Impact of draining hilly lands on runoff and on-site erosion: a case study from humid Ethiopia

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ABSTRACT: The use of drainage ditches on farmland has an impact on erosion processes both on-site and off-site, though their environmental impacts are not unequivocal. Here we study the runoff response and related rill erosion after installing drainage ditches and assess the effects of stone bunds in north Ethiopia. Three different land management systems were studied in 10 cropland catchments around Wanzaye during the rainy season of 2013: (1) the exclusive use of drainage ditches (locally called *feses*), (2) the exclusive use of stone bunds, and (3) a mixture of both systems. Stone bunds are an effective soil and water conservation technique, making the land more resistant against on-site erosion, and allowing *feses* to be installed at a larger angle with the contour. The mean rill volumes for the 10 studied cropland catchments during the rainy season of 2013 was $3.73 \pm 4.20 \, \mathrm{m}^3 \, \mathrm{ha}^{-1}$ corresponding to a soil loss of $5.72 \pm 6.30 \, \mathrm{ton} \, \mathrm{ha}^{-1}$. The establishment of *feses* causes larger rill volumes ($R = 0.59$, $N = 10$), although *feses* are perceived as the best way to avoid soil erosion when no stone bunds are present. The use of *feses* increases event-based runoff coefficients (RCs) on cropland from *c.* 5% to values up to 39%. Also, a combination of low stone bund density and high *feses* density results in a higher RC, whereas catchments with a high stone bund density and low *feses* density have a lower RC. Peak runoff discharges decrease when stone bund density increases, whereas *feses* density is positively related to the peak runoff discharge. A multiple linear relation in which both *feses* and stone bund densities are used as explanatory variable, performs best in explaining runoff hydrograph peakedness ($R^2 = 83\%$). Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: drainage; stone bunds; soil conservation; peak runoff; degradation

Introduction

In traditional rural areas where soils have poor internal drainage and where the rainfall depth exceeds the evapotranspiration depth, drainage ditches are commonly established manually (Shiferaw, 2002; Turkelboom *et al.*, 2008; Monsieurs *et al.*, 2015b). Hydrogeomorphic impacts of drainage ditches have been reviewed by Monsieurs *et al.* (2015a), yet they state that it is hard to conclude on the final balance between the positive and negative effects following the use of drainage ditches. Overall, surface drainage ditches have a positive impact on aeration of the soil, crop growth and soil structure (e.g. Luthin, 1966; Robinson, 1990; Spaling and Smit, 1995; Zhang *et al.*, 2013). Yet, negative impacts concern off-site impacts such as higher peak runoff discharges, gully initiation, flooding, and an increase in sediment load, whereas on-site problems are less documented (Monsieurs *et al.*, 2015a).

Cropland management affects soil loss. The widespread traditional drainage ditches in the humid parts of Ethiopia are perceived as indigenous soil and water conservation (SWC) practices (e.g. Million, 1996; Herweg and Ludi, 1999; Zegeye *et al.*, 2010). Also Gessesse (2014) emphasizes that drainage ditches in the Lake Tana basin provide protection against erosion when properly constructed, i.e. with no excessive ditch gradients and appropriate depth. When the collected runoff is drained to common areas and the erosion features are not always clearly visible, farmers do not perceive traditional ditches as inducing erosion problems (Gessesse, 2014). On the one hand, Million (1996) states that drainage ditches in the Ethiopian highlands are not a useful SWC tool, but a simple drainage technique causing severe erosion hazards on steep slopes although croplands without drainage ditches were seriously affected by rill erosion. On the other hand, soil loss on cropland is reduced after stone bund implementation, but most of the studies related to this technique were conducted in semi-arid and subhumid areas (e.g. Gebremichael *et al.*, 2005; Vancampenhout *et al.*, 2006; Nyssen *et al.* 2007). Yet no quantitative studies and only scarce qualitative studies have been conducted to compare rates of soil loss from cropland where drainage ditches or stone bunds are implemented (e.g. Reij, 1996; Amsalu, 2006; Amsalu and de Graaff, 2007). Herweg and Ludi (1999) measured soil loss and runoff for different

SWC techniques applied in different climatic areas in Ethiopia including stone bunds and other versions of traditional drainage ditches, i.e. *Fanya Juu* and double ditches, both consisting of a small dam and a ditch. No significant soil loss differences between the SWC treatments were found and the effects on runoff and crop production were not clear. Graded structures were found to increase runoff, causing erosion of the drainage ditches and loss of precious moisture for crop production (Herweg and Ludi, 1999).

Hydrograph characteristics of runoff events are related to the type of erosion processes for which it is interesting to seek for a relation with land management practices. However, research on this topic is limited. Peak flow discharge and runoff volume drive the erosion process (Woodward, 1999). Channel erosion, and thus sediment transport will be larger when the runoff peak discharge increases (Simon and Rinaldi, 2006). In this study we focus on the hydrograph peakedness as artificial drainage is found to cause a higher peak runoff (Skaggs, 1994; Holden, 2004) and hence, higher erosion rates (Hooke, 1979). Different measures are used by different authors for expressing runoff peakedness of which we will discuss the following: (1) kurtosis (Fryirs and Brierley, 2012); (2) velocity of rise time (VRT, in s^{-1}), i.e. an index we developed for the increase of runoff discharge during a fixed period before the peak was reached, and (3) peak flow discharge over base time (QBT, in m^3 s^{-1}) (Gordon *et al.*, 2004). Conway and Millar (1960) found artificially drained areas to have an increased sensitivity of runoff response to rainfall causing higher peak flows. Armstrong and Garwood (1991) found lowered groundwater tables and reduced waterlogging in artificially drained plots, although their effects on peak flows were found to be small. Carluer and De Marsily (2004) state that in rural catchments, drainage ditches may accelerate the flow from the field to the river. But conversely, if the ditches are dry they may help the water to infiltrate (Marofi, 1999). Stone bunds reduce the quantity and eroding capacity of overland flow (Bosshart, 1997; Taye *et al.*, 2013). This was confirmed by Nyssen *et al.* (2007) who state that stone bunds bring positive off-site effect such as runoff reduction and flood regulation.

Rill erosion and gully formation are the most important processes causing soil loss by water which, together with the loss of rainwater (Poesen *et al.*, 2003), form a severe threat to the subsistence rainfed agriculture and the national economy of Ethiopia (Bewket and Sterk, 2003; Tebebu *et al.*, 2010). Thus lack of knowledge on (1) the process of gully erosion (off-site processes) and (2) the environmental impacts (on-site processes) of artificial drainage (Skaggs *et al.*, 1994) is problematic as it may lead to mismanagement in the basin. The off-site impacts of drainage ditches on cropland have been recently reported by Monsieurs *et al.* (2015b). The objectives of this paper are to understand the impact of both drainage ditches and stone bunds on the on-site runoff response and rill erosion.

Study Area

Lake Tana basin

Lake Tana is the largest lake in Ethiopia and its catchment covers some 16 500 km^2, including the lake area. The lake is situated in the north-western part of Ethiopia (between 11°00′ N and 12°50′N, 36°30′E and 38°20′E), forming a depression in the Ethiopian highlands at 1786 m above sea level (a.s.l.) (Setegn *et al.*, 2010). The climate in Lake Tana basin is 'cool to cold tropical highland monsoon' (Dargahi and Setegn, 2011). Rainfall is locally variable in the region, with a basin-wide annual average of 1421 mm (Conway, 2000) and 70%

of the total rainfall occurring in the *Kiremt* season (June–September). The soils of the Lake Tana basin are derived from weathered volcanic rocks (Poppe *et al.*, 2013). The majority of the basin has deep to very deep soils whereas soils on hill slopes are shallow or very stony (Easton *et al.*, 2010; Engda, 2010; Kebede *et al.*, 2011). The fertile soils on the lacustrine deposits and the weathering materials of the basalts make the Lake Tana basin an important region for Ethiopia (Colot, 2012).

