumite era (700 BCE). Preferred locations were at the margin between Vertisol areas and narrow alluvial valley bottoms which could be irrigated (Michels 1988). Human activity expanded from such preferential places to the present-day occupation of steep slopes for agriculture through a number of stages, including forest clearing and removal of remnant trees and shrubs.

In the Ethiopian highlands, livestock grazes on vast deforested areas, commonly called rangeland, as well as various types of climax grasslands: i.e. at high elevations, on Vertisols and on dry places (Klötzli 1977). Much in the same way as in forests and woodlands, vegetation cover decreases in grass- and rangeland. Most of the above-quoted studies of land use changes show, besides decreasing tree and shrub cover, an increase of the area occupied by ‘bare land’, ‘no vegetation’, ‘open areas’, and the like. Overgrazing of rangeland is a particular problem in the cereal zones of the highlands, where current stocking rates are well in excess of estimated optimum rates (Hurni 1993). Livestock plays a key role in the agricultural system of the highlands, providing energy (traction, manure used as fuel), food, fertiliser, insurance, and status (Kassa et al. 2002). Consequences of overgrazing on the environment are decreased surface roughness, compaction of fine textured soils, increased soil bulk density, decreased soil organic matter content, soil structure decay, and decreased hydraulic conductivity. All these factors contribute to decreased infiltration rates and increased runoff volumes. Mwendera et al. (1997) carried out experiments on grazing land with slope gradients <0.08 mm^{-1} in an area between Ambo and Addis Ababa. Comparing ungrazed, moderately, and heavily grazed land, they found significant differences in runoff volumes for slope gradients in the range of 0.05–0.08 mm^{-1}. Steady-state infiltration rates decreased significantly, even under light grazing intensity, and showed the effect of animal trampling on soil compaction (Mwendera and Saleem 1997). On cropland, stubble grazing (a widespread practice) dramatically decreases the infiltration capacity. Field observations also indicate that topsoil degradation by cattle trampling significantly contributes to soil erosion and sediment delivery to water reservoirs.

Repeat photography has also revealed that in the late nineteenth century, the landscapes were at least as barren as they are nowadays (Nyssen et al. 2009b). In recent years, since 1975, the tree cover has improved in 90 % of the analysed landscapes (Munro et al. 2008; Nyssen et al. 2008b). Exclosures (Aerts et al. 2009) have been established in former communal grazing land with the aim of forest restoration and land conservation. The establishment of exclosures was made possible by an important land tenure change in the 1980s, in which large feudal agricultural lands in the valley bottoms and other level areas were shared among the local farmers and this decreased the need of poor farmers to establish marginal farmlands on hillslopes. In these locations, exclosures could then be established after land reform (Rahmato 1994). Although centrally imposed, the implementation of exclosures is rather a bottom-up process. Participation is enhanced by the implementation of remunerated SWC activities and plantation works at the establishment of the exclosure. Location, area, local by-laws related to restrictions and management, instalment and payment of guards are most often decided at the local community level (Muys et al. 2014). The villagers are overall convincingly participating in reforestation and other conservation activities (Kumasi and Asenso-Okyere 2011). However, the encroachment by eucalypts remains a bottleneck for biodiversity. The benefits of planting these trees are largely for individual farmers, whereas the negative effects of this water-demanding tree are borne by the communities (Muys et al. 2014).

21.10.3 Social and Historical Impulses of Land Use and Cover Changes

It appears that rainfall variability, apart from the catastrophic impact of dry years on the degraded environment, cannot be

Fig. 21.6 Plough marks on large rock fragments and pedestal-supported boulders indicate that this 100–200-year-old *Juniperus* forest at Kuskuam near Debre Tabor has grown on previously degraded farmland. Forest re-growth has taken place, as also evidenced by the well-branched older tree in the centre of the photograph that used to grow in an open area (*Photograph* J. Nyssen, July 2011)

invoked to explain the current land degradation. Causes are to be found in changing land use and land cover, which are expressions of human impact (Reid et al. 2000; Feoli et al. 2002). Though deforestation and removal of other vegetation cover over the last 2,000–3,000 years have probably been a cyclic rather than a linear process (Fig. 21.6), studies on land use and land cover change show that, at present, there is a tendency of increasing removal of vegetation cover.

