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How soil conservation affects the catchment sediment budget – a comprehensive study in the north Ethiopian highlands

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ABSTRACT: 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) in Tigray, north Ethiopia, integrated catchment management has been implemented since 2004: stone bunds were built in the whole catchment, vegetation was allowed to re-grow on steep slopes and other marginal land, stubble grazing abandoned, and check dams built in gullies. Land use and management were mapped and analysed for 2000 and 2006, whereby particular attention was given to the quantification of changes in soil loss due to the abandonment of stubble grazing. 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 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. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: May Zeg-zeg; soil and water conservation; stubble grazing; Tigray; watershed management; non-grazing policy

Introduction

Sediment budgeting has rarely been used to assess the impact of catchment management for soil and water conservation (SWC). The latter is high on the agenda in Ethiopia, as limited agricultural intensification, combined with high population densities has resulted in increased pressure on the natural resources of the Ethiopian highlands, leading to important land degradation and erosion phenomena. Population growth is on the decline but remains high (2·6% in 2000–2005 versus 3·3% in 1990–1995) (ESA, 2008). Over the last decades, active SWC interventions have taken place, among other places in the northern highlands (Munro *et al.*, 2008; Nyssen *et al.*, 2008c).

Impact studies have demonstrated that investments in catchment management in the developing world do pay off in economic terms (Boyd and Turton, 2000; Holden *et al.*, 2005; Reij and Steeds, 2003). However, such impact studies typically do not include detailed hydrological or geomorphic components (Rohde and Hilhorst, 2001). Whereas numerous studies exist on the impact of individual SWC techniques, there are none or very few on the impact of a combination of SWC techniques on soil loss, sediment transport and sediment yield at the catchment scale.

An overall approach to assess the effectiveness of catchment management is the establishment of sediment budgets pre- and post-implementation. The sediment budget is defined as the accounting of sources, sinks and redistribution pathways of sediments in a unit region over a unit time (Slaymaker, 2003), or 'an accounting of the sediment sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin' (Reid and Dunne, 1996). By constructing a sediment budget a conceptual framework is created, which delivers a possibility to organize and interpret information, qualitative (process interaction) and quantitative (process rates), about erosion and sediment deposition. Geomorphologists use sediment budgets to investigate the relative importance of the different components and their

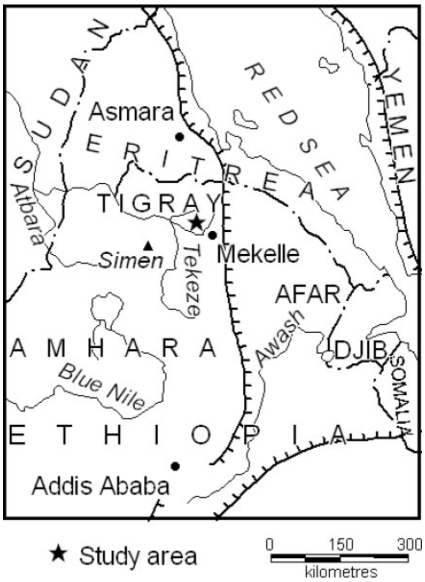

Figure 1. Location of the study area.

evolution. Which sediment source produces most of the sediment? How does the relative importance of the components change over time? These are two important questions that can be answered by the construction of a sediment budget. An important use of a sediment budget is to assess the impact of anthropogenic influences in an area.

Based on field measurements, Nyssen *et al.* (2008a) proposed a tentative sediment budget for the small May Zeg-zeg (MZZ) catchment in the Dogu'a Tembien district near Hagere Selam in Tigray, north Ethiopia (Figure 1). Measured soil loss rates by sheet and rill erosion on arable land (9·9 t ha^{-1} y^{-1}) were below the average measured elsewhere in Ethiopia (42 t ha^{-1} y^{-1}) which was ascribed to (1) rock fragment cover on the fields, (2) the use of SWC structures which decrease runoff length, and (3) yearly precipitation depth and total rain intensity, which are lower in northern Ethiopia (Nyssen *et al.*, 2008a; 2009c).

The assessment of the impact of SWC measures on soil loss at catchment scale was done by comparing two sediment budgets. The most famous of such diachronic sediment budget studies was conducted by Trimble (1981, 1983, 1999) in Coon Creek Basin, Wisconsin, where sediment budgets were constructed and compared for the periods 1853–1938, 1938–1975 and 1975–1993.

In Tigray, land-use changes resulting from the implementation of catchment management, particularly the establishment of exclosures, lead to changes in the sediment budget. The construction of check dams in the gully system resulted in an additional sediment sink. Other changes due to the implementation of SWC techniques (optimizing stone bund density, and non-grazing policy) lead to changes in the magnitude of the processes.

Here we use catchment sediment budgets to measure the impacts of SWC techniques on (a) soil loss, (b) soil conservation, (c) sediment trapping and (d) sediment transport in the river system.

Materials and Methods

Study area

Environmental settings and geomorphological processes have been studied in the typical north Ethiopian highland MZZ catchment which has a sub-humid climate with high seasonality (Nyssen *et al.*, 2005). SWC measures, especially stone bund building (Figure 2) and the establishment of exclosures (vegetation restoration; Figure 3), have been implemented as part of routine land management activities that were started around 1980. As part of outreach accompanying research in the region around Hagere Selam, an integrated catchment programme was set up in 2004 in the MZZ catchment by researchers in cooperation with a local non-governmental organization (NGO). 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 (Amanuel and Nyssen, 2003; Nyssen *et al.*, 2003b; 2009b).

Fieldwork was conducted in the MZZ catchment during the rainy seasons (July to October) of 2000 and 2006. Besides these specific field measurement campaigns, many observations were made during related research in the catchment (Descheemaeker *et al.*, 2006c; Desta *et al.*, 2005; Nyssen *et al.*, 2000a, 2000b, 2001, 2002, 2003b, 2004b, 2005, 2006a, 2006b, 2008b, 2009c, 2009d; Vancampenhout *et al.*, 2006).

Figure 2. Stone bunds in the MZZ catchment induce retention of runoff (August 2006). This figure is available in colour online at www.interscience.wiley.com/journal/espl

Soil conservation components of the MZZ Integrated Catchment Management Project

The MZZ Integrated Catchment Management Project includes the implementation of site-specific conservation techniques

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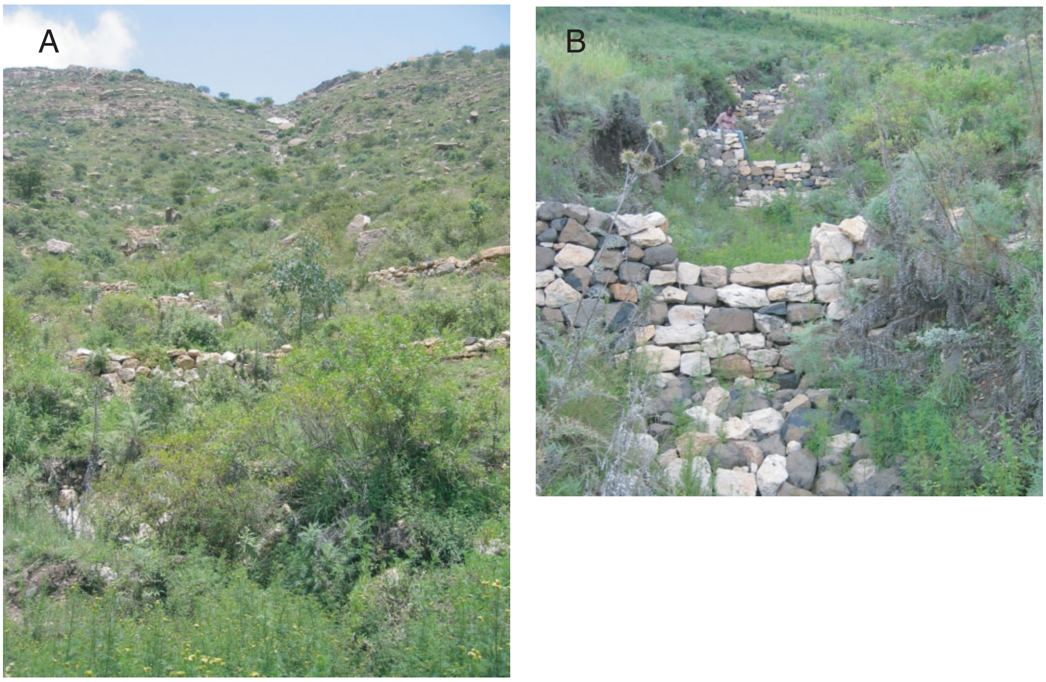

Figure 3. Soil erosion control techniques in MZZ: (A) exclosures on steep slopes and (B) check dams in a gully, where absence of grazing enhances soil stabilization through rapid vegetation growth (August 2006). This figure is available in colour online at www.interscience.wiley.com/journal/espl

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.

Stone bunds

Stone bunds to enhance SWC have been introduced in Tigray since the 1970s (Munro *et al.*, 2008) and may be defined as embankments of stones built along the contour across sloping land to reduce or stop the velocity of overland flow and consequently to reduce soil erosion (Figure 2) (Desta *et al.*, 2005; Vancampenhout *et al.*, 2006). Farmers build these walls with large (>10 cm) rock fragments. As part of catchment management, additional trenches were dug behind the stone bunds, increasing their runoff and sediment trapping effectiveness (TE) (Figure 2).

Short-term effects of stone bunds are the reduction of slope length and the creation of small retention basins for runoff and sediment. They reduce the volume and erosivity of overland flow. The medium- and long-term effects include the reduction in slope gradient of the soil surface by forming bench terraces and the development of vegetation cover on the bunds themselves (Nyssen *et al.*, 2007). In the study area, stone bunds reduce annual soil loss due to sheet and rill erosion on average by 68% (Desta *et al.*, 2005). The positive effects of stone bunds on water harvesting, runoff reduction and crop yield have been assessed by Vancampenhout *et al.* (2006).

Exclosures

Exclosures are areas closed for grazing and cultivation, commonly found on steep slopes and other degraded marginal lands, often downslope from a sediment source area (Figure 3A). The objectives of exclosures are rehabilitation of degraded land, production of grass for fodder and thatching, wood for fuel and construction and non-wood forest products such as honey (Bedru *et al.*, 2008). In the Dogu'a Tembien district, demarcation and management of set-aside areas lies within the responsibility of the local authority.

About 12% of the area is occupied by exclosures. Several positive effects of exclosures can be observed. Natural vegetation is regenerating, runoff and sheet and rill erosion are drastically reduced, the soil is stabilized, soil moisture availability is increased and a microclimate is reinstalled. But at the same time they cause more pressure on remaining grazing land, have little direct material or financial benefits for farmers and result in an abrupt shift for farmers from free grazing to stall feeding. Descheemaeker *et al.* (2006a, 2006c) discuss sediment deposition rates within exclosures, which are correlated to vegetation density in their upper part. A negative exponential relationship between thickness of recently deposited sediment and distance from the upper edge of the exclosures was observed. Exclosures have a high sediment trapping capacity: i.e. 70 to 99% with a mean value of 55 t ha^{-1} y^{-1} (Descheemaeker *et al.*, 2006c). Therefore, where slope gradients are not too steep at their upper side (<50%), exclosures 50–60 m wide should be sufficient to trap nearly all the incoming sediment.

