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Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia

Jan Nyssen,[1]* Wim Clymans,[2] Katrien Descheemaeker,[3] Jean Poesen,[2] Ine Vandecasteele,[4] Matthias Vanmaercke,[2] Amanuel Zenebe,[2,5] Marc Van Camp,[4] Mitiku Haile,[5] Nigussie Haregeweyn,[5] Jan Moeyersons,[6] Kristine Martens,[4] Tesfamichael Gebreyohannes,[7,8] Jozef Deckers[2] and Kristine Walraevens[4]

[1] *Department of Geography, Ghent University, B-9000 Gent, Belgium*
[2] *Department of Earth and Environmental Sciences, K.U.Leuven, B-3001 Heverlee, Belgium*
[3] *International Water Management Institute/International Livestock Institute, Addis Ababa, Ethiopia*
[4] *Department of Geology, Ghent University, B-9000 Gent, Belgium*
[5] *Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia*
[6] *Royal Museum of Central Africa, B-3080 Tervuren, Belgium*
[7] *Department of Hydrology, Free University of Brussels, B-1050 Brussels, Belgium*
[8] *Department of Geology, Mekelle University, Mekelle, Ethiopia*

Abstract:

Impact studies of catchment management in the developing world rarely include detailed hydrological components. Here, changes in the hydrological response of a 200-ha catchment in north Ethiopia are investigated. The management included various soil and water conservation measures such as the construction of dry masonry stone bunds and check dams, the abandonment of post-harvest grazing, and the establishment of woody vegetation. Measurements at the catchment outlet indicated a runoff depth of 5 mm or a runoff coefficient (RC) of 1·6% in the rainy season of 2006. Combined with runoff measurements at plot scale, this allowed calculating the runoff curve number (CN) for various land uses and land management techniques. The pre-implementation runoff depth was then predicted using the CN values and a ponding adjustment factor, representing the abstraction of runoff induced by the 242 check dams in gullies. Using the 2006 rainfall depths, the runoff depth for the 2000 land management situation was predicted to be 26·5 mm (RC = 8%), in line with current RCs of nearby catchments. Monitoring of the ground water level indicated a rise after catchment management. The yearly rise in water table after the onset of the rains (ΔT) relative to the water surplus (WS) over the same period increased between 2002–2003 (ΔT/WS = 3·4) and 2006 (ΔT/WS >11·1). Emerging wells and irrigation are other indicators for improved water supply in the managed catchment. Cropped fields in the gullies indicate that farmers are less frightened for the destructive effects of flash floods. Due to increased soil water content, the crop growing period is prolonged. It can be concluded that this catchment management has resulted in a higher infiltration rate and a reduction of direct runoff volume by 81% which has had a positive influence on the catchment water balance. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS catchment management; curve number; ponding adjustment factor; runoff coefficient; water table; watershed

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INTRODUCTION

Impact studies have demonstrated that investments in catchment management in the developing world do pay off in economic terms (see for instance Boyd and Turton, 2000; Reij and Steeds, 2003; Holden *et al.*, 2005). However, such impact studies rarely (see for instance Kerr *et al.*, 2002) include detailed hydrological components, although catchment management is generally regarded as a major determinant of hydrological processes (Whitmore, 1967; Satterlund and Adams, 1992; Haigh and Křeček, 2000; Brooks *et al.*, 2003; Harris *et al.*, 2004). Quantitative impact studies may include thorough comparisons of hydrological processes in nearby located similar 'twinned' catchments (Bosshart, 1998b; Shipitalo *et al.*, 2000; Huang *et al.*, 2003; Serrano-Muela *et al.*, 2005), statistical comparisons of several (generally homogenous but small) catchments (Bingner, 1996; Shipitalo and Edwards, 1998; Shipitalo *et al.*, 2006), model simulations with ground truthing (O'Loughlin *et al.*, 1989; Bingner, 1996; Twery and Hornbeck, 2001), and process monitoring and quantification over several years before and after catchment management (Dragoun and Harrold, 1971; Schwab *et al.*, 1993; Kuhnle *et al.*, 1996; Huang *et al.*, 2003; Huang and Zhang, 2004; Bewket and Sterk, 2005; Mu *et al.*, 2007; Lacombe *et al.*, 2008). General tendencies include increased infiltration and decreased direct runoff after catchment management (Whitmore, 1967; Satterlund and Adams, 1992; Schwab *et al.*, 1993; Kuhnle *et al.*, 1996; Shipitalo and Edwards, 1998; Twery and Hornbeck, 2001; Huang *et al.*, 2003; Bruijnzeel, 2004; Descheemaeker *et al.*, 2006b; Shipitalo *et al.*, 2006; Mu *et al.*, 2007; Lacombe *et al.*, 2008). Effects of extreme events on runoff response may vary

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* Correspondence to: Jan Nyssen, Department of Geography, Ghent University, B-9000 Gent, Belgium. E-mail: jan.nyssen@ugent.be

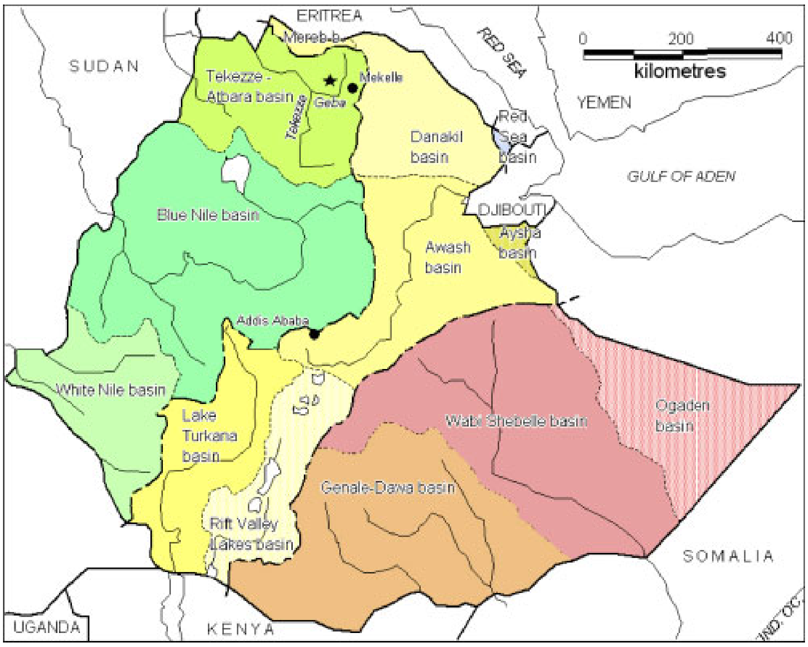

Figure 1. Major drainage basins in Ethiopia and location of the study area ( ). The bold dashed line (———) represents major water divides between the Mediterranean Sea basin (west), the Rift Valley endorheic basins (centre), and Indian Ocean basin (east)

between study areas (Huang *et al.*, 2003; Huang and Zhang, 2004), but most commonly peak flows are levelled down but remain strong after catchment management (Dragoun and Harrold, 1971). Generally, spring discharge and base flow, of uttermost importance in semi-arid areas, are on the rise after catchment management (Dragoun and Harrold, 1971; Huang and Zhang, 2004). Yet, there are claims that no well-documented case exists where reforestation and soil conservation measures have produced a significant increase in base flow (Bruijnzeel, 2004).

Total runoff volume is higher in the absence of forest or conservation measures (Harrold *et al.*, 1962; Dragoun and Harrold, 1971; Bruijnzeel, 2004); yet such high runoff amounts at the peak of the rainy season are of no use since there is no need for irrigation water at that time. Such high volumes and the concomitant high sediment load also lead to reservoir sedimentation. Despite challenging case studies (*sensu* Bruijnzeel, 2004), the working hypothesis remains that catchment management in semi-arid areas may lead to better water availability in the dry season which is of far greater importance than decreases in direct runoff during the rainy season.

