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

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

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

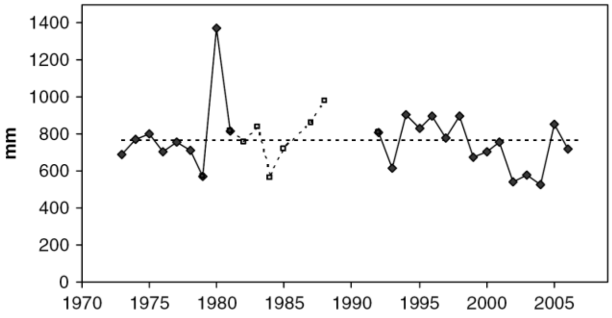


Figure 4. Annual precipitation in Hagere Selam. Annual average is 762 (±171) mm. Source: National Meteorological Agency (www.ethiomet.gov.et), except 1992–1994: Dogu'a Tembien Agricultural Office. Missing data correspond to the period of civil war and the years thereafter. A tentative reconstruction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

Fig. 1.

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

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

Table 1

In prevision of the upcoming management programme, and in order to be able to investigate its impact, rainfall (Table 1), water table and spring monitoring were undertaken starting from 2001 and lasted till 2007. Intense investigations took place in the rainy season of 2006. The studies concerned the surface hydrology of the catchment, the hydrogeology, and the impact of catchment management on the hydro(geo)logy.

1. Hydrogeological studies

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

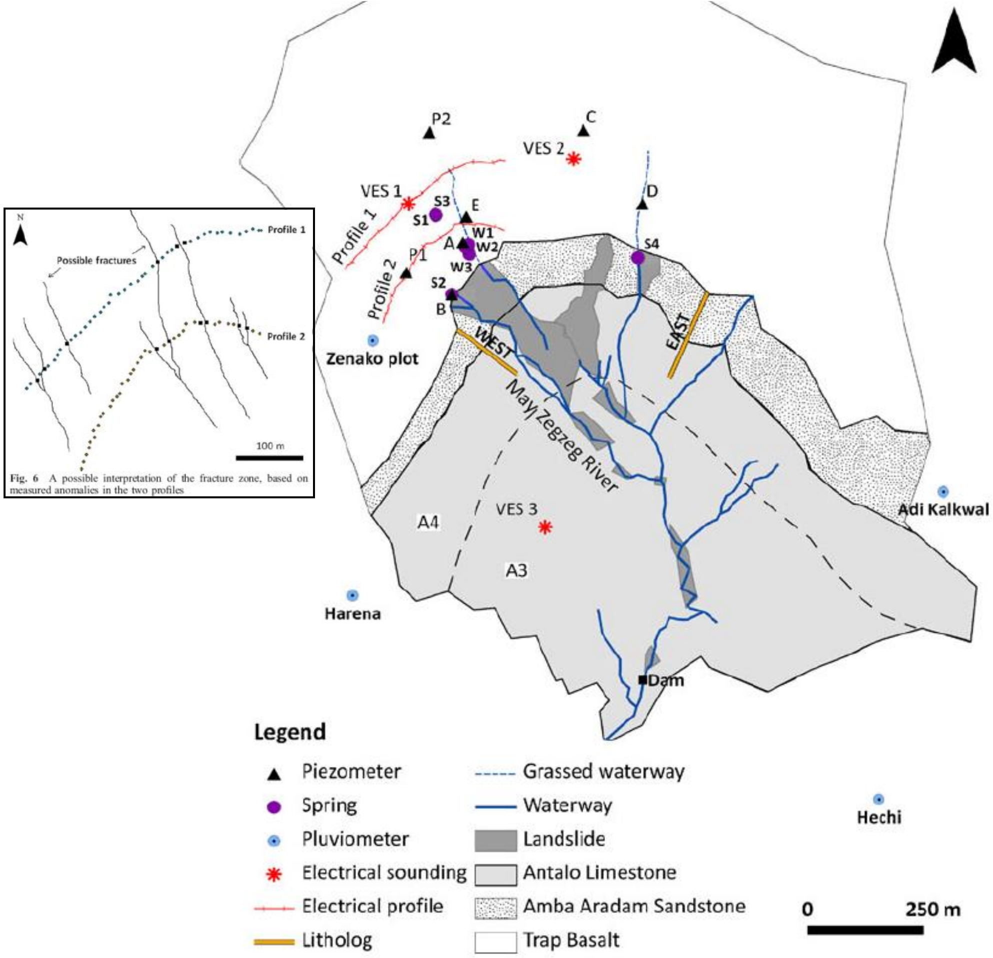


Fig. 6 A possible interpretation of the fracture zone, based on measured anomalies in the two profiles

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

Fig. 2.