In the Lake Tana basin, stone bunds have been found to reduce surface runoff and soil loss (Schürz *et al.*, 2013; Brenner et al., 2013). Other research confirms the positive off-site and on-site effects of stone bunds (Haregeweyn, 2015). But over a longer time span, possible negative consequences such as concentration of runoff, ponding of water, piping under structures or the creation of fertility gradients have to be taken into account (Nyssen *et al.*, 2007; Alt *et al.*, 2009). On-site conservation methods on farmland are still in an experimental stage and not widely practiced.

Land surface management in Kizin and Wonzima catchments

Fieldwork was conducted in the Kizin and Wonzima catchments near the village of Wanzaye during the rainy season (July–September) of 2013 (Figure 1). Both catchments are moderately to dominantly cultivated. They are part of the Gumara sub-basin (1236 km^2). Soils in the Gumara sub-basin are Eutric Vertisols, Eutric Fluvisols, Chromic Luvisols, Eutric Leptosols, and a dominance of Haplic Luvisols (Colot, 2012; Poppe *et al.*, 2013).

Land management practices in the study area are strongly related to the highly seasonal rainfall pattern. Three practices are applied around Wanzaye as well as in the wider region: (1) stone bunds, (2) drainage ditches (locally called *feses*), and (3) the combined use of both techniques (Monsieurs *et al.*, 2015a, 2015b). The combined use of stone bunds and *feses* is not exclusive for the area around Wanzaye. Reij *et al.* (1996) state that for regions with annual rainfall approaching 1000 mm or more, combinations of SWC practices (for example stone bunds) and drainage ditches in farm fields with a risk of waterlogging, are common (e.g. in the Mandara mountains, north Cameroon).

We opted to work at a catchment scale rather than at a plot-scale as plot-scale studies show limitations of which the decisive one was the restriction to extrapolate results from runoff plots to catchments (Nyssen *et al.*, 2004, 2010a; Awulachew *et al.*, 2008). Ten cropland catchments (CAs) have been selected based on *feses* density and presence or absence of stone bunds, and delineated by a handheld global positioning system (GPS) (Garmin eTrex). Catchment areas range from 0.27 ha (CA 10) to 4.21 ha (CA 3), with a mean catchment area of 1.65 ± 1.25 ha. The average slope gradient of the 10 catchments ranges between 0.06 and 0.23 m m^{-1} (Table I). General analyses of stone bund density, *feses* density, surface rock fragment cover, soil depth, catchment slope gradient, angle between established *feses* and the contour; *feses* gradient and total rill volume per area are based on measurements from these 10 catchments. Stone bund and *feses* densities vary among the 10 study catchments (Table I), with a mean *feses* density of 254 ± 179 m ha^{-1}, and mean stone bund density (SBD) of 277 ± 340 m ha^{-1}. One catchment without drainage ditches (CA 2) and one without stone bunds (CA 6) were selected as well. Although we are aware of the potential effects of footpaths on runoff (Harden, 1992; Ziegler *et al.*, 2000; Turkelboom *et al.*, 2008), footpaths are not included for the calculation of *feses*
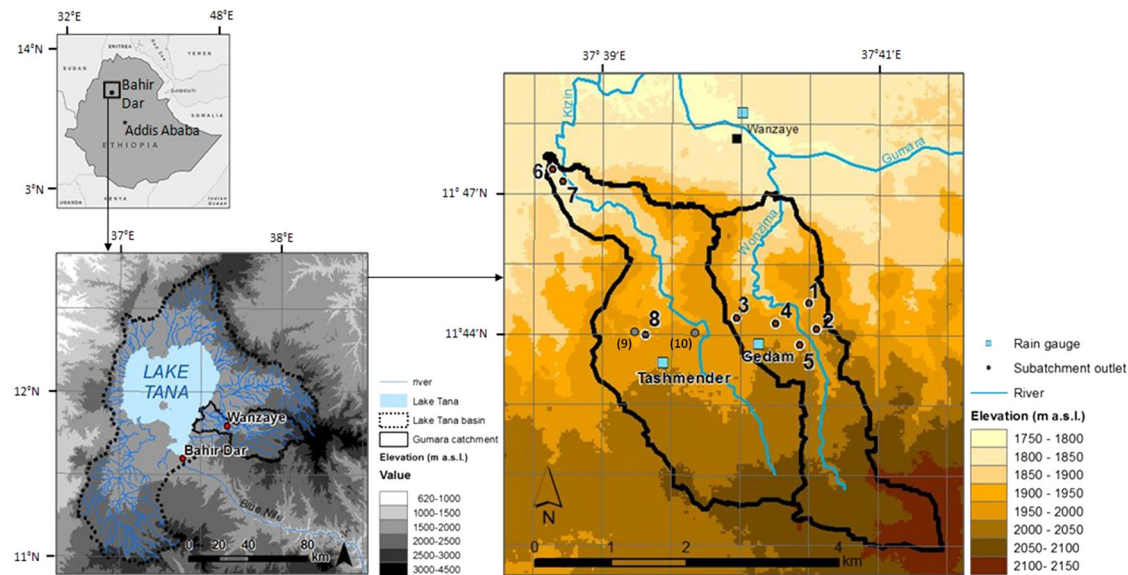
Figure 1. Location of the study area in Ethiopia and the 10 selected subcatchments and rain gauges in the Lake Tana basin. The map on the right shows the subcatchments Kizin (on the left) and Wonzima (on the right). Two outlier catchments (9 and 10) are marked by a grey dot. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table I. Characteristics of the 10 studied cropland catchments (CA)

CA	Area (ha)	ASG ($m\,m^{-1}$)	TFL (m)	FD ($m\,ha^{-1}$)	TSL (m)	SBD ($m\,ha^{-1}$)
1	1.94	0.20	404	209	1021	528
2	1.76	0.06	0	0	789	448
3	4.21	0.08	1038	247	306	73
4	3.51	0.09	187	53	1364	388
5	1.63	0.06	683	418	454	278
6	1.44	0.06	584	406	0	0
7	0.73	0.07	57	78	276	379
8	0.56	0.06	106	188	353	626
9	0.41	0.11	177	431	20	50
10	0.27	0.23	135	510	0	0
Minimum	0.27	0.06	0	0	0	0
Maximum	4.21	0.23	1038	510	1364	626
Mean	1.65	0.10	337	254	458	277
Standard deviation	1.25	0.06	335	179	462	233

Note: average slope gradient (ASG), total *feses* length (TFL), *feses* density (FD), total stone bund length (TSL), stone bund density (SBD).

density to study exclusively the impact of land surface management on runoff response.

Runoff analyses revealed two catchments (CA 9 and CA 10) to be erratic as more than 80% of the runoff events show runoff coefficients (RCs) exceeding 100% and runoff peak values are found to be outliers. For these reasons both catchments were excluded from runoff analyses, though kept for further analyses on on-site soil erosion. Possible sources of error are: (1) underestimation of the area contributing to runoff; (2) the assumption of uniform flow at the outlet; (3) erratic field measurements of the slope gradient at the outlet channels; (4) erratic field measurements of the routine flow depths; (5) underestimation of rainfall depth as local events in the catchment area were not all captured. Although the latter is not very likely because rainfall was found to be equally distributed over the study area.