A few studies were conducted in the African Highlands (Whitmore, 1967; Rockstrom, 2000; Walmsley *et al.*, 2001; Bewket and Sterk, 2005; Hurni *et al.*, 2005; Descheemaeker *et al.*, 2006b, 2008; Girmay *et al.*, 2009; Stroosnijder, 2009) showing the importance of optimal use of both 'green' (stored in the soil and available to plants) and 'blue' water (runoff and stream base flow that may be tapped, transported, and used elsewhere) (Stroosnijder, 2009), which allowed to make direct linkages to improved livelihoods (Rockstrom, 2000; Walmsley *et al.*, 2001; Falkenmark, 2004; Collick, 2008).

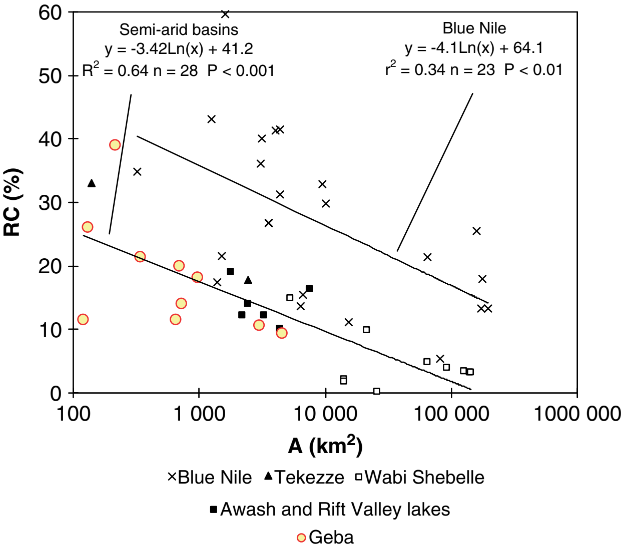

Figure 2. Annual RCs versus drainage area (*A*) for catchments of the basins of the Blue Nile (USBR, 1964; Gamachu, 1977; Conway, 2000), Tekezze (Hunting Technical Services, 1976), Wabi Shebele (Bauduin and Dubreuil, 1973), Awash, and Rift Valley lakes (Gamachu, 1977; Moreda and Bauwens, 1998; Vallet-Coulomb *et al.*, 2001). See Figure 1 for locations. Observation periods were from 3 to 30 years, with the exception of a few (USBR, 1964) data, which cover 1 or 2 years only (after Nyssen *et al.*, 2004). RCs (1–4 years observations) measured recently in major streams of the Geba catchment (Zenebe, 2009; Vanmaercke *et al.*, 2010) which surrounds the May Zeg-Zeg catchment are highlighted

Direct runoff has been measured in Ethiopia (Figure 1) at various temporal and spatial scales (from runoff plot to basin). Annual RCs for large catchments ($A \geq 100$ km^2) show decreasing RCs with increasing catchment area (Figure 2). Several characteristics of the Blue Nile basin explain its higher RC: presence of *openfield*, large Vertisol areas and much rain. The larger catchments of the Blue Nile include Lake Tana. Despite the significant evaporation from this lake, RCs are still larger than those for catchments with similar dimensions belonging to the other basins. For this reason, the Blue Nile basin is considered separately from the Tekezze, Awash, and Wabi Shebele basins (Figure 2), which are mainly situated in dry sub-humid to arid regions (Engida, 2000). In the Wabi Shebele basin, decreasing RC with increasing catchment area has been explained by (1) the fact that the small catchments are mostly situated in the headwaters where nearly impervious, basalt-derived soils dominate and (2) a smaller mean annual basin precipitation and higher evaporation in the larger catchments which include (semi)arid lowlands (Bauduin and Dubreuil, 1973). Despite the wide data scatter for the Blue Nile basin, it can be observed that RCs are larger than in the other basins although they follow a parallel trend (Figure 2). Decreasing RC with increasing catchment area in the Blue Nile basin is thought to be a result of (1) runoff transmission losses, evaporation (from land and lake surface) and possibly lithological heterogeneity and (2) smaller rain depth and larger potential evapotranspiration depth in the western areas of the Blue Nile catchment along the border with Sudan. These areas reduce the overall runoff depth for the whole catchment (Conway, 1999).

At the scale of small catchments in Ethiopia, soil and water conservation (SWC) activities are currently the most widespread form of agricultural intensification (*sensu* Turton and Bottrall, 1997; Zaal and Oostendorp, 2002; Adégbidi *et al.*, 2004), particularly in the uplands. Initially, mainly physical structures were introduced (e.g. stone and soil bunds, check dams) but starting from the 1980s it has been realized that vegetation restoration and protection (grass strips, exclosures, and non-grazing policy) are also important and are less costly (Chadhokar and Abate, 1988; Krüger *et al.*, 1997; Descheemaeker *et al.*, 2006a,b). Positive effects of individual SWC measures (both physical and biological) on hydrology and soil loss were found in a variety of agro-ecological zones and under various land uses (El Swaify and Hurni, 1996; Gebremichael *et al.*, 2005; Descheemaeker *et al.*, 2006b, 2008; Nyssen *et al.*, 2006, 2007, 2009a; Vancampenhout *et al.*, 2006; Collick, 2008), potentially clearing the way for a more sustainable agricultural system. Relatively low RCs, recently measured in the Geba catchment (Figure 2) (Zenebe, 2009; Vanmaercke *et al.*, 2010), also tend to reflect the impact of SWC activities that have taken place over the last decades.

Generally, RCs from small (<200 m^2) runoff plots are very variable (0–50%) (Table I), which is attributed to the large range of experimental conditions. Besides different slope gradients, local differences in soil texture, land use, vegetation cover, organic matter content, rock fragment cover, and SWC practices result in a wide range of infiltration rates obtained from runoff plots (Abiyo, 1987; Mwendera and Saleem, 1997; Descheemaeker *et al.*, 2006b). Results from runoff plots may certainly not be extrapolated to catchments.

In order to improve their effectiveness, individual indigenous and introduced SWC technologies can be combined as a starting point for integrated conservation programmes (Herweg and Ludi, 1999; Nyssen *et al.*, 2000b). The expected benefits of enhanced SWC in Ethiopia (El Swaify and Hurni, 1996; Hurni *et al.*, 2005) are (1) control of upland soil erosion, (2) reduction in sediment load of the region's rivers, (3) improvement in the hydrologic regime, including reduced peak flows (Figure 3), and (4) addressing food security needs of Nile basin states. There is clearly a possibility of joint gains: rainfed agriculture in the Ethiopian Highlands benefits from SWC, whereas irrigated agriculture in downstream regions benefits from decreased sediment load and improved base flow (El Swaify and Hurni, 1996; Waterbury and Whittington, 1998).

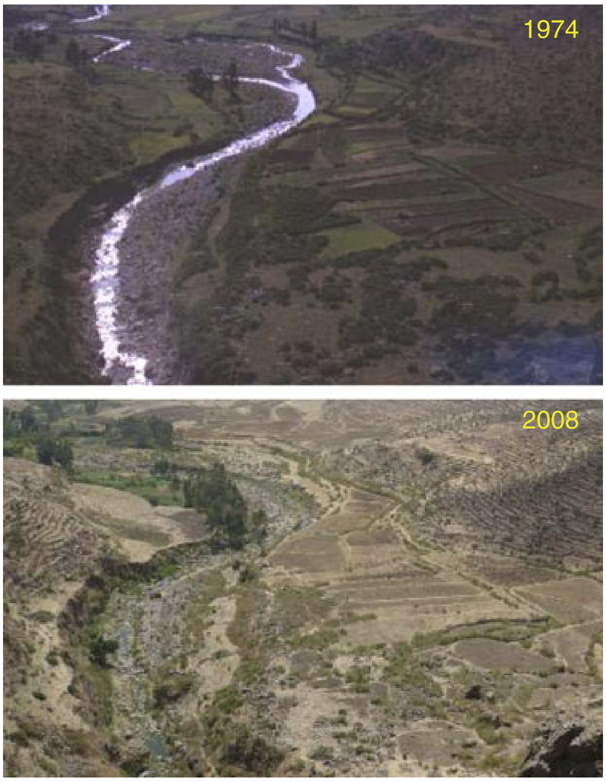

Figure 3. The Calamino river at Debri near Mekelle, looking downstream in 1974 (upper; photo R. N. Munro) and 2008 (lower). Major changes of this tributary of Tekezze river are the recolonization of the river bed by woody perennials (*Rumex nervosus, Nicotiana glauca*) indicating decreased peak flows. Improved base flow is used for irrigating cash crops in the valley bottom whereas slopes have been terraced between 1974 and 2008

Despite the large number of studies on individual SWC measures, impact studies on integrated catchment management are rare, particularly in tropical, semi-arid highlands. Hence, this paper aims at analysing the hydrological impacts of catchment management and the implications for livelihoods through a case study in May Zeg Zeg (MZZ), a representative catchment in the Nile headwaters.