Check dams in gullies

Two hundred forty-two check dams have been built in 2004 as part of the integrated catchment management; check dams are 1–2 m high barriers constructed of dry masonry and placed across gullies (Figure 3B). Check dams reduce the effective slope of the channel, thereby reducing the velocity of flowing water, allowing sediment to settle and reducing channel erosion. The control effects of check dams on runoff and peak discharges lead to a stabilization of the gully system (Nyssen *et al.*, 2004b).

Stubble grazing and non-grazing policy

Stubble grazing (*sensu* Landau *et al.*, 2000) leads to trampling of the soil surface which induces compaction and decreases surface roughness, reduces vegetation cover and lowers organic matter supply to the topsoil (since cattle dung in Ethiopia is collected as an energy source). Hence, it induces land degradation and is therefore often linked with unsustainable land management (Nyssen *et al.*, 2004a). Non-grazing policy

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refers to closing arable land for grazing purposes, allowing a reduction of soil loss, decreased compaction and higher organic matter addition and water supply to the topsoil.

In general, lack of alternatives for livestock feeding and absence of incentives that could compensate for it, as well as poor location of target areas and weak participation, make that the non-grazing policy for arable land in north Ethiopia is restricted to a few selected and closely monitored areas, without yet a real take up by the communities (Lenaerts *et al.*, 2009). The catchment where the MZZ management programme is executed was selected in such a way that it is located at a certain distance from villages and guards are paid to protect it from entering livestock. Two of the three villages surrounding the catchment tend to have adopted the non-grazing policy on arable land, whereas the third village does not, which is most probably linked to heterogeneity in livestock ownership (Berhanu *et al.*, 2004).

Sediment budgeting

According to Marston and Pearson (2004) there are four basic steps in the construction of a sediment budget: (1) delineation of the geomorphologic system; (2) identification of active processes and spatial distribution of erosion, transport and storage within the geomorphologic system inclusive of the connections between them; (3) budgeting of each component in space and time; (4) constructing a balance between sediment production, sediment deposition and sediment yield. The balance is made following the principle of mass conservation. The sediment production (input) equals the sediment yield (output) and the change in sediment storage.

An important issue is the sufficient precision when comparing two sediment budgets (Reid and Dunne, 2003). Both surveys need to be conducted in a similar way and should be comparable.

The MZZ catchment was subdivided in land units depending on their topographical position (e.g. on top of a cliff), homogenous characteristics (e.g. slope gradient) or the presence of a SWC approach (e.g. non-grazing policy). The land units had natural or parcel boundaries and might hold different land-use types. Within a land unit, the different land-use types were described by mean values for different characteristics (e.g. slope, stone bund density, rock fragment cover and vegetation cover). Land-use maps for 2000 and 2006 were established through field surveying. The appropriate temporal scales were selected whereby parameters of the sediment budget for 2000 resulted from three years of experimental data collection (1999–2001). The 2006 sediment budget represents the situation after implantation of SWC measures, allowing a detailed comparison of both sediment budgets.

Characterization of land use

Land-use types

Land use was classified as cropland (comprising rainfed, temporary fallow, and irrigated land), grassland, exclosures, housing and rangeland (Nyssen *et al.*, 2008b). The land-use class of rain-fed cropland includes different crop production systems: one system based on a three year rotation of tef-grass pea-cereals, one system based on a two year rotation of cereals-horse beans, and a very flexible crop production system in the lower part of the catchment allowing various crops with the notable exception of beans (Nyssen *et al.*, 2008b). The irrigated gardens are land with a structural practice of irrigation. According to the farmers, irrigation in this area became possible because there is more water in the river throughout the year after upper slopes were converted from rangeland to exclosure. Tef fields, which are occasionally irrigated with runoff diverted from gullies towards the end of the rainy season, are not included in this category.

As suggested by the Food and Agriculture Organization (FAO, 1988), the land-use types of rangeland and grasslands were defined following the specific objectives of the survey. Rangeland was defined here as areas that are grazed by livestock during at least one period of the year. All rangeland in the catchment is owned by the local village communities, and often some restrictions (type of livestock, period of the year) exist. Rangeland is used not only for grazing livestock, but also for collection of fuelwood. Grasslands are defined in this study as areas that have as main function to produce grass that can be harvested through cut-and-carry.

Exclosures are aimed at protecting natural resources (vegetation, soil and water); the communities also harvest grass and wood out of most exclosures or intend to do so.

Farms and housing compounds areas have been measured around the outer wall. In each land unit, measurements of slope gradient were done by clinometer (Suunto), at representative places over the total land unit length and in both directions, allowing to calculate the average slope gradient (accuracy: ±1%) per land unit.

When stone bunds were present, two slopes were measured: the current slope (measured from the top of stone bund till the foot of the upslope stone bund) and the initial slope of the soil surface before implementation of stone bunds, an estimate was made by measuring from the middle of the lower field below the bund to the middle of the upper field.

Vegetation cover (in a percentage; accuracy: ±10%) was visually estimated for the different land units. Topsoil texture classes were assessed in the field (McRae, 1988).

Land-use mapping

Land use of the study area was mapped in 2000 (Naudts, 2001) and 2006 (Clymans, 2007) with a handheld global positioning system (GPS) (e-Trex Euro, Garmin), whereby homogenous land uses, larger than 20 m in their largest dimension were mapped individually. The land-use maps were produced in a geographical information system (GIS) environment (MapInfo Professional 6·0).

The temporal comparison of the 2000 and 2006 maps used the same classification in both years and the maps were subdivided in the same land units (Figure 4).

Sources and sinks of sediment

This study looked at the total sediment mass produced by water erosion in one year. Other geomorphological processes [tillage erosion (Nyssen *et al.*, 2000b), mass movements (Nyssen *et al.*, 2003a), rock fragment displacements (Nyssen *et al.*, 2006b)] are responsible for important sediment fluxes within the catchment, but do not contribute to the final sediment export (Nyssen *et al.*, 2008a); hence they were not included in the analysis of the sediment budget.

At the side of sediment production, four sources were considered, three comprising the total sediment mass produced by sheet and rill erosion for (a) cropland, (b) exclosures and grassland and (c) rangeland, and one (d) for sediment produced by gully erosion.

Part of the eroded sediment is deposited again within the catchment behind check dams or stone bunds, within exclosures or as debris fans.

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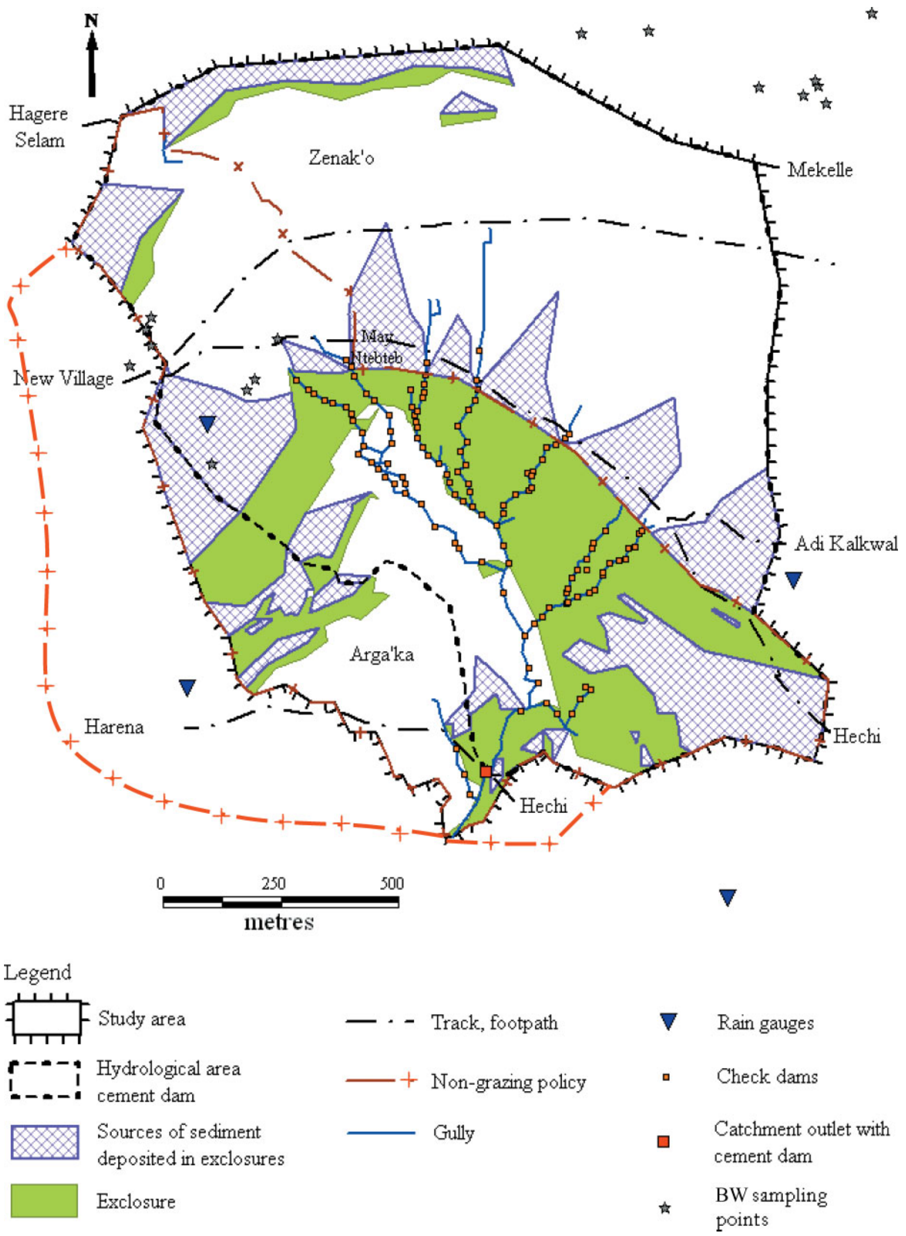

Figure 4. MZZ catchment with location of SWC techniques (in 2006) as well as research instrumentation. BW stands for above-ground biomass. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Sheet and rill erosion

Sheet and rill erosion (ShR) are two main erosion processes, responsible for 67% of the total mass of soil loss in the MZZ catchment before catchment management (Nyssen *et al.*, 2008a). The total sediment production (in t y^{-1}), due to sheet and rill erosion, of the catchment can be calculated as:

$$ShR_s = \sum_{i=1}^{n} SR_s \cdot A_{i,s} \quad (1)$$

and

$$ShR_{tot} = \sum_{s=1}^{n} ShR_s \quad (2)$$

where ShR_s is the soil loss by sheet and rill erosion for one land-use category (in t y^{-1}); ShR_{tot} is the soil loss by sheet and rill erosion within the catchment (in t y^{-1}); SR_s is the specific soil loss rate (in t ha^{-1} y^{-1}) for a land-use category *s*; $A_{i,s}$ is the area (in hectares) of land unit *i*, for land-use category *s*.

Soil loss rates were measured in 1998–2001 for the different land-use types of the catchment (Table I) by Nyssen *et al.* (2009c), complemented with calculated average soil loss rates for non-grazed arable land in 2006.