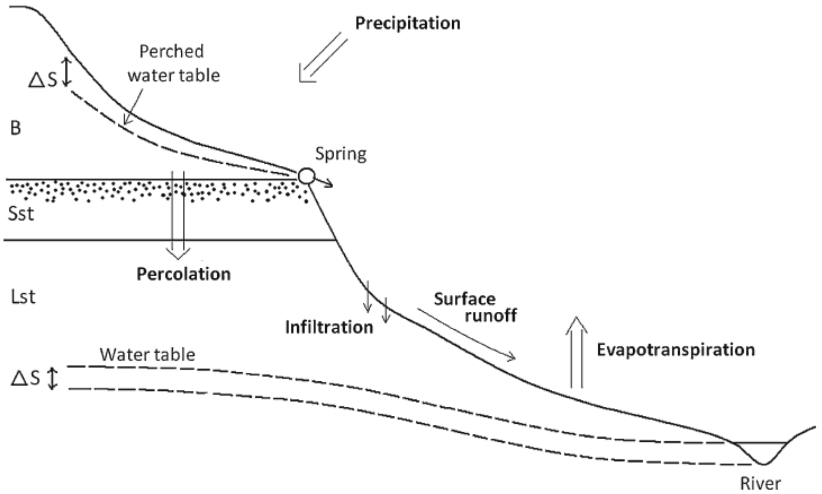


Fig. 4 The hydrological cycle represented in a schematic cross-section of the May Zegzeg catchment. Abbreviations used are basalt (*B*), sandstone (*Sst*) and limestone (*Lst*) for the lithologies, and *ΔS* for the change in soil water storage. Not to scale

Fig. 3.

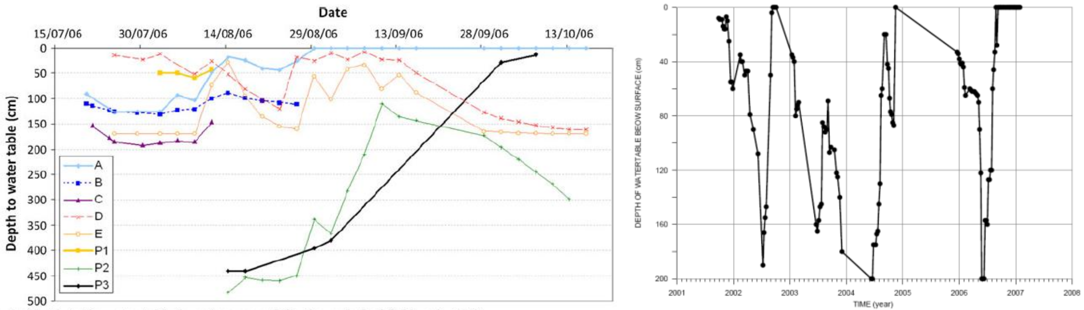
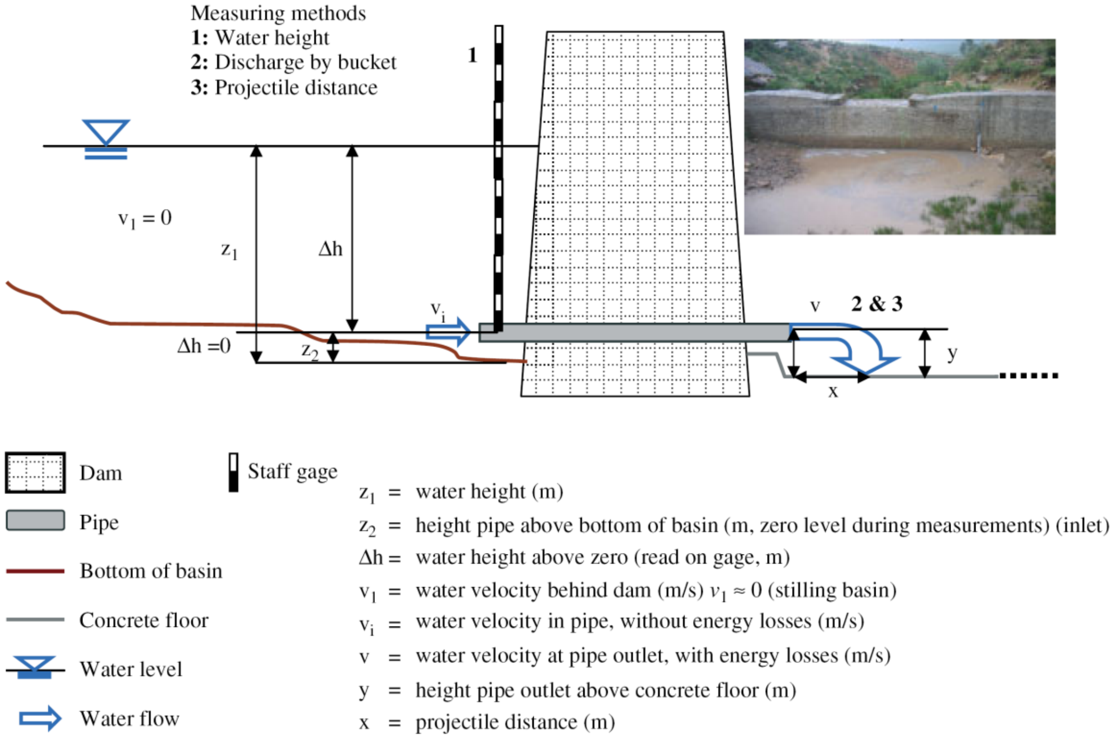