STUDY AREA

The MZZ catchment (200 ha), situated near the town of Hagere Selam (13°40′N, 39°10′E) and *ca* 50 km to the

Table I. Annual rainfall and runoff data for selected experimental plots in the Ethiopian Highlands

Location	°N	°E	SG (%)	A (m^2)	n	years	P (mm)	R (mm)	RC (%)	Land use	Source
Melkassa	8°24′	39°20′	10–11	80		2	806	367	45·5	Bare fallow	Abiyo (1987)
Afdeyu	15°41′	38°35′	31	180	1	3	382	162	42·4	Traditional cultivation	Herweg and Ludi (1999)
Afdeyu	15°41′	38°35′	31	180	1	3	382	87	22·8	Traditional cultivation, with grass strips	Herweg and Ludi (1999)
Debre Zeit	8°45′	38°59′	4–8	20		1	350[a]	80	22·9	Rangeland, very intense grazing	Mwendera and Saleem (1997)
Debre Zeit	8°45′	38°59′	4–8	20		1	350[a]	22	6·3	Rangeland, no grazing	Mwendera and Saleem (1997)
Debre Zeit	8°45′	38°59′	0–4	20		1	350[a]	34·5	9·9	Rangeland, very intense grazing	Mwendera and Saleem (1997)
Debre Zeit	8°45′	38°59′	0–4	20		1	350[a]	7·3	2·1	Rangeland, no grazing	Mwendera and Saleem (1997)
Maybar	11°07′	39°19′	28	180	1	4	1211	24	2·0	Traditional cultivation	Herweg and Ludi (1999)
Maybar	11°07′	39°19′	28	180	1	4	1211	16·7	1·4	Traditional cultivation, with grass strips	Herweg and Ludi (1999)
Hunde Lafto	8°40′	40°25′	21	180	1	3	935	12	1·3	Traditional cultivation	Herweg and Ludi (1999)
Hunde Lafto	8°40′	40°25′	21	180	1	3	935	6·6	0·7	Traditional cultivation, with grass strips	Herweg and Ludi (1999)
Andit Tid	9°46′	39°47′	24	180	2	5	1358	354	26·1	Traditional cultivation	Herweg and Ludi (1999)
Andit Tid	9°46′	39°47′	24	180	2	5	1358	236	17·4	Traditional cultivation, with grass strips	Herweg and Ludi (1999)
Adi Gudom	13°14′	39°32′	3	95	2	1	422[a]	65·3	15·5	Traditional cultivation	Gebreegziabher *et al.* (2009)
Adi Gudom	13°14′	39°32′	3	95	2	1	422[a]	25·5	6·0	Permanent-bed-based conservation agriculture	Gebreegziabher *et al.* (2009)

SG, slope gradient; A, plot area; n, number of replicates; year, number of years of observation; P, mean annual precipitation; R, mean annual runoff; RC, runoff coefficient ($100 \times R\ P^{-1}$).

[a] Within measurement period (<1 year).

west of north Ethiopia's Tigray regional capital Mekelle (Figure 1), was selected for this study as it is characterized by high elevations (2100–2650 m a.s.l.) and a subhorizontal structural relief, typical for the north Ethiopian Highlands. The local geology comprises subhorizontal series of alternating hard and soft Antalo limestone layers, some 400-m thick, overlain by Amba Aradam sandstone (Hutchinson and Engels, 1970). These Mesozoic sedimentary rocks are covered by two series of Tertiary lava flows, separated by silicified lacustrine deposits (Merla, 1938; Arkin *et al.*, 1971; Merla *et al.*, 1979). Erosion, in response to the Miocene and Plio-Pleistocene tectonic uplifts (*ca* 2500 m), resulted in the formation of tabular, stepped landforms, reflecting the subhorizontal geological structure. The uppermost levels of the landscape at about 2500–2800 m a.s.l. are formed in the basalt series. Other structural levels correspond to the top of the Amba Aradam sandstone and to the top of hard layers within the Antalo limestone (Nyssen *et al.*, 2003a). The Atbara–Tekezze river system drains the runoff from the study area to the Nile. The main rainy season (>80% of total rainfall) extends from June to September but is preceded by 3 months of dispersed and less intense rains (Nyssen *et al.*, 2005). Average yearly precipitation is 762 mm; whereas the years 2000, 2001, 2005, and 2006 correspond to the average rainfall situation, the years 2002–2004 were well below average (Figure 4). High rain erosivity is due to relatively large drop size and concomitant kinetic energy (Nyssen *et al.*, 2005).

Cropped fields are the dominant land use (around 65%) in the study area. The agricultural system in the north Ethiopian Highlands has been characterized as a 'grain–plough complex' (Westphal, 1975). The main crops are barley (*Hordeum vulgare* L.), wheat (*Triticum* sp.), and tef (*Eragrostis tef*), an endemic cereal crop. Various species of pulses are also an important part of the crop rotation. Soil tillage is carried out with ox-drawn ard ploughs (Nyssen *et al.*, 2000a; Gebregziabher *et al.*, 2006). Livestock (cattle, sheep, and goats) is a major component of the agricultural system and grazes freely, including stubble grazing after harvesting. Steep slopes ($>0{\cdot}3$ m m^{-1}) are mainly under rangeland, parts of which have been set aside recently to allow vegetation recovery (exclosures) (Descheemaeker *et al.*, 2006a).

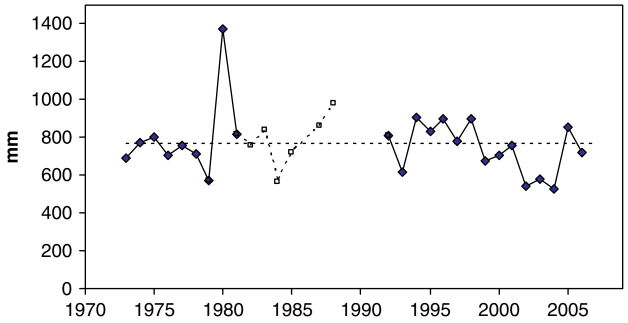

Figure 4. Annual precipitation in Hagere Selam. Annual average is 762 (±171) mm. Source: National Meteorological Agency (www.ethiomet.gov.et), except 1992–1994: Dogu'a Tembien Agricultural Office. Missing data correspond to the period of civil war and the years thereafter. A tentative reconstruction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

SWC measures, especially stone bund building and the establishment of exclosures (vegetation restoration), have been implemented as part of routine land management activities that were started in the 1980s. 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 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. More specifically the project included the implementation of site-specific conservation techniques aimed at increasing water infiltration and conserving soil, i.e. the construction of dry masonry stone bunds on all land and check dams in gullies, the abandonment of post-harvest grazing, and the set aside of degraded rangelands, which results in exclosures (Figure 5) (Hadera and Nyssen, 2003; Nyssen *et al.*, 2003b, 2009b).

METHODS

The research objective has been achieved by studying the changes in hydrology of the MZZ catchment within the period 2000–2006, before (<2004) and after (>2004) catchment management, particularly with regard to direct surface runoff, base flow, and water table. Contrasts have also been made with larger catchments within which MZZ is nested.

Survey of bio-physical features of the catchment

A field survey of relevant bio-physical features was conducted in the MZZ catchment during the rainy season (July–October) of 2006. A detailed land use map was made using GPS (Clymans, 2007), whereby the same land use classes were used as those of the observed counterfactual, an earlier survey in 2000, before catchment management (Naudts, 2001; Nyssen *et al.*, 2008, 2009b). Stone bund densities and land management practices were also mapped. Runoff storage volumes behind SWC structures (stone bunds and trenches) were measured. All dry masonry check dams in gully beds were located by GPS, and their storage volumes measured.