Effect of stubble grazing abandonment on sheet and rill erosion rates

All soil loss rates used in this study (Table I) were obtained in the Dogu'a Tembien district, and mostly within the MZZ catchment. However, major changes occurred since 2000 on arable land with the introduction of a non-grazing policy resulting in lower sediment production. Hence, corrections needed to be made for (1) greater mulch/vegetation cover during the small spring rains and (2) larger biomass content in topsoil during the rainy season. The effect on sediment production will be larger for change in mulch/vegetation cover (Gyssels *et al.*, 2005) than for an increase in biomass in the topsoil. Yet, the actual major soil loss events are situated in the rainy season, when the land has been tilled, thus the second correction factor will have a larger effect.

In June 2006, at the beginning of the rainy season and before the first tillage operation, all above-ground biomass was collected from different 3 m × 3 m sample plots (BW

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Table I. Measured mean soil loss rates by sheet and rill erosion (in t ha^{-1} y^{-1}) for each land-use category in the MZZ catchment (after Nyssen *et al.*, 2009c)

Land-use category	Average yearly soil loss rate (t ha^{-1} 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.

sampling points, on Figure 4). In total 17 plots were sampled, nine within the MZZ catchment (Zenak'o) in non-grazed cropland and eight outside the catchment in a nearby cropland with stubble grazing (Ziban Kerkata), in similar soil and topographical positions. All plant material (stubble, crop residue, weeds) was removed from the topsoil and other characteristics were noted: i.e. topsoil texture, vegetation and mulch cover (in a percentage, visually estimated before the removal of the above-ground biomass), rock fragment cover and previous crop type. In the laboratory all plant residues were weighed and per sample, a conversion factor to dry biomass was obtained by oven drying a subsample, following procedures of Smit *et al.* (2000) and De Baets *et al.* (2006). In the next step a correction factor was established for the sediment production due to sheet and rill erosion. Typical relations between relative sheet and rill erosion and soil cover (in a percentage) are of the negative exponential type (Elwell and Stocking, 1976; Gilley *et al.*, 1986; Gyssels *et al.*, 2005; Smets *et al.*, 2008; Snelder and Bryan, 1995). Based on the 17 plots a calibration curve was set up between above-ground biomass and vegetation cover.

Calculated through an exponential relation (Gilley *et al.*, 1986; Gregory, 1982):

$$VC = 100(1 - e^{-b\mathrm{BW}}) \quad (3)$$

where VC represents vegetation cover (in a percentage); BW represents the above-ground biomass (in kg m^{-2}); b is a regression coefficient. VC was converted into relative erosion values, compared to land without VC, by using (Gyssels *et al.*, 2005):

$$Er_{BW} = e^{-u\mathrm{VC}} \quad (4)$$

where Er_{BW} represents the relative erosion in comparison to land without VC; *u* is the experimental coefficient (>0), indicating the effectiveness of the VC in reducing interrill and rill erosion rates.

Based on the ratio between non-grazing and stubble grazing, the average soil loss rate was corrected by:

$$SR_{BW,NG} = SR \times Er_{BW,NG}/Er_{BW,SG} \quad (5)$$

where $SR_{BW,NG}$ represents the soil loss rate for non-grazing (in t ha^{-1} y^{-1}), corrected for impact of BW; SR is the soil loss rate pre-catchment management (in t ha^{-1} y^{-1}); $Er_{BW,NG}$ is the relative erosion of a non-grazed cropland in comparison to land without VC, taking into account BW; $Er_{BW,SG}$ is the relative erosion of a stubble grazing area in comparison to land without VC, taking into account BW.

In a second step, a correction for additional biomass strength within the topsoil after tillage was estimated. All BW is ploughed under over an average tillage depth of 0·075 m (Nyssen *et al.*, 2000b), where the plant material reinforces the topsoil and decreases the sediment production due to sheet and rill erosion. The concentration of buried biomass (SD) was calculated by dividing the BW by tillage depth (0·075 m). The effect of SD on sheet and rill erosion (Er_{SD}) is (Foster, 2005; Gyssels *et al.*, 2005):

$$Er_{SD} = e^{-n\mathrm{SD}} \quad (6)$$

where Er_{SD} is the relative erosion, accounting for buried BW; SD is the buried biomass (in kg m^{-3}); *n* is the experimental coefficient, set at 0·6 (Foster, 2005).

Based on the ratio between buried biomass under non-grazing and stubble grazing conditions, the soil loss rate was then corrected with an equation similar to Equation 5.

In a third step, the two correction factors were combined to estimate a new average soil erosion rate for non-grazed cropland. To determine the relative importance of both correction factors, the year was divided in two periods. Arable land is covered with additional above-ground biomass from October (end of rainy season and harvest) till May. In May more than 50% of the arable land is ploughed for the first time. From May till October there is additional soil erosion resistance due to biomass incorporated in the plough layer. As 90% of the annual rain falls between May and October and rain intensity and kinetic energy are also larger (Nyssen *et al.*, 2005), it can be assumed that on average 95% of the water erosion occurs in the period May till October.

The final correction equation for the average soil loss rate of non-grazed cropland, based on the soil loss rate of cropland with stubble grazing, is:

$$SR_{NG} = SR \times (0{\cdot}05 \times Er_{BW,NG}/Er_{BW,SG} + 0{\cdot}95 \times Er_{SD,NG}/Er_{SD,SG}) \quad (7)$$

where SR_{NG} is the soil loss rate corrected for the effect of non-grazing policy (in t ha^{-1} y^{-1}); $Er_{SD,NG}$ is the relative erosion of a non-grazed cropland in comparison to land without VC, taking into account buried biomass; $Er_{SD,SG}$ is the relative erosion of a stubble grazing area in comparison to land without VC, taking into account buried biomass.

Gully erosion

For the sediment budget of 2000 an average gully erosion rate of 4·1 t ha^{-1} y^{-1}, measured in MZZ by Nyssen *et al.* (2006a) was used. In 2006 no new gullies had developed and in most gullies restoration (Figure 3B) is visible related to catchment management and lower runoff depths. Locally, minor gully bank erosion is still visible. Hence, for 2006 an area-specific short-term gully erosion rate of 1·1 t ha^{-1} y^{-1} was used (Nyssen *et al.*, 2006a) based on a comparison between the present-day change in volume of four similar gully systems in the study area and their total volume and estimated age, showing a slow down in gully development (Nyssen *et al.*, 2006a).

For both years, total soil loss was calculated as:

$$Gull = SR_G \times A \quad (8)$$

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where Gull represents the total soil loss by gully erosion within the catchment (in t y^{-1}); SR_G is the specific soil loss rate by gully erosion (in t ha^{-1} y^{-1}); A is the catchment area (in hectares).

Sediment trapping behind check dams

Before catchment management, control of the main gully draining the catchment proved difficult and the few earlier established check dams had all been washed away. Since the implementation of catchment management, 242 check dams have been built in the gully system to combat gully erosion and to stabilize the gullies (Figure 3B). The check dams functioned as sediment traps or sediment sinks over three years (2004–2006) and the mass of deposited sediment was assessed as:

$$CH_{tot} = \sum_{i=1}^{n} \frac{V_{ch,i} dBD_i}{3} \quad (9)$$

where CH_{tot} is the total sediment mass deposited yearly behind check dams (in t y^{-1}); $V_{ch,i}$ is the volume (in m^3) deposited behind check dam i over the three year period since their construction; dBD_i is the dry bulk density (in t m^{-3}).

The gully system with check dams was mapped with GPS. For the estimation of the total sediment volume trapped behind check dams subsamples were used: volume measurements were carried out behind 121 check dams (50%). Generalized geometrical shapes were used to assess total sediment storage volumes; besides the most common pyramidal shape with a triangular base (Figure 5), other shapes sometimes occurred, such as beams and pyramids with a rectangular base. Depth measurements were made by augering until the original soil surface was retrieved or rocks prevented from augering. Sometimes, sediment was deposited in between two check dams, triggered by vegetative obstacles or reduction of slope gradient inducing a lower transport capacity. The same methodology was used for assessing these volumes as for deposition behind check dams. The total sediment volume deposited behind check dams (Equation 9) accounts for both deposition behind and in between check dams.

Dry sediment bulk density (dBD) measurements were made for a representative sample of check dams (12%), distributed over all gullies, whereby dBD was determined from core ring samples of 100 cm^3 that were oven dried for 48 hours at a temperature of 105 °C.

Sediment trapping behind stone bunds

A second sediment sink are the stone bunds, which have been built over large areas of the Tigray Highlands during the last two decades (Nyssen *et al.*, 2007). The off-site effects, such as improved hydrological conditions in the catchment (Nyssen *et al.*, 2009d) and decreased sediment yield (Nigussie *et al.*, 2005), are definitely positive but the on-site effects call for a more detailed analysis.

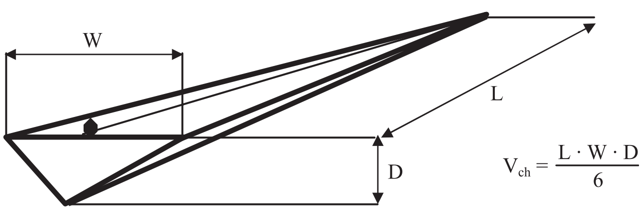

Figure 5. Schematic representation (perspective) of the most common shape of sediment deposition behind check dams in a gully: black dot represents the deepest point, depth (*D*, in metres), length (*L*, in metres) and width (*W*, in metres)

Sediment trapped by stone bunds was calculated as:

$$SB = TE_{i,sb} \times SR_i \times A_i \quad (10)$$

and

$$SB_{tot} = \sum_{i=1}^{n} SB_i \quad (11)$$

where: SB_i is the total sediment mass deposited behind stone bunds (in t y^{-1}) in a land unit i; $TE_{i,sb}$ represents the sediment trapping effectiveness for stone bunds in land unit i; SR_i is the area-specific soil loss rate (in t ha^{-1} y^{-1}) in land unit i; A_i is the area of land unit i; SB_{tot} is the total sediment mass deposited behind stone bunds (in t y^{-1}) within the catchment.

A stone bund density map for the MZZ catchment in 2000 was created by Naudts (2001). Since 2004, new stone bunds have been built and existing stone bunds were optimized (i.e. building and renewal of stone bunds, digging trenches) resulting in a higher stone bund density in the catchment and higher TE of the stone bunds. Stone bund densities for the various land units have been measured in 2006 by running several downslope transects. The number of stone bunds over transect distance was converted to average stone bund densities (in m ha^{-1}).

Based on typical values for sediment trapping effectiveness (TE_{sb}) of stone bunds depending on their quality (Nyssen *et al.*, 2007), we used TE_{sb} values for the various combinations of land use and stone bund density that occurred in the catchment in 2000 and 2006 (Table II).