Feses in the Kizin and Wonzima catchments are established using the *maresha* ard plough, drawn by a pair of oxen (Nyssen *et al.*, 2010b); they have a mean top width of 27 ± 9 cm ($N = 41$); a mean depth of 12 ± 2 cm ($N = 37$); are made at an average angle with the contour of $44.7° \pm 7.2°$ ($N = 96$); and a mean gradient of 0.055 ± 0.054 $m\,m^{-1}$ ($N = 96$) (Monsieurs *et al.*, 2015a).

Feses are constructed on places where runon water accumulates, independently from the type of crops grown in the field plots where the *feses* are made. Also in other parts of Ethiopia, topography is a determining factor for the construction of the drainage ditches as it controls where runoff is concentrating (Million, 1996; Gessesse, 2014). If possible, *feses* are constructed with their outlet towards a common pathway. The depth of the *feses* is chosen in such a way that the farmer is able to plough and destroy the *feses* the following year. *Feses* are perceived by the local farmers as the best physical soil conservation technique when stone bunds are lacking. However, all farmers are aware of their negative implications as well. *Feses* constructed perpendicular to the contour are perceived by most farmers as mismanagement of the farmland as they lead to intense soil erosion in the *feses*, turning them into ephemeral gullies. Each year, locations of the *feses* within a farmer's plot are changed, to prevent long-term erosion at these sites.

Materials and Methods

Rainfall measurements

Rain gauges, similar to the National Meteorological Services Agency (NMSA) gauge in Wanzaye were installed in Gedam and Tashmender villages from 15 July 2013 to 4 September 2013 (Figure 1). They have been enclosed by a fence to protect them from disturbing factors and a minimum distance of 3 m to any kind of obstacles, including trees, was kept. Secondary school students have been trained to record every evening (daytime precipitation) and every morning (night-time precipitation) at 07:00 and 18:00 (GMT + 3), the volume of water in the rain gauge using a graded cylinder. Their records were regularly checked for their quality and precision to minimize data errors. Rainfall data from rain gauges in Gedam and Tashmender have been attributed to the subcatchments located within the rain gauge's catchment.

Rill erosion measurements

According to Zegeye *et al.* (2010), the maximum rill development (number and dimensions) in the Debre Mewi watershed

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in the Lake Tana basin is attained in August. Hence, rill erosion in the study area has been measured at the end of August 2013. Analyses are based on the calculated rill volumes, because these volumes comprise all dimensions of the rill (length, depth, width), rather than on rill density (in m ha^{-1}) as this only comprises the rill length (Zegeye *et al.*, 2010). The rill volume was measured from its starting point up to the point where the eroded soil was deposited by measuring the length, width and depth. Depth and width of the rills were measured at a point along the rill being representative for the entire rill. Rill width was measured at half depth of the rill to represent the mean width and to approach the cross-section as a trapezium which best reflects the field conditions. Total rill volume per area (TRA; in m^3 ha^{-1}) was calculated as the sum of the volume of each rill (in m^3) in a catchment divided by the catchment area (in hectares). Soil loss by rill erosion (in ton ha^{-1}) was calculated by multiplying the catchment-averaged measured bulk density with the total rill volume per ha. Soil samples were taken in the topsoil layer with Kopecky core rings (100 cm^3) three times throughout the rainy season at two fixed sites per catchment for determining bulk density.

Runoff discharge calculations

Runoff discharge calculations at the catchment outlet were based on routine flow depth measurements and rating curves. A data collector for each catchment was trained to conduct routine flow depth measurements, i.e. recording for every day-time rainfall event runoff depth measured with a graded ruler at the outlet channel with an interval of five minutes. Routine flow depths are converted to continuous runoff discharge series by a rating curve (Descheemaeker *et al.*, 2008; Nyssen *et al.*, 2010a; Rodriguez-Blanco *et al.*, 2013):

$$Q = a \, h^b \tag{1}$$

where Q (in m^3 s^{-1}) is discharge, h (in metres) is the flow depth and a and b are fitting parameters. Discharges for different flow depths were calculated using the Manning formula (Manning, 1891), assuming uniform flow, and expert-based estimations of their Manning coefficient n. The cross-sectional area and wetted perimeter for these flow depths were calculated using a two-dimensional (2D) drawing program (DraftSight) after detailed recording of the cross-section for each outlet. Subsequently, rating curves in the form of Equation (1) could be constructed for all catchments. The procedure for estimating the roughness coefficient in the Manning formula is generally subjective for which the accuracy depends on the applicants' experience (Coon, 1995). To decrease the subjectivity, eight scientists (geomorphologists) of the Ghent and Bahir Dar Universities who are familiar with the Manning formula and its parameters have been asked to give their estimation for Cowan's parameters (Cowan, 1956) determining the roughness coefficient based on photographs of the outlet channel. We took the mean of the estimates for each parameter to estimate the roughness coefficient n.

For each rainfall event, peak flow discharge (Q_p), total runoff (in millimetres), and runoff coefficient (RC, %) were calculated. The RC was calculated as a fraction of the measured daytime rainfall, resulting in underestimations of the RC if daytime rainfall comprised rainfall event(s) prior to or after the runoff measurement.

Hydrograph characteristics

Hydrographs were plotted for the measured runoff events, and their shape compared for the different catchments. For the calculation of the hydrograph peakedness (kurtosis, VRT, and QBT) only the events that have been measured from the beginning up to the end, i.e. rising and falling limb are captured, were incorporated. Continuous percolating baseflow through the channels has not been taken into account as the discharge was negligible compared to storm runoff discharge. The kurtosis is a measure of the peakedness of the hydrograph histogram (Hood *et al.*, 2007). A minimum value of the kurtosis is -3, for which the histogram is flat; a graph with a kurtosis of zero is normally distributed; and a graph with a kurtosis higher than zero (until infinity) is more sharp than if it was normal distributed. In general, 'a low-kurtosis hydrograph has a broad, low-amplitude peak, is more rounded and has a shorter tail' and 'a high-kurtosis distribution has a sharper peak and longer, fatter tails' which reflects a flash flow regime (Fryirs and Brierley, 2012). Furthermore, we developed an index for the increase of runoff discharge during a period of 10 minutes before the peak was reached, normalized for daily rainfall and the catchment area:

$$\mathrm{VRT} = \frac{Q_p - Q_t}{P \, A} \tag{2}$$

where Q_t is discharge at t minutes before Q_p, both normalized by daytime rainfall (P, in millimetres) at the date of the runoff event and catchment area (A, in m^2). For Q_t, $t = 10$ minutes was used because data at a time longer than 10 minutes before Q_p was not always available. QBT is another measure of hydrograph peakedness calculated as the peak flow discharge to base time ratio. The base time is the duration of direct runoff production in the hydrograph considered (Gregory and Walling, 1968; Gordon *et al.*, 2004). For detailed analyses we prefer the kurtosis above the use of VRT or QBT as a measure of the hydrograph peakedness for the following reasons: (1) VRT is only a measure for peakedness during rise time and does not comprise the data of the falling limb of the hydrograph; (2) VRT is limited by $t = 10$ minutes for Q_t for the data of the study area; (3) base time used for QBT is not accurate as runoff events could not always be totally captured; (4) kurtosis is widely used as a measure for hydrograph peakedness (Hood *et al.*, 2007; Kumar and Chatterjee, 2005; Tardif *et al.*, 2009; Graf, 2010; Fryirs and Brierley, 2012). Also the peak flow discharge will be used as a measure for peakedness, which has been normalized by the catchment area ($Q_p \, A^{-1}$), enabling a comparison between the study areas.