Figure 5. Partial view of the managed May Zeg-Zeg catchment, with check dams in the gully, exclosure at the back and stone bunds in farmland and in the exclosure

Daily precipitation measurements

Four rain gauges installed in and nearby the catchment (Figure 6), were constructed with simple materials: a cylinder made from two metal tins was fixed vertically in cement, on top of a 1·5-m high tower; a strong plastic bottle, with a funnel fixed at its top was inserted in the tins (Nyssen *et al.*, 2005). Rain gauges were read daily (at 8 AM) by secondary school students residing in the neighbourhood. Observations covered 7 years (2000–2006) for three rain gauges, except for one rain gauge (Zenak'o), where there are some missing years. Minor temporal data gaps, due to defect rain gauges, were filled up using a regression curve fitted between available data of the defect rain gauge and neighbouring stations. Using the Thiessen Polygon method, weighted average daily rainfall depths in the study catchment were obtained (Clymans, 2007).

Monitoring of the groundwater table position

The groundwater table was monitored weekly between 2002 and 2006 in the main valley bottom (which is not incised at that location) where the water table is at the highest position in the catchment (Figure 6). Here, Tertiary basalts overlay sandstone which acts as an aquiclude. A piezometer, with a PVC tube of 63 mm across with an open bottom end, was placed in a 2-m deep augered borehole. The tube was perforated with heated nails to form a sieve, which helped quicken the equilibrium of the water level within the tube with the ground water table at its position. The soil around the top of the piezometer was compacted and the tube itself surrounded with rocks and covered by a large rock to

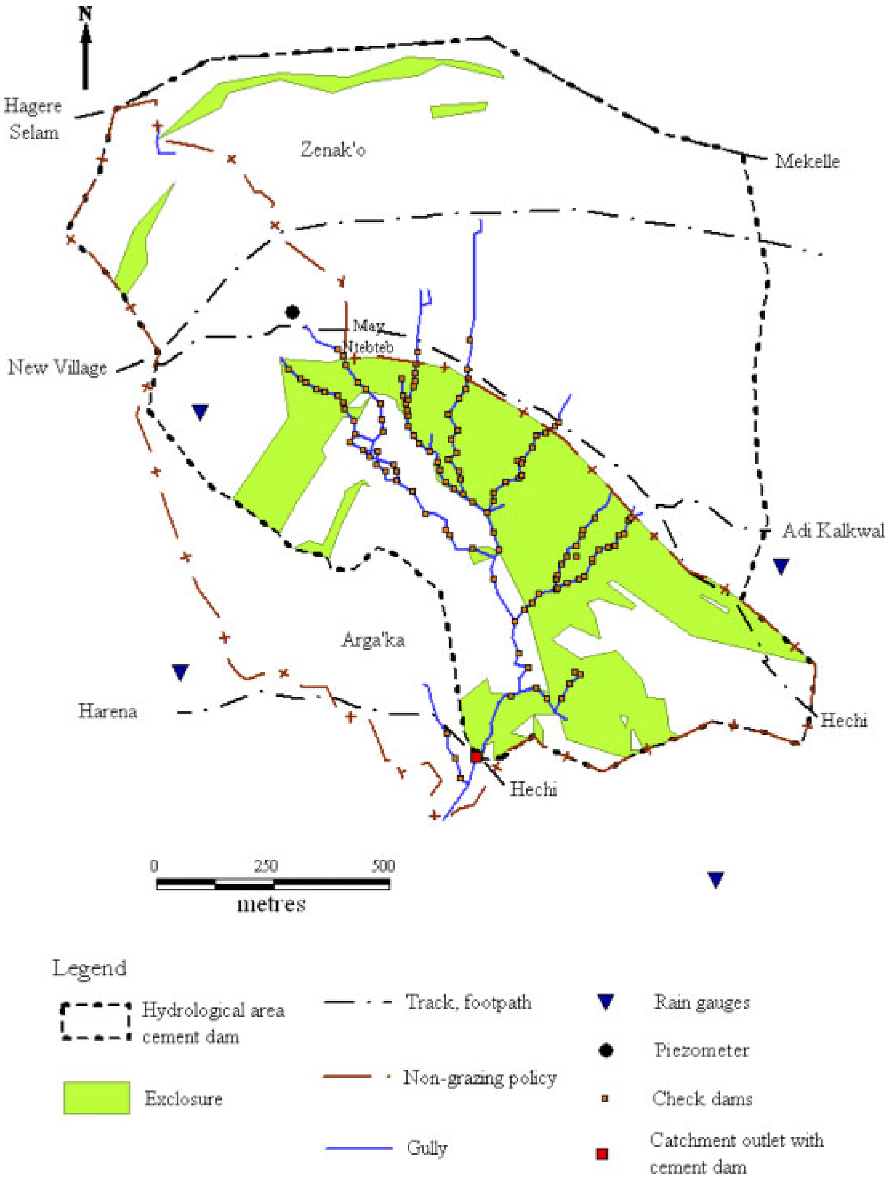

Figure 6. Map of May Zeg-Zeg catchment in 2006, with location of measurement installations and some major SWC interventions

reduce direct infiltration of rainfall and surface runoff. Depth from the soil surface to the water level was measured weekly by metre stick (±0·01 m).

Runoff discharge at the catchment's outlet

Near the catchment's outlet, a cement dam (Figure 7) was built for irrigation purposes. During the rainy season the outlet pipe is opened entirely because natural rains supply sufficient water for crop production in the downstream areas. From 13 July to 8 September 2006, measurements of runoff discharge were conducted at the dam. Runoff discharges (Equation (1)) were based on water height measurements and related pipe outlet discharge at the cement dam (Figure 7). Adding up two runoff discharges, (1) runoff discharge overtopping the cement dam and (2) runoff discharge at the pipe outlet, allowed calculating outgoing runoff volumes:

$$Q_{\mathrm{out}} = Q_{\mathrm{overflow}} + Q_{\mathrm{pipe}} \qquad (1)$$

$$V_{\mathrm{p}} = \sum_{\Delta t}^{n} Q_{\mathrm{out}} \qquad (2)$$

where: Q_{out} = outgoing runoff discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$),
Q_{overflow} = runoff discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$) at the dam crest,
Q_{pipe} = runoff discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$) at pipe outlet,
V_{p} = outgoing volume (m^3) per event.

The dam had a rectangular shaped crest (or overflow) for which runoff discharge (Q_{overflow}) was calculated from depth measurements (every 2 min) following classic hydraulics procedures (Simon, 1981).

Estimations of runoff discharge at the pipe outlet (Q_{pipe}) were based on three measurements conducted in the field (Figure 7): (1) water height behind the dam (measured with a gauge every 15 min during the rainfall events), (2) discharge measurement with bucket, and (3) projectile distance of the water at the pipe outlet.