Sediment trapping by exclosures

A third sediment sink in the catchment are the exclosures. The effect of closing is the regeneration of grasses, shrubby and woody vegetation on steep slopes. The exclosures are generally established on steep slopes downslope from sediment source areas, which were mapped by GPS both for the 2000 and 2006 situations (Figure 4). The basic assumption was that all sediment produced in the sediment delivery area upslope of the exclosures and that was not trapped behind the stone bunds, was then trapped in the exclosures. This also means that all sediment produced in exclosures was redeposited within exclosures. This is confirmed by the fact that in 2006 there were no signs of active debris fan building on level land at the foot of exclosures. For the small 'catchments of exclosures', total soil loss was calculated, the mass of which was corrected by the mass trapped behind stone bunds. The difference between the sediment produced by sheet and rill erosion and the sediment trapped behind stone bunds in the 'catchment of exclosures' gives the sediment trapped in exclosures.

$$EX_s = \sum_{i=1}^{n} \left(ShR_i - SB_i \right) \quad (12)$$

$$EX_{tot} = \sum_{s=1}^{n} EX_s \quad (13)$$

where EX_s is the total sediment mass deposited within exclosures (in t y^{-1}) for a catchment s draining to an exclosure; ShR_i is the soil loss by sheet and rill erosion (in t y^{-1}) for a land unit i in a catchment draining to an exclosure; SB_i is the total sediment mass deposited behind stone bunds (in t y^{-1}) in land unit i; EX_{tot} is the total sediment mass deposited within exclosures (in t y^{-1}) in the catchment.

Sediment deposited in debris fans

The mass of sediment deposited in debris fans (DF) in 2000 was assessed by Nyssen *et al.* (2008a); in 2006, a new survey of active debris fan areas was carried out.

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Table II. Sediment trapping effectiveness (TE) of stone bunds (SB) for different land-use types in 2000 and 2006 (based on Nyssen *et al.*, 2007)

Land use	TE of stone bunds in 2000		TE of stone bunds in 2006	
Cropland/rainfed, irrigated and fallow	No SB	0%	No SB	0%
	SB density <200 m ha^{-1}; besides broad spacing, the quality of the SB was rather low in 2000	20%	SB density <200 m ha^{-1}; SB have been rebuilt in 2004 and new SB have a higher TE	40%
	200 m ha^{-1} < SB density <400 m ha^{-1}	40%	As in 2000 – but the SB are new	60%
	SB density >400 m ha^{-1}; TE close to the average value calculated by (Desta *et al.*, 2005)	60%	As in 2000 – but the SB are new and result in a higher TE than the average	80%
Exclosures	No SB	0%	No SB	0%
	SB density <400 m ha^{-1}; SB in exclosures are or rather low quality, the higher average slope gradient in exclosures results also in a lower TE than cropland	20%	As in 2000 – but the SB are new	40%
	SB density >400 m ha^{-1}	40%	As in 2000 – but the SB are new	60%
Rangeland	No SB	0%	No SB	0%
	SB density <400 m ha^{-1}; SB are easily broken due to high runoff rates and roaming livestock	10%	As in 2000	10%
	SB density >400 m ha^{-1}	20%	As in 2000	20%
Grassland	No SB	0%	No SB	0%
	When SB are present (rarely) they have a high TE; factors controlling this are low sediment production rates and low slope angles resulting in lower runoff volumes.	80%	As in 2000	80%

Catchment sediment yield

Sediment yield (SY) is the mass of sediment leaving the catchment, both as suspended load, and as bedload, which in our case is negligible because coarse sediment is trapped behind check dams in the gully system. SY was assessed by two methods:

(1) By establishing sediment budgets where SY is the difference between the above calculated sediment sources and sediment sinks:

$$SY = ShR_{tot} + Gull_{tot} - (CH_{tot} + SB_{tot} + EX_{tot} + DF_{tot}) \quad (14)$$

(2) By runoff discharge measurements and suspended load sampling:

$$SY_p = \sum_{\Delta t}^{P} Q_{out} \cdot SC \quad (15)$$

$$SY_{tot} = \sum_{P=1} SY_p \quad (16)$$

where SY_p is the sediment yield (in kilograms) during a rainfall event; Q_{out} is the outgoing runoff discharge (in m^3 s^{-1}) at a given moment during the event; SC is the suspended sediment concentration (in kg m^{-3}) at a given moment during the event; SY_{tot} is the total sediment yield (in kilograms) for all rainfall events of the year 2006.

Runoff discharge measurements at the catchment outlet were carried out throughout the rainy season of 2006 (Nyssen *et al.*, 2009d). Every day, rainfall depth measurements were also conducted. Sediment yield estimates for 2006 are based on (1) a regression between runoff discharge and suspended sediment concentration, and (2) a regression between sediment yield of a rainfall event and rain depth.

At a cement dam, located nearby the catchment outlet, 38 runoff samples were taken for analysis of sediment concentration in the period 25 July 2006 and 5 September 2006 (rainy season) (Figure 6). Sampling was spread over the rainy season, over various runoff discharges and at both the rising and falling limbs of flash floods. Runoff samples of known volume were filtered (Whatman paper No. 12) and sediment mass was determined in the laboratory by oven drying the filter papers at 105 °C for 24 hours.

Both the cement dam and an upslope constructed siltation pond (by gabions) also captured sediment in suspension which normally, in absence of both structures, would have left the catchment. These volumes were also taken into account as sediment yield. Sediment deposits behind both dams (Figure 6) were measured at the end of the rainy season: the total sediment deposition area (measured by theodolite) was multiplied by average sediment thickness over embedded, painted flat stones, installed before the rains started.

Results

Land use and land-use changes

The study area consists of two parts, the upper part (Zenak'o) and the lower part (Argak'a) separated by a sandstone-limestone

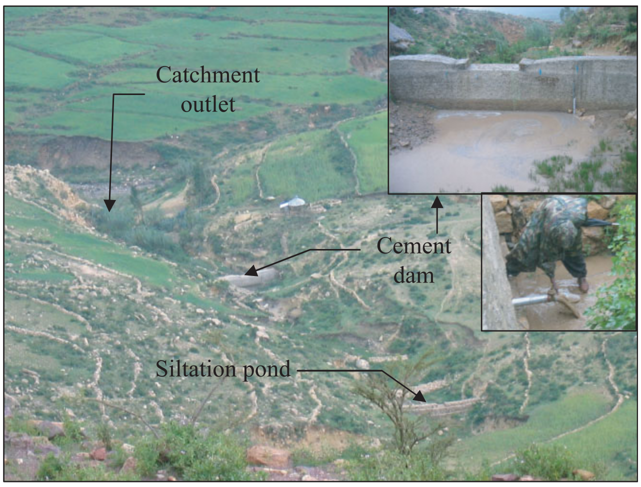

Figure 6. Measurement sites for sediment yield at the outlet of MZZ catchment (August 2006). Runoff sediment yield measurements took place at the pipe outlet of the cement dam, which was continuously opened as no irrigation water was needed during the rainy season. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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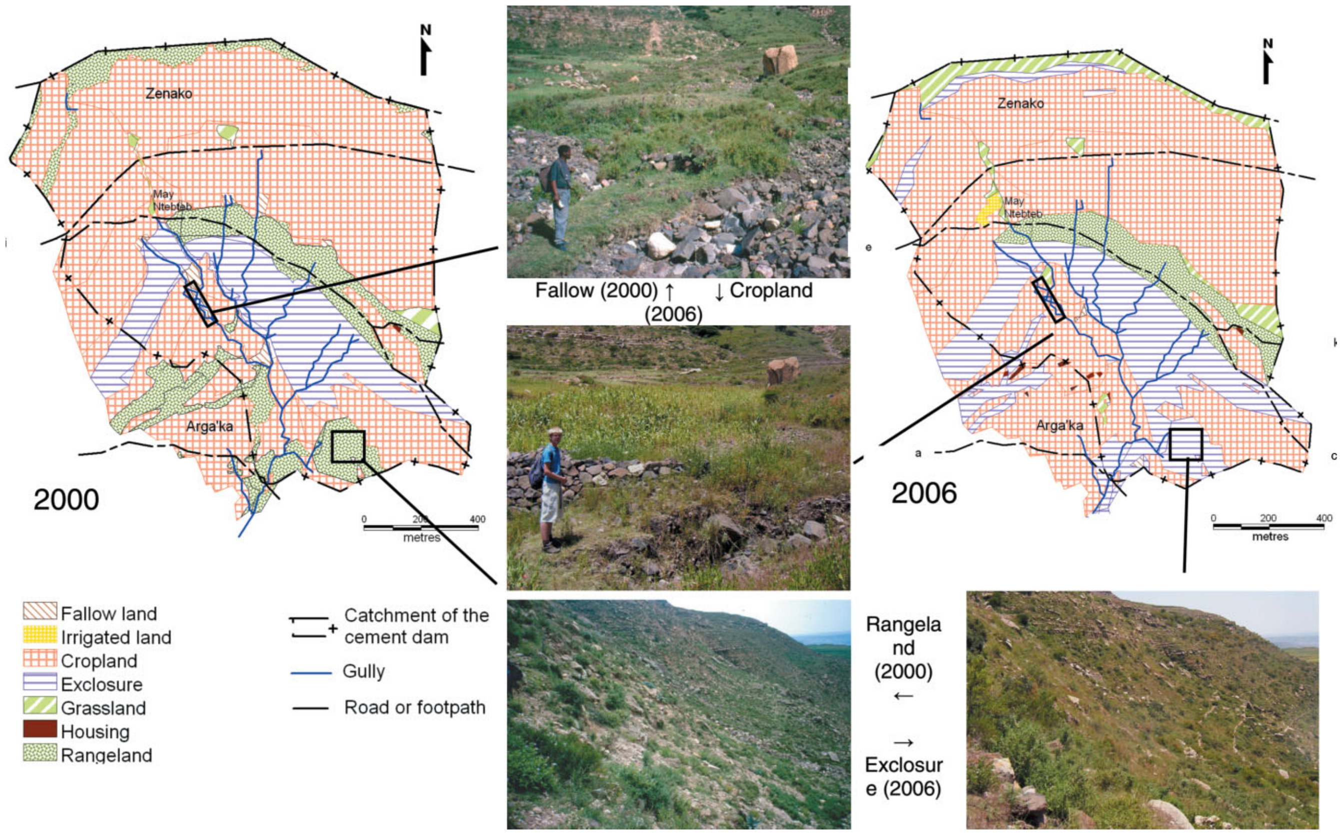

Figure 7. Land-use maps of MZZ catchment in 2000 and 2006 with photographs of typical land uses in both years. Based on Naudts (2001), Clymans (2007) and field observations over 1997–2008. This figure is available in colour online at www.interscience.wiley.com/journal/espl

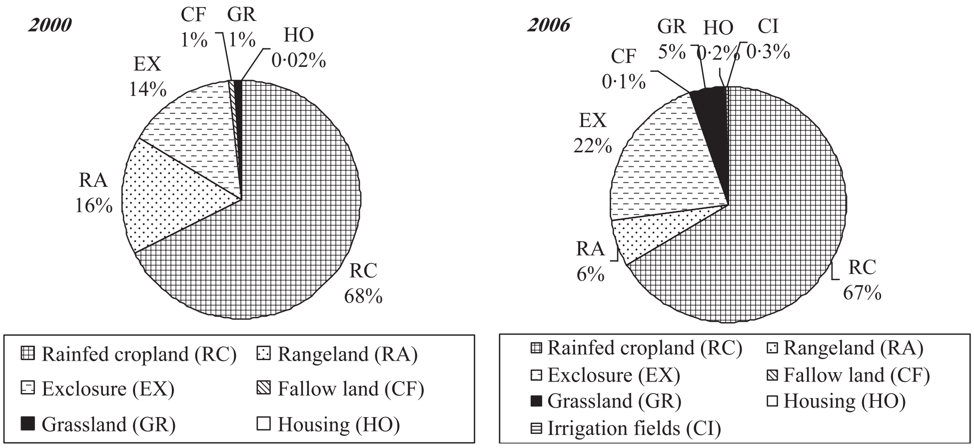

Figure 8. Relative areas of land use types in 2000 and 2006.

cliff. The road from Mekelle to Hagere Selam, on the ridge, defines the northern border of the catchment. For the assessment of the sediment budget the catchment was split up in (1) the partial, hydrological, catchment draining to the cement dam (164·9 ha or 88·1%) for which all necessary data were available (Figure 4) and (2) a rest catchment (22·3 ha or 11·9%) as the remnant area for which not all data were available.