Fig. 4. Water levels (depth to the water table in cm) measured for the period of fieldwork, 2006

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



z_1 = water height (m)
z_2 = height pipe above bottom of basin (m, zero level during measurements) (inlet)
Δh = water height above zero (read on gage, m)
v_1 = water velocity behind dam (m/s) $v_1 \approx 0$ (stilling basin)
v_i = water velocity in pipe, without energy losses (m/s)
v = water velocity at pipe outlet, with energy losses (m/s)
y = height pipe outlet above concrete floor (m)
x = projectile distance (m)

Schematic representation of the cement dam where runoff measurements were made at the catchment outlet (for location se

Fig. 5.

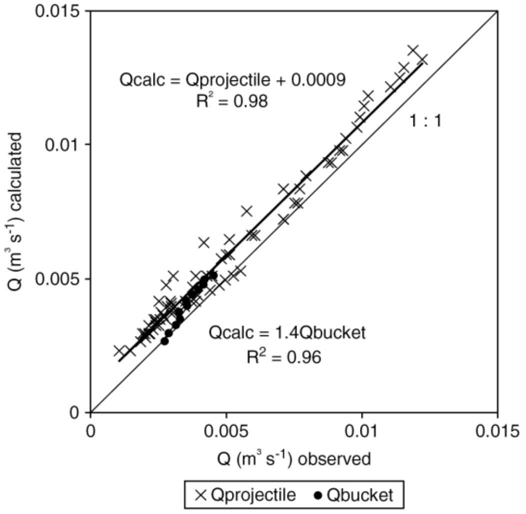


Figure 8. Calculated runoff discharge (Q_{calc}, $m^3\ s^{-1}$, based on Bernoulli's equation) as a function of observed runoff discharges [Q_{obs}, $m^3\ s^{-1}$, based on (1) projectile trajectory method (crosses) and (2) direct runoff discharge measurements with bucket (dots) at the pipe outlet]

Fig. 6.

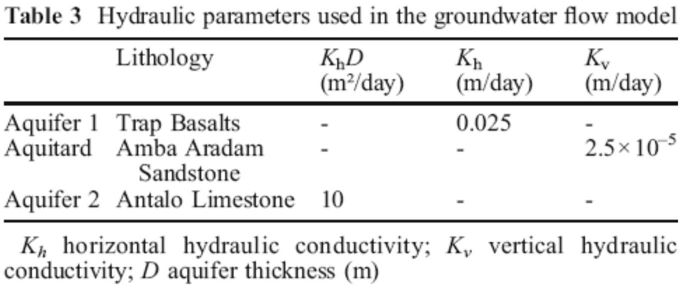


Table 3 Hydraulic parameters used in the groundwater flow model

	Lithology	K_hD (m²/day)	K_h (m/day)	K_v (m/day)
Aquifer 1	Trap Basalts	-	0.025	-
Aquitard	Amba Aradam Sandstone	-	-	2.5×10^{-5}
Aquifer 2	Antalo Limestone	10	-	-

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

Table 2.