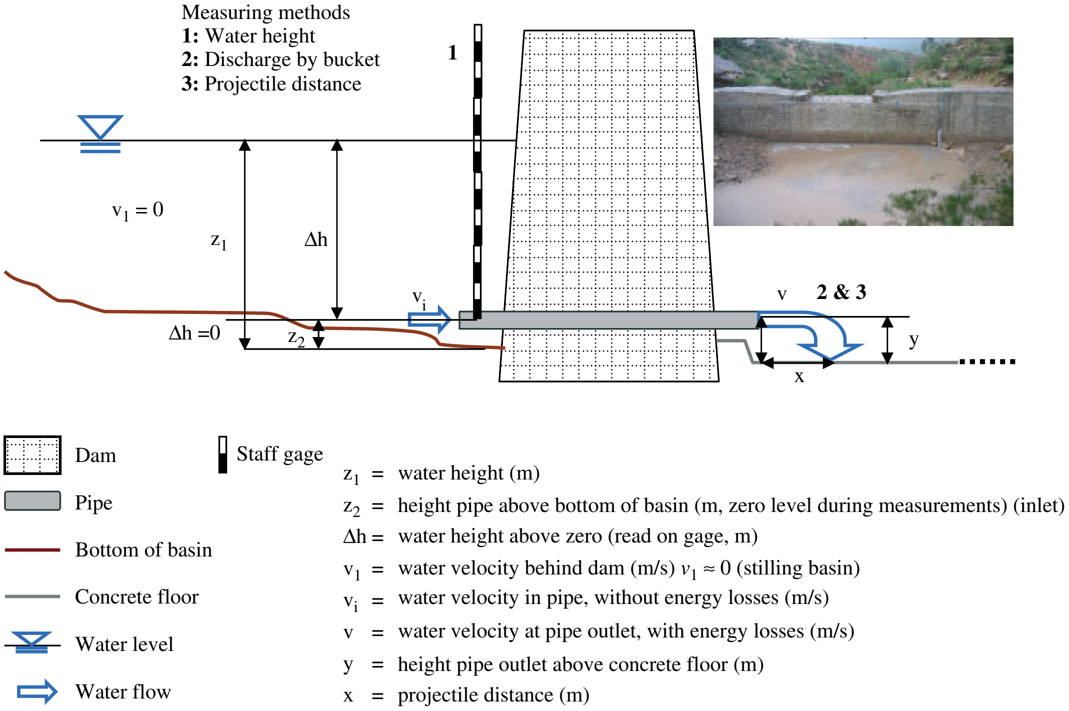

Figure 7. Schematic representation of the cement dam where runoff measurements were made at the catchment outlet (for location see Figure 6)

The purpose of these measurements was to calculate runoff discharges with the theoretical Bernoulli equation (Simon, 1981) using the water height [(1) in Figure 7] and to correct where necessary with field observations on (2) and (3).

At the outlet of the pipe, direct runoff discharges were also calculated by measuring the time to fill a bucket [(2) in Figure 7] with known volume. For each water height an average discharge rate was calculated. However, the range of water heights linked with runoff discharges is limited: for a water height of 0·3 m and above, the forces of squirting water were so high that no accurate runoff discharge measurements could be made by bucket.

Indirect runoff discharge measurements were also conducted, based on the Purdue trajectory method (Bos, 1978), in which an object with a certain horizontal starting velocity at a point y above the ground reaches the surface at a point with distance x from the starting point. Field measurements of x and y gave the opportunity of assessing the starting velocity [(3) in Figure 7] and hence runoff discharge at the pipe outlet.

Finally, the end of some falling limbs of daily runoff discharge, missed out in the field measurements because of early darkness, was reconstructed based on a careful analysis in which these incomplete series data were compared with the complete series of 13 August 2006. Differences in water depths behind the dam (seen as a proxy for runoff discharges) with 13 August 2006 and moment in event were used to estimate the lacking data.

Runoff prediction with the curve number method

The daily runoff in small rural catchments can be estimated based on the curve number (CN) method (SCS, 2004), for which a simplified infiltration and runoff model (i.e. Horton model) and empirical approaches were used. The CN reflects the reaction of an area with a certain land use, soil, and vegetation properties in terms of direct overland flow. The relationship between CN, storage parameter (S), and daily runoff discharge is:

$$R = \frac{(P - 0{\cdot}2S)^2}{P + 0{\cdot}8S} \quad \text{when } P \geq 0{\cdot}2S, \text{ and}$$

$$R = 0 \text{ when } P < 0{\cdot}2S \qquad (3)$$

$$S = \frac{25\,400}{\text{CN}} - 254 \qquad (4)$$

where: R = runoff (mm),
P = rainfall (mm),
S = storage parameter (mm),
CN = curve number.

This method was developed based on rainfall and runoff data from small drainage basins in the United States and became a widely used method to predict runoff in catchments ranging in size from 0·25 ha to 1000 km^2 (Boughton, 1989). However, also the data obtained from smaller runoff plots is used for CN determination (Auerswald and Haider, 1996; Hawkins and Ward, 1998). Here, the approach to evaluate changes in catchment runoff was first to calibrate the SCS CNs for the catchment's land units, using a combination of the results of catchment runoff measurements obtained in this study and CNs obtained from runoff plots in an earlier study (Descheemaeker *et al*., 2008). Then these values were applied to the catchment with its land use and management as it was in 2000, but using the 2006 rainfall data, in order to interpret differences in catchment runoff in terms of management of the catchment. The

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

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

various runoff sinks created by catchment management were accounted for (1) through incorporation of the effect of stone bunds and decreased stubble grazing in the CN, (2) through application of the 'pond and swamp adjustment factor' (SCS, 1986), and (3) by decreasing the effective runoff-producing area with those areas whose runoff is absorbed in exclosures (Descheemaeker *et al.*, 2009).

Runoff at larger (10^3 km^2) catchment scale

The runoff data obtained in MZZ catchment were compared with those of surrounding, larger catchments. Intensive measuring campaigns were conducted during the rainy seasons of 2004–2007 at 10 stations on rivers, all within 50 km from the study catchment (Zenebe, 2009; Vanmaercke *et al.*, 2010). At each runoff measuring station, digital pressure transducers were installed, which recorded the flow depth on a continuous basis. Flow velocity was measured daily as well as each time that a large difference in flow depth was noted. Area of flow section was measured for each flow depth. These measurements allowed calculating the runoff discharge for each specific flow depth. Hence, the continuous flow depth series could be converted to continuous runoff discharge series by means of rating curves. Such runoff measurements were also carried out in the Enda Selasse catchment (121 km^2), which drains MZZ catchment. These measurements were made in the period from 12 July until 10 September 2006, covering the largest part of the rainy season.

RESULTS AND DISCUSSION

Precipitation

Total yearly rainfall depth for the different rain gauges showed great spatial variability in 2006, the year when runoff measurements were conducted. Hechi received 764 mm (for locations, see Figure 6); Adi Kalkwal, 535 mm; Harena, 697 mm; and Zenak'o, 661 mm; and the area-weighted average (Thiessen method) was 626 mm for the study area. The period June–October contributed to approximately 70% of the yearly rains.

The 2006 annual rainfall in the catchment is well in range with the average of 629 mm for the period 2001–2006 (Table II). Seasonality was however below average with (1) a drier main rainy season and (2) a wetter spring rainy season.

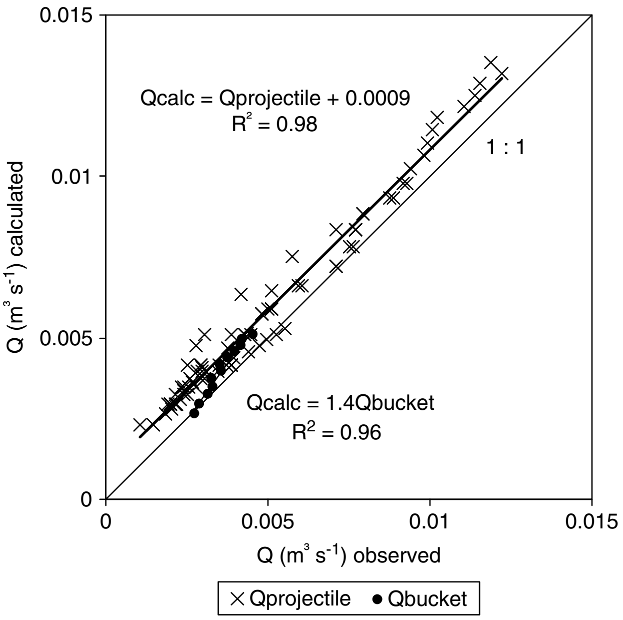

Figure 8. Calculated runoff discharge (Q_{calc}, m^3 s^{-1}, based on Bernoulli's equation) as a function of observed runoff discharges [Q_{obs}, m^3 s^{-1}, based on (1) projectile trajectory method (crosses) and (2) direct runoff discharge measurements with bucket (dots) at the pipe outlet]

Direct catchment runoff and RC

Runoff discharge. At the MZZ catchment outlet, direct and indirect (bucket and Purdue trajectory methods) measurements were done, which allowed verifying the discharges derived from Bernoulli's equation. A systematic overestimation of the Bernoulli runoff discharge (Figure 8) seems to indicate a systematic error. The most appropriate explanation is that energy losses to the pipe were underestimated, most probably due to the fact that the pipe offers more than the theoretical resistance, which is among others related to the existence of a closing mechanism at the pipe outlet. Based on these findings the coefficient for energy losses in the Bernoulli equation was adjusted so that estimated and observed runoff discharge correspond to a 1 : 1 equation (Clymans, 2007).