Land use in MZZ is inherently intensive rainfed peasant cultivation of cereals and pulses (67% or 125 ha in 2006) with scattered scrub and grass vegetation and rock outcrops. Next, exclosures (closed areas) covered 22% (41 ha) followed by rangeland with 6·5% (12·2 ha). Grassland occupied almost 5% (9 ha). Furthermore there were smaller land-use categories like housing (0·3%), irrigated cropland (0·3%), and fallow land (0·1%) (Figure 7). In the year 2000, rainfed cropland covered 67·5% of the study area while rangeland covered 16% (30 ha) and exclosures 14·2% (27·5 ha). The other land-use categories were only small: fallow land (0·94%), grassland (0·83%) and housing (0·02%). Irrigated fields were only present in the form of a few irrigated gardens.

The total area covered by rainfed crop was almost constant from 2000 to 2006. The most important change in land use (Figure 8) was the decrease of rangeland with 17 × 8 ha. Only one-third of the original rangeland remained in 2006. This was concomitant with an increase in exclosures with 13·3 ha and in grassland with 7·5 ha. Hence, the area of exclosures was almost doubled and grassland cover in 2006 was even the eight-fold of 2000.

Important changes of rangeland into exclosures were observed in the lower part of the catchment (Arga'ka). This is related to the implementation of the non-grazing policy in that area, which had already a positive effect on vegetation cover, although it was still less than that on most steep slopes (older exclosures). In the northern part along the ridge road, rangeland that was used by passing herds to the market town of Hagere Selam has been converted into grassland. Also here a transition of degraded land to a densely vegetated area was noticed. Fallow land disappeared almost completely in 2006, while irrigated cropland was a new land-use category in the study area. There was also an expansion of farms and compounds in the area. The establishment of irrigated fields within the study area indicates improved water supply due to higher infiltration rates in the upper catchment (Nyssen *et al.*, 2009a, 2009d). These steep slopes between the upper part (Zenak'o) and lower part (Argak'a) of the MZZ catchment were covered with exclosures at both periods (east–west band on the land-use maps, Figure 7). In 2006, degraded rangeland still formed an important sediment source for exclosures and check dams at the east of the catchment. In this strip-like degraded rangeland, free grazing was allowed since the inhabitants of the nearby village opposed closing it. In the lower Argak'a there was a mixture of rainfed cropland and rangeland in 2000 or exclosures in 2006. Although slopes are relatively gentle, soils are less fertile and soil erosion in the past led to frequent outcropping of calcic and petrocalcic horizons. Fallow land at unstable gully heads and debris fans in 2000 was mostly converted to arable land in 2006 (Figure 7).

Specific soil loss rates in cropland

Before estimating soil loss rates per land unit, the impact of the non-grazing policy needed to be assessed. Using Equations 3, 4 and 5, links were established, for non- and stubble grazing areas, between above-ground biomass, vegetation and stubble cover and relative erosion. These relations are consistent with those found elsewhere (Gilley *et al.*, 1986; Gregory, 1982; Gyssels *et al.*, 2005) and allowed the calculation of the corrected soil loss rate induced by mulch cover for the period before ploughing (Table III).

The non-grazing policy increased mean surface cover by vegetation and straw mulch at the end of the rainy season from 23% to 46%. Between vegetation cover and relative erosion a negative exponential relationship exists (Elwell and Stocking, 1976; Gilley *et al.*, 1986; Gyssels *et al.*, 2005; Smets *et al.*, 2008; Snelder and Bryan, 1995) whereby, at low values, a small increase in vegetation cover results in a large decrease of relative erosion. Hence, it is estimated that (Table III) during the early spring rains, before tillage, soil loss due to sheet and rill erosion on arable land under non-grazing was reduced to one-third of the original mass of sediment produced on cropland.

Table III. Correction factors for sheet and rill erosion rates in non-grazing arable land, as induced by above-ground biomass before tillage occurs, and additional biomass incorporated in the plough layer

	Stubble grazing	Non-grazing
Above-ground biomass before tillage occurs		
BW[a] ($t\ ha^{-1}$) (±standard deviation)	0·18 (±0·09)	0·42 (±0·21)
VC[b] (%)	23 (±5)	46 (±23)
Er_{BW}[c]	0·33 (0·16 – 0·68)[d]	0·10 (0·02 – 0·46)[d]
Additional biomass incorporated in the plough layer		
SD[e] ($kg\ m^{-3}$) (±standard deviation)	0·23 (±0·26)	0·56 (±0·28)
Er_{SD}[f]	0·87	0·71

[a] Mean above-ground biomass on unploughed arable plots in June 2006.
[b] Vegetation and straw mulch cover.
[c] Relative erosion rate taking into account the effect of above-ground biomass, in comparison to bare, whereby Er_{BW} = 1 for land with total absence of stubble, weeds and mulch and Er_{BW} = 0 for land with a full cover; calculated using Equation 4, with coefficient u = 0·0492.
[d] Between brackets minimum and maximum value, related to values taken by coefficient u used in Equation 4.
[e] Biomass incorporated in the 7·5 cm deep plough layer.
[f] Relative erosion rate accounting for the effect of buried biomass, in comparison to land without vegetation cover (Equation 6, with coefficient n = 0·6), whereby Er_{SD} = 1 for land with total absence of stubble, weeds and mulch, and Er_{SD} = 0 for land with full cover.

Yet, most rains fall in the rainy season when fields are ploughed; there is little vegetation cover, but additional incorporated biomass strengthens the soil in the plough layer. This increase in soil resistance had also a decreasing effect on soil loss (Equation 6; Table III).

Combining both correction factors (Equation 7), taking into account their relative importance, the average soil loss rate for cropland without stubble grazing was assessed at 7·9 $t\ ha^{-1}\ y^{-1}$, which corresponds to a reduction of approximately 21% due to incorporated residue in the plough layer and mulching. This value was applied to cropland under non-grazing policy in the year 2006.

Sediment budgets for 2000 and 2006

Rates of the various geomorphic processes were calculated for the catchment in 2000 and 2006 (Table IV) and flow charts were established where the geomorphic processes and their rates are visualized (Figure 9).

Sediment production: the sediment sources

The mean specific soil loss rate for water erosion decreased from 14·3 ± 5 $t\ ha^{-1}\ y^{-1}$ in 2000 to 9 ± 3 $t\ ha^{-1}\ y^{-1}$ in 2006.

Based on their area and characteristic average soil loss rates, assessed by Nyssen *et al.* (2008a, 2009c) and corrected where necessary for the year 2006 (Table I), soil loss calculations for each land-use class were made.

In 2000 the total soil loss rate by sheet and rill erosion in the entire catchment was 1901 ± 855 $t\ y^{-1}$, corresponding to a specific rate of 10·2 ± 4·6 $t\ ha^{-1}\ y^{-1}$. With a total rate of 1277 ± 837 $t\ y^{-1}$, cropland produced the major part of the total rate due to sheet and rill erosion. Furthermore rangeland produced 530 ± 161 $t\ y^{-1}$ while exclosures and grassland were responsible for 94 ± 69 $t\ y^{-1}$. Although rangeland (17·4 ± 5·6 $t\ ha^{-1}\ y^{-1}$) had a higher specific soil loss rate than cropland (9·9 ± 6·5 $t\ ha^{-1}\ y^{-1}$), the total rate for cropland was higher due to its large fraction of the catchment (69% or 129 ha).

In 2006 the total rate for sheet and rill erosion in the entire catchment was calculated at 1470 ± 537 $t\ y^{-1}$, corresponding to a specific rate of 7·9 ± 2·9 $t\ ha^{-1}\ y^{-1}$. The non-grazing policy introduced in large parts of the catchment from 2004 onwards, had resulted in a lower specific soil loss rate on cropland (7·9 $t\ ha^{-1}\ y^{-1}$) compared to cropland where stubble grazing is allowed (9·9 $t\ ha^{-1}\ y^{-1}$). Although total cropland area remained roughly the same, the total rate on cropland was reduced to 1109 $t\ y^{-1}$ (–14%). The remaining 360 $t\ y^{-1}$ was produced by sheet and rill erosion on rangeland (212 ± 64 $t\ y^{-1}$) and on exclosures and grassland (149 ± 106 $t\ y^{-1}$). Land conversion to exclosure explains the reduction of the total rate for rangeland.

Exclosures have a far lower specific soil loss rate, i.e. 3·5 ± 2·6 $t\ ha^{-1}\ y^{-1}$ against 17·4 $t\ ha^{-1}\ y^{-1}$ for rangeland. Compared to 2000, the total rate by sheet and rill erosion was reduced with 441 $t\ y^{-1}$ or 23%. Whereas in 2000 sheet and rill erosion accounted for 71% of the total sediment production by water erosion, this share increased to 88% in 2006, which is explained

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Table IV. Rates of geomorphic processes in the MZZ catchment (187 ha)

Process	Land use	2000 Area (ha)	2000 Specific rate (t ha^{-1} y^{-1})	2000 Total rate (t y^{-1})	2006 Area (ha)	2006 Specific rate (t ha^{-1} y^{-1})	2006 Total rate (t y^{-1})
Sheet and rill erosion in cropland[a]	Cropland (grazing)	129	9·9 ± 6·6	1277 ± 837	62	9·9 ± 6·6	609 ± 405
	Cropland (non-grazing)	0	7·9 ± 5·2	0	63	7·9 ± 5·2	500 ± 330
	Subtotal	129	9·9 ± 6·6	1277 ± 837	125	8·9 ± 4·2	1109 ± 522
Sheet and rill erosion in exclosures and grassland[b]	Exclosures	27	3·5 ± 2·6	93 ± 69	41	3·5 ± 2·6	143 ± 106
	Grassland	2	0·7	1	9	0·7	6
	Subtotal	28	3·3 ± 2·5	94 ± 69	50	3·0 ± 2·0	149 ± 106
Sheet and rill erosion in rangeland[b]		30	17·4 ± 5·6	530 ± 161	12	17·4 ± 5·6	212 ± 64
Total sheet and rill erosion		187	10·2 ± 4·6	1901 ± 855	187	7·9 ± 2·9	1470 ± 537
Gully erosion[c]		187	4·1 ± 1·9	767 ± 364	187	1·1 ± 0·8	206 ± 146
Sediment production (water erosion)		187	14·3 ± 5·0	2668 ± 929	187	9 ± 3·0	1676 ± 556
Sediment deposition	Check dams[d]	0	0	0	187	0·9 ± 0·04	170 ± 7
	Stone bunds[e]	164	3·1 ± 0·6	503 ± 103	166	5·0 ± 1·2	836 ± 207
	Exclosures[f]	26	11·9 ± 3·0	311 ± 79	41	7·7 ± 3·1	312 ± 126
	Debris fans[g]	187	1·4	263	187	0	0
	Total	187	5·8 ± 0·7	1077 ± 130	187	7·1 ± 1·3	1319 ± 242
Sediment yield		187	8·5 ± 5·0	1591 ± 938	187	1·9 ± 3·2	357 ± 607

[a] Specific rate based on Nyssen *et al*. (2008a), based on mean monitored rates and adaptation for non-grazing according field measurements in 2006 (Table I).
[b] Specific rate based on Nyssen *et al*. (2008a), based on mean monitored rates.
[c] Specific rate based on Nyssen *et al*. (2006a), based on measurements of gully volumes and their age.
[d] Volume measurements during summer of 2006 for a three year period, in 2000 check dams were absent.
[e] TE based on Desta *et al*. (2005) and Nyssen *et al*. (2007).
[f] TE based on Descheemaeker *et al*. (2006c).
[g] Based on Nyssen *et al*. (2008a).