At this stage, it appears necessary to briefly outline the social and historical causes of this human impact. Under feudalism (until 1974), agricultural techniques stagnated for centuries (Crummey 2000). Until the 1940s, the Agricultural Department's only effective activity was collecting the agricultural tax (Joyce 1943). Investment in agriculture started only in 1950s and was in the beginning mostly oriented towards export crops such as coffee (*Coffea arabica L.*), grown in southern Ethiopia. Therefore, there was limited agricultural investment in the highlands, where subsistence production dominated (Ståhl 1990; Mulugetta 1992). Until the late 1970s, sharecropping prevented the farmers from investing in their farmlands. Impoverishment led them to prefer immediate returns, even if it induced environmental degradation (Taddesse 1995). On the other hand, recent land redistributions in order to allocate landless households had a positive impact on land productivity (Benin and Pender 2001). To increase agricultural production, most trees and shrubs between the farmlands and on steep slopes were cleared during the nineteenth and twentieth centuries, thereby increasing runoff and soil erosion (Ståhl 1974; Girma and Jacob 1988; Ståhl 1990). In short, in situations of poverty and social insecurity, short-term survival prevailed over medium- and long-term conservation issues.

21.11 Human Reaction to Land Degradation

21.11.1 Agricultural Intensification and Land Rehabilitation

Faced with a deteriorating environment, society reacts in order to maintain/improve agricultural production, often leading to changes in the production system (Boserup 1981), an innovative process in which modern science needs to be involved (Blaikie and Brookfield 1987; Ståhl 1990). The present-day rise in food production in Ethiopia (Fig. 21.7) can, besides re-established climatic conditions, also be attributed to a variety of human interventions at different levels (Nyssen et al. 2004a). Extension of cropped area and increased grazing pressure is still possible. However, limited space is left for this and productivity decreases. Giglioli (1938a, b) and Joyce (1943) already reported the widespread use of indigenous SWC technology since a long time. Such indigenous technologies can be used as a starting point, but need improvement in order to increase their ecological efficiency (Hurni 1998; Nyssen et al. 2000a).

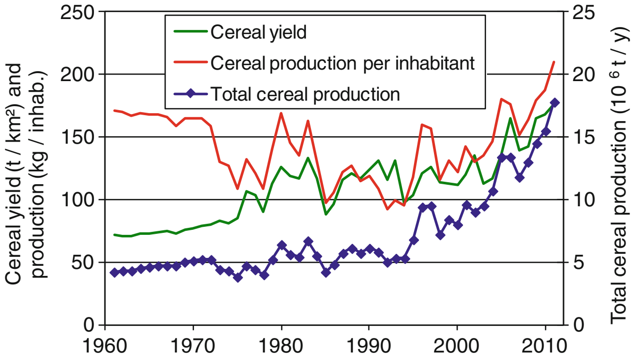

Fig. 21.7 Agricultural intensification in Ethiopia is evidenced by cereal production trends (data retrieved from http://faostat.fao.org)

Nowadays, changes in the agricultural system appear such as haymaking ('cut and carry') (Hurni 1986), partially from exclosures (i.e. land under strict conservation management, often controlled by the community), which are increasingly being organised in the most affected northern highlands (Tekle et al. 1997; Shitarek et al. 2001; Aerts et al. 2004, 2009; Descheemaeker et al. 2006b) and which lead to sediment trapping and enhanced soil fertility status (Elias and Scoones 1999; Descheemaeker et al. 2006a; Mekuria et al. 2007).

Different pathways of agricultural intensification are possible in Ethiopia. Mineral fertilising should not be the overall option, given scarce capital resources. Due to decreased landholdings, a shift in the soil tillage system to gardening and minimum tillage (on self-mulching Vertisols) may be suggested (Astatke et al. 2002; Araya et al. 2012), as well as an extension of the cropping period on Vertisols (Tedla et al. 1999). Asnakew et al. (1994) obtained good maize yields with rock fragment mulching and no-tillage.

Besides these conservation measures, Ethiopia strongly invested in agricultural inputs, particularly fertilisers and improved seeds. As a result, total food production is now higher than ever; also food production per capita in 2005–2010 was 160 % of that in 1985–1990 (Fig. 21.7).

21.11.2 Soil and Water Conservation

The main agricultural intensification observed in Ethiopia is certainly the now widespread catchment management activities (Fig. 21.8). Throughout the Ethiopian highlands, it is apparent that many SWC structures, established during the 1980s, remain in place and are often maintained. Their destruction is not as widespread as stated by Rahmato (1994), often the farmers accept and adopt these structures. Many, probably most of the soil bunds throughout Welo, have evolved into full-grown lynchets. Even in the high rainfall Ankober area, soil bunds have often been 'opened' to allow drainage, but are still in place over most of their length.