Results

Rainfall characteristics

Pluviograms for rain gauges in Gedam, Tashmender and Wanzaye (rain gauge of the NMSA) are presented in Figure 2. Independent samples t-tests in SPSS showed no significant difference in the distribution of daily and monthly rainfall depths for these three rain gauges. Hence, we assume that rainfall was equally distributed over the whole study area during the research period. Mean rainfall depth around Wanzaye during the period of fieldwork in 2013 for (15–31) July was 372.35 ± 5.78 mm, for (1–31) August 377.03 ± 4.77 mm and for (1–4) September 66.02 ± 5.15 mm. Variations are calculated as standard deviations, also for further analyses. When comparing August 2013 to the 20-year mean (1992–2012) precipitation measured by the NMSA in Bahir Dar (i.e. 387.2 ± 110.1 mm), 2013 seems not an exceptional year regarding precipitation.
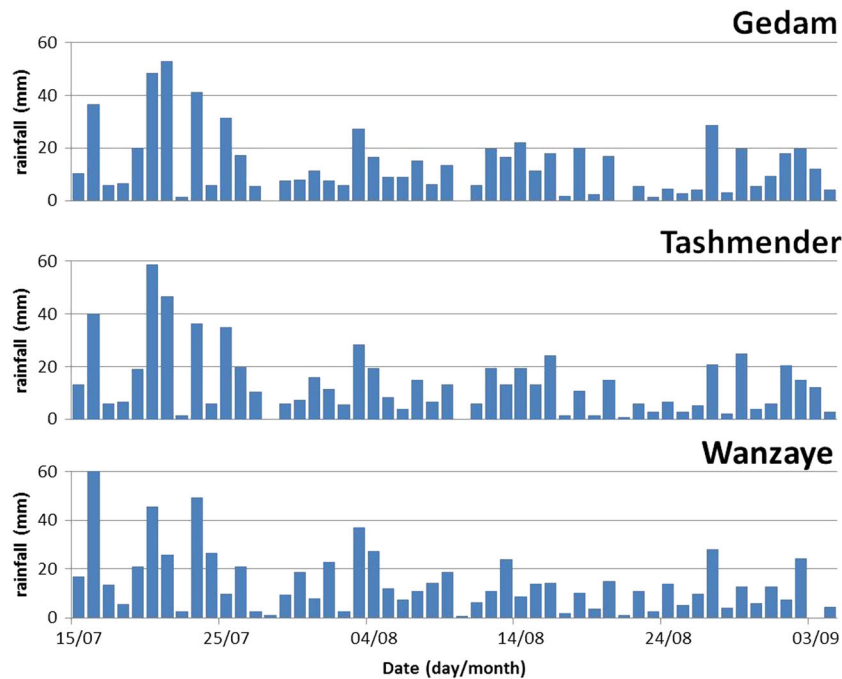
Figure 2. Pluviograms for three rain stations during the rainy season of 2013 around Wanzaye (Ethiopia). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Environmental conditions during fieldwork

Catchment-averaged soil depths range from 0.17 m to 0.77 m. Mean soil depth for all catchments is 0.42 ± 0.20 m ($N = 39$). The study area around Wanzaye was found to be very stony with an overall surface rock fragment cover of $66.7 \pm 26.1\%$ ($N = 38$). To check whether the average soil moisture content for the successive soil sampling campaigns changed over time, a repeated measures analysis of variance (ANOVA) test in SPSS was performed. We found no significant effect (significance level $\alpha = 0.05$) of sampling moment on gravimetric soil moisture content, i.e. the antecedent soil moisture conditions remained similar during the research period. Measured dry bulk densities ranged from 1.31 g cm^{-3} (CA 2) to 1.74 g cm^{-3} (CA 1). The total average (time- and space-averaged) dry bulk density is 1.56 ± 0.11 g cm^{-3} ($N = 60$), which is high compared to bulk density values from other studies in Ethiopia (Nyssen *et al.*, 2000; Descheemaeker *et al.*, 2006; Mekuria *et al.*, 2012).

Table II shows the correlations between SBD, *feses* density (FD), surface rock fragment cover, soil depth, catchment slope gradient, angle between established *feses* and the contour, and *feses* gradient. A negative correlation was found between SBD and FD ($R = -0.72*$, $N = 10$; *refers to its significance at $\alpha = 0.05$ also for the figures hereafter), which is a government

policy that forbids making *feses* where stone bunds were constructed at governmental initiative (Monsieurs *et al.*, 2015b). The following relationship for *feses* density and stone bund density (both in m ha^{-1}), has been established:

$$FD = 409\text{-}0.558\,SBD \quad R^2 = 0.52, N = 10 \quad (3)$$

Both the slope (i.e. the coefficient for SBD) and the intercept are significant ($\alpha = 0.05$). SBD explains 52% of the variability in FD. No other landscape elements from Table II could be found to explain the variability of FD.

FD and soil depth are negatively correlated ($R = -0.40$, $N = 10$), which can be attributed to the fact that soil depth affects the water retention properties (Kassa *et al.*, 2010) as shallow soils get saturated more quickly causing runoff by saturation excess (e.g. Martinez-Mena *et al.*, 1998; Liu *et al.*, 2008). Hence we assume that *feses* are made to avoid a saturated topsoil on shallow soils. Though we should be cautious when interpreting these findings because the catchments selected for our analyses were mainly situated in the hills, hence having relatively shallow soils that get easily saturated. Yet, *feses* are also made in deep (mainly clay) soils located in more gently sloping areas for which several studies indicate that the valley bottoms are common places of saturation by excess runoff (Engda *et al.*, 2011; Dagnew *et al.*,

Table II. Correlation (R) matrix between stone bund density (SBD, in m ha^{-1}); *feses* density (FD, in m ha^{-1}); surface rock fragment cover (Stone, %); soil depth (s_depth, in metres); dry soil bulk density (BD, in g cm^{-3}); catchment slope gradient (c_gradient, in m m^{-1}); angle between established *feses* and the contour (f_contour, in degrees); and *feses* gradient (f_gradient, in m m^{-1})

	FD	Stone	s_depth	BD	c_gradient	f_contour	f_gradient
SBD	−0.72*	0.21	−0.05	0.15	−0.17	0.75*	0.28
FD		0.15	−0.40	−0.13	0.37	−0.67*	−0.04
Stone			−0.79*	−0.50	0.68*	0.03	0.34
s_depth				0.52	−0.64*	0.10	−0.30
BD					−0.19	0.51	0.30
c_gradient						−0.12	0.55
f_contour							0.30

Significant correlations for $\alpha = 0.05$ are marked by an asterisk (*significant at $\alpha = 0.05$). All correlations are based on 10 observations.