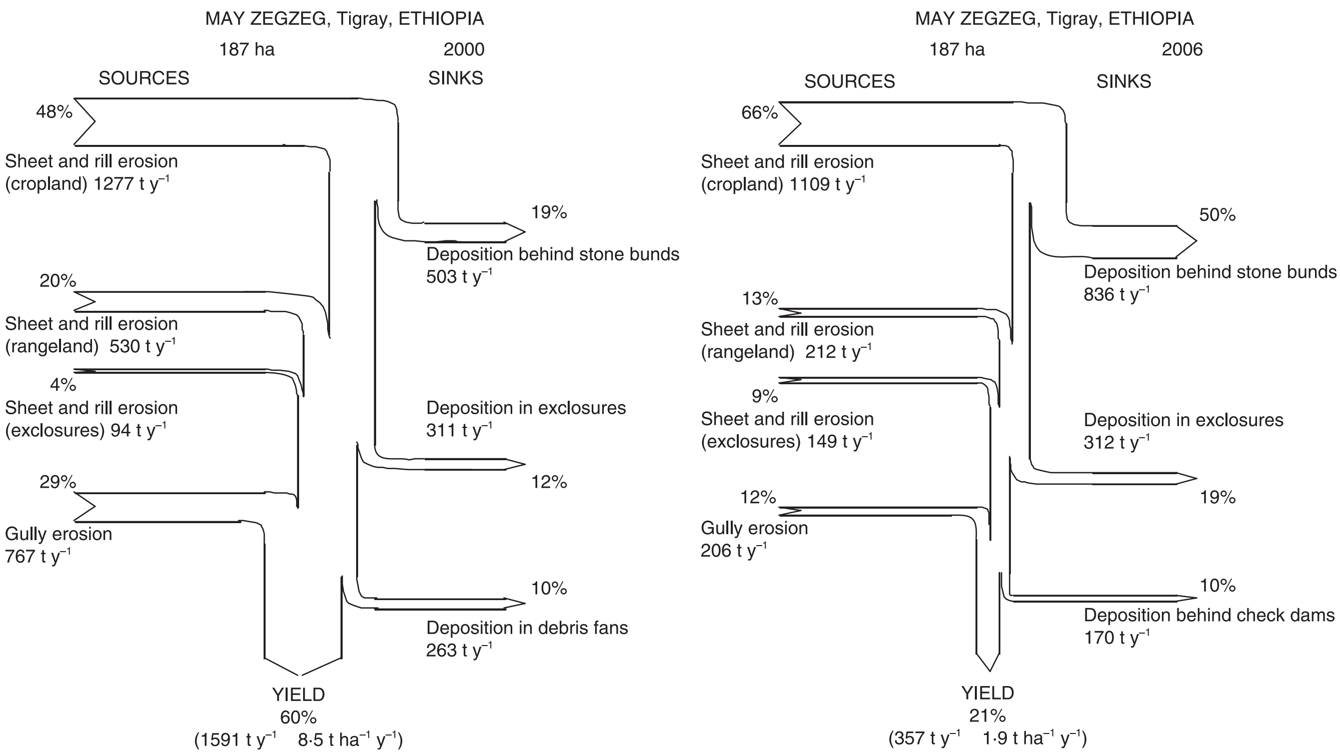

Figure 9. Sediment budgets for MZZ catchment in 2000 (left) and 2006 (right) with computation of sediment sources and sinks. Width of arrows is proportional to sediment masses involved.

by the relatively stronger decrease in sediment production by gullies.

While gully erosion was relatively active in 2000, in 2006 only at some places gully bank erosion was visible. A low specific soil loss rate, measured in recent years in nearby catchments (see earlier section) was used allowing the assessment of the gully erosion rate in 2006 at 206 ± 146 t y^{-1}, a reduction with 561 t y^{-1} (–73%) since 2000.

The total rate of sediment production by water erosion was 1676 ± 556 t y^{-1} (or 9 t ha^{-1} y^{-1}) in 2006, which is a decrease with 992 t ha^{-1} y^{-1} (–37%) since 2000, out of which 57% is explained by the reduction in gully erosion rates.

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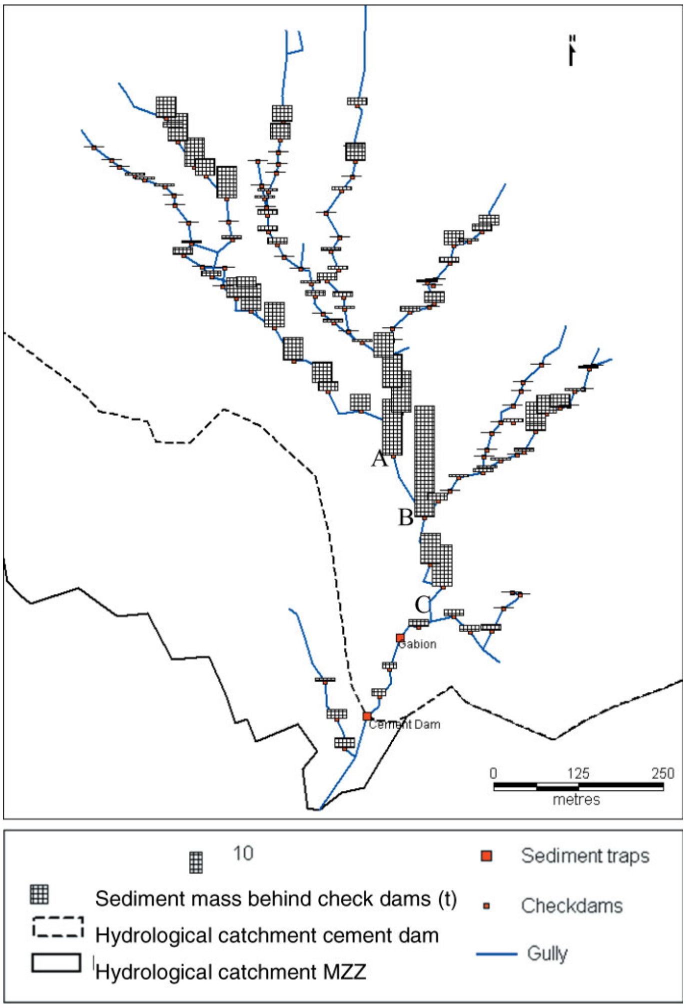

Figure 10. Measured sediment deposition (in tons) behind check dams in MZZ; A, B and C are junctions in the gully system. See Figure 4 for location in the catchment of the gully system with check dams. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Sediment storage: the sediment sinks

Gully as well as sheet and rill erosion are the dominant sediment sources in the catchment. Part of this sediment is deposited again within the catchment behind check dams in gully channels, or stone bunds in the intergully areas, within exclosures or debris fans. Whereas 40% of produced sediment was redeposited within the catchment in 2000, in 2006 this had increased to 79%.

Check dams have been installed in early 2004 to stop further development of gullies and to rehabilitate the gully beds. The check dams have functioned as sediment sinks since then. Over a period of three years (2004–2006) the total sediment mass trapped behind the check dams was measured at 511 t (Figure 10). Hence, 170 ± 7 t y^{-1} was deposited behind the check dams, corresponding to 13% of the total mass of deposited sediment within the catchment in 2006. It might be expected that these check dams will loose their TE when getting filled up with sediment. However with the current vegetation re-growth within the gullies it is likely that the vegetation will gradually complement the physical structures (Reubens *et al.*, 2009) (Figure 3B). Most sediment is deposited in the main lower gully system (Arga'ka). At gully confluences most sediment is accumulated (Figure 10). Less sediment is deposited behind check dams in the upper gully reaches on steeper slopes. This is attributed to the smaller capacity of these check dams in comparison to those on gentle slopes and to higher erosion rates in the drainage area of these check dams (e.g. strongly degraded rangeland in the eastern part of the catchment). At concave sites (mostly at junctions) a major part of coarser material (gravel and sand fractions of upslope eroded soil and gully banks) is deposited. In 2000, at such places deposition took place in debris fans. Gullies from the northwest have deposited most of the sediment (mostly finer black clay mixed with coarser material) before reaching junction A (Figure 10). Most of the sediment is trapped upstream of junction C with a maximum of more than 30 t behind the check dam at junction B. Most sediment is delivered by the eastern part of study area due to the presence of a large area of degraded rangeland, resulting in rapid infilling of small basins behind check dams.

A second sediment sink in the catchment are the stone bunds (Figure 2) built in cropland, rangeland and exclosures. A large part of the catchment was already covered with broad-spaced stone bunds in 2000 (164 ha) and in 2006 stone bunds covered 166 ha. The TE was improved by increasing stone bund density (Figure 11), the restoration of old stone bunds and digging of runoff collection trenches behind the bunds (Figure 2A). In 2000 the average specific trapping rate for stone bunds was $3{\cdot}1 \pm 0{\cdot}6$ t ha^{-1} y^{-1} or 503 ± 103 t y^{-1} while in 2006 the mean specific rate equalled $5 \pm 1{\cdot}2$ t ha^{-1} y^{-1} or 836 ± 207 t y^{-1} (Table IV). The increase is due to higher density of bunds, higher sediment storage capacity in the trenches behind the bunds, and the average better quality. This means an increase of the total trapping rate with 327 t y^{-1} (60%) between 2000 and 2006. In both years stone bunds were the major sediment sink in the study area, explaining 47% and 63% of the sediment deposition in 2000 and 2006.