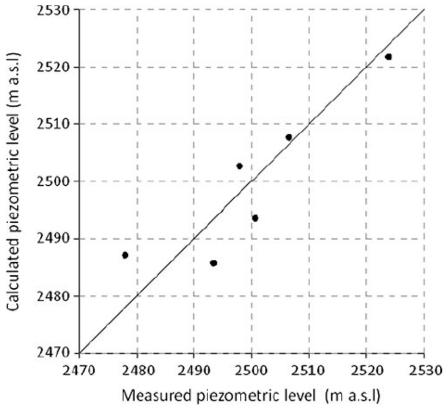


Fig. 7. **Fig. 12** A comparison of measured and calculated piezometri water levels in the Trap Basalts

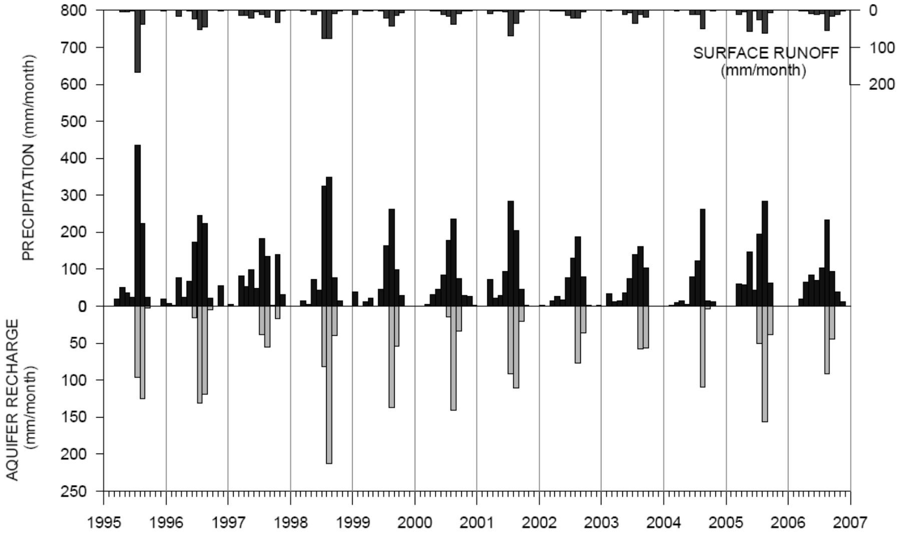


Fig. 8. Precipitation, calculated runoff and aquifer recharge (1995-2006)

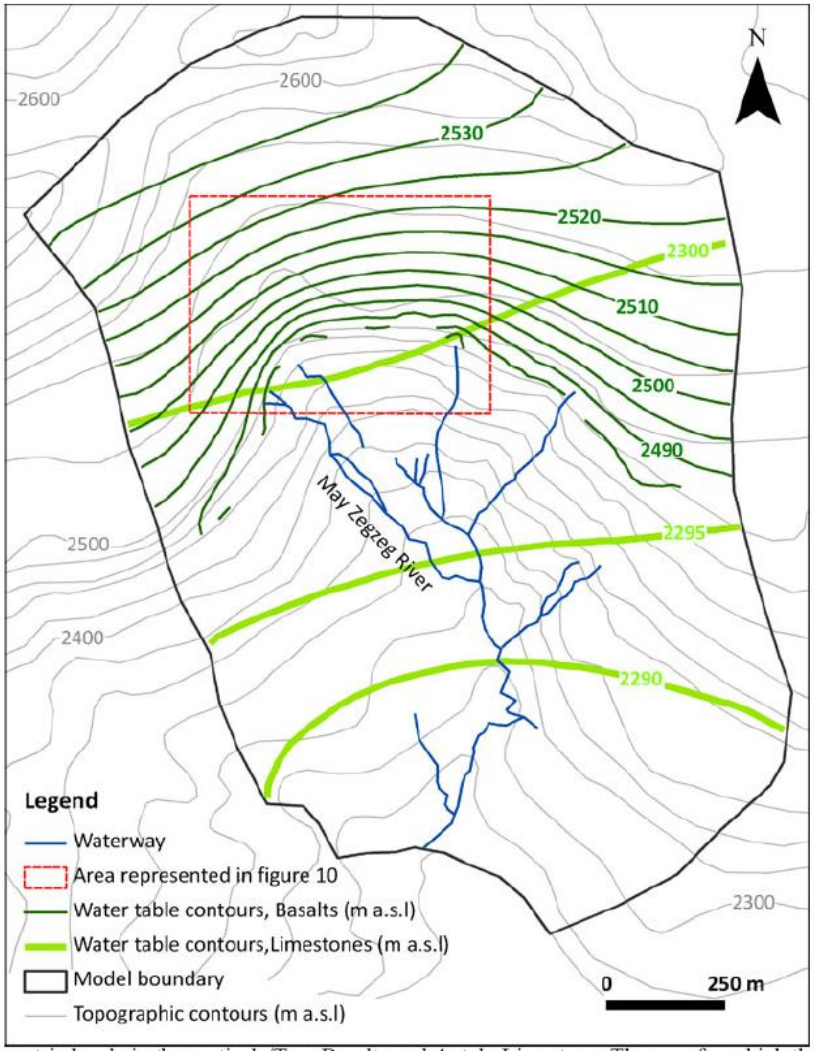


Fig. 9. Calculated piezometric levels in the vertisols/Trap Basalts and Antalo Limestone. The area for which the