2015). Despite the consensus on the fact that surface rock fragment cover protects cropland from soil erosion by water (e.g. Wischmeier and Smith, 1978; Poesen *et al.*, 1994; Nyssen *et al.*, 2001, 2007), a strong negative correlation is found in the study area between soil depth and surface rock fragment cover ($R = -0.79$*, $N = 10$; Monsieurs *et al.*, 2015a). This correlation is the result of the underlying correlation between rock fragment cover and catchment slope gradient ($R = 0.68$*, $N = 10$; Monsieurs *et al.*, 2015a), as thin soils occur on steep slopes (e.g. Poesen *et al.*, 1998; Hopp and McDonnell, 2009; Easton *et al.*, 2010). The latter was confirmed for our study area where the catchment slope gradient is negatively correlated with soil depth ($R = -0.64$*, $N = 10$; Monsieurs *et al.*, 2015a). The correlations between SBD, FD and the angle of the *feses* with the contour reveal contrasting behaviours, i.e. SBD being highly positive correlated ($R = 0.75$*, $N = 10$), and FD highly negative correlated ($R = -0.67$*, $N = 10$) to the angle between the *feses* and the contour.

Rill volumes correlated with environmental conditions

The TRA (in $m^3 ha^{-1}$) and total soil loss per area (in ton ha^{-1}), that occurred by the end of August, varies over the 10 study areas (Table III). A maximum TRA and soil loss per hectare was found for CA 10 (13.19 $m^3 ha^{-1}$; 19.66 ton ha^{-1}) and a minimum for CA 2 (0.17 $m^3 ha^{-1}$, 0.25 ton ha^{-1}). The mean volume of rill erosion per hectare for all catchments was 3.73 $\pm 4.20\ m^3 ha^{-1}$ and the mean corresponding soil loss was 5.72 ± 6.30 ton ha^{-1}. TRA comprises all rills in the 10 catchment whereas for further analyses, only rills for which the origin of the rill formation was clearly visible in the field, as illustrated in Figures 3A and 3B, have been categorized. A distinction has been made for rills which were formed by stone bunds or *feses* overflow, i.e. runoff flowing over the *feses* banks. Also rills formed on a thin soil layer or plough pan were visible in the field (Figures 3C and 3D) yet will not be further analysed as this is out of the scope of this paper. For all 10 catchments, 41% of the formed rills were initiated by *feses*, in contrast to 16% by stone bunds.

SBD and TRA are negatively correlated ($R = -0.50$, $N = 10$; Table IV), whereas the correlation between FD and TRA is positive ($R = 0.59$, $N = 10$; Table IV). Rill erosion in a *feses* catchment is illustrated in Figure 4. TRA showed strong correlations with catchment slope gradient ($R = 0.54$, $N = 10$) and soil depth ($R = -0.46$, $N = 10$).

Table III. Total rill volume per hectare (TRA) (in $m^3 ha^{-1}$) and the total soil loss (in ton ha^{-1}) for the 10 cropland catchments (CA)

CA	TRA ($m^3 ha^{-1}$)	Total soil loss (ton ha^{-1})
1	0.99	1.58
2	0.17	0.25
3	0.20	0.32
4	0.57	0.89
5	4.01	6.53
6	1.65	2.56
7	7.08	11.68
8	8.34	12.10
9	1.09	1.67
10	13.19	19.66
Minimum	0.17	0.25
Maximum	13.19	19.66
Mean	3.73	5.72
Standard deviation	4.20	6.30

Runoff response for different land management systems

Runoff depth and runoff coefficients

Over CA 1 to CA 8, the Manning roughness coefficient rated by a team of geomorphologists ranged from 0.043 (CA 8) to 0.089 (CA 2) (Figure 5) and the mean *n* is 0.061 ± 0.017.

The calculated runoff depth for all measured daytime runoff events in the eight catchments are summarized in Table V. Average of the sum of daytime runoff for 15–31 July was 13.0 ± 17.1 mm, for 1–31 August 19.4 ± 12.0 mm and for 1–4 September 5.4 ± 7.9 mm for all study catchments around Wanzaye. Variations in runoff will be discussed by the variation in RCs. An example for the runoff events measured on 14 August is illustrated by hydrographs in Figure 6. Rainfall depth measured that day was 20.9 mm. For CA 6 and CA 7(2), data might not have been gathered from the beginning of the runoff event. Peak flow discharges for these runoff events ranged from 0.003 $m^3\ s^{-1}$ for CA 7(2) to 0.15 $m^3\ s^{-1}$ for CA 3.

RCs for all measured runoff events in the eight catchments are summarized in Table V. A minimum mean RC was found for CA 2 (5.1%) and a maximum for CA 3 (38.8%). The mean RC over all study areas is 21.7 ± 9.8%. Independent samples *t*-tests in SPSS show that RCs of CA 2 are significantly smaller than all other catchments. FD is found to be positively correlated with RC ($R = 0.48$, $N = 8$) in contrast with SBD which is negatively correlated with the RC ($R = -0.18$, $N = 8$).

Runoff hydrographs

A summary of the normalized peak flow discharge, kurtosis, VRT and QBT for all measured runoff events is presented in Table VI. For CA 1, 13 out of 14 events were not captured from the beginning, thus no statistics could be made for this catchment. The kurtosis for the individual hydrographs varied for different events and for different catchments. Contrasting values for kurtosis of the hydrographs for runoff events on 14 August are shown in Figure 6 where the maximum value in Figure 6 was found for CA 3 (3.76) and a minimum for CA 7(1) (−0.80).

High positive correlations are found between the three hydrograph peakedness measures: kurtosis, VRT and QBT (Table VII). The same trends are visible for these measures: hydrograph peakedness is negatively correlated with SBD and positively correlated with FD. Also for the normalized peak flow discharge the same tendency is found with SBD and FD (Table VII).

To understand the impact of *feses* and stone bunds on the erosion processes, a relation for kurtosis representing peakedness has been sought, as channel erosion and sediment transport will be higher when the peak runoff discharge increases (Simon and Rinaldi, 2006). Models where SBD and FD were used separately have a lower R^2 or are not significant respectively. Highest significance was found using a multiple regression for kurtosis (k):

$$k = -0.002\ \mathrm{FD}\ -\ 0.005\ \mathrm{SBD}\ +\ 1.80$$
$$\left(R^2\ =\ 0.826,\ N = 7, p = 0.03\right) \tag{4}$$

This regression is significant ($\alpha = 0.05$) and FD and SBD are explaining 83% of the kurtosis variability.