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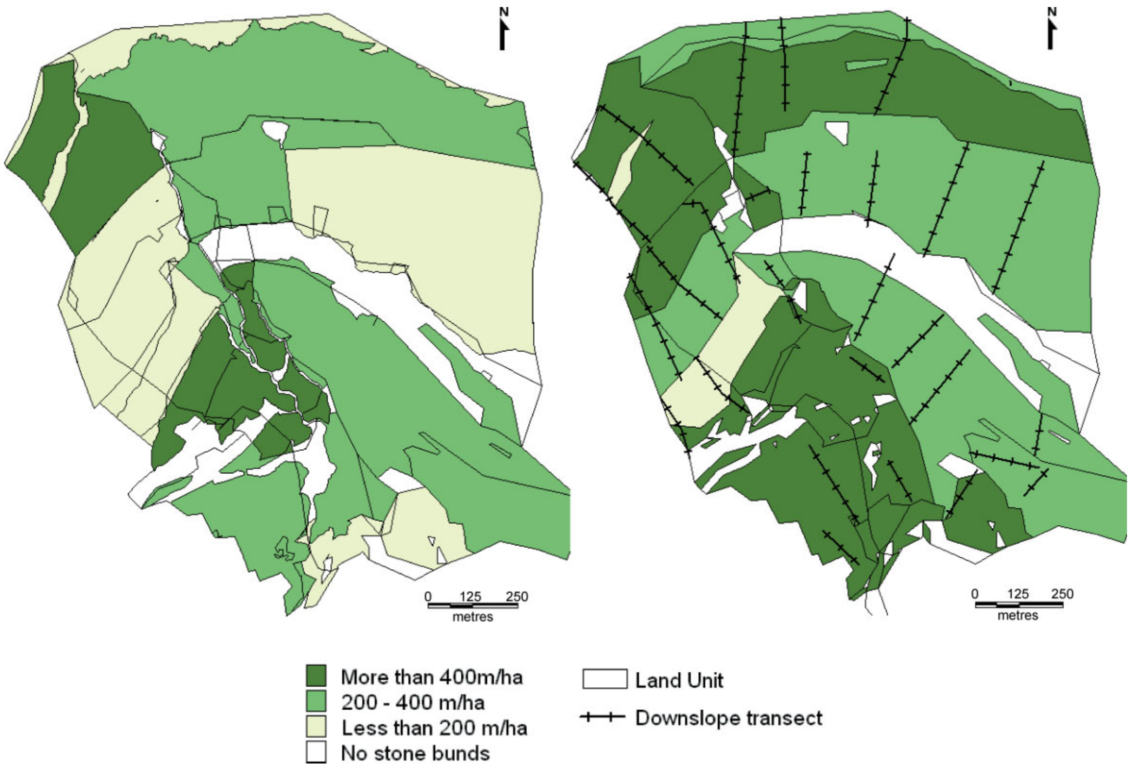

Figure 11. Stone bund densities in 2000 (left) and 2006 (right), based on Naudts (2001) and Clymans (2007). Position of the 2006 downslope transects for measurement of stone bund density is indicated. This figure is available in colour online at www.interscience.wiley.com/journal/espl

For 2000, the total rate of sediment deposition in exclosures was 311 ± 79 t y^{-1}, on an area of 26 ha or a specific rate of $11{\cdot}9 \pm 3{\cdot}0$ t ha^{-1} y^{-1}. The deposition rate in exclosures for 2000 obtained in this study is far less than the one predicted by Nyssen *et al.* (2008a); this is related to the limited sediment supply (due to relatively small source areas) so that the full sediment trapping capacity of exclosures (as used by Nyssen *et al.*, 2008a) cannot be fulfilled. Although the area of the exclosures had expanded by 15 ha between 2000 and 2006, more or less the same sediment mass was deposited within exclosures (312 ± 126 t y^{-1}). The reason why the specific trapping rate of 2006 ($7{\cdot}7 \pm 3{\cdot}1$ t ha^{-1} y^{-1}) was lower than that of 2000 is related to increased sediment trapping behind stone bunds in cropland upslope of exclosures. The specific deposition rate for exclosures was calculated based on area and soil loss rates in the hydrological catchments, upslope of the exclosures divided by the total area of exclosures (Figure 4). Exclosures can only trap the sediment mass that originates in the upslope area. In 2000 this equalled 311 t y^{-1} for 27 ha exclosures whereas in 2006 it equalled 312 t y^{-1} for 41 ha exclosures. In 2006, the increased area draining to exclosures was compensated for by higher sediment deposition rates behind stone bunds resulting in a lower specific soil loss rate. Deposition within exclosures explains 29% and 24% of the total sediment deposition within the catchment in 2000 and 2006, respectively.

In 2000 stone bunds and exclosures trapped 43% of the sediment produced by sheet and rill erosion before the sediment could enter the gully system. In 2006 they trapped 78% of the total sediment produced by sheet and rill erosion.

With regard to debris fans, for the year 2000 the value assessed by Nyssen *et al.* (2008a) was used. Total sediment deposition rate in debris fans was 263 t y^{-1}, equalling a specific rate of $1{\cdot}4$ t ha^{-1} y^{-1}. For 2000, debris fans were held responsible for 24% of total sediment deposited within the catchment. In 2006 there was no active debris fan building; hence the sediment mass deposited in the catchment in debris fans was zero. This is related to a strong decrease in gully erosion and the very high sediment TE of the check dams, especially for coarse sediment (sand and rock fragments). Sediment that was deposited in debris fans, which invaded farmed fields in 2000 (263 t y^{-1}), is now deposited behind check dams (hence within gully beds) (170 t y^{-1}) or further upslope behind stone bunds and in exclosures.

In 2000, 1077 ± 131 t y^{-1}, or 40% of the sediment produced by water erosion, was trapped within the catchment. In 2006 the total deposition rate of 1319 ± 242 t y^{-1} corresponds to 79% of produced sediment trapped due to catchment management. Between both years the specific deposition rate increased from $5{\cdot}8 \pm 0{\cdot}7$ t ha^{-1} y^{-1} to $7{\cdot}1 \pm 1{\cdot}3$ t ha^{-1} y^{-1}, despite decreased sediment production.

Sediment export: the sediment yield

Subtracting sediment sinks from sediment sources gives sediment yield, the sediment mass leaving the catchment. For 2000 the sediment yield was 1591 ± 938 t y^{-1}, leading to a specific soil loss rate for the entire catchment (187 ha) of $8{\cdot}5 \pm 5{\cdot}0$ t ha^{-1} y^{-1}. The specific soil loss rate in 2006 equalled $1{\cdot}9 \pm 3{\cdot}2$ t ha^{-1} y^{-1} which corresponds to a total sediment yield of 357 ± 607 t y^{-1}. Sediment yield was reduced by 78% (1234 t y^{-1}) between 2000 and 2006. Major controlling factors are the reduction of gully erosion, reduction of sheet and rill erosion due to land-use changes (i.e. conversion from rangeland to exclosures), the non-grazing policy and the larger TE of stone bunds.

The sediment delivery ratio (SDR) or the ratio of sediment yield to the total sediment mass produced by water erosion equals:

$$SDR = \frac{SY}{SL} \tag{17}$$

where SY represents the sediment yield (in t y^{-1}); SL the total soil loss (in t y^{-1}) by water erosion. For the MZZ catchment (187 ha) SDR was $0{\cdot}60$ in 2000 and $0{\cdot}21$ in 2006.

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Table V. Measured and estimated sediment yield (SY) for MZZ catchment in 2006

Month	Rainfall (mm)		Sediment yield (t)[a]
January	0		0
February	0		0
March	43		22
April	67		12
May	88		30
June	90		29
July	104		21
August	212		93
September	68		10
October	25		7
November	8		1
December	3		0
Total	**708**		**224**
Sediment deposition behind[b]	Volume (m^3)	dBD ($t\ m^{-3}$)	Total rate ($t\ y^{-1}$)
Cement dam	14	0·93	13
Siltation pond	8	0·82	7
Total			**20**
Total measured SY			**244**
Specific rate ($t\ ha^{-1}\ y^{-1}$)			**1·5**
Total estimated SY[c]			**317 ± 556**
Specific rate ($t\ ha^{-1}\ y^{-1}$)			**1·9 ± 3·4**

[a] Suspended sediment yield based on runoff discharge and suspended sediment concentration measurements.
[b] Methodology similar to check dam volume measurements.
[c] From sediment budget 2006 (Table IV), adapted to the catchment of the cement dam (164 ha).

Measured sediment yield

Based on runoff discharge and sediment concentration measurements during the rainy season (25 July 2006–5 September 2006) estimations of sediment yield were made on a daily basis (Clymans, 2007) and the following relationships were obtained between daily precipitation (P, in $mm\ d^{-1}$) and sediment yield (SY, in $t\ d^{-1}$):

(1) $SY = 1{\cdot}06\ P - 7$ ($R^2 = 0{\cdot}76$) for the first part of the rainy season (extrapolated from 15 October to 13 August), with a threshold value of $P = 6{\cdot}6\ mm\ d^{-1}$ before runoff is generated;
(2) $SY = 0{\cdot}3\ P - 2{\cdot}5$ ($R^2 = 0{\cdot}68$) for the second part of the rainy season (13 August to 15 October), with a threshold value of $P = 8{\cdot}3\ mm\ d^{-1}$.

These relationships were used to estimate the total sediment mass leaving the catchment during 2006. In addition, the sediment trapped in front of the siltation pond and the cement dam was taken into account for the total sediment yield.

The total measured SY for 2006 (Table V) equals 244 $t\ y^{-1}$ corresponding to a specific rate of 1·5 $t\ ha^{-1}\ y^{-1}$, and is composed of sediment actually leaving the catchment (224 $t\ y^{-1}$) and deposited behind both dams (20 $t\ y^{-1}$). According to the calculations, rain showers during the main rainy season (June until October) were responsible for about 72% of the total sediment yield, August accounting for almost 41% of it. Although there are inaccuracies in the estimated sediment yield, the calculated value corresponds well to the measured sediment yield. Both values are of the same magnitude and differ only by about 70 $t\ y^{-1}$. This strengthens the assumption that the magnitude of the different geomorphic processes in the sediment budget represents well the reality.

Discussion

Impact of integrated catchment management on sediment budget

Positive effects of individual SWC measures on soil loss have been reported in various studies (see for instance, for Ethiopia: Bosshart, 1998; Descheemaeker *et al.*, 2006c; Desta *et al.*, 2005; Feleke, 1987; Mitiku *et al.*, 2006; Nigussie *et al.*, 2005; Nyssen *et al.*, 2000a, 2004b, 2006b, 2007; Vancampenhout *et al.*, 2006). This study aimed to assess the impact of integrated management on the sediment budget. After comparison of the sediment budgets before (i.e. in 2000) and after implementation of catchment management (i.e. 2006), the most striking results are (1) a reduction of sediment production due to water erosion by 37·5% (i.e. from 14·3 to 9 $t\ ha^{-1}\ y^{-1}$), (2) an increased sediment deposition behind and within SWC measures by 21·8% (i.e. from 5·8 to 7·1 $t\ ha^{-1}\ y^{-1}$), and (3) a decreased sediment yield by 77·7% (i.e. from 8·5 to 1·9 $t\ ha^{-1}\ y^{-1}$), thanks to (1) and (2).

Sediment yield was also measured at the catchment's outlet during the rainy season and a realistic value was estimated for 2006. Despite inaccuracies in the estimated sediment yield (3), both values are similar. The effects of SWC measures on sediment yield are remarkable: with a reduction of 77·7%, i.e. from 8·5 ± 5 to 1·9 ± 3·2 $t\ ha^{-1}\ y^{-1}$, MZZ scores far below the average of other, larger, basins in Tigray (10·5 ± 4·5 $t\ ha^{-1}\ y^{-1}$; Nigussie *et al.*, 2005).