Local knowledge and farmers' initiatives are integrated with these introduced technologies at various degrees (Gaspart et al. 1997; Nyssen et al. 2000a, 2004a, 2008b,

Fig. 21.8 Catchment rehabilitation in the sub-humid May Zeg-zeg catchment (Tigray); trenches behind the stone bunds enhance infiltration and decrease catchment runoff response (*Photograph* K. Herweg, May 2005)

2009a; Haile et al. 2006; Gebresamuel et al. 2009). The efficiency of particular techniques cannot be discussed in depth here; the reader is referred to specialised publications (Herweg and Ludi 1999; SCRP 2000; Nyssen et al. 2004c, 2007a, 2009a, 2010; Gebremichael et al. 2005; Haregeweyn et al. 2006; Vancampenhout et al. 2006; Wondumagegnehu et al. 2007; Alemayehu et al. 2009; Reubens et al. 2009; Gebreegziabher et al. 2009; Araya et al. 2011; Lanckriet et al. 2012; Muys et al. 2014; Gebreyohannes et al. 2014).

21.12 Conclusions

Ethiopia is on the map for research on land resources and implementation of sustainable land management (SLM) (Haile et al. 2006). Future research priorities are identified. Cornerstones of SLM include forest development in critical places (Descheemaeker et al. 2006b, 2009), over sufficiently large areas, as demonstrated through the dramatic changes that occurred on the Rift Valley escarpment near Alamata (Gebreyohannes et al. 2014).

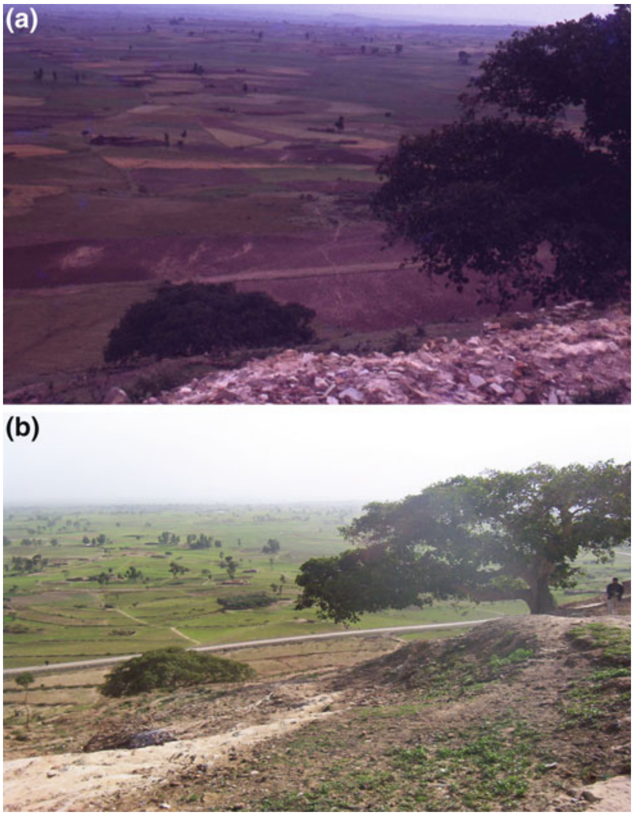

Fig. 21.9 Soil and water conservation activities in the Tsinkaniet plain have led to a situation where overland flow strongly decreased in 2006 (**b**—*photograph* J. Nyssen) as compared to 1975 when evidence of flooding is clearly visible at the footslope (**a**—*photograph* R.N. Munro). At the far end, in 2006, a reservoir mainly fed by groundwater is visible

SWC activities also enhance rain infiltration rates during the short but heavy storms and improve the situation with regard to flooding, soil erosion, and groundwater recharge (Nyssen et al. 2009a, 2010). The current land tenure system in which an equality of land holdings is attempted, favours solidarity among the farmers to undertake communal catchment management activities (Kumasi and Asenso-Okyere 2011; Taye et al. 2013). Besides the need for collecting a wide set of original data, conceptually, in all related research, a good comprehension of the hydrological balance is needed. Further, for nutrient, sediment, and water-related processes, it is important to understand the occurrence of sinks and to keep the scale concept in mind. These principles are at the base of the successful implementation of catchment management activities in northern Ethiopia (Fig. 21.9). In this regard, the impacts of the May Zeg-zeg catchment management could be monitored in detail (Nyssen et al. 2009a, 2010; Walraevens et al. 2009) and future development scenarios could be elaborated (Lanckriet et al. 2012).

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