Adding up the calculated values for daily runoff yielded a total runoff depth of 5·1 mm or an average RC of 1·6% for the rainy season. This RC of MZZ stays well below the RC of nearby larger catchments. Total runoff depth in July–September 2006 at the Enda Selasse catchment outlet, which drains MZZ, was 55 mm, with a corresponding RC of 15%. Although this runoff depth comprises the base flow of the river, the main part of the runoff (an estimated 76%) occurred during short, but intense, flash floods (Zenebe, 2009; Vanmaercke *et al.*, 2010).

Impact of physical SWC measures on RC. A reasonable explanation for this low RC in MZZ catchment is the positive influence of SWC measures. Most of the measures taken in MZZ reduce runoff by trapping overland flow, for instance in trenches behind stone bunds or in small basins behind check dams.

Table III. Values of storage parameter S and assumptions used to calculate S for land use and management classes on arable land in May Zeg-Zeg catchment in 2006

Land use and management	Area (ha)	%	S (mm)
Fallow land	0·1	0·1	29·8[b]
Cropland (free grazing, no stone bunds[a])	3·0	2·4	x[c]
Cropland (free grazing, stone bunds of medium quality[a])	35·0	27·4	$x + 2$[d]
Cropland (free grazing, good stone bunds[a])	18·1	14·2	$x + 6$[e]
Cropland ('zero' grazing, no stone bunds[a])	1·5	1·1	$x + 5$[f]
Cropland ('zero' grazing, stone bunds of medium quality[a])	4·9	3·9	$x + 5 + 2$[d,f]
Cropland ('zero' grazing, good stone bunds[a])	22·7	17·8	$x + 5 + 6$[e,f]
Exclosure (no stone bunds[a])	0·0	0·0	301·9[g]
Exclosure (stone bunds of medium quality[a])	5·0	3·9	303·9[d]
Exclosure (good stone bunds[a])	29·5	23·1	307·9[e]
Grassland	0·8	0·6	301·9[g]
Grassland with dense runoff collector trenches	3·0	2·3	307·9[e]
Rangeland	4·0	3·2	29·8[b]
Land accounted for in CN calculation	127·5	100·0	
Land draining to sinks (exclosures)	37·1		NA
Total	164·7		

[a] Good quality stone bunds (density >400 m ha^{-1}; trenches in good state), medium quality (density 200–400 m ha^{-1} and trenches in good state, or density >400 m ha^{-1} but absence of trenches behind the bunds), and no or poor stone bunds (density <200 m ha^{-1}, no trenches, many collapsed stone bunds).

[b] Calculation with Equation (4), using a CN value of 89·5, weighted average of rangeland CNs measured at plot scale ($n = 702$) (Descheemaeker *et al.*, 2008).

[c] $S = x$, to be determined in the study.

[d] For stone bunds of medium quality, dynamic storage depth behind stone bunds and in trenches estimated at 2 mm.

[e] For stone bunds of good quality, dynamic storage depth in trenches estimated at 6 mm.

[f] Increased storage depth resulting from 'zero' grazing estimated at 5 mm.

[g] Calculation with Equation (4), using a CN value of 45·7, weighted average of CNs for medium to old exclosures, measured at plot scale ($n = 2163$ plot-event data) (Descheemaeker *et al.*, 2008).

The impact of runoff storage in the trenches behind stone bunds was calculated. Trenches are typically 0·5 m wide, 0·25 m deep, and 0·75 m long, per metre of stone bund length. This can be recalculated to water storage depth (mm) by multiplying it with average stone bund density in the area (372·3 m ha^{-1}), which leads to a static storage capacity of 35 m^3 ha^{-1} or 3·5 mm. This means that rainfall producing runoff below 3·5 mm will not leave the field. In real conditions, water infiltration during the filling of the trenches leads to a dynamic storage capacity, which is higher than 3·5 mm. Taking this into account, the dynamic storage capacity (Morin and Kosovsky, 1995; Spence, 2007) of arable land that is covered with dense stone bunds (around 500 m ha^{-1}; on 34% of the catchment area) was estimated at 6 mm.

Calibrated curve numbers for the catchment. For semi-natural vegetation, experimentally obtained CN values in nearby catchments (Descheemaeker *et al.*, 2008) were used as a starting point. For cropland, with and without stone bunds, CN values were computed based on a combination of the measured catchment runoff values and the known CN values for semi-natural vegetation, which occupies all land that is not cropland (the built-up area in the catchment is negligible). On a storm basis, the following computations were made. The storm runoff at catchment scale could not be directly linked to CNs at land unit scale, since 242 check dams (1–2 m high) within the channels induce an important runoff abstraction. To take into account the effects of these in-gully structures, leading to smaller runoff depths at catchment scale than at plot scale, the 'pond and swamp adjustment factor' [F_p; Table 4-2, (SCS, 1986)] was used. In particular, the lowest possible value of this adjustment factor ($F_p = 0{\cdot}72$), initially foreseen for 5% pond surface spread throughout the catchment, was adopted. This relatively strong adjustment is justified by the fact that the temporary ponds created behind the check dams in this study are not spread but rather concentrated in the drainage lines, the location where they contribute most to abstraction.

CN values for arable land with good stone bunds, with poor quality stone bunds (small storage volume), and without stone bunds were then obtained using the 2006 field estimates of dynamic runoff storage capacity in the trenches. Relative values were attributed to the storage parameter S for these different land management techniques (Table III) whereby an increase of S by 6 mm was attributed for dynamic runoff storage in trenches on cropland 'with good stone bunds', and 2 mm for 'medium stone bunds'. The catchment area producing direct runoff was also reduced by those areas draining into exclosures, where all runoff was retained by vegetation and infiltrates (Descheemaeker *et al.*, 2009). Furthermore, due to strongly decreased soil compaction by livestock trampling and increased presence of stubble, cropland under zero grazing (in reality: strongly reduced grazing) was considered as resulting in 'good hydrologic conditions' as opposed to 'poor hydrologic conditions' in free grazing area; both notions according to SCS

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

Land use and management type	2000			2006		
	CN[b]	Area (ha)	%	CN[b]	Area (ha)	%
Fallow land	89·5	1·6	1·1	89·5	0·1	0·1
Cropland (free grazing, no stone bunds[a])	79·9	25·7	17·8	79·9	3·0	2·4
Cropland (free grazing, stone bunds of medium quality[a])	79·4	63·3	43·9	79·4	35·0	27·4
Cropland (free grazing, good stone bunds[a])	78·5	11·1	7·7	78·5	18·1	14·2
Cropland ('zero' grazing, no stone bunds[a])	78·7	0·0	0·0	78·7	1·5	1·1
Cropland ('zero' grazing, stone bunds of medium quality[a])	78·2	0·0	0·0	78·2	4·9	3·9
Cropland ('zero' grazing, good stone bunds[a])	77·3	0·0	0·0	77·3	22·7	17·8
Exclosure (no stone bunds[a])	67·3[c]	24·4	16·9	45·7[d]	0·0	0·0
Exclosure (stone bunds of medium quality[a])	66·6	0·0	0·0	45·5	5·0	3·9
Exclosure (good stone bunds[a])	65·6	0·0	0·0	45·2	29·5	23·1
Grassland	45·7	0·9	0·6	45·7	0·8	0·6
Grassland with dense runoff collector trenches	45·2	0·0	0·0	45·2	3·0	2·3
Rangeland	89·5	17·1	11·9	89·5	4·0	3·2
Land involved in CN calculation		144·1	100·0		127·5	100·0
Land draining to sinks	NA	19·8		NA	37·1	
TOTAL		163·9	100·0		164.7	100·0
Catchment weighted average CN			**78·5**			**68·9**

[a] Good quality stone bunds (density >400 m ha^{-1}; trenches in good state), medium quality (density 200–400 m ha^{-1} and trenches in good state, or density >400 m ha^{-1} but absence of trenches behind the bunds), and no or poor stone bunds (density <200 m ha^{-1}, no trenches, many collapsed stone bunds).