Effectiveness of soil erosion control practices

The changes in sediment budget are all attributed to changes in land use and in land management; both are directly (e.g. effect of non-grazing policy on ShR) or indirectly (e.g. effect of increased infiltration on gully erosion) related to the implementation of catchment management. However, these changes did not occur in the same grade for each component of the sediment budget. Catchment management is very effective in reducing gully erosion and ShR on rangeland. Basically reduction in gully erosion can be attributed to all SWC measures which have an effect on runoff. Hence, stone bunds with trenches are very effective in reducing runoff coefficients but also check dams and exclosures play a major role in stabilizing the gully system at the lower catchment. Reduced ShR on rangeland can be fully attributed to land-use change i.e. conversion of rangeland into exclosures, which are very effective in reducing soil loss on steep slopes which are not suitable for agricultural activities. Furthermore, the non-grazing policy has a positive effect on soil loss in cropland but compared with other components reduction of sediment production due to ShR on cropland is relatively low. This stresses the importance of conservation agriculture (e.g. no tillage, non-grazing, stubble and soil surface management) to reduce on-site effects (McHugh *et al.*, 2007; Tewodros *et al.*, 2009).

While distinguishing the most effective SWC measure for reduction of sediment production is not straightforward given the interactions, it is less complex for sediment deposition. First rank stone bunds, followed by exclosures and check dams. Over a period of six years, only significant changes (+60%)

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in sediment deposition are observed for stone bunds. The effectiveness of stone bunds in trapping sediment is high (up to 80% on cropland). Although exclosures also act as effective (100% or 55 t ha^{-1} y^{-1}) sediment traps, an areal extension did not lead to a higher sediment deposition within exclosures. This should not surprise since exclosures are only capable of trapping the sediment mass delivered by its sediment source area. SWC measures in the sediment source areas of exclosures resulted in less sediment delivered to and trapped within exclosures. Hence, the lowering of the specific sediment deposition rate (11·9 to 7·7 t ha^{-1} y^{-1}) for exclosures is rather a positive sign than a negative. Whereas check dams and debris fans are each others diachronous equivalents, the sediment mass trapped behind check dams in 2006 is smaller than the debris fan build-up in 2000. Also here a reduction of specific deposition rate stresses the rather positive effects on sediment production (e.g. reduction of gully erosion) and sediment deposition (e.g. TE of stone bunds) in the sediment source area. Absence of deposition in debris fans in 2006, however, is related to the very high sediment TE of the check dams, especially for texture sizes of sand and larger.

Changes in sediment production and deposition between 2000 and 2006 are best visualized on sediment budget maps (Figure 12). For each unit, the difference between sediment deposition and sediment production was calculated. Sediment production by gully erosion and sediment deposition behind check dams were not incorporated. The result are two maps with specific soil loss rates (in t ha^{-1} y^{-1}) for each land unit, sediment sources (positive) and sediment sinks (negative) can be distinguished. Figure 12(C) reflects the changes in specific soil loss rate (in t ha^{-1} y^{-1}) since 2000, where negative values correspond mostly to the already mentioned decreased sediment input into exclosures.

Both exclosures and non-grazing policy are effective and cost efficient SWC measures for soil loss reduction and for sediment deposition, but appropriate awareness creation is needed for local farmers to promote their benefits. Yet, in the absence of stone bunds and check dams, the effectiveness of exclosures and non-grazing policy will be reduced tremendously, as large runoff volumes will occur and rills and gullies will develop, resulting in a higher sediment production rate. Besides, gullies without check dams in exclosures will allow sediment transit, whereby the exclosures' effectiveness in trapping sediment will be confined to smaller sediment source areas. Reversely, if only stone bunds are implemented, these will reduce runoff and trap sediment on gentle sloping areas, but on steep and degraded slopes, without maintenance, they will loose their effectiveness rather rapidly (due to infilling and destruction by flood events).

Considering SWC techniques only individually is not correct. For instance, stone bunds are the most effective SWC measure on gentle sloping areas. They reduce runoff and erosion and take up a minimum of space. Non-grazing policy on gentle sloping areas is also effective but without stone bunds the positive effect will be neutralized by increased concentrated overland flows and rill and later gully development will occur. Exclosures are certainly not an option on gentle sloping areas: the need to have sufficient farmland for food production remains a prime concern in Tigray (Nyssen *et al.*, 2008b). Exclosures are most suitable on steep slopes which are not

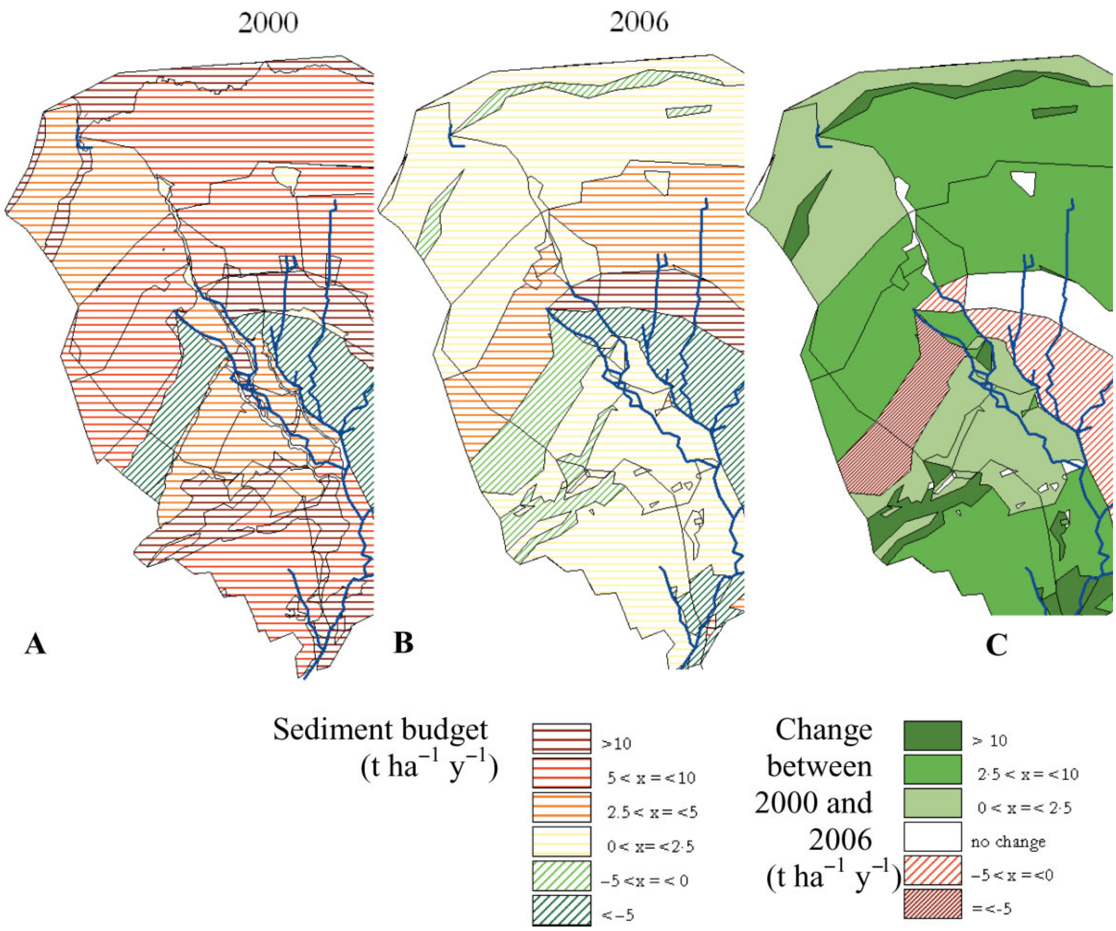

Figure 12. Sediment budget (sediment production minus sediment deposition = sediment yield) (in t ha^{-1} y^{-1}) for each land unit in 2000 (A) and 2006 (B). Sediment delivery areas (sources) are positive (horizontal line pattern) and sediment deposition areas (sinks) are negative (skew line pattern). (C) Changes between 2000 and 2006 with improvements (plain tones) and declines (line pattern), related to decreased sediment input. Gully erosion and deposition behind check dams are not represented. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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qualified for cropping, possibly complemented with stone bunds to improve infiltration and regeneration of vegetation (Descheemaeker *et al.*, 2006b, 2008).

Qualitatively we can evaluate such a catchment management programme by considering the benefits for the farmers. Natural uptake of water is lengthened due to an increased water table over a longer interval (Nyssen *et al.*, 2009d). Irrigated gardens (with a greater crop variability) within the gully bottom and banks indicate also that farmers are less fearful of flash floods, and that previously degraded areas now contribute to their income, as also seen elsewhere in Tigray (Fikir *et al.*, 2009). Locally conversion of the gully system into arable land takes place. Overall, land degradation is reduced in the study area.

Conclusions

This study provides a significant improvement of an earlier sediment budget study in the same catchment (Nyssen *et al.*, 2008a) as it used a diachronous comparison of sediment budgets to assess the impacts of catchment management. Where positive effects of individual SWC techniques on soil loss have been documented in various studies, we assessed the impact of an integrated catchment management programme on sediment production and deposition, indicating that impacts on the sediment budget are positive and improvements significant.

Increased infiltration and lower runoff rates lead to lower soil loss rates and a higher sediment deposition rate within the catchment. This is proven by the comparison of two sediment budgets: before (2000) and after implementation (2006). Major conclusions are: (1) a reduction of sediment production due to water erosion (–37·5%, from 14·3 to 9 t $ha^{-1}\ y^{-1}$), (2) an increased sediment deposition behind and within SWC measures (+21·8 % from 5·8 to 7·1 t $ha^{-1}\ y^{-1}$), (3) a lower sediment yield thanks to (1) and (2) (–77·7%, from 8·5 to 1·9 t $ha^{-1}\ y^{-1}$).

The strongly reduced total soil loss rate is attributed to land-use changes or a change in specific soil loss rate, both are directly (e.g. effect of non-grazing policy on ShR) or indirectly (e.g. effect of increased infiltration on gully erosion) related to the implementation of SWC measures. Changes did not occur in the same degree for each component. Catchment management is very effective in reducing gully erosion and sheet and rill erosion on rangeland (i.e. after closing). Basically, the reduction of gully erosion rates can be attributed to all SWC measures which have an effect on runoff. For instance, stone bunds with trenches are very effective in reducing runoff coefficients. Furthermore, the non-grazing policy has a positive effect on soil loss for cropland but compared to other components of the sediment budget, the reduction of sediment production by ShR on cropland is relatively low. This stresses the importance of conservation agriculture to reduce on-site effects. The major sediment deposition within the catchment occurs behind stone bunds. Although exclosures also act as effective sediment traps, their areal extension did not lead to a higher sediment deposition within exclosures. This should not surprise since exclosures are only capable of trapping the sediment mass originating in its sediment source area. The lowering of the specific deposition rate in exclosures stresses the positive changes with regard to sediment production (e.g. non-grazing policy) and sediment deposition (e.g. TE of stone bunds) in the sediment source areas. The study furthermore showed the benefits of a global catchment management intervention over individually implemented SWC measures. Positive effects are very effective in convincing farmers to implement SWC measures. Following an integrated catchment management approach is the most advisable and desirable way to combat land degradation in Tigray and other semi-arid areas, whereby a participatory approach offers the best guarantees to succeed in managing land degradation.

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