Discussion

Effect of surface drainage by *feses* and stone bunds on rill erosion

From the observations and the discussions with the farmers around Wanzaye, we understand that the establishment of *feses* consists of striking a balance between the *feses*' impact on erosion and their soil protecting effects. Farmers perceive
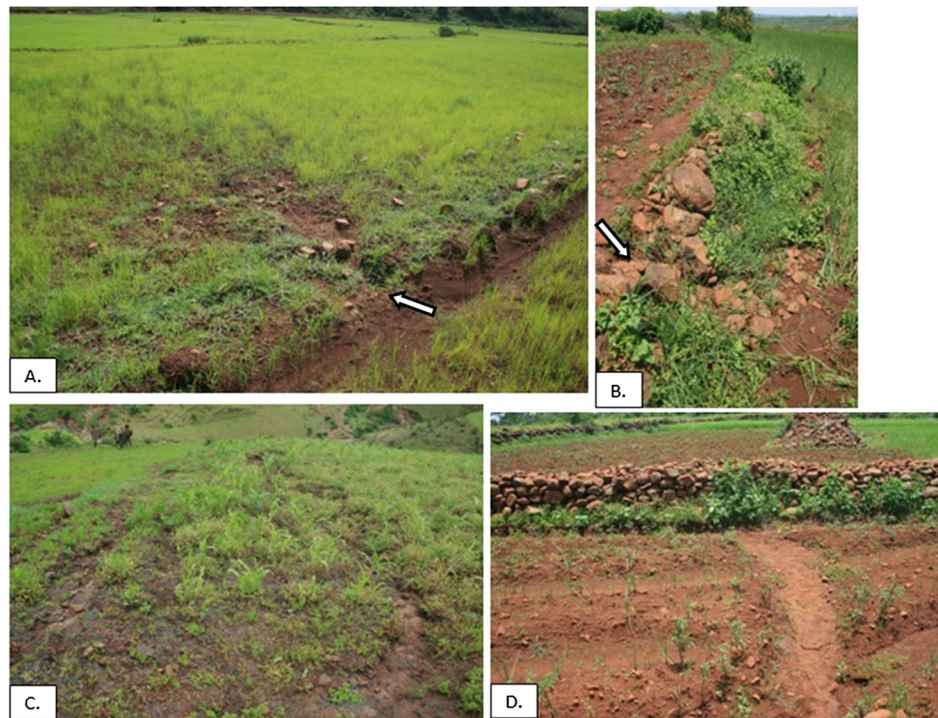
Figure 3. Rill formation originating from *feses* (A) or stone bund (B) overflow, and on a thin soil layer (C) or plough pan (D) around Wanzaye (Ethiopia). Overflow causing rill formation is indicated by an arrow. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table IV. Correlation (*R*) between total rill volume per area (TRA, in m^3 ha^{-1}) and stone bund density (SBD, in m ha^{-1}); *feses* density (FD, in m ha^{-1}); surface rock fragment cover (stone, %); soil depth (s_depth, in metres); dry soil bulk density (BD, in g cm^{-3}); catchment slope gradient (c_gradient, in m m^{-1}); angle between established *feses* and the contour (f_contour, in degrees); and *feses* gradient (f_gradient, in m m^{-1}). All correlations are based on 10 observations

	TRA
SBD	−0.50
FD	0.59
stone	0.26
s_depth	−0.46
BD	−0.25
c_gradient	0.54
f_contour	−0.53
f_gradient	−0.27

the construction of *feses* at a large angle with the contour as a mismanagement of the land as the *feses* are then eroded fast and become rills or even gullies. Whereas, a strong negative correlation was found between the angle of the constructed *feses* with the contour and the total rill erosion volume ha^{-1} (*R* = −0.53, *N* = 10; Table IV), implying that *feses* at a small angle with the contour induce more rill erosion volume due to overflowing water. This was also confirmed by the number of rills initiated by *feses*. We observed a strong positive correlation between the angle of the constructed *feses* with the contour and SBD (*R* = 0.75*, *N* = 10), whereas this correlation is highly negative for FD (*R* = −0.67*, *N* = 10). This implies that if SBD is higher, *feses* are constructed at a larger angle with the contour. In contrast, if the FD is higher, *feses* are constructed at a smaller angle with the contour. This may be due to the fact that stone bunds are perceived by farmers as a good SWC tool, and a high FD is estimated to be sufficient in runoff evacuation even at lower gradients.

A strong positive correlation between TRA and FD has been found (*R* = 0.59, *N* = 10; Table IV). By contrast, a negative correlation between TRA and SBD (*R* = −0.50, *N* = 10; Table IV) for the 10 studied cropland catchments was obtained. It shows a clear distinct trend for both SWC practices: *feses* cause larger rill volumes than stone bunds. This is confirmed by the fraction of rills initiated by *feses* (41%), which is higher than that for stone bunds (16%). Also farmers are aware of rill erosion, although they conclude that *feses* are still the best way to avoid soil erosion when no stone bunds are present.

The soil loss calculated for the study area (Table III) can only be compared with values for exclusively rill erosion in other studies, as our values would be underestimations compared to the total soil loss which also includes soil losses by interrill erosion. The TRA are low compared to those found by Bewket and Sterk (2003) on cultivated fields in the north-western highlands of Ethiopia. They measured 22.5 m^3 ha^{-1} rill volume for a catchment with gentle slopes and 55.5 m^3 ha^{-1} rill volume for a catchment with steep slopes whereas we measured a mean TRA of 3.73 ± 4.20 m^3 ha^{-1} (Table III). Zegeye *et al.* (2010) found an average soil loss by sheet and rill erosion of 27 ton ha^{-1} in the Debre Mewi watershed (part of the Lake Tana basin), while the maximum soil loss found around Wanzaye is 19.66 ton ha^{-1} by rill erosion only. More comparable values have been found by Awulachew *et al.* (2010) who conducted a Soil and Water Assessment Tool (SWAT) based runoff and sediment yield model analysis for the Gumara catchment. They produced a map of 18 sub-basins in the Gumara watershed for which the averaged sediment yields were presented ranging from 0 to 22 ton ha^{-1} yr^{-1}. Wanzaye is situated in a sub-basin producing on average 6 to 10 ton ha^{-1} yr^{-1}. Nyssen *et al.* (2008) found in the northern Ethiopian Highlands an averaged measured soil loss by sheet and rill erosion on cropland of 9.9 ± 13.2 ton ha^{-1} yr^{-1}, which is below the Ethiopian average, i.e. 42 ton ha^{-1} yr^{-1} (Hurni, 1990). This wide range of soil loss by rill erosion found in the Ethiopian Highlands originates from the site specific variables controlling the amount of rill erosion: e.g. surface rock fragment content (Nyssen *et al.*, 2001); SWC practices (Zegeye *et al.*, 2010, Taye *et al.*, 2013); depth and intensity of rain (Nyssen *et al.*,
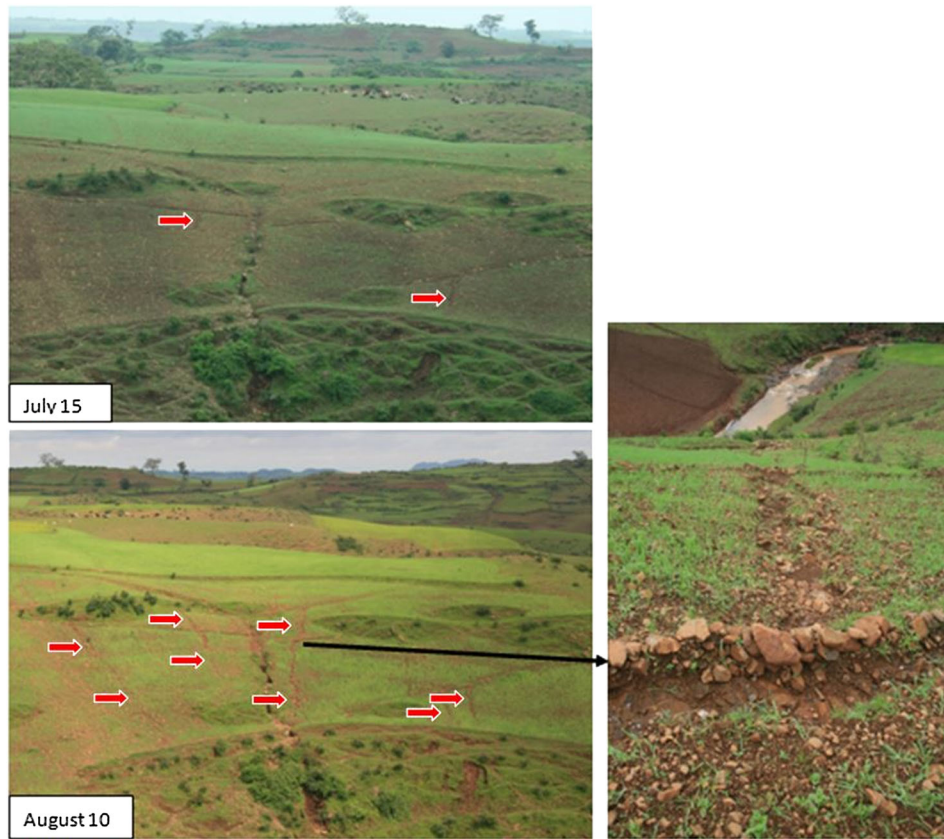
Figure 4. *Feses* catchment on 15 July 2013 (upper) when only two small rills are present (indicated with a red arrow). On 10 August 2013 (lower), several new rills have developed in this catchment. The farmer has restored the *feses* by removing sediment from the *feses* and by reconstructing the *feses'* edge with stones and soil (Wanzaye, Ethiopia). This figure is available in colour online at wileyonlinelibrary.com/journal/espl
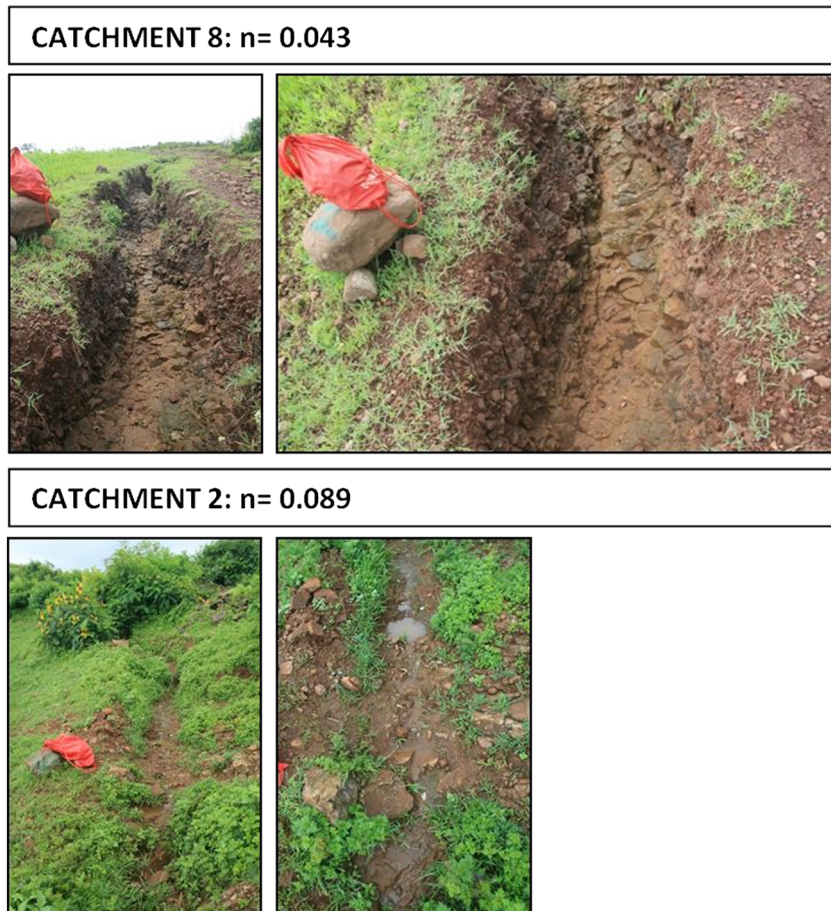