2. Impact of catchment management

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

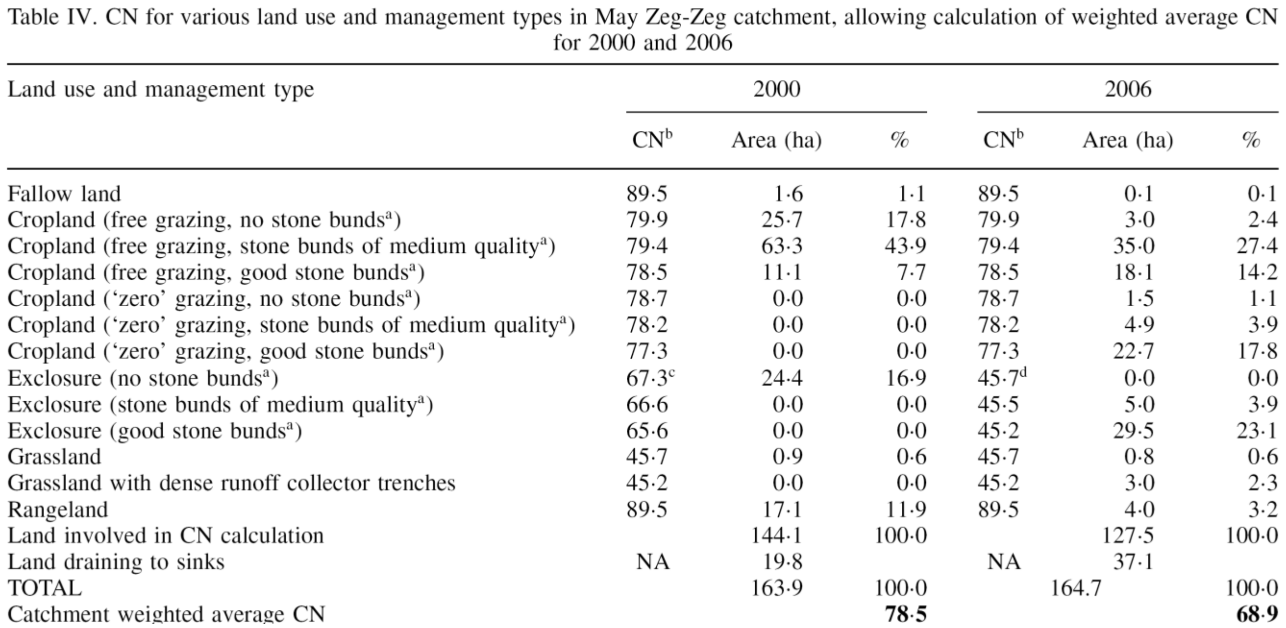
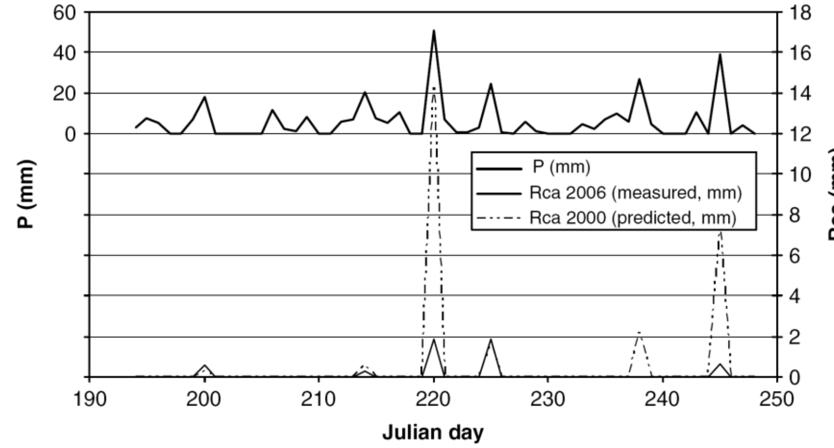


Table IV. CN for various land use and management types in May Zeg-Zeg catchment, allowing calculation of weighted average CN for 2000 and 2006

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

Table 3.



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

Fig. 10.

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

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

	Period	ΔT (cm)	P (mm)	WS (mm)	$\Delta T/P$	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

Table 4.

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

Fig. 11.

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