[b] Obtained from (Descheemaeker *et al*., 2008) and Table III.

[c] Young- to medium-aged exclosures.

[d] Medium- to old-aged exclosures.

(2004). The difference between good and poor hydrologic condition leads to differences in water storage capacity ranging from 3 to 27 mm. A conservative value of 5 mm for the impact of increased storage resulting from 'zero' grazing was adopted. Given this parameterization (Table III), finding the suitable value for S in cropland (without any catchment management activity) will then automatically determine the values of S on the managed croplands. Iteratively, values of S were tested, and at every iteration, CN values for every land use and management class calculated as well as area-weighted CN which allowed predicting catchment runoff, using Equations (3) and (4) and involving the pond adjustment factor F_{p}. In the process, values were assigned to S, until the value was found that allowed matching predicted runoff with observed runoff.

To account for the effects of antecedent moisture condition on runoff production, the recorded data were first split into three groups based on the rainfall depth of the previous 5 days ($P_5 < 12{\cdot}5$ mm; $12{\cdot}5 \text{ mm} < P_5 < 27{\cdot}5$ mm; $P_5 > 27{\cdot}5$ mm) (SCS, 2004). Due to the small number of heavy rain events that resulted in significant runoff, results on these partial analyses appeared unreliable and it was decided to make an analysis involving the whole data series of the rainy season. The area-weighted average CN that allowed matching observed and predicted runoff was 68·9. Next, the iterative injection of values for S (unmanaged cropland) allowed selecting the best fit set of CN that resulted in an average CN of 68·9 for the treated catchment (Table IV). Weighted average CN for the catchment before catchment management was then computed at 78·5.

Changes in catchment runoff induced by the implementation of SWC measures. In the next step, the obtained set of CN values was then applied to the catchment as it was in 2000, in order to calculate hypothetical runoff using the 2006 events, with equation

$$R_{\mathrm{CA}} = F_{\mathrm{p}} \times R \tag{5}$$

where: R_{CA} = runoff depth at catchment scale (mm),

F_{p} = ponding adjustment factor, with values of 1 in 2000 (no check dams) and 0·72 in 2006 (numerous check dams),

R = runoff depth at land unit scale (mm), calculated with Equation (3).

Total runoff depth measured from 15 July 2006 till 4 September 2006 was 5·1 mm, resulting in an RC of 1·6%; calculations with Equations (3) and (5) for 2000 using the 2006 daily rainfall depths lead to a predicted total runoff depth of 26·5 mm, or RC of 8%. Comparison of runoff rates pre- and postcatchment management clearly shows that there are large differences in runoff depth for most rain events (Figure 9).

In small catchments in Ethiopia, some relatively low RCs are explained by specific physical conditions (Table V). In the case of the Dombe 'twinned' catchments, dense vegetation between the fields facilitates infiltration (Bosshart, 1998b), and a significant difference in runoff volume was observed between two similar catchments of which one has been treated by physical conservation measures and the other has not been treated. Small catchments are very sensitive to human intervention. The estimated RC of 8% before catchment management is in line with RCs of nearby (larger)

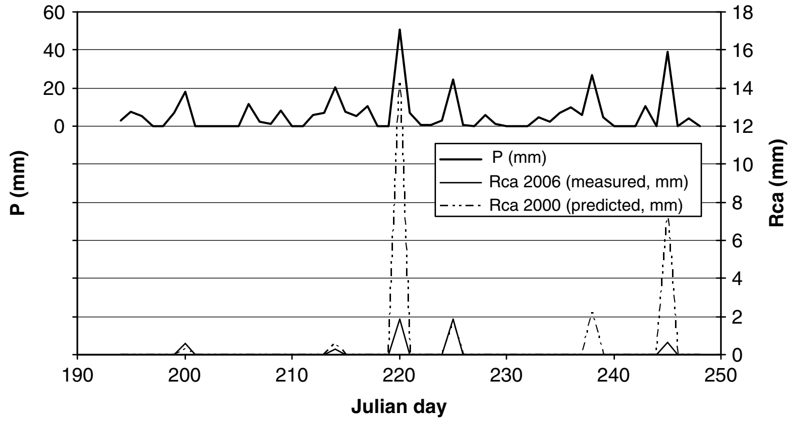

Figure 9. Runoff depth at catchment scale (R_{CA}), as measured in 2006 (after catchment management) and predicted for 2000 (before catchment management), based on 2006 rainfall data (P)

Table V. Runoff data for selected small catchments in the Ethiopian Highlands

Catchment	°N	°E	Altitude range (m)	Area (km^2)	Period (years)	Mean annual precipitation[a] P (mm)	Mean annual runoff[a] R (mm)	Runoff coefficient $(100 \times R P^{-1})$	Source
Anjeni	10°23′	37°31′	100	1·13	10	1615·8 (±238·4)	731.0	45·2	Bosshart (1998a) and Liu *et al.* (2008)
Dombe (without SWC)	7°28′	38°22′	125	0·94	12	1308·0 (±249·4)	246·3 (±158·2)	18·8	Bosshart (1998b)
Dombe (with SWC)	7°28′	38°22′	105	0·73	12	1308·0 (±249·4)	148·7 (±111·1)	11·4	Bosshart (1998b)
Hunde Lafto	8°41′	40°24′	352	2·37	11	935	80	9	Herweg and Stillhardt (1999)
Maybar	11°07′	39°19′	328	1·13	12	1211	324	27	Herweg and Stillhardt (1999) and Liu *et al.* (2008)
Andit Tid	9°48′	39°43′	504	4·77	10	1379	754	55	Herweg and Stillhardt (1999a and Liu *et al.* (2008)
Dizi	8°12′	35°33′	224	6·73	4	1512	73	5	Herweg and Stillhardt (1999)
Afdeyu (Eritrea)	15°41′	38°35′	210	1·61	7	382·5 (±123·7)	19·6 (±16·5)	5·1	Bosshart (1997)
May Zeg-Zeg (before catchment management, simulated)	13°39′	39°11′	550	1·65	1	629	26·5	8	This study
May Zeg-Zeg (after catchment management)	13°39′	39°11′	550	1·65	1	629	5·1	1·6	This study

[a] Standard deviation between brackets.

catchments, with RC values for the rainy season varying between 7·5% and 26·3% (average: 18·6%) (Zenebe, 2009; Vanmaercke *et al.*, 2010) These RC values, however, are based on the total runoff volume, comprising also the base flow of the rivers. Therefore, these RC values slightly overestimate the actual percentage of rainfall that runs directly off. Nevertheless, a dominant part of the total runoff volumes of these catchments occurred during flash floods, caused by the direct runoff of rain.

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

The effect of the decrease in catchment runoff after implementation of SWC measures could be observed in the field where farmers take advantage of the decreased runoff response to re-establish farmland in areas previously affected by severe gully erosion (Figure 10).

Effects of integrated catchment treatment on ground water level

Measurements of the water table height in the piezometer located in the upper valley bottom taken from 2002 onwards allow a comparison of water levels over time (Figure 11). It should be noted that the extremes of the position of the water table could not be measured: actual values of the water level will have been slightly over the surface at the end of the rainy season, and in several years deeper than 200 cm (bottom of the piezometer) by the end of the dry season.

Overall, the water level sinks slowly during the dry season and reaches a minimum level just before the start of the rainy season (June), during which water levels rise quickly (Figure 11). The sharp decrease from day 120 onwards in 2006 is related to the extraction of ground water for irrigation. Clearly, SWC measures increase infiltration and cause a rise in the water table and improved water availability over time. Variability of the water table over the period 2001–2006 was also influenced by rainfall depth and seasonality, as well as by integrated catchment management since 2004.