Figure 5. Illustration of minimum (CA 8) and maximum (CA 2) Manning roughness coefficient (*n*) among the eight study catchments around Wanzaye (Ethiopia). Left: oblique view; right: plan view of the main channel. Approximate dimensions (height × length) of the red bag are 50 cm × 25 cm. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table V. Total measured daytime runoff depth (DR) in summer 2013 around Wanzaye (Ethiopia) for (1) 15–31 July, (2) 1–31 August and (3) 1–4 September in the eight studied cropland catchments (CA). Mean event-based runoff coefficient (RC), and the statistics for each of these catchments are shown in the right part: number of observations (N), standard deviation (SD), minimum (Min) and maximum (Max) runoff coefficient

	DR (mm)							
	(1)	(2)	(3)	RC (%)	N	SD	Min	Max
CA 1	32.5	15.3	10.9	28.8	16	23.1	0.5	74.2
CA 2	1.4	5.0	0.4	5.1	16	4.1	0.2	13.7
CA 3	46.8	35.0	0.0	38.8	13	22.8	14.1	73.6
CA 4	4.9	14.1	4.6	19.2	13	9.3	4.5	39.6
CA 5	9.0	33.8	22.8	24.6	17	16.5	5.8	62.9
CA 6	0.4	14.5	1.1	17.6	11	16.3	2.3	59.0
CA 7	3.8	7.0	1.5	12.6	12	8.8	2.7	28.6
CA 8	4.8	30.6	2.1	27.0	12	25.9	1.1	82.8
Min	0.4	5.0	0.0	5.1				
Max	46.8	35.0	22.8	38.8				
Mean	13.0	19.4	5.4	21.7				
SD	17.1	12.0	7.9	9.8				

2005); soil types (Barthès and Roose, 2002); and geomorphology (Billi and Dramis, 2003). For the area around Wanzaye, we believe that two factors explain the relatively low soil loss by rill erosion: (1) a high surface rock fragment cover, and (2) the applied SWC practices which seem to have a positive effect on the rate of rill erosion. Besides the application of stone bunds in the study area, which is generally perceived as a good management tool for erosion control (Nyssen *et al.*, 2007), also *feses* are used as an indigenous practice for erosion control. Zegeye *et al.* (2010) conclude their research on soil erosion in the Lake Tana basin by stating that *feses* are 'generally effective and should be an integral part of any soil and water management practices proposed by soil conservation designers', p. 305. Hence, both SWC practices around Wanzaye (stone bunds and *feses*) are approved to be good tools against on-site soil erosion, yet a difference between both is emphasized further in this study.