The average water levels for 2002, 2003, 2004, and 2006 (Table VI) give a good indication of variation in water depth over time. To test the impact of catchment management on ground water level, a comparison was made between the years preceding catchment management (records for 2002 and 2003) and after it (2006). Water table depth measurements for 2001 and 2005 were too few to allow comparison and 2004 was a transitional year during which stone bunds were constructed. The period during which the water table remained at the soil surface was remarkable in 2006, from 29 August 2006 till January 2007, although calculated water surplus (WS) was less in 2006 than in 2002 (Table VII). Surplus occurs when rainfall depth is greater than potential evapotranspiration and the soil is at its field capacity. Then actual evapotranspiration equals potential evapotranspiration and surplus water is available for overland flow or ponding. In contrast to the fall in water level towards the end of the year, as in 2003 for example, the high water table in 2006 is an indication that water was stored in the

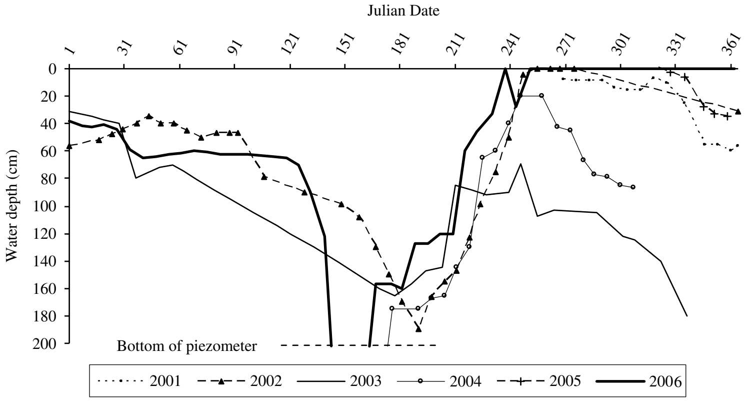

Figure 11. Water table fluctuations throughout the year in the upper valley bottom (see Figure 6): water depth below the soil surface was measured with a piezometer

Table VI. Yearly average depth to the water table in the piezometer (T) and total annual precipitation, recorded at the nearest rain gauge (P)

	T (cm)	P (mm)
2002	64·8	577·4
2003	103·7	548·3
2004	100·2	529·7
2006	50·7	660·9

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

	Period	ΔT (cm)	P (mm)	WS (mm)	$\Delta T/P$	ΔT/WS
2002	10 July–13 September	190	406·2	56	0·47	3·39
2003	27 June–4 September	96	345·5	29	0·28	3·31
2004	19 June–4 September	>200	460·8	95	>0·43	>2·11
2006	10 June–26 August	>200	359·6	18	>0·56	>11·11
Average		171.5	393·03	49·5	0·44	4·98

upper part of the catchment by SWC structures and has infiltrated.

Another indication of the positive effect of catchment management on water conservation is the rapid recharge of the water table from a very deep water table (due to water abstraction for irrigation—Figure 12A) to a water table reaching the soil surface, in 2006 (Figure 11). If infiltration rate has indeed increased after installation of the stone bunds, then the water table should show a greater rise in level for the same amount of rainfall. The ratio of maximal water table rise (ΔT) over rainfall (P) for that period was calculated to allow this comparison (Table VII). The years before installation of stone bunds (2002 and 2003) show an average ratio ($\Delta T/P$) of 0·38. The ratio for 2006 is >0·56 which is >46% increase from 2002 to 2003. When the rise in water table is given relatively to the WS over that period (Vandecasteele, 2007; Walraevens *et al*., 2009), an even larger difference is seen between 2006 ($\Delta T/\mathrm{WS} > 11{\cdot}1$) and the previous years ($\Delta T/\mathrm{WS} = 3{\cdot}4$). From these data, it can be inferred that the SWC structures built in 2004 have indeed had a significant and positive impact on the water table and its recharge in the catchment.

Emerging springs and irrigated fields (Figure 12A) are other indicators for a better hydrology and water supply in the study area brought about by integrated catchment management. Irrigated fields in the lower gully system (Figure 12B) also indicate that farmers are less frightened for flash floods which have a destructive effect on crops and parcels. The duration of natural uptake of water by rainfed crops is also prolonged due to greater soil water content over a longer period.

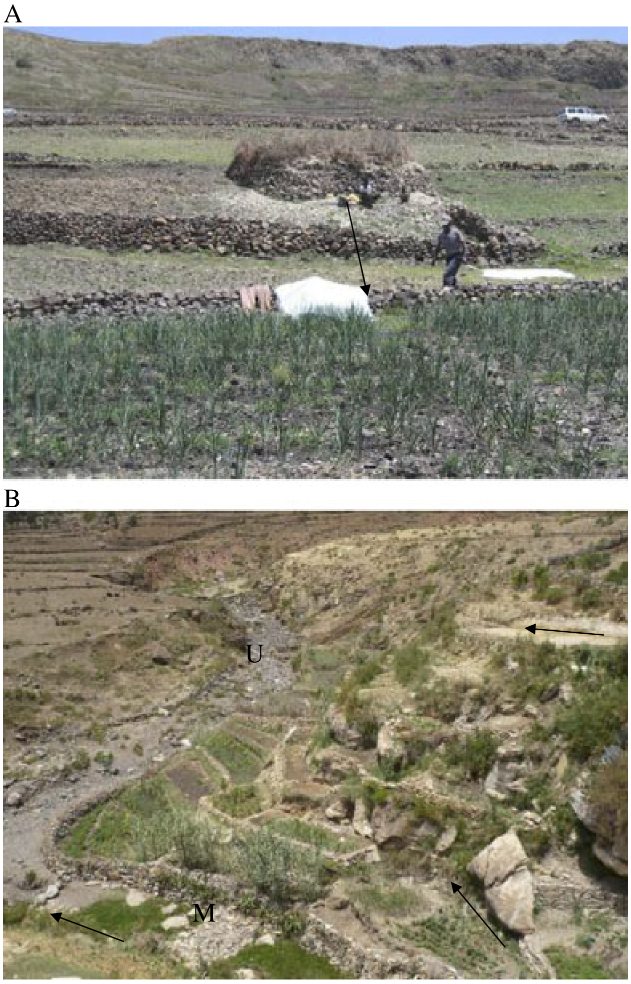

Figure 12. Irrigated vegetable gardens (A) in the upper part of the catchment (nearby the piezometer; photo Karl Herweg) and (B) in the lower gully system, with M indicating the outlet of the managed catchment, and U the outlet of the unmanaged catchment. Runoff flow directions in the channels are towards the lower left of photo B and arrows in both photographs indicate major irrigation canals

There may be observations where forestation of catchments leads to decreased base flow (Bruijnzeel, 2004); obviously, if reforestation with water-consuming tree species is the main catchment management technique, this will lead to high evapotranspiration and possibly decreased spring discharges (Harrold *et al*., 1962; Dragoun and Harrold, 1971; Bruijnzeel, 2004). In the MZZ case, where catchment management is carried out through physical SWC structures—modified surface management and less water-demanding, generally indigenous tree species—positive impact on hydrology was demonstrated. Whereas this certainly contributes to irrigation development in the lower part of the catchment, the higher infiltration rates seem to benefit above all to *in situ* crop growth.

CONCLUSIONS

Overall, the impacts of catchment management on the hydrology are positive in MZZ. The main observed changes in hydrology are the decrease of the annual

RC by 81% (from 8% before catchment management down to 1·6% after catchment management), the rapid recharge of the groundwater table after the dry season and the prolonged water supply at springs. These changes indicate that SWC measures increase infiltration and spread runoff in time. Besides their positive effect on hydrology, increased infiltration and lower runoff lead to lower soil loss rates and a higher sediment deposition rate within the catchment (Nyssen *et al.*, 2009c).

The reduced runoff and higher infiltration rates have a positive influence on the water balance in the MZZ catchment. Increased water availability leads to higher crop yield and crop diversity due to irrigation. Indications for an improvement of the water balance are an increased base flow and groundwater table, the appearance of springs in the gully channels, the establishment of cropland and rehabilitation of former vegetation cover in the gully system, and the creation of irrigated fields in the upper and lower parts of the MZZ catchment.

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