Analysis of peak runoff response

An average RC of 59% has been estimated by Dessie *et al.* (2015) for the Gumara basin in 2012 and 2013. This is three times the mean RC we measured in 2013 (21.7 %) for the area
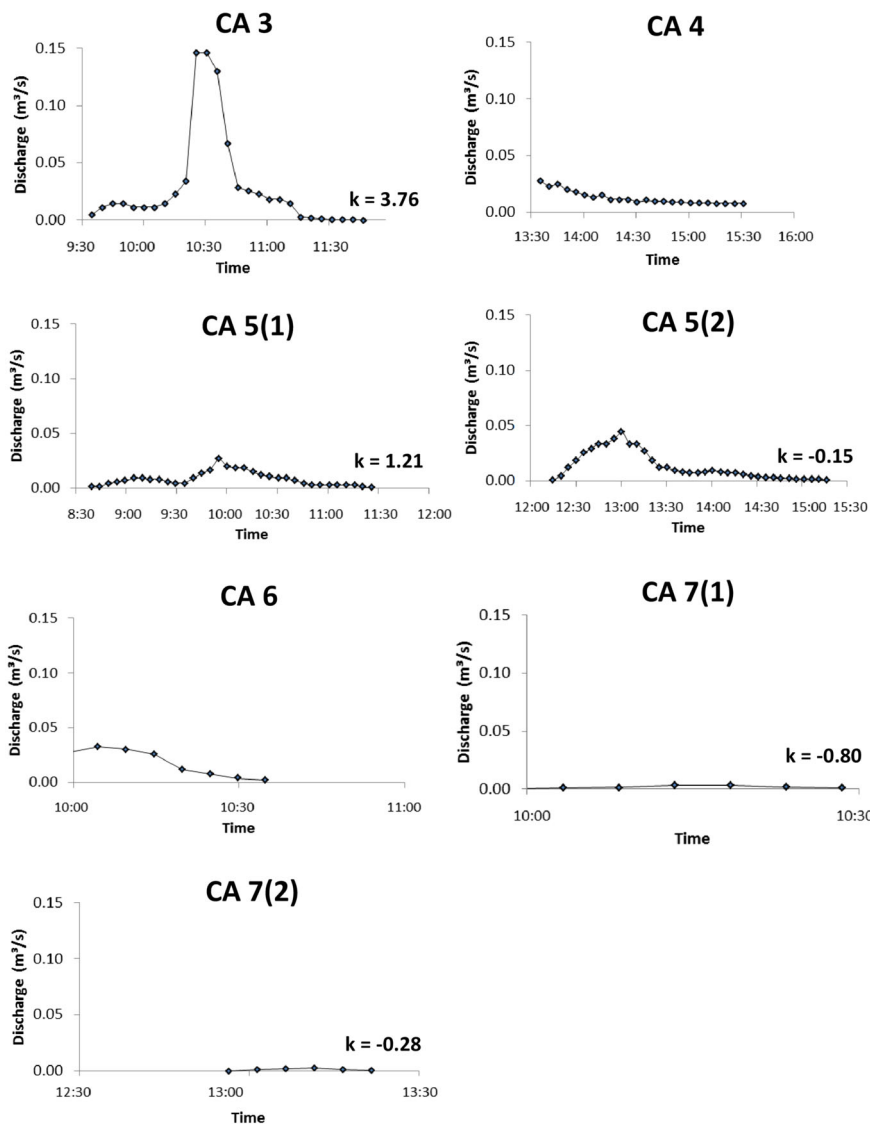

Figure 6. Hydrographs for runoff events measured at the outlets of study areas on 14 August around Wanzaye (Ethiopia). Values for the kurtosis (k) of the hydrograph is shown for events where rising and falling limb were captured.

Table VI. Mean normalized peak flow discharges (Q_p A^{-1}, in m s^{-1}) and hydrograph peakedness measures: kurtosis, velocity of rise time (VRT, in s^{-1}), and Q_p/base time (QBT, in m^3 s^{-1}) for eight subcatchments (CA) around Wanzaye (Ethiopia)

	Q_p A^{-1}	kurtosis	VRT	QBT
CA 1	3.10E-06			
CA 2	5.20E-07	−0.31	5.75E-11	0.020
CA 3	6.50E-06	1.24	3.02E-10	0.467
CA 4	6.34E-07	−0.62	1.89E-11	0.015
CA 5	1.38E-06	−0.36	8.62E-10	0.014
CA 6	1.09E-06	0.88	7.17E-10	0.017
CA 7	6.13E-07	−0.59	5.15E-11	0.008
CA 8	1.58E-06	0.13	6.00E-11	0.008

Table VII. Correlation (R) matrix for stone bund density (SBD), *feses* density (FD), kurtosis, velocity of rise time (VRT), Q_p over base time (QBT), and the normalized peak flow discharge (Q_p A^{-1}). All correlations are based on seven observations

	SBD	FD	kurtosis	VRT	QBT
Q_p A^{-1}	−0.47	0.26	0.76*	0.98*	0.98*
SBD		−0.61	−0.67	−0.54	−0.50
FD			0.52	0.29	0.13
kurtosis				0.76*	0.71
VRT					0.98*

*Significant at $\alpha = 0.05$.

around Wanzaye which constitutes the Gumara basin. Different variables explain this discrepancy. First of all, measurements around Wanzaye are event-based during the day. Night-time runoff and continuous baseflow were not measured. When cumulated in time, this slow percolating subsurface water can produce an important volume of runoff that we did not incorporate in our analyses. Our results support the model results of Dessie *et al.* (2014), which indicate that for the Gumara basin the direct runoff accounts for 18 to 19% of the total runoff. Also the moment of measuring (i.e. study period falls in an average dry or wet year) matters, as the rainfall conditions (intensity) have an important role concerning runoff generation (Descheemaeker *et al.*, 2006). The mean RC for the study area around Wanzaye was also influenced by the local slope gradients, soil texture, land use, vegetation cover, organic matter and rock fragment cover (Feleke, 1987; Mwendera and Mohammed, 1997), which may explain the lower-than-expected mean RC.

SWC activities that have taken place over the last decades lowered the RCs in Ethiopia (Nyssen *et al.*, 2010a; Haregeweyn *et al.*, 2015). This is also reflected by the RC for CA 2 which comprises exclusively stone bunds (448 m ha^{-1}), resulting in a significantly smaller RC (5.1%, Table V) than that for the other catchments. Yet, when stone bunds are combined with drainage ditches, the RC will be higher as observed for CA 8 with a mean RC of 27.0%, SBD of 626 m ha^{-1} and FD of 188 m ha^{-1}. Although no significant correlation could be found, it seems that a combination of low SBD and high FD results in a higher RC, whereas catchments with a high SBD and low FD have a lower RC. The positive correlation between the RC and FD indicates that the use of *feses* induces a higher runoff response.

From the data around Wanzaye, two distinct trends are observed. First of all, hydrograph peakedness decreases when SBD increases. This is an evident result as stone bunds have proven their efficiency in capturing and temporarily storing

runoff water in a catchment (e.g. Herweg and Ludi, 1999; Gebremichael *et al.*, 2005; Nyssen *et al.*, 2007; Taye *et al.*, 2013). Conversely, a higher FD results in a higher hydrograph peakedness, which is similar to the natural drainage network (Horton 1932, 1945; Chorley and Morgan, 1962; Gregory and Walling, 1968). Thus we could not confirm the positive effect of the use of drainage ditches on soil water storage capacity as mentioned by, for example, Horton (1945), Thomasson (1975), and Wilkinson *et al.* (2010). The best model explaining kurtosis of the runoff hydrographs was a multiple regression equation where SBD and FD explain 83% of its variability (Equation (4)). So by incorporating information of both land management techniques, their effects on the runoff peakedness is best described. Improper land management and hence soil erosion driven by high peak flows can be mitigated whilst an adapted management system is designed taking SBD and FD into account.

Conclusion

During the rainy season of 2013, the on-site impact of drainage ditches (*feses*) and stone bunds on rill erosion and runoff characteristics have been measured around Wanzaye (north Ethiopia). We found that the establishment of *feses* is the result of a balance that the farmers make between the *feses'* impact on erosion and their soil protecting effect. Stone bunds are an effective SWC technique, which allows *feses* to be constructed at a greater angle with the contour. On-site rill erosion is larger when *feses* are present, although *feses* are perceived as the best way to avoid soil erosion when no stone bunds are present. Mean area-specific volume of rills in the study area equals 3.7 ± 4.2 m^3 ha^{-1}, corresponding to 5.7 ± 6.3 ton ha^{-1} of soil loss. The use of *feses* increases event-based RCs on cropland from *c.* 5% to values up to 39%. Also, a combination of low SBD and high FD results in a higher RC, whereas catchments with a high SBD and low FD have a lower RC. Peak flow discharge decreases when SBD increases, whereas the opposite is found for FD. A multiple linear relation of both land management techniques (*feses* and stone bunds) performs best in explaining the variability of runoff peakedness ($R^2 = 83$%). Soil erosion driven by high peak flows can be mitigated whilst a management system is designed taking SBD and FD into account.

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